Shop & Trades

First edition | 10 units | 50 lessons | A video for every lesson

FIRST EDITION

Course guide

This course teaches the practical arts that keep a household running and a country built: fasteners and adhesives, woodworking, home construction, home electrical work, heating and air conditioning, welding, 3D printing, small engines and automobiles. Each of the ten units takes one trade, tells the true story of how it came to be, explains the physics and chemistry underneath it, and then puts tools in the student's hands for a real shop project: a fastener pull-out test, a glue-strength test, a step stool, a framed wall, a practice electrical board, a home HVAC inspection, a weld-joint test, a printed part, a mower tune-up and a full vehicle inspection.

Every lesson follows the same path. **The story** is a real moment: Henry Maudslay's screw-cutting lathe, Harry Coover's accidental super glue, the balloon frames of 1830s Chicago, Edison's Pearl Street station, Willis Carrier at the Brooklyn printing plant, the Liberty ships, Chuck Hull's first printed part, Nikolaus Otto's four-stroke engine and Charles Kettering's self-starter. Then **how they figured it out**, then **the science** with worked examples (torque and clamp force, board feet, R-values, Ohm's law and breaker loads, tons of cooling, weld heat input, compression ratios and brake hydraulics), and finally **in the shop**: how a skilled tradesperson actually does the job, and where the homeowner's work ends and the licensed professional's begins.

Safety is taught as part of the craft, not as an afterthought. Students learn live–dead–live testing on an unpowered practice board, why a mower's spark-plug wire comes off before the blade is touched, why nobody works under a car held only by a jack, and why refrigerant and gas lines belong to licensed technicians. Along the way they meet the trades as honorable vocations, from Bezalel, "filled with the spirit of God … in all manner of workmanship," to the carpenter of Nazareth. *Fabricando fit faber*: by making, one becomes a maker.

> Videos were chosen lesson by lesson from trusted teaching sources and working tradespeople with clean channels: The Engineering

> Mindset, Practical Engineering, Engineering Explained, Animagraffs, This Old House, Essential Craftsman, Paul Sellers and other woodworkers, Lincoln Electric and other welding educators, CNC Kitchen and Prusa Research for 3D printing, ChrisFix for cars, and others. Every video was checked in preview for content and safe practice. Some open with a sponsor message; skip it. A video shows how a professional does a job; it is never permission to do that job without the supervision and safety steps in the lesson.

Start with Lesson 1.1 →

Who it is for

Written for students in grades 9–12 who have completed Algebra I. Students work fairly independently, with a parent or mentor who checks calculations and is present for every project that involves power tools, heat, fuel, vehicles or household electricity. No welder, 3D printer or car lift is required: each lesson gives an alternative (a library makerspace, a community-college open lab, a shop teacher or a tradesperson mentor). A basic homeowner's tool set, a multimeter and the hardware-store materials listed below cover nearly every project.

How to use this course

1. **The weekly rhythm.** The course has 50 lessons in ten units, each taught in three sessions of about 50 minutes: (1) the video, the story and core ideas, and the worked examples; (2) the shop project and shop notebook; (3) the practice set and corrections. After each unit comes a test day; review days and exams follow Units 5 and 10. At five sessions a week the course fills about 33 weeks.
2. **Story, science, shop.** Read the core ideas carefully, then close the page and explain to a parent what problem the inventors faced, what they learned and how the trade does it today. Work every worked example on paper before looking at the steps.
3. **Safety first, every time.** Read the lesson's safety note aloud with the supervising adult before starting the shop project, and set out the protective gear before the tools. If a step calls for an adult, wait for one. If you are not sure a circuit is dead, it is live.
4. **Practice sets and corrections.** Each lesson has 8–12 practice problems from easy to challenge, with answers, including diagnosis questions where you play the

tradesperson. Do them without looking, check, and rework every miss in the correction session.

5. **Picture study.** Each lesson has one public-domain picture: an engraving of an 18th-century workshop, a patent drawing, a historic photograph of riveters, welders or mechanics, or a painting of a forge. Look at it quietly for two minutes, put it away, describe what you saw, then answer the questions about how the work was done.
6. **The shop notebook.** Keep one notebook for the year: sketches, wiring diagrams, data tables, diagnostic flowcharts, measurements and maintenance logs. Tradespeople who write things down make fewer mistakes and get called back.
7. **Unit tests, midterm and final.** Each unit ends with a 100-point test with an answer key. The midterm covers Units 1–5 and the final covers the whole year.
8. **Mentors and field trips.** Wherever you can, invite a tradesperson to show you their work: an electrician, an HVAC technician, a welder, a carpenter, a small-engine shop or a mechanic. Most are glad to teach a serious student, and many apprenticeships begin with such a conversation.

Scope and Sequence

UNIT 1 · WEEKS 1–4

The Science of Attaching: Screws, Bolts and Fasteners

Screws, bolts, nails and rivets: thread standards from Maudslay to ISO metric, torque and clamp force, bolt grades and how connections fail.

1.1 The Screw: From Archimedes to Maudslay's Lathe

1.2 Screws versus Bolts: Thread Anatomy and Standards

1.3 Torque, Preload and Clamp Force

1.4 Bolt Grades, Strength and Failure

1.5 Nails, Rivets, Pins and Choosing a Fastener

UNIT 2 · WEEKS 4–7

Adhesives: The Chemistry of Sticking

How glue holds: adhesion and cohesion, wood glues, epoxy, super glue and hot melt, and when to glue, fasten or both.

2.1 How Glue Works

2.2 Wood Glues: Hide Glue to PVA

2.3 Epoxy and Two-Part Chemistry

2.4 Super Glue, Hot Melt, Contact Cement and Construction Adhesives

2.5 Choosing the Joint: Glue, Fasteners or Both

UNIT 3 · WEEKS 7–10

Woodworking

Wood as a material, hand tools and sharpening, power-tool safety, joinery and finishing, ending with a finished step stool or toolbox.

3.1 Wood as a Material: Cells, Grain and Movement

3.2 Measuring, Marking and Hand Tools

3.3 Power Tools and Shop Safety

3.4 Joinery: Fitly Joined Together

3.5 Finishing and a Finished Piece: The Step Stool

UNIT 4 · WEEKS 10–13

Home Construction

How a house is built: foundations, framing, roofs and the building envelope, insulation, plumbing, drywall, codes and permits.

4.1 Foundations: Building upon the Rock

4.2 Framing: From the Balloon Frame to the Platform

4.3 Roofs and the Building Envelope: Shedding Water

4.4 Insulation, Air and Moisture

4.5 Plumbing, Drywall, Codes and Permits

UNIT 5 · WEEKS 13–17

Basic Home Electrical

Household electricity from the power plant to the receptacle: circuits, wire and breakers, shock and GFCIs, live–dead–live testing, and when to call an electrician.

5.1 From Power Plant to Panel

5.2 Circuits, Wire and Breakers

5.3 Shock, Grounding, GFCI and AFCI

5.4 Working Safely: Switches and Receptacles

5.5 Lighting, Codes and When to Call an Electrician

UNIT 6 · WEEKS 17–20

HVAC: Heating, Cooling and Air

Heating, ventilation and air conditioning: heat and humidity, furnaces and combustion safety, the refrigeration cycle, heat pumps, air flow and maintenance.

6.1 Heat, Humidity and Comfort

6.2 Furnaces, Boilers and Combustion Safety

6.3 The Refrigeration Cycle

6.4 Heat Pumps and Efficiency

6.5 Air Flow, Ducts, Filters and Maintenance

UNIT 7 · WEEKS 20–23

Welding: Science and Uses

The science of welding: from the forge weld to the electric arc, the weld pool and the heat-affected zone, the main processes, joints and defects, and welding as a career.

7.1 Joining Metal: Forge Welding to the Electric Arc

7.2 The Science of the Arc and the Weld Pool

7.3 Welding Processes: Stick, MIG, Flux-Core, TIG, Oxy-Fuel and Spot

7.4 Joints, Strength, Distortion and Defects

7.5 Welding Safety, Uses and Careers

UNIT 8 · WEEKS 23–26

3D Printing

3D printing: its inventors, how an FDM printer works, CAD and slicing, designing for strength and fit, and materials and real-world uses.

8.1 From Stereolithography to RepRap: How 3D Printing Began

8.2 How an FDM Printer Works

8.3 From CAD to Slicer

8.4 Designing for Printing: Strength and Tolerances

8.5 Materials and Real-World Uses

UNIT 9 · WEEKS 27–30

Small Engines

Small engines: the four-stroke and two-stroke cycles, fuel and the carburetor, ignition and compression, and a full mower tune-up and diagnosis.

9.1 The Four-Stroke Cycle

9.2 Two-Stroke Engines

9.3 Fuel, Air and the Carburetor

9.4 Ignition, Compression and the Governor

9.5 Maintenance and Troubleshooting

UNIT 10 · WEEKS 30–33

Auto Mechanics

Auto mechanics: how a car works, fluids, brakes, tires and steering, the electrical system and diagnostics, and routine maintenance and roadside skills.

10.1 How a Car Works: From the Model T to Today

10.2 The Engine and Its Fluids

10.3 Brakes, Tires and Steering

10.4 The Electrical System and Diagnostics

10.5 Routine Maintenance and Roadside Skills

Weekly pacing calendar

WEEK	PLAN
1	• Day 1: Lesson 1.1 The Screw: From Archimedes to Maudslay's Lathe: video, teaching and worked examples • Day 2: Lesson 1.1: shop project and notebook • Day 3: Lesson 1.1: practice set and corrections

WEEK	PLAN
	• Day 4: Lesson 1.2 Screws versus Bolts: Thread Anatomy and Standards: video, teaching and worked examples • Day 5: Lesson 1.2: shop project and notebook *Five sessions a week of about 50 minutes. Families on a four-day week can combine the practice day of one lesson with the teaching day of the next.*
2	• Day 1: Lesson 1.2: practice set and corrections • Day 2: Lesson 1.3 Torque, Preload and Clamp Force: video, teaching and worked examples • Day 3: Lesson 1.3: shop project and notebook • Day 4: Lesson 1.3: practice set and corrections • Day 5: Lesson 1.4 Bolt Grades, Strength and Failure: video, teaching and worked examples
3	• Day 1: Lesson 1.4: shop project and notebook • Day 2: Lesson 1.4: practice set and corrections • Day 3: Lesson 1.5 Nails, Rivets, Pins and Choosing a Fastener: video, teaching and worked examples • Day 4: Lesson 1.5: shop project and notebook • Day 5: Lesson 1.5: practice set and corrections
4	• Day 1: Unit 1 test • Day 2: Lesson 2.1 How Glue Works: video, teaching and worked examples • Day 3: Lesson 2.1: shop project and notebook • Day 4: Lesson 2.1: practice set and corrections • Day 5: Lesson 2.2 Wood Glues: Hide Glue to PVA: video, teaching and worked examples
5	• Day 1: Lesson 2.2: shop project and notebook • Day 2: Lesson 2.2: practice set and corrections • Day 3: Lesson 2.3 Epoxy and Two-Part Chemistry: video, teaching and worked examples • Day 4: Lesson 2.3: shop project and notebook • Day 5: Lesson 2.3: practice set and corrections
6	• Day 1: Lesson 2.4 Super Glue, Hot Melt, Contact Cement and Construction Adhesives: video, teaching and worked examples • Day 2: Lesson 2.4: shop project and notebook • Day 3: Lesson 2.4: practice set and corrections

WEEK	PLAN
	• Day 4: Lesson 2.5 Choosing the Joint: Glue, Fasteners or Both: video, teaching and worked examples • Day 5: Lesson 2.5: shop project and notebook
7	• Day 1: Lesson 2.5: practice set and corrections • Day 2: Unit 2 test • Day 3: Lesson 3.1 Wood as a Material: Cells, Grain and Movement: video, teaching and worked examples • Day 4: Lesson 3.1: shop project and notebook • Day 5: Lesson 3.1: practice set and corrections
8	• Day 1: Lesson 3.2 Measuring, Marking and Hand Tools: video, teaching and worked examples • Day 2: Lesson 3.2: shop project and notebook • Day 3: Lesson 3.2: practice set and corrections • Day 4: Lesson 3.3 Power Tools and Shop Safety: video, teaching and worked examples • Day 5: Lesson 3.3: shop project and notebook
9	• Day 1: Lesson 3.3: practice set and corrections • Day 2: Lesson 3.4 Joinery: Fitly Joined Together: video, teaching and worked examples • Day 3: Lesson 3.4: shop project and notebook • Day 4: Lesson 3.4: practice set and corrections • Day 5: Lesson 3.5 Finishing and a Finished Piece: The Step Stool: video, teaching and worked examples
10	• Day 1: Lesson 3.5: shop project and notebook • Day 2: Lesson 3.5: practice set and corrections • Day 3: Unit 3 test • Day 4: Lesson 4.1 Foundations: Building upon the Rock: video, teaching and worked examples • Day 5: Lesson 4.1: shop project and notebook
11	• Day 1: Lesson 4.1: practice set and corrections • Day 2: Lesson 4.2 Framing: From the Balloon Frame to the Platform: video, teaching and worked examples • Day 3: Lesson 4.2: shop project and notebook • Day 4: Lesson 4.2: practice set and corrections

WEEK	PLAN
	• Day 5: Lesson 4.3 Roofs and the Building Envelope: Shedding Water: video, teaching and worked examples
12	• Day 1: Lesson 4.3: shop project and notebook • Day 2: Lesson 4.3: practice set and corrections • Day 3: Lesson 4.4 Insulation, Air and Moisture: video, teaching and worked examples • Day 4: Lesson 4.4: shop project and notebook • Day 5: Lesson 4.4: practice set and corrections
13	• Day 1: Lesson 4.5 Plumbing, Drywall, Codes and Permits: video, teaching and worked examples • Day 2: Lesson 4.5: shop project and notebook • Day 3: Lesson 4.5: practice set and corrections • Day 4: Unit 4 test • Day 5: Lesson 5.1 From Power Plant to Panel: video, teaching and worked examples
14	• Day 1: Lesson 5.1: shop project and notebook • Day 2: Lesson 5.1: practice set and corrections • Day 3: Lesson 5.2 Circuits, Wire and Breakers: video, teaching and worked examples • Day 4: Lesson 5.2: shop project and notebook • Day 5: Lesson 5.2: practice set and corrections
15	• Day 1: Lesson 5.3 Shock, Grounding, GFCI and AFCI: video, teaching and worked examples • Day 2: Lesson 5.3: shop project and notebook • Day 3: Lesson 5.3: practice set and corrections • Day 4: Lesson 5.4 Working Safely: Switches and Receptacles: video, teaching and worked examples • Day 5: Lesson 5.4: shop project and notebook
16	• Day 1: Lesson 5.4: practice set and corrections • Day 2: Lesson 5.5 Lighting, Codes and When to Call an Electrician: video, teaching and worked examples • Day 3: Lesson 5.5: shop project and notebook • Day 4: Lesson 5.5: practice set and corrections • Day 5: Unit 5 test
17	• Day 1: Review day for the midterm

WEEK	PLAN
	• Day 2: Midterm exam • Day 3: Lesson 6.1 Heat, Humidity and Comfort: video, teaching and worked examples • Day 4: Lesson 6.1: shop project and notebook • Day 5: Lesson 6.1: practice set and corrections
18	• Day 1: Lesson 6.2 Furnaces, Boilers and Combustion Safety: video, teaching and worked examples • Day 2: Lesson 6.2: shop project and notebook • Day 3: Lesson 6.2: practice set and corrections • Day 4: Lesson 6.3 The Refrigeration Cycle: video, teaching and worked examples • Day 5: Lesson 6.3: shop project and notebook
19	• Day 1: Lesson 6.3: practice set and corrections • Day 2: Lesson 6.4 Heat Pumps and Efficiency: video, teaching and worked examples • Day 3: Lesson 6.4: shop project and notebook • Day 4: Lesson 6.4: practice set and corrections • Day 5: Lesson 6.5 Air Flow, Ducts, Filters and Maintenance: video, teaching and worked examples
20	• Day 1: Lesson 6.5: shop project and notebook • Day 2: Lesson 6.5: practice set and corrections • Day 3: Unit 6 test • Day 4: Lesson 7.1 Joining Metal: Forge Welding to the Electric Arc: video, teaching and worked examples • Day 5: Lesson 7.1: shop project and notebook
21	• Day 1: Lesson 7.1: practice set and corrections • Day 2: Lesson 7.2 The Science of the Arc and the Weld Pool: video, teaching and worked examples • Day 3: Lesson 7.2: shop project and notebook • Day 4: Lesson 7.2: practice set and corrections • Day 5: Lesson 7.3 Welding Processes: Stick, MIG, Flux-Core, TIG, Oxy-Fuel and Spot: video, teaching and worked examples
22	• Day 1: Lesson 7.3: shop project and notebook • Day 2: Lesson 7.3: practice set and corrections • Day 3: Lesson 7.4 Joints, Strength, Distortion and Defects: video, teaching and worked examples

WEEK	PLAN
	• Day 4: Lesson 7.4: shop project and notebook • Day 5: Lesson 7.4: practice set and corrections
23	• Day 1: Lesson 7.5 Welding Safety, Uses and Careers: video, teaching and worked examples • Day 2: Lesson 7.5: shop project and notebook • Day 3: Lesson 7.5: practice set and corrections • Day 4: Unit 7 test • Day 5: Lesson 8.1 From Stereolithography to RepRap: How 3D Printing Began: video, teaching and worked examples
24	• Day 1: Lesson 8.1: shop project and notebook • Day 2: Lesson 8.1: practice set and corrections • Day 3: Lesson 8.2 How an FDM Printer Works: video, teaching and worked examples • Day 4: Lesson 8.2: shop project and notebook • Day 5: Lesson 8.2: practice set and corrections
25	• Day 1: Lesson 8.3 From CAD to Slicer: video, teaching and worked examples • Day 2: Lesson 8.3: shop project and notebook • Day 3: Lesson 8.3: practice set and corrections • Day 4: Lesson 8.4 Designing for Printing: Strength and Tolerances: video, teaching and worked examples • Day 5: Lesson 8.4: shop project and notebook
26	• Day 1: Lesson 8.4: practice set and corrections • Day 2: Lesson 8.5 Materials and Real-World Uses: video, teaching and worked examples • Day 3: Lesson 8.5: shop project and notebook • Day 4: Lesson 8.5: practice set and corrections • Day 5: Unit 8 test
27	• Day 1: Lesson 9.1 The Four-Stroke Cycle: video, teaching and worked examples • Day 2: Lesson 9.1: shop project and notebook • Day 3: Lesson 9.1: practice set and corrections • Day 4: Lesson 9.2 Two-Stroke Engines: video, teaching and worked examples • Day 5: Lesson 9.2: shop project and notebook
28	• Day 1: Lesson 9.2: practice set and corrections • Day 2: Lesson 9.3 Fuel, Air and the Carburetor: video, teaching and worked examples

WEEK	PLAN
	• Day 3: Lesson 9.3: shop project and notebook • Day 4: Lesson 9.3: practice set and corrections • Day 5: Lesson 9.4 Ignition, Compression and the Governor: video, teaching and worked examples
29	• Day 1: Lesson 9.4: shop project and notebook • Day 2: Lesson 9.4: practice set and corrections • Day 3: Lesson 9.5 Maintenance and Troubleshooting: video, teaching and worked examples • Day 4: Lesson 9.5: shop project and notebook • Day 5: Lesson 9.5: practice set and corrections
30	• Day 1: Unit 9 test • Day 2: Lesson 10.1 How a Car Works: From the Model T to Today: video, teaching and worked examples • Day 3: Lesson 10.1: shop project and notebook • Day 4: Lesson 10.1: practice set and corrections • Day 5: Lesson 10.2 The Engine and Its Fluids: video, teaching and worked examples
31	• Day 1: Lesson 10.2: shop project and notebook • Day 2: Lesson 10.2: practice set and corrections • Day 3: Lesson 10.3 Brakes, Tires and Steering: video, teaching and worked examples • Day 4: Lesson 10.3: shop project and notebook • Day 5: Lesson 10.3: practice set and corrections
32	• Day 1: Lesson 10.4 The Electrical System and Diagnostics: video, teaching and worked examples • Day 2: Lesson 10.4: shop project and notebook • Day 3: Lesson 10.4: practice set and corrections • Day 4: Lesson 10.5 Routine Maintenance and Roadside Skills: video, teaching and worked examples • Day 5: Lesson 10.5: shop project and notebook
33	• Day 1: Lesson 10.5: practice set and corrections • Day 2: Unit 10 test • Day 3: Review day for the final • Day 4: Final exam

Materials

Shop notebook (graph-paper composition book) and a scientific calculator

For sketches, diagrams, data tables, calculations with units and maintenance logs, all year.

Safety glasses (ANSI Z87.1), hearing protection, work gloves, nitrile gloves and a dust mask

Required for every shop project that involves tools, chemicals, heat or engines.

Basic hand tools: tape measure, combination square, claw hammer, screwdrivers (slotted, Phillips, square), adjustable wrench, a socket set, pliers, utility knife, a handsaw and a chisel

The homeowner's tool kit; used in nearly every unit.

Cordless drill/driver with bits

Woodworking, fastener tests and construction projects.

A digital multimeter, a non-contact voltage tester and a plug-in receptacle tester

For Unit 5 and the car battery in Unit 10.

Practice electrical board: a plywood scrap, a plastic electrical box, a single-pole switch, a 15 A receptacle, cover plates, about 6 feet of 14/2 NM cable, wire nuts and a wire stripper

Unit 5. It is never plugged in or connected to any power source.

Assorted fasteners and adhesives: wood and machine screws, bolts, nuts and washers, nails, a few pop rivets; wood glue, epoxy, cyanoacrylate, a low-temperature hot-glue gun and construction adhesive

Units 1 and 2 tests.

Lumber: a few 2×4s, 1×4 or 1×6 pine boards, and some scrap plywood; sandpaper and a wood finish

Units 3 and 4 builds.

A luggage scale or hanging scale, a bucket and sand or water for loads, clamps

Pull-out and glue-strength tests.

Free CAD software: Tinkercad or Onshape (a parent sets up the account)

Unit 8. A 3D printer is optional; a library makerspace or an online print service works.

Access to a gasoline lawn mower or other small engine, a spark-plug socket, feeler gauge, fresh oil and an air filter

Unit 9 tune-up. A family or neighbor's mower is ideal.

Access to a family car, its owner's manual, a tire-pressure gauge, a tread-depth gauge (or a penny), jack stands and wheel chocks

Unit 10 inspections and roadside skills, always with an adult.

Optional: a propane torch, a fire extinguisher and a non-flammable work surface

For adult-supervised heat-treating and copper-pipe soldering in Unit 7.

Grading

Grades come from practice sets, shop projects, the shop notebook, unit tests, the midterm and the final. A calculation earns full credit when the formula, the substitution with units and the answer with its unit are all shown. A shop project earns full credit when it is done safely, measured honestly, recorded and checked.

PART	%
Practice sets and corrections	**15**
Shop projects (safe practice, measurement, finished work)	**25**
Shop notebook	**10**
Unit tests	**30**
Midterm exam	**10**
Final exam	**10**

Scale: A 90–100, B 80–89, C 70–79, D 60–69. Below 60: review and retake the test or redo the project with help.

- Grade practice sets on completion and corrections: every missed problem reworked correctly earns back its credit.
- In tests, give partial credit for a correct setup with units even if the arithmetic slips.
- Safety is part of the grade: a project done without the required protective gear or supervision earns no credit until it is redone properly.

- Keep each unit's portfolio project (reports, photos, logs and the finished pieces) in one folder; together they make a strong transcript portfolio.
- For a transcript, this course is a full-year, one-credit elective in career and technical education, industrial arts or applied technology.

A NOTE TO PARENTS

You do not need to be a tradesperson to guide this course. Read the story with your student, ask them to explain the science back to you, check that every calculation has units, and above all be the safety officer: you are present for every project with power tools, heat, fuel, a vehicle or household electricity, and you hold the line on safety glasses and on the steps the lesson says need an adult.

The course is deliberately honest about limits. Students learn to replace a receptacle on a practice board and to change a furnace filter, but not to open an electrical panel or a refrigerant line; they learn the science of welding but weld only in a supervised shop. That is how the trades themselves work: apprentices learn under a master before they work alone. If your student catches the spark, look for a shop class, a community-college course, a 4-H or FFA project, or a tradesperson in your church willing to take on a helper for a summer.

Throughout, the course treats skilled work as a vocation of service. Bezalel was filled with the Spirit for craftsmanship, and our Lord worked as a carpenter. A furnace that runs safely, wiring that will not start a fire and brakes that stop a car are ways of loving our neighbors. *Fabricando fit faber*: by making, one becomes a maker.

UNIT 1

The Science of Attaching: Screws, Bolts and Fasteners

Everything in a house, a car or a shop is held together by something. In this unit you will learn the science behind the humble screw thread, the difference between screws and bolts, how a tightened bolt works as a stretched spring, how strong bolts of each grade are and how they fail, and when to choose a nail, a rivet, a pin or an anchor instead.

The stories are of craftsmen and engineers who changed how the world fastens things: Henry Maudslay and his screw-cutting lathe, Whitworth and Sellers and their thread standards, P. L. Robertson and Henry Phillips and their screw drives, Gerhard Junker and his loosening machine, the riveting gangs of the Eiffel Tower and the Empire State Building, and the sobering lesson of the Hyatt Regency walkways. You will measure threads, calculate torque and preload, test locking methods, load-test model connections, and pull nails and screws out of wood with a bucket of sand.

PREREQUISITES

- Algebra I: solving formulas for one variable, squares and square roots, scientific notation
- Area of a circle, $A = \frac{\pi}{4}d^2$, and unit conversions (inches and millimeters, pounds and newtons)
- Basic hand tools: a tape measure, a drill/driver and a hammer, used with safety glasses

MASTERY CHECKLIST

- ☐ I can explain the screw as an inclined plane and calculate pitch, lead, helix angle and mechanical advantage.
- ☐ I can read inch and metric thread callouts, tell a screw from a bolt by its use, and choose drive types, pilot holes and thread engagement.
- ☐ I can use $T = K D F$ to relate torque and preload, explain why bolts loosen, and tighten a wheel correctly.
- ☐ I can identify bolt grades and property classes and calculate tensile, proof and shear capacities.
- ☐ I can explain galvanic corrosion and the Hyatt Regency connection failure.
- ☐ I can calculate nail and screw withdrawal, explain riveting, and choose the right fastener for a job.

OPTIONAL KITS FOR THIS UNIT

- **Portland Bolt technical guides**: A bolt manufacturer's free technical library: thread pitch charts, grade and head-marking guides, tensile and proof strengths, and torque information; useful for Lessons 1.2–1.4. No purchase needed.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

1.1	**The Screw: From Archimedes to Maudslay's Lathe**	3 sessions of 50 minutes
1.2	**Screws versus Bolts: Thread Anatomy and Standards**	3 sessions of 50 minutes

1.3	**Torque, Preload and Clamp Force**	3 sessions of 50 minutes
1.4	**Bolt Grades, Strength and Failure**	3 sessions of 50 minutes
1.5	**Nails, Rivets, Pins and Choosing a Fastener**	3 sessions of 50 minutes

Unit 1 Test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. Use $A_t = 0.7854(D - 0.9743/n)^2$ where needed. The test is worth 100 points.

1. **5 pts**
   Find the pitch of a 5/16-18 thread in inches and millimeters.

2. **6 pts**
   A screw jack has a 4.0 mm lead and a 0.20 m handle. Find its ideal mechanical advantage. If it is 30% efficient, what force on the handle lifts 6,000 N?

3. **5 pts**
   What did Maudslay's screw-cutting lathe make possible, and why were Whitworth's and Sellers's standards needed afterward?

4. **5 pts**
   Define screw and bolt by their intended use. Which is a lag screw?

5. **5 pts**
   Decode "#10-32 × 3/4" and give the major diameter.

6. **8 pts**
   Find the dry torque ($K = 0.20$) to preload a 3/8-16 Grade 5 bolt to 75% of its proof load (proof strength 85,000 psi).

7. **6 pts**
   Explain what happens if the bolt in the last problem is oiled ($K = 0.15$) but tightened to the same torque.

8. **6 pts**

   Describe Junker's test and its main finding. Name two locking methods that work and one that does not.

9. **6 pts**

   A steel bolt ($A = 0.110$ in^2, $E = 30 \times 10^6$ psi) has a 2.0 in grip and 5,000 lb preload. How much does it stretch?

10. **7 pts**

    Find the tensile capacity of an M10 $\times$ 1.5 class 8.8 bolt ($A_t = 0.7854(d - 0.9382P)^2$).

11. **6 pts**

    A 1/2 in Grade 8 bolt (tensile 150,000 psi) is in single shear with its shank in the shear plane. Estimate its ultimate shear capacity.

12. **6 pts**

    You are the tradesperson. A customer wants to use stainless-steel screws to attach aluminum trim on a boat. What do you advise?

13. **6 pts**

    Find the withdrawal resistance of a 10d common nail ($D = 0.148$ in) driven 2.0 in into Douglas fir ($G = 0.50$).

14. **6 pts**

    Why does a hot rivet clamp the plates it joins?

15. **5 pts**

    Choose a fastener and give a reason: (a) roof sheathing to rafters; (b) a trailer fender to its bracket where the back cannot be reached; (c) a heavy shelf on a concrete wall.

16. **12 pts**

    Short essay. Using the Hyatt Regency walkway collapse, explain why a change to how something is fastened must be checked by calculation, and describe what a responsible tradesperson or engineer does before approving a change.

ANSWER KEY

1. $1/18 = 0.0556$ in $= 1.41$ mm.
2. IMA $= 2\pi(0.20)/0.004 \approx 314$; AMA $= 94$; $6{,}000/94 \approx 64$ N.
3. It let a precise screw be copied exactly, so nuts and bolts could be made in quantity to match. But each shop still chose its own threads; standards made threads interchangeable between shops and across a nation.
4. A bolt is used with a nut through clearance holes and tightened by turning the nut; a screw goes into a tapped hole or forms its own thread and is turned by its head. A lag screw is a screw.
5. Numbered size 10, so $0.060 + 0.013(10) = 0.190$ in; 32 TPI (fine); 3/4 in long.
6. $A_t = 0.0775$ in^2; proof 6,590 lb; preload 4,940 lb;
   $T = 0.20(0.375)(4{,}940) \approx 371$ in $\cdot$ lb ≈ 31 ft $\cdot$ lb.
7. Preload rises to $371/(0.15 \times 0.375) \approx 6{,}600$ lb, right at the proof load. The bolt may stretch permanently; lubricated threads need a lower torque.
8. Junker slid a clamped joint sideways while measuring bolt tension; sideways slip caused rapid self-loosening. Nylon-insert nuts, threadlocker, wedge-locking washers, safety wire and cotter pins work; split lock washers do little.
9. $\delta = \dfrac{5{,}000 \times 2.0}{0.110 \times 30 \times 10^6} \approx 0.0030$ in.
10. $A_t = 0.7854(10 - 1.407)^2 = 58.0$ mm^2; $800 \times 58.0 = 46{,}400$ N ≈ 46 kN.
11. $0.6 \times 150{,}000 \times 0.196 \approx 17{,}700$ lb.
12. Stainless is fine for the screw, but aluminum is more active and will corrode where they touch in salt water. Isolate them with nylon washers or sleeves and bed the screws in marine sealant; or use aluminum-compatible fasteners.
13. $1380(0.1768)(0.148) \approx 36.1$ lb/in; $\times 2.0 \approx 72$ lb.
14. It is set while red-hot and shrinks as it cools; the plates prevent it from shortening freely, so it is stretched past yield and pulls the plates together with a large clamp force.
15. (a) Nails (or code-listed staples) per the nailing schedule: fast, ductile, in shear. (b) Blind (pop) rivets or bolts with locknuts; blind rivets if the back is unreachable. (c) Concrete sleeve or wedge anchors (or screw anchors) rated for the load.
16. Model answer: the change from continuous rods to two rods seemed minor and made fabrication easier, but it doubled the load on the fourth-floor connections,

which were already below code; the nuts pulled through and 114 people died. Any change to a connection changes the load path. A responsible person traces the load path, calculates the new forces and capacities, compares them with the code and a safety factor, asks the designer when unsure, documents the approval, and refuses to proceed until the change is shown to be safe.

PORTFOLIO PIECE: A FASTENER BOARD AND TEST REPORT

Finish your labeled fastener identification board (at least 20 fasteners, each with callout, drive type, grade where marked and a typical use), and mount a thread pitch gauge or a card of thread drawings beside it.

Write a three- to five-page fastener test report that combines your Unit 1 experiments: the C-clamp mechanical advantage, the torque–preload measurements of K, the shake test, and the nail and screw pull-out tests. Include data tables, graphs, comparisons with the formulas, sources of error, and your fastener decision table.

LOOK FOR	WHAT IT MEANS
Identification	Every fastener is correctly identified with a correct callout, drive and use; grades are read correctly.
Measurement	Tests are fair (one change at a time), repeated at least three times, and recorded with units.
Calculation	Mechanical advantage, K, preload and withdrawal predictions are calculated correctly and compared honestly with measurements.
Judgment	The decision table and conclusions show sound reasoning about load direction, materials, corrosion and safety.
Presentation	The board is neat and durable; the report is organized, labeled and clearly written.

1.1 The Screw: From Archimedes to Maudslay's Lathe

OBJECTIVES

- Explain the screw as an inclined plane wrapped around a cylinder and calculate pitch, lead, threads per inch and helix angle.
- Calculate the ideal and actual mechanical advantage and the efficiency of a screw jack or clamp, and explain why most screws hold their load.
- Tell how Henry Maudslay's screw-cutting lathe, Whitworth's 1841 standard and William Sellers's 1864 standard made interchangeable parts possible.

> **Warm-up.** Find three things in your house that use a screw thread but are not fasteners (a jar lid, a C-clamp, a faucet, a light bulb, a bench vise, an office chair). For each one, write what the thread does: lift, clamp, seal, adjust or hold. Then turn a jar lid and count how many turns it takes to come off.

WATCH

Screw Threads

Laney Machine Tech · 9:48

https://www.youtube.com/watch?v=IA851C9ixjQ

> **WHEN TO WATCH**
> After the science paragraph. Pause when he wraps the paper triangle into a helix and do it yourself with a pencil.

Note: A college machine-shop instructor explains the screw as a wrapped inclined plane, the 60° vee thread and how thread sizes are written. You will use the second half again in Lesson 1.2.

BACKUP VIDEO

History of Lathes | The Henry Ford's Innovation Nation

The Henry Ford · 3:35

https://www.youtube.com/watch?v=r93mR4lnmm4

With the story. The curator shows a Maudslay production lathe from about 1804, one of the oldest precision machine tools in the world.

KEY TERMS

helix

The curve made by wrapping a straight sloped line around a cylinder; the path a screw thread follows.

pitch (P)

The distance from one thread crest to the next, measured along the axis. Metric threads give it in millimeters.

threads per inch (TPI)

The number of thread crests in one inch of length; the reciprocal of the pitch in inches, $n = 1/P$.

lead (L)

How far the screw advances in one full turn. For an ordinary single-start thread the lead equals the pitch.

lead screw

A precise long screw on a lathe that drives the cutting tool along the work at an exact rate, so the lathe can cut a thread of exact pitch.

interchangeability

Making parts so accurately to a standard that any nut fits any bolt of the same size, wherever it was made.

CORE IDEAS

The story. For most of history every screw was made by hand. A craftsman scribed a spiral on a rod, cut and filed it out, then made a nut to fit that one screw. Nuts and bolts were kept together in pairs, because no other nut would fit. Henry Maudslay (1771–1831), a London blacksmith who had trained under the lock maker Joseph Bramah, changed that. Around 1797–1800 he built screw-cutting lathes in which an accurate *lead screw* drove a *slide rest* carrying the cutting tool, and gears linked the lead screw to the spinning work. With change gears he could cut any pitch he wanted, again and again. His shop built the famous block-making machines for the Royal Navy at Portsmouth (designed with Marc Brunel, about 1803–1808), which turned out more than a hundred thousand pulley blocks a year with unskilled operators. His workmen included Joseph Whitworth, James Nasmyth, Richard Roberts and Joseph Clement, who spread his methods across Britain.

How they figured it out. Maudslay faced a puzzle: to cut an accurate screw you need an accurate lead screw, but where does the first accurate screw come from? He worked by patient correction: cutting a screw, measuring it against a standard length, finding the error, and cutting a better one, and he lapped screws in long nuts that averaged out small local errors. He kept a bench micrometer his workmen

called the “Lord Chancellor” to settle any argument about size. Forty years later the problem was no longer one shop but a whole nation of shops, each with its own threads. In 1841 Joseph Whitworth collected screws from workshops across Britain, averaged them, and proposed one thread angle (55°, with rounded crests and roots) and one number of threads per inch for each diameter. In 1864 William Sellers of Philadelphia proposed an American system to the Franklin Institute: a 60° thread with flat crests and roots, easier to cut and check with simple tools. The U.S. Navy and the railroads adopted it. Because British and American threads still did not match, in 1948–49 the United States, Britain and Canada agreed on the *Unified* inch thread (60°). Most of the world now uses the ISO metric thread, also 60°, with the pitch given in millimeters.

The science. Cut a right triangle from paper and wrap it around a pencil: the sloping edge becomes a helix. A screw thread is an inclined plane wrapped around a cylinder. In one full turn, a point on the thread climbs one *lead* L while it travels around a circle of circumference πd. So the slope of the thread, the *helix angle* λ, is given by $\tan\lambda = L/(\pi d_p)$, using the pitch diameter d_p. Ordinary fastener threads have helix angles of only about 2–4°, a very gentle ramp. If you turn a handle of radius R once, your hand travels $2\pi R$ while the screw advances only L, so by conservation of work the ideal mechanical advantage is $\mathrm{IMA} = 2\pi R/L$. Friction eats much of that: real screw jacks are often only 20–40% efficient. That is not all bad. When friction is large compared with the slope (roughly when the friction coefficient exceeds $\tan\lambda$, or when the efficiency is under 50%), the screw is *self-locking*: the load cannot turn it backward, so the jack holds the car and the nut stays put.

In the shop. A tradesperson reads a thread with a *thread pitch gauge* (a fan of toothed leaves) and a caliper, or by trying it in a nut-and-bolt checker board at the hardware store. Inch threads are described by threads per inch; metric threads by pitch: M8 $\times$ 1.25 means 8 mm diameter and 1.25 mm from crest to crest. Never force a nut that tightens after a turn or two; you have either the wrong thread or a crossed thread. To start a nut squarely, turn it backward until you feel it click down onto the first thread, then turn it forward by hand.

On the job. Machinists and tool-and-die makers still cut threads on lathes much like Maudslay’s, though today the lead screw is usually replaced by a computer-

controlled ball screw, itself a precise thread. A machinist apprenticeship takes about four years and leads to steady, skilled work in every industry that makes things.

PICTURE STUDY

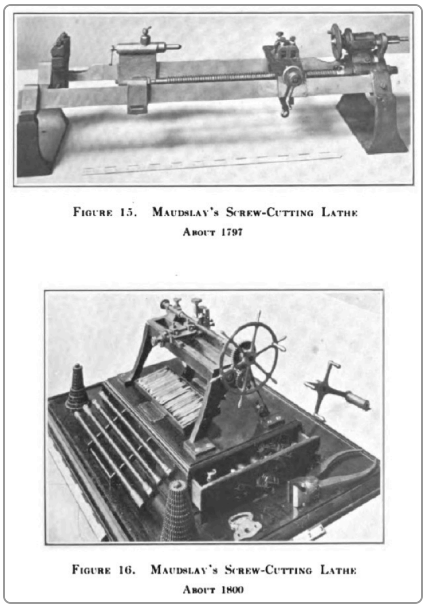


FIGURE 15. MAUDSLAY'S SCREW-CUTTING LATHE
ABOUT 1797

FIGURE 16. MAUDSLAY'S SCREW-CUTTING LATHE
ABOUT 1800

Maudslay's Screw-Cutting Lathes, Unknown photographer (published by Joseph Wickham Roe), Lathes of about 1797 and 1800; photographs published 1916 · Photographs (book plates) · From J. W. Roe, *English and American Tool Builders* (1916)

Image: Wikimedia Commons, public domain

These are the two screw-cutting lathes Henry Maudslay built around 1797 and 1800. They look plain, but they changed the world: with them a screw could be copied exactly, and from them came standard threads and interchangeable parts.

Look closely

- Find the long lead screw running along the bed. Which part does it move?
- Find the slide rest that holds the cutting tool. Why must it slide without wobbling?
- Look at the bed. Why do you think Maudslay made it of iron with flat, straight bars instead of wood?
- On the later lathe, look for gears linking the spindle to the lead screw. What would changing those gears change?

Talk about it

1. If the spindle turns once while the lead screw turns once, and the lead screw has 8 threads per inch, what pitch will the new thread have?
2. Why did a precise lathe matter more to the world than one precise screw?

3. What does a standard (like Whitworth's or Sellers's) do that a single good machine cannot?

Safety first. Wear safety glasses when clamping the bathroom scale: plastic can crack under clamp pressure. Stay well below the scale's rated capacity and keep fingers out from between the jaws.

SHOP PROJECT

Measuring a Screw's Mechanical Advantage

You will measure the threads of a C-clamp, calculate its ideal mechanical advantage, then measure what it really does by clamping a bathroom scale and pulling on the handle with a luggage scale. The difference between ideal and actual is friction, and it is also why the clamp holds.

You will need

- A C-clamp with a sliding T-handle (4–6 in size) or a bench vise
- A digital bathroom scale and two scraps of 3/4 in plywood about 4 in square to protect it
- A digital luggage scale and a short loop of strong string
- A ruler or caliper; a thread pitch gauge if available
- A sheet of paper, scissors and a pencil; light machine oil
- Safety glasses; shop notebook

Steps

1. **Paper helix.** Cut a right triangle 20 cm long and 5 cm tall. Wrap it around a pencil starting with the tall edge. Measure the slope angle of the triangle with a protractor and note that it is the helix angle of the paper "thread."
2. **Read the thread.** Count the clamp screw's crests over 1 in (or check with a pitch gauge). Record threads per inch and calculate the pitch and lead.
3. Measure the handle radius R: the distance from the screw's axis to where your string will pull. Calculate the ideal mechanical advantage $2\pi R/L$.
4. **Predict.** Assume 25% efficiency. What clamping force should a 2 lb pull on the handle produce?
5. Set the bathroom scale on the floor with plywood pads above and below its platform, and close the clamp lightly over the pads so the scale reads a few pounds. (If the clamp is too small for the scale, measure a slimmer stack: a kitchen scale works with smaller forces.) Put on safety glasses.
6. Loop the string over the end of the handle and pull with the luggage scale at right angles to the handle until the clamp just turns. Record the luggage-

scale force and the bathroom-scale reading. Repeat in steps until the bathroom scale reaches about half its capacity: at least five readings.

7. Calculate the actual mechanical advantage and efficiency for each reading. Graph clamp force against handle force; the slope is the AMA.
8. Release the string. Does the clamp hold its force? Write why, using the word self-locking.
9. **Change one thing.** Back off the clamp, put two drops of oil on the threads and the swivel pad, and repeat steps 5–7.
10. **Check your work.** Compare dry and oiled efficiency with your prediction. Name two sources of error (the scale's spring flexes, the pull was not square, friction at the swivel pad).

Tips

- Pull slowly and read the luggage scale at the moment the handle starts to turn.
- Bathroom scales are designed for loads spread on the platform; the plywood pads spread the load.
- If the scale reads in kilograms, work in newtons (1 kg on the scale ≈ 9.81 N).

Check your work

- ☐ I can measure threads per inch and compute pitch, lead and ideal mechanical advantage.
- ☐ My graph gives an actual mechanical advantage and an efficiency, dry and oiled.
- ☐ I can explain why a low-efficiency screw holds its load.

SHOP NOTEBOOK

1. A labeled drawing of the paper helix and of one unwrapped turn of a thread as a ramp, with lead, circumference and helix angle marked.
2. Your C-clamp data table (handle force, clamp force, AMA, efficiency) and graph, dry and oiled.
3. A timeline of the screw: Archimedes's water screw, Roman screw presses, Maudslay's lathe (c. 1800), Whitworth (1841), Sellers (1864), Unified threads (1948–49), ISO metric.

KEY FORMULAS

$$P = \frac{1}{n}\ (\text{in}), \quad n = \frac{25.4}{P_{\text{mm}}}$$

$$L = N_{\text{starts}}\, P$$

$$\tan\lambda = \frac{L}{\pi d_p}$$

$$\text{IMA} = \frac{2\pi R}{L}, \quad \text{AMA} = \frac{F_{\text{out}}}{F_{\text{in}}}, \quad \eta = \frac{\text{AMA}}{\text{IMA}}$$

From history. Before Whitworth, the Royal Navy and the railways kept stores of nuts and bolts for each maker's machines, because nothing was interchangeable. Whitworth also championed precise flat surfaces, made by scraping three plates against one another until all three matched, and measuring machines that could detect a millionth of an inch. Sellers, a Quaker machine-tool builder, argued that the simpler flat-topped thread would let ordinary shops make standard threads cheaply, and he was right.

WORKED EXAMPLES

Example 1. A bolt is marked 1/4-20. Find its pitch in inches and millimeters. How many full turns does a nut need to travel 3/4 in along it?

Show solution

1. Pitch is the reciprocal of threads per inch: $P = 1/20 = 0.050$ in.
2. Convert: $0.050 \text{ in} \times 25.4 \text{ mm/in} = 1.27$ mm.
3. A single-start thread advances one pitch per turn:
   $0.75 \text{ in} \div 0.050 \text{ in/turn} = 15$ turns.

Answer: $P = 0.050$ in $= 1.27$ mm; 15 turns.

Example 2. A screw jack has a single-start thread with a 6.0 mm lead. You push on its handle 0.30 m from the screw's axis. Find the ideal mechanical advantage. If the jack is 25% efficient and you push with 120 N, what load can it lift?

Show solution

1. Ideal mechanical advantage: $\mathrm{IMA} = \dfrac{2\pi R}{L} = \dfrac{2\pi(0.30\ \mathrm{m})}{0.0060\ \mathrm{m}} = 314.$
2. Actual mechanical advantage: $\mathrm{AMA} = \eta \cdot \mathrm{IMA} = 0.25 \times 314 = 78.5.$
3. Load: $F_{\text{out}} = 78.5 \times 120\ \mathrm{N} \approx 9{,}400\ \mathrm{N}$, about the weight of a 960 kg mass.
4. Because the efficiency is below 50%, the jack is self-locking: the load will not spin the handle backward.

Answer: IMA ≈ 314; about 9,400 N (9.4 kN).

Example 3. Find the helix angle of a 1/4-20 thread (pitch diameter about 0.2175 in) and of an M6 × 1.0 thread (pitch diameter about 5.35 mm). Will each be self-locking if the effective friction coefficient is 0.15?

Show solution

1. 1/4-20: $\tan\lambda = \dfrac{0.050}{\pi(0.2175)} = \dfrac{0.050}{0.6833} = 0.0732$, so $\lambda \approx 4.2^\circ$.
2. M6 × 1.0: $\tan\lambda = \dfrac{1.0}{\pi(5.35)} = \dfrac{1.0}{16.81} = 0.0595$, so $\lambda \approx 3.4^\circ$.
3. Both values of $\tan\lambda$ are well below 0.15, so friction easily holds both threads: they are self-locking under a steady load.

Answer: $\approx 4.2^\circ$ and $\approx 3.4^\circ$; both self-locking.

Example 4. A British Whitworth 1/2 in bolt has 12 threads per inch. An American (Unified coarse) 1/2 in nut has 13. Why won't the nut go on? Compare where the 12th thread of each lands.

Show solution

1. Whitworth: 12 threads span $12 \times \frac{1}{12} = 1.000$ in.
2. Unified: 12 threads span $12 \times \frac{1}{13} = 0.923$ in.
3. After 12 threads the two helixes are 0.077 in apart, more than one and a half thread depths, and the flank angles differ too (55° and 60°). The nut binds after a turn or two.

Answer: The pitches differ by 1/12 − 1/13 in per thread; the error adds up to 0.077 in over 12 threads, so the threads cannot engage.

PRACTICE

1. Easy Find the pitch of a 3/8-16 thread in inches and in millimeters.

   Show answer

   $1/16 = 0.0625$ in $= 1.59$ mm.

2. Easy An M8 × 1.25 bolt has about how many threads per inch?

   Show answer

   $25.4/1.25 \approx 20.3$ TPI.

3. Easy Conceptual. Explain in two sentences why a screw thread is an inclined plane.

   Show answer

   If you unwrap one turn of a thread you get a straight ramp whose length is the circumference and whose rise is the lead. Turning the screw slides the load up that ramp, trading a long path for a small rise.

4. Medium How many turns does a nut need to travel 1.5 in on a 3/8-16 bolt?

   Show answer

   $1.5 \div (1/16) = 24$ turns.

5. **Medium** A bench vise screw has 8 threads per inch (single start). You push the handle 6.0 in from the axis. Find the ideal mechanical advantage.

   Show answer

   $2\pi(6.0)/0.125 \approx 302$.

6. **Medium** If the vise in the last problem is 25% efficient and you push with 30 lb, about what clamping force does it give?

   Show answer

   $0.25 \times 302 \times 30 \approx 2{,}300$ lb.

7. **Medium** A two-start thread has a 2.0 mm pitch. What is its lead, and how many turns move it 20 mm?

   Show answer

   Lead $= 2 \times 2.0 = 4.0$ mm; $20/4.0 = 5$ turns. Two-start threads are used on jar lids and pen caps for quick closing.

8. **Hard** Find the helix angle of an M10 × 1.5 thread (pitch diameter about 9.03 mm). Is it self-locking with friction coefficient 0.15?

   Show answer

   $\tan\lambda = 1.5/(\pi \cdot 9.03) = 0.0529$, $\lambda \approx 3.0^\circ$; yes, 0.053 is far below 0.15.

9. **Hard** Maudslay's problem. A lathe's lead screw is too long by 0.001 in for every foot. You cut a 3 ft screw with it. What is the error in the new screw, and why can't a lathe cut a screw more accurate than its own lead screw without some extra method?

   Show answer

   About $3 \times 0.001 = 0.003$ in too long over 3 ft. The tool simply copies the lead screw's motion, errors and all, so improving accuracy needs measurement against a better standard and correction (Maudslay's repeated cutting, measuring and lapping).

10. Hard You are the tradesperson. A customer brings a 1/4 in bolt from an old British machine. It has 20 threads per inch, yet a new 1/4-20 UNC nut feels loose and wobbly on it. Explain.

Show answer

It is probably a 1/4 in British Standard Whitworth bolt, which also has 20 TPI but a 55° thread angle with rounded crests and roots. The 60° Unified nut touches it only at the crests or roots of the flanks, so it fits loosely and will not carry full load. Find a Whitworth nut.

11. Challenge A screw jack has a 5.0 mm lead and a 0.25 m handle. You measure that a 60 N push lifts a 4,000 N load. Find the jack's efficiency and say whether it is self-locking.

Show answer

Work out per turn: $4000 \times 0.0050 = 20$ J; work in: $60 \times 2\pi(0.25) = 94.2$ J; $\eta = 20/94.2 \approx 21\%$. Below 50%, so it is self-locking and holds the load without a brake.

COMMON MISTAKES

- Confusing pitch with threads per inch. Pitch is a distance; TPI is a count. $P = 1/n$.
- Forgetting that lead and pitch differ on multi-start threads.
- Using the handle's whole length as R instead of the distance from the screw's axis to where the force is applied.

Make it a game · Pitch and Lead Quick Draw. Your parent names a thread, such as 20 threads per inch, or a pitch of 1.5 mm. You state the pitch or TPI, the lead for a single start and how far one turn advances, in 10 seconds. Then explain why a screw jack holds its load. Five correct in a row sets a record to beat.

Scripture. "Seest thou a man diligent in his business? he shall stand before kings; he shall not stand before mean men." (Proverbs 22:29, KJV)

Maudslay was a blacksmith's apprentice whose careful, diligent work built machines for the Royal Navy and trained a generation of engineers. Skilled, careful work is honorable work.

1.2 Screws versus Bolts: Thread Anatomy and Standards

OBJECTIVES

- Tell a screw from a bolt by its intended use, and name the parts of a thread: major, minor and pitch diameters, pitch, crest, root, flank and thread angle.
- Read inch and metric thread callouts such as 1/4-20 × 1, #10-24 and M8 × 1.25 × 30, and calculate numbered machine-screw diameters.
- Choose among wood, machine, sheet-metal, lag and drywall screws and among slotted, Robertson, Phillips and Torx drives, and drill the right pilot and clearance holes.

> **Warm-up.** Empty a junk drawer or a coffee can of mixed hardware onto a tray. Sort it into piles any way you like. Then write one sentence explaining your rule. Did anything not fit any pile?

WATCH

Robertson, Phillips, and the History of the Screwdriver

The History Guy: History Deserves to Be Remembered · 16:25

https://www.youtube.com/watch?v=R-mDqKtivuI

> **WHEN TO WATCH**
> With the story paragraph. Then go back to the second half of the Lesson 1.1 video (Laney Machine Tech) for reading thread callouts.

Note: A clean, well-researched history of screws and screwdrivers, with patent drawings and factory photographs. A brief image of an antique wheel-lock gun mechanism appears as an early use of screws.

BACKUP VIDEO

What is the Difference Between a Bolt and a Screw? | Fastener Basics 1

Würth Industry USA · 3:26

https://www.youtube.com/watch?v=-HaByqLxxMo

With the first science paragraph: two fastener professionals explain the definitions used in the industry.

KEY TERMS

bolt

A headed, externally threaded fastener meant to pass through holes in the parts and be tightened by turning a nut.

screw

A headed, externally threaded fastener meant to be turned by its head into a tapped hole or into material where it forms its own thread.

major diameter

The largest diameter of a thread, measured over the crests; the nominal size, such as 1/4 in or 8 mm.

minor diameter

The smallest diameter, measured at the roots of an external thread.

pitch diameter

The diameter at which the thread ridge and the groove are equally wide; where the flanks of bolt and nut actually bear.

cam-out

A driver bit climbing out of a screw's recess under torque, which strips the recess and can slip into the work or your hand.

CORE IDEAS

The story. In 1906 or so, a Canadian salesman named Peter L. Robertson was showing a spring-loaded screwdriver when the blade slipped out of a slotted screw and cut his hand. He set out to make a screw that a driver could not slip out of, and in 1908 he invented the square-socket screw; he patented it in Canada in 1909 and built a factory in Milton, Ontario. Robertson screws drove faster, stayed on the driver tip, and are still the favorite of Canadian carpenters. Ford used them in its Canadian plants, but Robertson would not license the design on Ford's terms, so it never spread widely in the United States. Instead, in the 1930s an Oregon businessman, Henry F. Phillips, bought a cross-recess design from its inventor, John P. Thompson, improved it and patented it in 1936. General Motors used Phillips screws on the 1936 Cadillac, power drivers on the assembly line found them quick to start, and within a few years nearly every American carmaker used them.

How they figured it out. Each new drive solved a problem the last one created. The slot is easy to make but the blade slides sideways. The Phillips recess centers the bit automatically, which was just what fast assembly lines needed, but its sloped walls push the bit back out under high torque (*cam-out*). Robertson's square has nearly

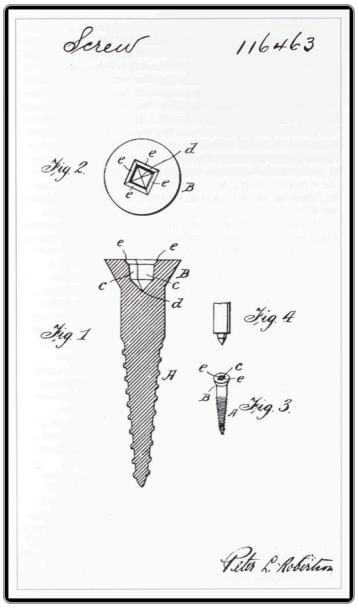
straight walls and holds the bit, but needs the right size. In 1967 the Camcar company introduced the six-lobed Torx drive, whose almost vertical lobes transmit high torque with very little push-out; it is now standard in cars, electronics and structural wood screws. The lesson is a good engineering habit: name the failure, then change the shape that causes it.

The science. What makes a screw a screw and a bolt a bolt is the intended use, as the industry standard (ASME B18.2.1) and U.S. Customs both define it: a *bolt* is meant to go through clearance holes and be tightened by turning a *nut*; a *screw* is meant to be turned by its head into a tapped hole or to cut or form its own thread. A thread is described by its **major diameter** (over the crests), **minor diameter** (at the roots), **pitch diameter** (where the flanks bear), **pitch** and **thread angle** (60° for Unified and metric). In the United States, a callout like **1/4-20 × 1** means 1/4 in major diameter, 20 threads per inch and 1 in long (measured from under the head for most heads; overall for flat countersunk heads). **UNC** is the coarse series (1/4-20), **UNF** the fine series (1/4-28). Sizes below 1/4 in are numbered: the major diameter of a #N machine screw is $0.060 + 0.013N$ inches, so #10 is 0.190 in. Metric callouts give diameter, pitch and length in millimeters: $\mathrm{M}8 \times 1.25 \times 30$. The fit class (2A for bolts, 2B for nuts) is the ordinary tolerance; 3A/3B is tighter.

In the shop. Machine screws and **cap screws** have straight threads for tapped holes and nuts. **Wood screws** taper and have coarse threads and often a smooth shank, so they pull the top board tight against the bottom one. **Sheet-metal screws** are hardened and self-tapping. **Lag screws** (often wrongly called lag bolts) are big wood screws with hex heads turned by a wrench. **Drywall screws** have bugle heads that dimple the paper without tearing it; they are hard and brittle and must never be used where a structural connection is called for. In wood, drill a *clearance hole* (the size of the shank) through the top piece so the threads grab only the bottom piece, and a *pilot hole* about the size of the root (minor) diameter in hardwood, a little smaller in softwood, to prevent splitting. In metal, the length of thread engaged matters: about one diameter of engagement in steel, one and a half to two diameters in aluminum or cast iron, so the bolt breaks before the threads strip.

On the job. Industrial fastener distributors such as Fastenal and Würth employ specialists who identify thousands of fastener types, and every trade, from electricians to auto technicians, uses the vocabulary of this lesson daily. Being able to read “3/8-16 × 1-1/2 Grade 5” at a glance is a basic trade skill.

PICTURE STUDY



Robertson's Socket-Head Screw, Peter L. Robertson (patent drawing), 1909 · Patent drawing · Canadian Patent Office

Image: Wikimedia Commons, public domain

Patent drawings are an engineer's way of explaining an idea so exactly that someone else could build it. This one shows the square socket that Robertson hoped would end slipping screwdrivers.

Look closely

- Find the square socket in the screw head. Is it straight-sided or tapered?
- Find the matching driver tip. Why would a slight taper help the screw stay on the bit?
- Look at the threads of the screw. Is this a wood screw or a machine screw? How can you tell?
- Find the section view (a drawing sliced through the middle). What does it show that the outside view cannot?

Talk about it

1. Why does a square socket resist cam-out better than a slot?
2. Why might a factory owner in 1910 care whether a screw stayed on the driver tip?
3. What does a patent require an inventor to explain, and why?

> **Safety first.** Wear safety glasses when driving screws and drilling. Clamp small workpieces instead of holding them by hand near the bit, and keep your other hand away from the line the driver would take if it slipped.

SHOP PROJECT

A Fastener Identification Board and a Pilot-Hole Test

You will identify and label a collection of real fasteners on a reference board you can keep in your shop, then run a fair test to find the best pilot hole for a wood screw in a hardwood and a softwood.

You will need

- A coffee can or bag of mixed screws, bolts, nuts and washers (or buy a small assortment)
- A thread pitch gauge (inch and metric) and a caliper or ruler; a nut-and-bolt thread checker if you have one
- A piece of 1/2 in plywood about 12 × 18 in, small labels, a fine marker and some hot glue or small screws
- Scrap pine and a hardwood such as oak or maple, each about 1 × 3 × 12 in
- #8 × 1-1/2 in wood screws; drill bits 1/16, 3/32, 7/64, 1/8 and 9/64 in; a drill/driver with a numbered clutch
- Safety glasses; shop notebook

Steps

1. Sort the collection into bolts, machine screws, wood screws, sheet-metal screws, lag screws, drywall screws, nuts and washers. Note anything you cannot place.
2. For each threaded fastener, measure the major diameter with the caliper and the pitch with the gauge. Write its full callout (for example 1/4-20 × 1 or M6 × 1.0 × 20) and its drive type.
3. Choose at least 15 different fasteners and mount them on the plywood with a label under each: name, callout, drive, and one good use.
4. **Pilot-hole test: predict.** Which pilot size will hold best in pine? In oak? Which will split the wood near an end?
5. Mark five positions on each board, each 3/4 in from one end, so splitting is possible. Drill one pilot hole at each position, a different size each (none, 1/16 or 3/32, 7/64, 1/8, 9/64 in). Label them.

6. Drive a screw into each hole with the drill on its clutch. Start on a low clutch setting and raise it one step at a time until the screw seats. Record the clutch setting needed, whether the wood split, and whether the screw stripped.
7. Try to pull each screw out by hand with a claw hammer under a scrap block (gentle, even prying), and rank how hard each was to remove.
8. Make a data table and pick the best pilot size for each wood. Compare with a published pilot-hole chart.
9. **Improve it.** Repeat your best pine and best oak holes at the middle of the board, far from the end. Does the best size change when splitting is no longer a risk?

Tips

- Hold the drill square to the board; a tilted pilot hole makes a tilted screw.
- Wrap a piece of tape on the bit as a depth stop: drill as deep as the screw's threaded length.
- Keep the fastener board near your bench; you will use it all year.

Check your work

☐ I can read and write thread callouts for inch, numbered and metric threads.

☐ My data table shows which pilot hole works best in each wood, and why.

☐ I can explain the difference between a screw and a bolt by use.

SHOP NOTEBOOK

1. A large, labeled cross-section of a thread showing major, minor and pitch diameters, pitch, crest, root, flank and the 60° thread angle.
2. Sketches of the four drive types with arrows showing how the turning force acts on the recess walls.
3. Your pilot-hole data table and a one-paragraph conclusion.

KEY FORMULAS

$D_{\#N} = 0.060 + 0.013\,N \text{ in}$

$P = 1/n, \qquad \text{threads engaged} = \dfrac{\text{engagement length}}{P}$

From history. The Phillips cross recess is often said to have been designed to cam out on purpose so assembly-line drivers would not over-tighten screws. Phillips's patents actually emphasize self-centering and fast driving; cam-out was a side effect that later designs, such as Pozidriv (1960s) and Torx (1967), set out to reduce. Robertson's company remained independent in Milton, Ontario, for decades, and a Canadian is still likely to reach for a square bit first.

WORKED EXAMPLES

Example 1. Decode the callout "1/4-20 × 1 UNC hex cap screw." Is it a screw or a bolt?

Show solution

1. 1/4: major diameter 0.250 in.
2. 20: threads per inch, so $P = 0.050$ in.
3. × 1: length 1 in, measured from under the head to the tip.
4. UNC: Unified coarse series. A hex cap screw may be used with a nut (as a bolt) or in a tapped hole (as a screw); its use decides the name.

Answer: 1/4 in diameter, 20 TPI coarse thread, 1 in long; a bolt if used with a nut, a screw in a tapped hole.

Example 2. Find the major diameter of a #10 machine screw. Compare the pitch of #10-24 and #10-32.

Show solution

1. Diameter: $D = 0.060 + 0.013(10) = 0.190$ in.
2. #10-24: $P = 1/24 = 0.0417$ in.
3. #10-32: $P = 1/32 = 0.0313$ in. The fine thread is used where vibration or thin material calls for more threads per length.

Answer: 0.190 in; pitches 0.0417 in and 0.0313 in.

Example 3. An M8 × 1.25 cap screw goes into a tapped hole in an aluminum bracket. How deep should the thread engagement be, and how many threads does that give? What if the part were steel?

Show solution

1. Aluminum is softer than the steel screw, so use about $2D = 16$ mm of engagement.
2. Threads engaged: $16 \text{ mm} \div 1.25 \text{ mm} = 12.8$.
3. In steel, about $1D = 8$ mm, or 6.4 threads, is enough for the screw to break before the threads strip.

Answer: About 16 mm (12.8 threads) in aluminum; about 8 mm in steel.

Example 4. You are the tradesperson. Choose the fastener for each job and give one reason: (a) deck boards to pressure-treated joists; (b) drywall to wood studs; (c) a heavy door hinge to a pine jamb; (d) a lawn-mower handle to its bracket.

Show solution

1. (a) Coated or stainless exterior deck screws rated for treated lumber: the copper in treated wood corrodes plain steel.
2. (b) Coarse-thread drywall screws: the bugle head dimples the paper without tearing it.
3. (c) Wood screws, with at least one long screw per hinge reaching the stud behind the jamb, in pilot holes so the jamb does not split.
4. (d) A bolt with a washer and nylon-insert locknut through the clearance holes, because the joint vibrates and must come apart for storage.

Answer: Deck screws; drywall screws; wood screws with pilot holes (one long into the stud); bolt and locknut.

PRACTICE

1. Easy Decode M10 × 1.5 × 40.

Show answer

Metric thread, 10 mm major diameter, 1.5 mm pitch, 40 mm long.

2. Easy Is a lag “bolt” really a bolt? Explain.

Show answer

No. It is turned by its head into wood and forms its own thread, so by definition it is a screw: a lag screw.

3. Easy Name four drive types and one strength of each.

Show answer

Slotted: simple and cheap. Robertson (square): holds the bit, little cam-out. Phillips: self-centering, quick on assembly lines. Torx: high torque with almost no cam-out.

4. Medium Find the major diameter of a #8 screw.

Show answer

$0.060 + 0.013(8) = 0.164$ in.

5. Medium What is the pitch of a #6-32 thread?

Show answer

$1/32 = 0.03125$ in.

6. Medium Is 3/8-24 coarse or fine? What is the coarse thread for 3/8 in?

Show answer

Fine (UNF). The coarse thread is 3/8-16.

7. Medium A chart calls for a 1/8 in pilot hole for a #8 wood screw in oak but 3/32 in in pine. Explain the difference.

Show answer

Hardwood is dense and splits or stops the screw if the hole is too small, so the pilot is about the root diameter. Softwood compresses, so a smaller pilot lets the threads bite into more wood and hold better.

8. Hard You are the tradesperson. A European bicycle part has an M6 bolt, and a 1/4-20 nut from the hardware store will not thread on, though 6 mm and 1/4 in (6.35 mm) seem close. Explain with numbers.

Show answer

The pitches differ: M6 has 1.0 mm pitch; 1/4-20 has $25.4/20 = 1.27$ mm. After a few turns the threads are out of step and bind. Use an M6 × 1.0 nut.

9. Hard A screw keeps stripping out of a particleboard shelf. Give the diagnosis and two good fixes.

Show answer

Particleboard has weak, crumbly fibers and little withdrawal strength; the threads have crushed the hole. Fixes: move to fresh material and use coarse-thread particleboard or confirmat screws in correct pilot holes; or glue in a hardwood dowel and screw into it; or use a through-bolt or a threaded insert.

10. Hard Conceptual. Why does a Phillips bit cam out but a Torx bit rarely does?

Show answer

The Phillips recess walls slope, so turning force on them produces a component along the screw's axis that pushes the bit out; the user must push hard to resist it. Torx lobes are nearly parallel to the axis, so almost all the force turns the screw and very little pushes the bit out.

11. Challenge Use the tensile stress area formula $A_t = 0.7854\,(D - 0.9743/n)^2$ to compare a 1/4-20 and a 1/4-28 bolt of the same material. Which is stronger in tension, and by what percent?

Show answer

1/4-20: $0.7854(0.25 - 0.0487)^2 = 0.0318$ in^2; 1/4-28: $0.7854(0.25 - 0.0348)^2 = 0.0364$ in^2. The fine thread is about 14% stronger in tension because its shallower thread leaves more metal in the core.

COMMON MISTAKES

- Mixing metric and inch fasteners that look alike (M6 and 1/4 in, M8 and 5/16 in). Check with a gauge before forcing anything.
- Measuring a wood screw's length from the wrong place: flat heads are measured overall, round and pan heads from under the head.
- Using drywall screws for shelves, decks or framing. They are brittle and not rated for structural loads.
- Using a worn or wrong-size bit (a #1 Phillips in a #2 recess), which causes cam-out and stripped heads.

Make it a game · Thread Callout Decoder. Write callouts on slips of paper: 1/4-20 x 1, #10-24, M8 x 1.25 x 30. Draw one, decode it aloud in 15 seconds: diameter, threads per inch or pitch, length. Then label a sketch of a thread with major, minor and pitch diameters, crest and root. Your parent times you; beat your best round.

1.3 Torque, Preload and Clamp Force

OBJECTIVES

- Explain a tightened bolt as a stretched spring whose tension (preload) clamps the joint, and calculate bolt stretch with $\delta = FL/(AE)$.
- Use $T = KDF$ to find the torque for a desired preload, and explain how lubrication and friction change the result.
- Explain why bolts loosen under vibration (the Junker test), choose a locking method, and tighten wheel lug nuts with a torque wrench in a star pattern.

> **Warm-up.** Stretch a rubber band between two fingers and pinch a sheet of paper between them with it. Pull the paper out. Now double the band and try again. Write one sentence about what “clamp force” means and where it comes from.

WATCH

The Incredible Strength of Bolted Joints

The Efficient Engineer · 17:58

https://www.youtube.com/watch?v=XLzTB4KLCxU

> **WHEN TO WATCH**
> After the science paragraph and before Worked Example 3. Watch the joint-stiffness section twice.

Note: Clear 3D animations of preload, joint stiffness, shear joints and friction grip. There is a sponsor message near the start.

BACKUP VIDEO

Why do joints self-loosen? The Junker Test - Fastening Theory Part 3

Flexible Assembly Systems Inc · 2:01

https://www.youtube.com/watch?v=Jq38Oe6lMEg

With the “How they figured it out” paragraph: a short animation of Junker’s transverse-vibration machine.

KEY TERMS

preload

The tension put into a bolt when it is tightened; it equals the clamp force on the joint before any outside load.

torque

A turning effort: force times the perpendicular distance from the axis, in ft·lb, in·lb or N·m.

nut factor (K)

An experimental number in $T = KDF$ that lumps together thread and head friction; about 0.20 for dry steel and about 0.15 or less when lubricated.

joint stiffness

How much the clamped parts resist being squeezed; a stiff joint keeps most of an outside load out of the bolt.

self-loosening

A nut or bolt turning backward by itself, usually because the joint slips sideways under vibration.

threadlocker

An anaerobic adhesive that hardens in the airless gap between threads and stops them turning.

CORE IDEAS

The story. For a century engineers believed that nuts shook loose because of vibration along the bolt's axis. In 1969 a German engineer, Gerhard Junker, published a study (in an SAE paper) with a simple, brilliant machine: it clamped a bolted joint and slid one plate back and forth sideways by a tiny amount while a load cell recorded the bolt's tension. Under that sideways slip, ordinary nuts lost their clamp force in seconds, and the popular split lock washer did almost nothing to stop it. Junker showed that when the joint slips sideways, the thread and head friction momentarily lets go, and the slight ramp of the thread then lets the nut turn backward a little with each cycle. His machine became the standard test (now in DIN and ISO standards) for every locking device on the market.

How they figured it out. Junker's key move was to measure what actually mattered, the bolt's tension, while reproducing the motion seen in real machines. The cure followed from the cause: if sideways slip loosens the joint, then the first defense is enough preload that friction between the clamped plates prevents slip in the first place. The second defense is a device that stops rotation even when the joint slips: prevailing-torque nuts (nylon inserts or deformed threads), anaerobic threadlockers (developed by the chemist Vernon Krieble in Connecticut in the 1950s and sold as

Loctite), wedge-locking washer pairs, castle nuts with cotter pins, and safety wire, which aircraft mechanics twist through drilled bolt heads so each bolt pulls its neighbor tight. Toothed and split washers proved weak in Junker's test.

The science. A tightened bolt is a stiff spring. Its spring constant is $k = AE/L$, so a steel bolt stretches by $\delta = FL/(AE)$, only a few hundredths of a millimeter, while the clamped parts compress a little less. That stretch is the preload, and the preload is the clamp force. The torque you apply mostly fights friction: roughly half goes into friction under the head or nut, about 40% into thread friction, and only about 10% actually stretches the bolt. Engineers lump these into one experimental number, the **nut factor** K, in $T = KDF$, where D is the nominal diameter and F the preload. For dry plain steel $K \approx 0.20$; with oil or anti-seize it may be 0.15 or 0.12. That is why lubricating a bolt and then applying a dry torque spec can stretch it past its proof load. Because the clamped parts are usually several times stiffer than the bolt, an outside load that pulls the joint apart mostly reduces the clamp force and adds only a small fraction $C = k_b/(k_b + k_c)$ to the bolt's tension. A well-preloaded bolt barely feels a vibrating load, which is why preload protects against fatigue.

In the shop. Use a torque wrench wherever a manufacturer gives a torque value: wheels, engine parts, brakes, mower blades. A click wrench should be set, pulled smoothly until it clicks, and stored at its lowest setting; never use it as a breaker bar. Torque values assume clean threads and the lubrication the manual states. Tighten bolt patterns in a *star* (crisscross) sequence in two or three stages so the part seats flat; on a five-lug wheel the order is 1-3-5-2-4. Tighten lug nuts by hand, snug them in a star, lower the car so the tire bears weight, then torque to spec, and check again after the first 50–100 miles. Many engine head bolts are torque-to-yield: tightened by torque and then a set angle, and never reused.

Safety. Never work under a car held only by a jack; torque wheels with the tire on the ground or the car on jack stands on level, hard ground with wheels chocked.

PICTURE STUDY



Power House Mechanic Working on a Steam Pump, Lewis Wickes Hine, 1920 · Gelatin silver photograph · George Eastman Museum and other collections

Image: Wikimedia Commons, public domain

Lewis Hine photographed working people to show the dignity of their labor. This is his most famous picture of a mechanic: a man leaning his whole body into a wrench on the bolts of a steam pump in a power plant.

Look closely

- Find the wrench and the nut. Where is the mechanic putting his weight, and why does that give more torque?
- Count the bolts you can see on the flanges. Why are there so many around a circle?
- Look at the mechanic's posture. What would happen if the wrench slipped?
- Find the bolted joints that hold steam under pressure. What would leak if the preload were too low?

Talk about it

1. If he pulls 120 lb at 2 ft from the nut, what torque is he applying?
2. In what order should he tighten a ring of bolts on a flange, and why?
3. Hine wanted viewers to respect workers like this one. What skill and judgment does this job require?

> **Safety first.** Wear safety glasses for the shake test, and hold the jig with a clamp, not your hand, while striking it. When you torque real lug nuts, do it with the car on the ground or on jack stands, never with anyone under a car held by a jack.

SHOP PROJECT

Torque, Friction and Clamp Force on a Bathroom Scale

You will build a simple bolted press over a bathroom scale, measure the torque needed to make a given clamp force, and calculate the nut factor K dry and lubricated. Then you will run a home version of Junker's test to see which locking methods keep a nut tight.

You will need

- A digital bathroom scale
- A 2 × 6 base board about 24 in long and a 2 × 4 crossbar about 20 in long
- Two 1/4-20 threaded rods about 12 in long, four nuts and four flat washers; a wood block about 4 × 4 in
- A 7/16 in wrench (or socket) and a luggage scale, or a small inch-pound torque wrench
- Light oil; a paint pen
- For the shake test: two short scraps of 3/4 in plywood, 1/4-20 bolts with plain nuts, split lock washers, nylon-insert nuts and (optional) blue threadlocker; a rubber mallet; a clamp
- Safety glasses; shop notebook

Steps

1. Drill two 5/16 in holes through the base board 16 in apart and the same in the crossbar. Fix the threaded rods upright in the base with a nut and washer above and below.
2. Set the bathroom scale on the base between the rods, the wood block centered on it, and the crossbar over the rods resting on the block. Put a washer and nut on each rod above the crossbar.
3. **Predict.** With $K = 0.20$, what torque on each nut gives 100 lb per rod (200 lb on the scale)?
4. Tighten both nuts evenly, a little at a time. To measure torque, hook the luggage scale to the end of the wrench at a measured distance (say 6 in) and

pull at right angles. Record torque per nut and the scale reading at five levels up to about half the scale's capacity.

5. Compute the force per rod (scale reading ÷ 2) and $K = T/(DF)$ for each reading. Average them.
6. Release, put a drop of oil on each rod's threads and under each nut, and repeat steps 4–5. Compare the two values of K.
7. **Shake test.** Drill 3/8 in holes through two plywood scraps so a 1/4 in bolt can slip sideways. Make four joints: plain nut, split lock washer, nylon-insert nut, and threadlocker (let it cure 24 h). Tighten each to the same torque and draw a paint-pen line across nut and plywood.
8. Clamp the lower plate to the bench. Strike the upper plate sideways with the mallet, 25 blows each way. Record how far each paint line has rotated and whether the nut is still tight.
9. Rank the locking methods and compare with Junker's findings.
10. **Improve it.** Tighten the plain-nut joint to twice the torque and repeat. Does more preload help? Explain using friction between the plates.

Tips

- A small inch-pound torque wrench makes this easy, but the luggage-scale method works: torque = pull × distance.
- Keep the crossbar level; if one side rises, tighten that nut less.
- Do not exceed half the bathroom scale's capacity.

Check your work

- ☐ I measured K dry and oiled and can explain the difference.
- ☐ My shake test ranks locking methods and connects the result to preload and sideways slip.
- ☐ I can torque a wheel in a star pattern and explain why.

SHOP NOTEBOOK

1. A free-body sketch of a bolted joint: the bolt in tension, the plates in compression, the preload arrows, and an outside load.

2. Your torque–clamp force data table and a graph for dry and oiled threads, with K from each slope.
3. A labeled sketch of a five-lug wheel with the star sequence numbered.

KEY FORMULAS

$$T = KDF$$

$$k = \frac{AE}{L}, \qquad \delta = \frac{FL}{AE}$$

$$F_{\text{bolt}} = F_i + CP, \qquad C = \frac{k_b}{k_b + k_c}$$

$$T_{\text{actual}} = T_{\text{set}}\,\frac{L + E}{L}$$ (extension of length E in line with a wrench of length L)

$$1 \text{ ft} \cdot \text{lb} = 12 \text{ in} \cdot \text{lb} = 1.356 \text{ N} \cdot \text{m}$$

From history. The torque wrench is usually credited to Conrad Bahr, who worked for the New York City water department and patented a torque-indicating wrench in 1918 so that workers would stop over-tightening the bolts on water-main flanges. Today the most critical joints, such as wind-turbine and aircraft bolts, are tightened by measuring stretch directly with ultrasonic gauges, because torque varies with friction.

WORKED EXAMPLES

Example 1. A 1/2-13 Grade 5 bolt has a tensile stress area of 0.1419 in² and a proof strength of 85,000 psi. A common rule is to preload to 75% of the proof load. Find the preload and the dry torque ($K = 0.20$).

Show solution

1. Proof load: $85{,}000 \text{ psi} \times 0.1419 \text{ in}^2 = 12{,}060 \text{ lb}$.
2. Target preload: $0.75 \times 12{,}060 \approx 9{,}050 \text{ lb}$.
3. Torque: $T = KDF = 0.20 \times 0.50 \text{ in} \times 9{,}050 \text{ lb} = 905 \text{ in} \cdot \text{lb}$.
4. Convert: $905 \div 12 \approx 75 \text{ ft} \cdot \text{lb}$.

Answer: About 9,050 lb preload at about 75 ft·lb.

Example 2. Someone oils the same bolt ($K = 0.15$) but still applies 75 ft·lb. What preload results?

Show solution

1. Torque in in·lb: $905 \text{ in} \cdot \text{lb}$.
2. Solve $T = KDF$ for F: $F = \dfrac{905}{0.15 \times 0.50} \approx 12{,}070 \text{ lb}$.
3. That is right at the proof load: the bolt is on the edge of permanent stretch. With anti-seize ($K \approx 0.12$) it would be about 15,100 lb and yield.

Answer: About 12,000 lb, at the proof load. Lubrication changes the torque you need.

Example 3. An M10 steel bolt clamps a 40 mm thick joint. Treat the bolt as a 10 mm rod ($E = 200$ GPa). Find its spring constant and how far it stretches at a 25 kN preload.

Show solution

1. Area: $A = \frac{\pi}{4}(10 \text{ mm})^2 = 78.5 \text{ mm}^2$.
2. Spring constant: $k = \dfrac{AE}{L} = \dfrac{78.5 \times 200{,}000 \text{ N/mm}^2}{40 \text{ mm}} = 392{,}500 \text{ N/mm}$.
3. Stretch: $\delta = \dfrac{25{,}000 \text{ N}}{392{,}500 \text{ N/mm}} = 0.064 \text{ mm}$. Less than the thickness of a sheet of paper, yet it holds the joint with 25 kN.

Answer: $k \approx 3.9 \times 10^5 \text{ N/mm}$; stretch about 0.064 mm.

Example 4. A car's 1/2-20 wheel studs are torqued to 100 ft·lb. With $K = 0.20$, what clamp force does each stud give, and what is the total on a five-lug wheel? Express the torque in N·m.

Show solution

1. Torque: $100 \times 12 = 1{,}200$ in · lb.
2. Per stud: $F = \dfrac{1{,}200}{0.20 \times 0.50} = 12{,}000$ lb.
3. Total: $5 \times 12{,}000 = 60{,}000$ lb, which is what holds the wheel to the hub by friction.
4. In N·m: $100 \times 1.356 \approx 136$ N · m.

Answer: About 12,000 lb per stud, 60,000 lb total; 136 N·m.

PRACTICE

1. Easy Convert 80 ft·lb to in·lb and to N·m.

   Show answer

   960 in · lb; $80 \times 1.356 \approx 108$ N · m.

2. Easy Find the dry torque ($K = 0.20$) for a 3/8 in bolt preloaded to 4,000 lb.

   Show answer

   $0.20 \times 0.375 \times 4{,}000 = 300$ in · lb $= 25$ ft · lb.

3. Easy Conceptual. What did Junker's test show about split lock washers?

   Show answer

   Under sideways slip they lost preload almost as fast as plain nuts; they do little to prevent self-loosening.

4. Medium What preload does 30 ft·lb give on a dry 3/8-16 bolt?

   Show answer

   $F = 360/(0.20 \times 0.375) = 4{,}800$ lb.

5. **Medium** Give the star tightening order for a five-lug wheel and explain why it matters.

   Show answer

   1-3-5-2-4. Crisscrossing pulls the wheel evenly onto the hub so it seats flat; going around in a circle can cock the wheel and warp a brake rotor.

6. **Medium** You pull 40 lb on a wrench 15 in from the bolt. What torque in ft·lb?

   Show answer

   $40 \times 15 = 600 \text{ in} \cdot \text{lb} = 50 \text{ ft} \cdot \text{lb}$.

7. **Medium** A 12 in torque wrench set at 50 ft·lb drives a 3 in crowfoot extension in line with the handle. What torque reaches the bolt?

   Show answer

   $50 \times (12 + 3)/12 = 62.5 \text{ ft} \cdot \text{lb}$. Set the wrench to $50 \times 12/15 = 40 \text{ ft} \cdot \text{lb}$ instead.

8. **Hard** A 1/2 in steel bolt ($A = 0.196 \text{ in}^2$, $E = 30 \times 10^6$ psi) has a 3.0 in grip and 9,000 lb preload. How far does it stretch?

   Show answer

   $$\delta = \frac{9{,}000 \times 3.0}{0.196 \times 30 \times 10^6} = 0.0046 \text{ in}.$$

9. **Hard** You are the tradesperson. A riding mower's blade bolt keeps working loose. List your checks in order.

   Show answer

   Remove the spark-plug wire first. Check the bolt and special washer for wear or stretch and replace with the manufacturer's part (often a hardened bolt). Check the blade adapter, key and spindle for wear or a sheared key. Clean the threads, then torque to the manual's value with a torque wrench, using threadlocker only if the manual allows.

10. **Hard** A mechanic uses anti-seize ($K = 0.12$) on a 1/2-13 Grade 5 bolt whose dry spec is 75 ft·lb for 9,050 lb. What torque gives the right preload?

    Show answer

    $T = 0.12 \times 0.50 \times 9{,}050 = 543 \text{ in} \cdot \text{lb} \approx 45 \text{ ft} \cdot \text{lb}$.

11. **Challenge** A bolt has $k_b = 4.0 \times 10^5$ N/mm and the clamped parts $k_c = 1.2 \times 10^6$ N/mm. Preload is 20 kN. An outside load of 9.0 kN tries to pull the joint apart. Find the bolt tension, the remaining clamp force, and the outside load that would separate the joint.

    Show answer

    $C = 0.4/(0.4 + 1.2) = 0.25$. Bolt: $20 + 0.25(9.0) = 22.25$ kN. Clamp: $20 - 0.75(9.0) = 13.25$ kN. Separation: $P = 20/0.75 \approx 26.7$ kN. The bolt felt only a quarter of the load.

COMMON MISTAKES

- Thinking the torque value is the goal. Torque is only a way to estimate preload; friction changes the relationship.
- Applying a dry torque spec to oiled or anti-seized threads and over-stretching the bolt.
- Using an impact wrench to final-tighten lug nuts, which often over-tightens them unevenly.
- Reusing torque-to-yield head bolts or one-time locknuts.

> **Make it a game · Preload Spring Story.** Teach your parent why a tightened bolt acts like a stretched spring, without notes, in 60 seconds. Your parent quietly plants one wrong claim, such as 'more torque always means more clamp force regardless of lubrication', and you must catch it. Then compute torque from T = KDF for numbers your parent picks.

1.4 Bolt Grades, Strength and Failure

OBJECTIVES

- Read SAE grade and metric property-class head markings and state proof, yield and tensile strengths for Grades 2, 5 and 8 and classes 8.8 and 10.9.
- Calculate tensile stress area, proof load, tensile capacity and shear capacity of bolts, keeping threads out of shear planes.
- Explain galvanic corrosion and choose compatible fasteners, and explain how a changed connection detail caused the 1981 Hyatt Regency walkway collapse.

> **Warm-up.** Find three bolts on things around your house or garage (a lawn mower, a bicycle, a swing set, a trailer hitch). Look at the head. Draw any lines, numbers or letters you see. Guess what they mean.

WATCH

Strongest Bolt? Grades Explained & Dyno Tested For Science

Torque Test Channel · 20:17

https://www.youtube.com/watch?v=26fU7qM-pGc

> **WHEN TO WATCH**
> After the science paragraph. Note the order in which the grades fail and how each one breaks.

Note: A careful side-by-side test of Grade 2, 5 and 8 and metric 8.8 and 10.9 bolts to failure, with strength tables. The description has store links; ignore them.

BACKUP VIDEO

Hyatt Regency Walkway Collapse: Ethics Case Study No. 4

American Society of Civil Engineers (ASCE) · 14:32

https://www.youtube.com/watch?v=98l3Us8IU-I

With the story. A retired judge explains the engineering responsibility behind the collapse.

KEY TERMS

proof load

The largest tension a bolt can carry without any permanent stretch; it is tested on every lot of bolts.

yield strength

The stress at which a material begins to stretch permanently.

tensile strength

The highest stress a material reaches before it breaks.

tensile stress area

The effective cross-section of a threaded rod, between the minor and pitch diameters, used to compute its tensile strength.

single and double shear

A bolt cut across at one plane (two plates) or at two planes (three plates, as in a clevis); double shear carries about twice the load.

galvanic corrosion

Faster corrosion of the more active metal when two different metals touch in the presence of moisture.

CORE IDEAS

The story. On the evening of July 17, 1981, about 1,600 people gathered in the new Hyatt Regency hotel in Kansas City, Missouri, for a tea dance in its four-story atrium. Many stood on two suspended walkways, one at the second floor and one directly above it at the fourth. At 7:05 p.m. the fourth-floor walkway's connections tore loose and both walkways fell to the lobby floor. One hundred fourteen people died and more than two hundred were injured. It remains one of the deadliest structural failures in American history, and every engineering student now studies it.

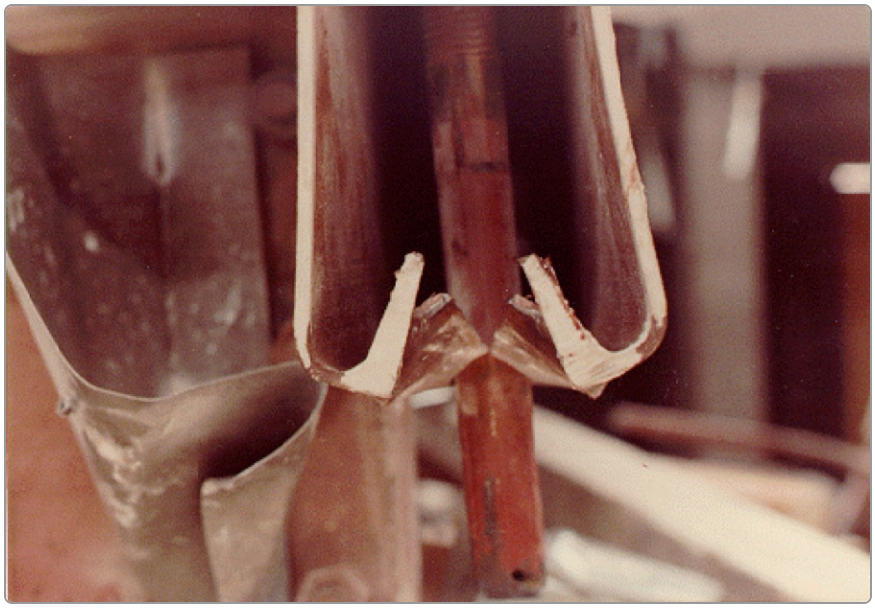
How they figured it out. Investigators from the National Bureau of Standards (now NIST) found the cause in one small detail. The original design hung both walkways from the ceiling on long, continuous steel rods. The fourth-floor walkway's box beams rested on nuts threaded onto the rods, and the second-floor walkway hung from the bottom of the same rods; each nut at the fourth floor carried only the fourth-floor walkway. During fabrication, a change was proposed because long rods threaded along their whole length were hard to make and install: one rod from the ceiling to the fourth floor, and a second rod from the fourth-floor beam down to the second floor. The change was approved without being checked by calculation. Now

the second-floor walkway hung from the fourth-floor beams, and the nut and the welded seam of each fourth-floor box beam carried *both* walkways: double the load. The nuts pulled through the box beams. Investigators also found that even the original connection was weaker than the Kansas City building code required. The engineers of record lost their licenses, and the profession made it clear that the engineer is responsible for checking every change to a connection. The lesson for every tradesperson: a "small" substitution in how something is fastened is an engineering change and must be checked.

The science. Bolt strength depends on the steel and its heat treatment. In the United States, SAE J429 grades are marked by radial lines on the head: **Grade 2** (no marks; low-carbon steel; proof 55,000 psi, tensile 74,000 psi for sizes to 3/4 in), **Grade 5** (three lines; medium-carbon steel, quenched and tempered; proof 85,000 psi, tensile 120,000 psi), and **Grade 8** (six lines; medium-carbon alloy steel, quenched and tempered; proof 120,000 psi, tensile 150,000 psi). Metric bolts carry their **property class** on the head: in **8.8** the first number is one hundredth of the tensile strength in MPa (800 MPa) and the second is the ratio of yield to tensile (0.8, so about 640 MPa yield); **10.9** means 1,000 MPa tensile and 900 MPa yield. A threaded rod breaks across its **tensile stress area**, $A_t = 0.7854\,(D - 0.9743/n)^2$ for inch threads or $A_t = 0.7854\,(d - 0.9382P)^2$ for metric. Capacity is strength times area. In **shear**, steel fails at about 60% of its tensile strength, and the area is the shank area if the smooth shank crosses the shear plane, or the much smaller root area if threads do. Stronger is not always better: Grade 8 is less ductile and gives less warning before it breaks, and some applications call for Grade 5 so the bolt bends before it snaps.

In the shop. Replace a bolt with one of the same grade or better, never with an unmarked hardware-store bolt, and use a nut of matching grade. Stainless steel (18-8) is corrosion resistant but only about as strong as Grade 2 to Grade 5, and it can gall (cold-weld) in a stainless nut; use anti-seize. Watch for **galvanic corrosion**: when two metals touch with water present, the more active one (aluminum, zinc) corrodes to protect the less active one (stainless, copper). Copper-based preservatives in pressure-treated lumber eat plain and thinly galvanized steel, so use hot-dip galvanized (often labeled G185) or stainless fasteners rated for treated wood. Isolate stainless bolts from aluminum with nylon washers and sealant. The Statue of Liberty's iron frame corroded where it touched the copper skin; the restoration completed in 1986 replaced the iron bars with stainless steel.

PICTURE STUDY



The Fourth-Floor Box Beam, Hyatt Regency, Lee Lowery Jr., P.E., 1981 · Photograph · Texas A&M engineering ethics collection, via Wikimedia Commons

Image: Wikimedia Commons, public domain

An engineer took this photograph on the first day of the investigation. It shows the end of a fourth-floor box beam where the hanger rod's nut tore through. We look at it soberly, because 114 people lost their lives, and because a careful look at one connection is exactly the habit that prevents such losses.

Look closely

- Find the two steel channels that make up the box beam. Where were they joined?
- Find the threaded hanger rod. Where would its nut and washer have sat?
- Look at how the flanges are bent and torn. Which way was the force pulling?
- Notice how small the failed area is compared with the whole walkway it held up.

Talk about it

1. The as-built design hung the lower walkway from this beam, so this nut carried about twice the load of the original design. Why?
2. Who should have checked the change from one continuous rod to two rods, and how?

3. What other “small” substitutions in your own shop work could change a load path?

Safety first. Wear safety glasses when loading the model walkways; paper connections fail suddenly. Keep weights low over a tray, and never stand on or under anything you are load-testing.

SHOP PROJECT

Two Ways to Hang a Walkway

You will build both Hyatt Regency hanger designs at small scale with string, card and coins, measure the force at the upper connection with a luggage scale, and load the models until one fails. Then you will survey real bolts and calculate their capacities.

You will need

- Card stock or foam board for two “walkway” trays about 4 × 12 in each, and strips of plain paper for the “box beam” connections
- Strong string (mason’s line) for the hanger “rods”; small washers or buttons as “nuts”
- A sturdy support: a broom handle across two chair backs
- Coins, washers or bags of rice as loads; a kitchen scale; a digital luggage scale
- Safety glasses; shop notebook

Steps

1. Build two identical walkway trays. At each end, glue a short strip of plain paper across the underside to act as the box beam that the “nut” bears on.
2. **Design A (original).** Hang a continuous string from the support through a hole at one end of the upper tray, knot a washer under the upper tray’s paper strip, and continue the same string down to the lower tray. Do the same at the other end.
3. **Design B (as built).** Use one string from the support to the upper tray (knotted under its strip) and a second, separate string from a second hole in the upper tray’s strip down to the lower tray.
4. **Predict.** For each design, what fraction of the lower tray’s weight passes through the upper tray’s paper strip?
5. Insert the luggage scale in the string just above the upper tray in each design, load each tray with the same weight (say 200 g), and record the reading. Then insert it in the string just below the upper tray and record again.

6. Make a table of measured forces and compare with P and $2P$.
7. Load both models equally, 50 g at a time on each tray, until a connection fails. Record the load and where it failed.
8. **Bolt survey.** Find six real bolts (a mower, a bike, a trailer, a swing set). Record diameter, thread, head marking, grade, and calculate each one's proof load.
9. **Galvanic check (optional).** In three cups of salt water place a steel nail touching copper wire, a steel nail touching aluminum foil, and a lone steel nail. Observe for a week and record which metal corrodes.
10. **Check your work.** Write a short report: what the measurements showed, why Design B failed first, and what an engineer should do before approving a fastening change.

Tips

- Use the same paper and the same washer size in both designs so the test is fair.
- Tare the luggage scale with the string attached.
- Photograph each failure; the way paper tears tells you where the stress was concentrated.

Check your work

- ☐ I measured the force through the upper connection in both designs and can explain why it doubled.
- ☐ I can identify bolt grades and calculate proof loads.
- ☐ I can explain why fastening substitutions must be checked.

SHOP NOTEBOOK

1. A load-path sketch of both walkway designs with arrows and forces labeled P and $2P$.
2. A table of SAE grades and metric classes with head marks, proof, yield and tensile strengths.
3. A galvanic-series strip from most active (magnesium, zinc, aluminum) to least active (copper, stainless, gold), with your corrosion observations.

KEY FORMULAS

$$\sigma = \frac{F}{A}$$

$$A_t = 0.7854\left(D - \frac{0.9743}{n}\right)^2 \text{ (inch)}, \quad A_t = 0.7854\,(d - 0.9382P)^2 \text{ (metric)}$$

$$F_{\text{proof}} = S_p A_t, \qquad F_{\text{break}} = S_u A_t$$

$$\tau_u \approx 0.6\,S_u, \qquad F_{\text{shear}} = \tau_u \times A \times (\text{number of shear planes})$$

From history. Bolts are proof-tested by the lot: a sample is loaded to the proof load and must return to its original length within 0.0005 in. Counterfeit and mismarked bolts became a serious problem in the 1980s, which led to the U.S. Fastener Quality Act of 1990; reputable distributors keep test certificates and manufacturer marks on the head as well as grade marks.

WORKED EXAMPLES

Example 1. Find the tensile stress area and proof load of a 3/8-16 Grade 8 bolt. What would a Grade 2 bolt of the same size carry?

Show solution

1. Stress area: $A_t = 0.7854\,(0.375 - 0.9743/16)^2 = 0.7854\,(0.3141)^2 = 0.0775$ in^2.
2. Grade 8 proof load: $120{,}000 \times 0.0775 \approx 9{,}300$ lb.
3. Grade 2 proof load: $55{,}000 \times 0.0775 \approx 4{,}260$ lb, less than half.

Answer: $A_t \approx 0.0775$ in^2; about 9,300 lb (Grade 8) vs 4,260 lb (Grade 2).

Example 2. Find the tensile capacity of an M12 $\times$ 1.75 class 10.9 bolt, and the load at which it yields.

Show solution

1. Stress area: $A_t = 0.7854\,(12 - 0.9382 \times 1.75)^2 = 0.7854\,(10.358)^2 = 84.3$ mm^2.
2. Tensile: $1{,}000$ N/mm^2 $\times$ 84.3 mm^2 $= 84{,}300$ N ≈ 84 kN.
3. Yield: $900 \times 84.3 \approx 75{,}900$ N ≈ 76 kN.

Answer: About 84 kN to break; about 76 kN to yield.

Example 3. A 1/2 in Grade 5 bolt holds a clevis (double shear), with the smooth shank across both shear planes. Estimate its ultimate shear capacity and the allowable load with a factor of safety of 3.

Show solution

1. Shank area: $A = \frac{\pi}{4}(0.5)^2 = 0.196$ in^2.
2. Shear strength: $\tau_u \approx 0.6 \times 120{,}000 = 72{,}000$ psi.
3. Two planes: $F = 72{,}000 \times 0.196 \times 2 \approx 28{,}300$ lb.
4. Allowable: $28{,}300 \div 3 \approx 9{,}400$ lb.

Answer: About 28,300 lb ultimate; about 9,400 lb allowable.

Example 4. Hyatt Regency. Suppose each walkway puts a load P on each hanger location. Compare the load carried by the nut under a fourth-floor box beam in the original and the as-built designs.

Show solution

1. Original: the continuous rod carries the second-floor load straight to the ceiling. The nut under the fourth-floor beam supports only that beam: load P.
2. As built: the upper rod ends at the fourth-floor beam and the lower rod hangs from that same beam. The fourth-floor beam must now carry its own walkway and pass on the second-floor walkway's load: $P + P = 2P$ through its nut and welded seam.
3. Doubling the load on a connection that was already below code left almost no margin.

Answer: P originally; $2P$ as built.

PRACTICE

1. Easy A bolt head has six radial lines. What grade is it, and what are its proof and tensile strengths?

   Show answer

   Grade 8: proof 120,000 psi, tensile 150,000 psi.

2. **Easy** What does “8.8” on a metric bolt mean?

   Show answer

   Tensile strength about 800 MPa; yield about 80% of that, 640 MPa.

3. **Easy** Conceptual. Explain the difference between proof, yield and tensile strength.

   Show answer

   Proof: highest stress with no permanent stretch (tested on each lot). Yield: where permanent stretch begins. Tensile: the maximum stress before breaking. Proof is a little below yield, and both are below tensile.

4. **Medium** Find the tensile stress area of a 5/16-18 bolt.

   Show answer

   $0.7854\,(0.3125 - 0.0541)^2 \approx 0.0524\ \text{in}^2$.

5. **Medium** Find the proof load of that bolt in Grade 5.

   Show answer

   $85{,}000 \times 0.0524 \approx 4{,}460\ \text{lb}$.

6. **Medium** Find the tensile capacity of an M8 $\times$ 1.25 class 8.8 bolt.

   Show answer

   $A_t = 0.7854\,(8 - 1.173)^2 = 36.6\ \text{mm}^2$; $800 \times 36.6 \approx 29{,}300\ \text{N} = 29.3\ \text{kN}$.

7. **Medium** An aluminum boat has stainless-steel bolts. Which metal corrodes, and how do you prevent it?

   Show answer

   The aluminum corrodes around the bolts (it is more active). Isolate the metals with nylon or plastic washers and sleeves and bed the bolts in sealant to keep water out.

8. Hard You are the tradesperson. A homeowner used ordinary electroplated nails to hang joist hangers on new pressure-treated lumber. What will happen, and what should be used?

Show answer

The copper preservative will corrode the thin zinc and then the steel, and the connection will weaken within years. Use the hanger maker's specified hot-dip galvanized (G185) or stainless nails or structural screws, matched to the hanger's coating.

9. Hard A fabricator proposes to replace one long threaded hanger rod with two short rods joined at a beam, "to make installation easier." As the engineer or the foreman, what do you check before saying yes?

Show answer

Trace the load path: does the beam or connection now carry loads it did not before? Calculate the new forces on the beam, nut, washer and welds, compare with their capacities and the code, and document the approval in writing. This is exactly the change that caused the Hyatt Regency collapse.

10. Hard A 3/8 in Grade 5 bolt is in single shear. Compare its capacity if the smooth shank crosses the shear plane (area 0.110 in^2) and if the threads do (root area about 0.068 in^2).

Show answer

Shank: $72{,}000 \times 0.110 \approx 7{,}900$ lb; threads: $72{,}000 \times 0.068 \approx 4{,}900$ lb. About 38% less. Choose bolt length so threads stay out of the shear plane.

11. Challenge A bracket must carry 6,000 lb with a factor of safety of 4. It uses two Grade 5 bolts in double shear with shanks in the shear planes. Find the smallest bolt diameter, then choose a standard size.

Show answer

Ultimate needed: 24,000 lb; four shear planes, so 6,000 lb each. Area: $6{,}000/72{,}000 = 0.0833\ \text{in}^2$; $d = \sqrt{4(0.0833)/\pi} = 0.326$ in. Choose 3/8 in (0.110 in^2) or larger, and check the plates for bearing and tear-out.

COMMON MISTAKES

- Assuming a bolt is strong because it is big. An unmarked Grade 2 bolt may carry less than half what a Grade 8 of the same size can.

- Letting threads fall in a shear plane, which cuts shear capacity sharply.
- Mixing stainless and aluminum, or plain steel and treated lumber, without protection.
- Approving a “minor” change in a connection without recalculating the load path.

> **Make it a game · Head Marking Match.** Draw bolt head markings on index cards: three radial lines for Grade 5, six for Grade 8, 8.8 and 10.9 numbers for metric. On the backs, write the proof strengths. Play memory match with your parent on the table. Explain, for each match, why threads should stay out of shear planes.

> **Scripture.** “But let every man take heed how he buildeth thereupon.” (1 Corinthians 3:10, KJV)
>
> Paul uses a builder’s warning that every tradesperson should take literally: the person who changes a detail is responsible for checking it.

1.5 Nails, Rivets, Pins and Choosing a Fastener

OBJECTIVES

- Tell wrought, cut and wire nails apart, use them to date old buildings, and read penny sizes.
- Calculate nail and screw withdrawal resistance with the NDS formulas and compare withdrawal with shear.
- Explain how hot rivets and aircraft rivets clamp and carry load, and choose the right fastener (nail, screw, bolt, rivet, pin or anchor) for a job using a decision table.

> **Warm-up.** Look at a wooden fence, deck, shed or old piece of furniture. Find at least three different kinds of fasteners. For each, guess whether it is pulled along its length (withdrawal) or pushed sideways (shear) when the thing is used.

WATCH

Do Nails or Screws Have the Most Holding Strength (not shear strength)? Let's find out!

Project Farm · 13:09

https://www.youtube.com/watch?v=kAxGAIFbqu4

> **WHEN TO WATCH**
> Before the shop project. Watch how he measures pull-out force, then design your own test to be just as fair.

BACKUP VIDEO

Do Screws Shear easier than Nails? Let's find out!

Project Farm · 13:30

https://www.youtube.com/watch?v=qmajKElnwfE

With the paragraph on withdrawal and shear: the same fasteners tested sideways, with very different results.

KEY TERMS

cut nail

A nail sheared from iron or steel plate by machine, with a rectangular, tapered shank and blunt tip; common from about the 1790s to the 1890s.

wire nail

A nail made from round drawn wire, with a pointed tip; the common nail of the twentieth century.

penny size (d)

The traditional length system for nails: 8d is 2-1/2 in, 10d is 3 in, 16d is 3-1/2 in.

withdrawal

A load that pulls a fastener out along its length.

rivet

A permanent fastener with a head on one end whose other end is upset (hammered or pressed) to form a second head.

blind rivet

A rivet set from one side of the work by pulling a mandrel, used where the back cannot be reached.

CORE IDEAS

The story. Between 1887 and 1889, Gustave Eiffel's company built a 300-meter iron tower in Paris from about 18,000 iron pieces joined by about 2.5 million rivets. The holes were drilled in the factory to within a tenth of a millimeter, so the parts went together like a giant kit. Four-man teams did the riveting: one heated the rivet in a small forge until it glowed red, one placed it in the hole, one held a heavy dolly against its head, and one hammered the other end into a second head. Forty years later the same craft raised the Empire State Building (1930–31) in just over a year. Lewis Hine photographed its riveting gangs high above Manhattan: the heater tossing a red-hot rivet, the catcher snagging it in a tin can, the bucker-up holding it, and the riveter driving it with a pneumatic hammer.

How they figured it out. Nails have their own history, and it helps carpenters date old houses. Before about 1800, every nail was hand-forged by a blacksmith, with a tapered square shank and a hammered head. In the 1790s American inventors built machines to cut nails from iron plate; Jacob Perkins, whom you will meet again in Unit 6 with his refrigeration machine, patented a nail-cutting machine in 1795. Cut nails, rectangular and tapered with blunt tips that crush rather than split the wood, framed most houses until the 1890s, when cheap steel wire made round wire nails

win. So: hand-wrought nails suggest before about 1800, cut nails roughly 1800–1890s, wire nails after. (Cut nails are still made for masonry and restoration.) Riveting changed too. Hot rivets were slow and needed a gang of skilled workers, so after high-strength structural bolts were standardized in 1951 and welding matured, bridges and buildings switched to bolts and welds. But riveting lives on in aircraft, where cold aluminum rivets are driven by the hundreds of thousands.

The science. A nail holds by friction: driving it pushes wood fibers aside, and they press back on the shank. The National Design Specification for Wood Construction gives the reference withdrawal resistance of a smooth nail per inch of penetration as $W = 1380\,G^{5/2}D$, where G is the wood's specific gravity and D the nail diameter in inches; for a wood screw it is $W = 2850\,G^{2}D$. Because a screw's threads lock into the wood, a screw resists withdrawal three or four times as well as a nail of the same size. But in **shear** (sideways), the soft steel of a common nail bends and keeps holding, while a hard, brittle screw (especially a drywall screw) can snap. That is why framing is nailed, why building codes give nailing schedules, and why structural screws are made of special tougher steel and carry code approvals. A hot rivet clamps as it cools: a red-hot steel rivet shrinks nearly 1% in length as it cools, far more than it can stretch elastically, so it yields and ends up pulling the plates together with a force near its yield strength. A cold aluminum aircraft rivet clamps less, and carries load mainly in shear and bearing against the hole.

In the shop. Choose the fastener by the load and the materials: **nails** for framing and sheathing in shear (fast, ductile, code-approved); **wood screws and structural screws** where withdrawal matters or parts must come apart (decks, cabinets, ledgers with approved screws); **bolts** for heavy or adjustable connections and metal parts; **rivets** for permanent, vibration-proof joints in thin metal (trailers, aircraft, gutters, using blind rivets when the back cannot be reached); **pins** (clevis pins with cotter pins, roll pins, dowel pins) for hinges and alignment; **anchors** for hollow walls and masonry (toggle bolts for heavy loads in drywall, sleeve or wedge anchors in concrete). Whenever possible, hang heavy loads on framing or arrange them so fasteners are in shear rather than withdrawal: a French cleat turns a pull-out load into a sideways load.

Safety. Wear safety glasses when nailing and riveting; nails ricochet and rivet mandrels snap off. Pneumatic nailers with a sequential trigger are safer than bump-fire triggers for beginners; keep your free hand well away from the nail's path.

PICTURE STUDY



Three Riveters, Lewis Wickes Hine, About 1930–31 · Gelatin silver photograph · Empire State Building construction series

Image: Wikimedia Commons, public domain

Lewis Hine climbed the Empire State Building with the ironworkers to photograph them at work. This picture shows a riveting team joining steel in the frame of what was then the tallest building in the world.

Look closely

- Find the riveting gun. Which end of the rivet is the man driving?
- Find the worker bracing on the other side of the beam. What is his job, and why must he push hard?
- Look at the rows of rivets already in the steel. Why are they in neat lines and evenly spaced?
- Look for safety equipment. What would a modern ironworker wear and use that these men did not?

Talk about it

1. Why does a hot rivet pull the plates together as it cools?
2. Why did builders later replace hot rivets with high-strength bolts?
3. What qualities of character does this kind of work require?

> **Safety first.** Wear safety glasses for nailing, screwing and the pull-out test. Hang the bucket low over the floor and stand to the side, because the board and bucket drop suddenly when a fastener lets go.

SHOP PROJECT

Pull-Out Test: Nails versus Screws

You will measure the withdrawal strength of several nails and screws with a bucket of sand and a luggage scale, compare the results with the NDS formulas, and build a decision table you can use for the rest of your life.

You will need

- Two scraps of 2 × 4 (spruce-pine-fir) about 12 in long
- Fasteners: 8d common nails, 8d ring-shank nails, 8d coated sinkers, #8 × 2 in wood screws, #8 × 2 in drywall screws (all driven the same depth)
- A 5-gallon bucket, sand or gravel, a scoop, and a digital luggage scale (or bathroom scale to weigh the bucket)
- A sturdy sawhorse or two chairs and a 2 × 4 to span between them; strong rope; a loop of wire or a nail-pulling hook made from a bent steel strap
- Hammer, drill/driver, 1/8 in bit for pilot holes; safety glasses; shop notebook

Steps

1. Mark five fastener positions on the face of one 2 × 4, at least 2 in apart and 1 in from the edges.
2. Drive each fastener exactly 1-1/4 in deep (mark the depth on the shank with tape). Drill pilot holes for the screws as the box suggests.
3. **Predict.** Using the NDS formulas, predict the withdrawal force for the common nail and the wood screw ($G \approx 0.42$).
4. Hang the board from the spanning 2 × 4 by a rope loop so one fastener points straight down. Hook the bucket to that fastener's head with the wire loop.
5. Add sand slowly with the scoop until the fastener pulls out. Weigh the bucket and sand with the luggage scale. Record the load.
6. Repeat for each fastener type, testing at least three of each in fresh positions (use the second board). Average the results.
7. Compare your averages with your predictions and with the Project Farm results. Explain any big differences (wood density, moisture, knots, coatings).

8. **Shear check.** Fasten a short 2 × 4 block to the face of a long one with a single fastener of each type, hang the long piece, and hang the bucket from the block so the fastener is pushed sideways. Record how each fails: bends, pulls through or snaps.
9. Build a decision table: rows for nails, wood screws, structural screws, drywall screws, bolts, rivets, pins and anchors; columns for withdrawal, shear, removable, cost, speed and typical uses.
10. **Improve it.** Repeat your weakest fastener with one change (a ring-shank instead of smooth nail, or a deeper drive) and measure the improvement.

Tips

- Add sand smoothly; a jerk adds a sudden load and gives a falsely low reading.
- Keep the fastener vertical so the pull is pure withdrawal.
- Record the wood's condition (knots, wet or dry) next to each result.

Check your work

- ☐ My data table gives average withdrawal and shear results for each fastener with at least three trials.
- ☐ I compared measured values with the NDS formulas and explained the differences.
- ☐ I can use my decision table to choose a fastener and defend the choice.

SHOP NOTEBOOK

1. Labeled drawings of a wrought nail, a cut nail and a wire nail, with the dates each was common.
2. Your pull-out and shear data tables with averages and a bar graph.
3. Your fastener decision table, and a sketch of a French cleat showing why it puts screws in shear.

KEY FORMULAS

$W_{\text{nail}} = 1380\, G^{5/2} D$ (lb per in of penetration)
$W_{\text{screw}} = 2850\, G^{2} D$ (lb per in of thread penetration)
$\delta = \alpha L\, \Delta T$
$F_{\text{rivet}} = \tau_u \cdot \frac{\pi}{4} d^2$

From history. High-strength structural bolts (ASTM A325) were standardized in the United States in 1951, and within twenty years hot riveting had almost vanished from building sites. Some historic bridges are still repaired with hot rivets by specialists, and aircraft makers still use solid rivets because they are light, reliable and easy to inspect. During World War II, aircraft factories trained thousands of new workers, many of them women, to drive aluminum rivets, and the riveter became a symbol of skilled factory work.

WORKED EXAMPLES

Example 1. Find the reference withdrawal resistance of a 16d common nail ($D = 0.162$ in) with 1.5 in of penetration in spruce-pine-fir ($G = 0.42$).

Show solution

1. Per inch: $W = 1380\,(0.42)^{2.5}(0.162)$.
2. $(0.42)^{2.5} = 0.42^2 \times \sqrt{0.42} = 0.1764 \times 0.648 = 0.1143$.
3. $W = 1380 \times 0.1143 \times 0.162 \approx 25.6$ lb/in.
4. Total: $25.6 \times 1.5 \approx 38$ lb. (Design values then apply adjustment factors.)

Answer: About 38 lb.

Example 2. Compare a #10 wood screw ($D = 0.190$ in) with 1.25 in of thread in the same wood.

Show solution

1. Per inch: $W = 2850\,(0.42)^{2}(0.190) = 2850 \times 0.1764 \times 0.190 \approx 95.5$ lb/in.
2. Total: $95.5 \times 1.25 \approx 119$ lb.
3. Per inch the screw holds $95.5 / 25.6 \approx 3.7$ times as well as the nail.

Answer: About 119 lb; about 3.7 times the nail per inch.

Example 3. A steel rivet with a 50 mm grip is driven at a temperature at which it fills the hole and grips at about 650 °C, then cools to 20 °C. Steel's expansion coefficient is $12 \times 10^{-6}/^{\circ}\mathrm{C}$. How much would it shrink if free? What stress would that be if it stayed elastic ($E = 200{,}000$ MPa)?

Show solution

1. Shrinkage: $\delta = \alpha L \Delta T = (12 \times 10^{-6})(50)(630) = 0.38$ mm.
2. Strain: $0.38/50 = 0.0076$.
3. Elastic stress: $200{,}000 \times 0.0076 \approx 1{,}500$ MPa, far above the yield strength of rivet steel (about 250 MPa).
4. So the rivet yields as it cools and ends up clamping the plates with a stress near its yield strength.

Answer: About 0.38 mm; the rivet yields and clamps at about its yield stress.

Example 4. An aircraft repair uses 1/8 in aluminum rivets with an ultimate shear strength of about 30,000 psi. How many are needed (single shear) to carry 5,000 lb with a factor of safety of 1.5?

Show solution

1. Area per rivet: $\frac{\pi}{4}(0.125)^2 = 0.0123$ in^2.
2. Strength per rivet: $30{,}000 \times 0.0123 \approx 368$ lb.
3. Required: $5{,}000 \times 1.5 = 7{,}500$ lb; $7{,}500/368 \approx 20.4$, so use 21 rivets (and check bearing and edge distance).

Answer: 21 rivets.

PRACTICE

1. Easy You find a nail in an old house with a rectangular, tapered shank, a blunt tip and a machine-made head. About when was it made?

   Show answer

   It is a cut nail, most likely from about 1800 to the 1890s.

2. Easy How long are 8d and 16d nails?

   Show answer

   8d: 2-1/2 in; 16d: 3-1/2 in.

3. **Easy** Name the four jobs in a hot-riveting gang.

Show answer

Heater, catcher, bucker-up (holder-on) and riveter (gun man).

4. **Medium** Find the withdrawal resistance per inch of an 8d common nail ($D = 0.131$ in) in Douglas fir ($G = 0.50$).

Show answer

$1380 \times 0.1768 \times 0.131 \approx 32$ lb/in.

5. **Medium** Find the withdrawal resistance per inch of a #8 wood screw ($D = 0.164$ in) in Douglas fir.

Show answer

$2850 \times 0.25 \times 0.164 \approx 117$ lb/in.

6. **Medium** Conceptual. If screws hold three or four times better in withdrawal, why are houses framed with nails?

Show answer

Framing loads are mostly shear. Common nails are ductile and bend instead of snapping, they are fast and cheap to drive, and building codes give nailing schedules tested for them. Ordinary screws are harder and can snap in shear unless they are rated structural screws.

7. **Medium** You must hang a 40 lb mirror on drywall where there is no stud. What anchor do you choose, and why not a plastic expansion anchor?

Show answer

A toggle bolt or a heavy snap-toggle anchor rated for the load, which spreads the load behind the drywall. Plastic expansion anchors rely on crumbly gypsum and can pull out. Better yet, move the hanger to a stud or use a French cleat across two studs.

8. **Hard** The Eiffel Tower has about 2.5 million rivets. If one riveting team set 300 rivets a day (an assumed rate), how many team-days of work is that? If 50 teams worked at once, about how many working days?

Show answer

$2{,}500{,}000 / 300 \approx 8{,}300$ team-days; $8{,}300 / 50 \approx 167$ days.

9. Hard You are the tradesperson. A deck's ledger board is pulling away from the house; it was attached with nails only. What is wrong, and what is the fix?

Show answer

The nails are loaded in withdrawal and shear by the deck and people on it, and they have pulled loose; nailed ledgers are not allowed by current codes. Support the deck temporarily, then fasten the ledger to the house's rim joist with through-bolts or code-listed structural ledger screws in the pattern the code or manufacturer specifies, with proper flashing. Have the repair permitted and inspected.

10. Hard A pop rivet joins two thin aluminum sheets. Name three ways the joint can fail and one rule that prevents tear-out.

Show answer

The rivet can shear; the sheet can tear out to the edge or crush around the hole (bearing); the rivet head can pull through thin sheet. Keep the rivet at least two diameters from the edge, and use backup washers in thin or soft material.

11. Challenge A heavy cabinet is hung on four #10 screws driven 1.5 in into studs ($G = 0.42$), loaded straight out in withdrawal. Find the total withdrawal resistance. Then explain how a French cleat changes the loading.

Show answer

Each: $95.5 \times 1.5 \approx 143$ lb; four: about 573 lb (reference value, before safety adjustments). A French cleat hangs the cabinet on a beveled strip screwed to the studs, so the screws carry the weight sideways in shear, which they resist far better, and the cabinet cannot tip out.

COMMON MISTAKES

- Loading fasteners in withdrawal when the job could put them in shear.
- Using drywall screws for structural connections; they snap.
- Using plastic expansion anchors in drywall for heavy loads.
- Driving nails too close to the end of a board, which splits it and destroys holding power.

Make it a game · Penny Size Pop Quiz. Your parent names a nail size, such as 8d, 16d or 3d. You state the length in inches within 10 seconds, then say whether it is better in withdrawal or shear. Switch to identifying wrought, cut and wire nails from a description. Keep a running score and beat your own best streak.

Scripture. “And I will fasten him as a nail in a sure place; and he shall be for a glorious throne to his father’s house.” (Isaiah 22:23, KJV)

A nail in a sure place, driven into sound wood, holds firm. Isaiah uses the picture of a well-placed fastener for a faithful steward on whom a household can depend.

UNIT 1

The Science of Attaching: Screws, Bolts and Fasteners

Everything in a house, a car or a shop is held together by something. In this unit you will learn the science behind the humble screw thread, the difference between screws and bolts, how a tightened bolt works as a stretched spring, how strong bolts of each grade are and how they fail, and when to choose a nail, a rivet, a pin or an anchor instead.

The stories are of craftsmen and engineers who changed how the world fastens things: Henry Maudslay and his screw-cutting lathe, Whitworth and Sellers and their thread standards, P. L. Robertson and Henry Phillips and their screw drives, Gerhard Junker and his loosening machine, the riveting gangs of the Eiffel Tower and the Empire State Building, and the sobering lesson of the Hyatt Regency walkways. You will measure threads, calculate torque and preload, test locking methods, load-test model connections, and pull nails and screws out of wood with a bucket of sand.

PREREQUISITES

- Algebra I: solving formulas for one variable, squares and square roots, scientific notation
- Area of a circle, $A = \frac{\pi}{4}d^2$, and unit conversions (inches and millimeters, pounds and newtons)
- Basic hand tools: a tape measure, a drill/driver and a hammer, used with safety glasses

MASTERY CHECKLIST

- ☐ I can explain the screw as an inclined plane and calculate pitch, lead, helix angle and mechanical advantage.
- ☐ I can read inch and metric thread callouts, tell a screw from a bolt by its use, and choose drive types, pilot holes and thread engagement.
- ☐ I can use $T = K D F$ to relate torque and preload, explain why bolts loosen, and tighten a wheel correctly.
- ☐ I can identify bolt grades and property classes and calculate tensile, proof and shear capacities.
- ☐ I can explain galvanic corrosion and the Hyatt Regency connection failure.
- ☐ I can calculate nail and screw withdrawal, explain riveting, and choose the right fastener for a job.

OPTIONAL KITS FOR THIS UNIT

- **Portland Bolt technical guides**: A bolt manufacturer's free technical library: thread pitch charts, grade and head-marking guides, tensile and proof strengths, and torque information; useful for Lessons 1.2–1.4. No purchase needed.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

1.1	**The Screw: From Archimedes to Maudslay's Lathe**	3 sessions of 50 minutes
1.2	**Screws versus Bolts: Thread Anatomy and Standards**	3 sessions of 50 minutes

1.3	**Torque, Preload and Clamp Force**	3 sessions of 50 minutes
1.4	**Bolt Grades, Strength and Failure**	3 sessions of 50 minutes
1.5	**Nails, Rivets, Pins and Choosing a Fastener**	3 sessions of 50 minutes

Unit 1 Test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. Use $A_t = 0.7854(D - 0.9743/n)^2$ where needed. The test is worth 100 points.

1. **5 pts**
   Find the pitch of a 5/16-18 thread in inches and millimeters.

2. **6 pts**
   A screw jack has a 4.0 mm lead and a 0.20 m handle. Find its ideal mechanical advantage. If it is 30% efficient, what force on the handle lifts 6,000 N?

3. **5 pts**
   What did Maudslay's screw-cutting lathe make possible, and why were Whitworth's and Sellers's standards needed afterward?

4. **5 pts**
   Define screw and bolt by their intended use. Which is a lag screw?

5. **5 pts**
   Decode "#10-32 × 3/4" and give the major diameter.

6. **8 pts**
   Find the dry torque ($K = 0.20$) to preload a 3/8-16 Grade 5 bolt to 75% of its proof load (proof strength 85,000 psi).

7. **6 pts**
   Explain what happens if the bolt in the last problem is oiled ($K = 0.15$) but tightened to the same torque.

8. **6 pts**

   Describe Junker's test and its main finding. Name two locking methods that work and one that does not.

9. **6 pts**

   A steel bolt ($A = 0.110$ in^2, $E = 30 \times 10^6$ psi) has a 2.0 in grip and 5,000 lb preload. How much does it stretch?

10. **7 pts**

    Find the tensile capacity of an M10 $\times$ 1.5 class 8.8 bolt ($A_t = 0.7854(d - 0.9382P)^2$).

11. **6 pts**

    A 1/2 in Grade 8 bolt (tensile 150,000 psi) is in single shear with its shank in the shear plane. Estimate its ultimate shear capacity.

12. **6 pts**

    You are the tradesperson. A customer wants to use stainless-steel screws to attach aluminum trim on a boat. What do you advise?

13. **6 pts**

    Find the withdrawal resistance of a 10d common nail ($D = 0.148$ in) driven 2.0 in into Douglas fir ($G = 0.50$).

14. **6 pts**

    Why does a hot rivet clamp the plates it joins?

15. **5 pts**

    Choose a fastener and give a reason: (a) roof sheathing to rafters; (b) a trailer fender to its bracket where the back cannot be reached; (c) a heavy shelf on a concrete wall.

16. **12 pts**

    Short essay. Using the Hyatt Regency walkway collapse, explain why a change to how something is fastened must be checked by calculation, and describe what a responsible tradesperson or engineer does before approving a change.

ANSWER KEY

1. $1/18 = 0.0556$ in $= 1.41$ mm.
2. IMA $= 2\pi(0.20)/0.004 \approx 314$; AMA $= 94$; $6{,}000/94 \approx 64$ N.
3. It let a precise screw be copied exactly, so nuts and bolts could be made in quantity to match. But each shop still chose its own threads; standards made threads interchangeable between shops and across a nation.
4. A bolt is used with a nut through clearance holes and tightened by turning the nut; a screw goes into a tapped hole or forms its own thread and is turned by its head. A lag screw is a screw.
5. Numbered size 10, so $0.060 + 0.013(10) = 0.190$ in; 32 TPI (fine); 3/4 in long.
6. $A_t = 0.0775$ in^2; proof 6,590 lb; preload 4,940 lb;
   $T = 0.20(0.375)(4{,}940) \approx 371$ in $\cdot$ lb ≈ 31 ft $\cdot$ lb.
7. Preload rises to $371/(0.15 \times 0.375) \approx 6{,}600$ lb, right at the proof load. The bolt may stretch permanently; lubricated threads need a lower torque.
8. Junker slid a clamped joint sideways while measuring bolt tension; sideways slip caused rapid self-loosening. Nylon-insert nuts, threadlocker, wedge-locking washers, safety wire and cotter pins work; split lock washers do little.
9. $\delta = \dfrac{5{,}000 \times 2.0}{0.110 \times 30 \times 10^6} \approx 0.0030$ in.
10. $A_t = 0.7854(10 - 1.407)^2 = 58.0$ mm^2; $800 \times 58.0 = 46{,}400$ N ≈ 46 kN.
11. $0.6 \times 150{,}000 \times 0.196 \approx 17{,}700$ lb.
12. Stainless is fine for the screw, but aluminum is more active and will corrode where they touch in salt water. Isolate them with nylon washers or sleeves and bed the screws in marine sealant; or use aluminum-compatible fasteners.
13. $1380(0.1768)(0.148) \approx 36.1$ lb/in; $\times 2.0 \approx 72$ lb.
14. It is set while red-hot and shrinks as it cools; the plates prevent it from shortening freely, so it is stretched past yield and pulls the plates together with a large clamp force.
15. (a) Nails (or code-listed staples) per the nailing schedule: fast, ductile, in shear. (b) Blind (pop) rivets or bolts with locknuts; blind rivets if the back is unreachable. (c) Concrete sleeve or wedge anchors (or screw anchors) rated for the load.
16. Model answer: the change from continuous rods to two rods seemed minor and made fabrication easier, but it doubled the load on the fourth-floor connections,

which were already below code; the nuts pulled through and 114 people died. Any change to a connection changes the load path. A responsible person traces the load path, calculates the new forces and capacities, compares them with the code and a safety factor, asks the designer when unsure, documents the approval, and refuses to proceed until the change is shown to be safe.

PORTFOLIO PIECE: A FASTENER BOARD AND TEST REPORT

Finish your labeled fastener identification board (at least 20 fasteners, each with callout, drive type, grade where marked and a typical use), and mount a thread pitch gauge or a card of thread drawings beside it.

Write a three- to five-page fastener test report that combines your Unit 1 experiments: the C-clamp mechanical advantage, the torque–preload measurements of K, the shake test, and the nail and screw pull-out tests. Include data tables, graphs, comparisons with the formulas, sources of error, and your fastener decision table.

LOOK FOR	WHAT IT MEANS
Identification	Every fastener is correctly identified with a correct callout, drive and use; grades are read correctly.
Measurement	Tests are fair (one change at a time), repeated at least three times, and recorded with units.
Calculation	Mechanical advantage, K, preload and withdrawal predictions are calculated correctly and compared honestly with measurements.
Judgment	The decision table and conclusions show sound reasoning about load direction, materials, corrosion and safety.
Presentation	The board is neat and durable; the report is organized, labeled and clearly written.

UNIT 2

Adhesives: The Chemistry of Sticking

Glue is one of the oldest building materials and one of the most advanced. In this unit you will learn why anything sticks at all, how traditional and modern wood glues work, how a resin and a hardener cross-link into epoxy, how super glue, hot melt, contact cement and construction adhesives each set, and how to decide between glue, fasteners or both.

The stories run from the glued furniture of Tutankhamun's tomb and the gecko's foot to the wooden de Havilland Mosquito, the Gougeon brothers' epoxy boats, Harry Coover's accidental super glue and the hard lessons of Aloha Airlines Flight 243. You will measure contact angles, test surface preparation, break glue joints with a bucket of sand, measure the heat of curing epoxy, build an adhesive chart for your shop, and discover why bonded joints must be designed for shear.

PREREQUISITES

- Unit 1: stress $\sigma = F/A$, shear, factor of safety and the bucket-of-sand test method
- Algebra I: ratios and proportions, solving formulas, exponents
- Basic chemistry vocabulary: molecule, polymer, reaction (helpful but taught where needed)

MASTERY CHECKLIST

- ☐ I can explain adhesion, cohesion and wetting, and use contact angle to predict bonding.
- ☐ I can prepare surfaces for bonding and diagnose adhesive, cohesive and substrate failures.
- ☐ I can choose and use hide glue, PVA, yellow and waterproof wood glues, and plan a glue-up with the right pressure and time.
- ☐ I can mix epoxy by volume or weight, explain cross-linking and exotherm, and use epoxy safely.
- ☐ I can explain how CA, hot melt, contact cement, polyurethane, silicone and construction adhesives set, and choose among them.
- ☐ I can design joints for shear rather than peel and decide when to glue, fasten or both.

OPTIONAL KITS FOR THIS UNIT

- **WEST SYSTEM epoxy (user manual and product guide)**: The Gougeon brothers' company publishes free, detailed guides to epoxy use, fillers and safety; useful for Lesson 2.3. Epoxy from any maker works for the projects.
- **Titebond glue guides**: Free technical data (open time, clamp time, water resistance, strength) for wood glues and construction adhesives; useful for Lessons 2.2 and 2.4.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

2.1 How Glue Works

3 sessions of 50 minutes

2.2	**Wood Glues: Hide Glue to PVA**	3 sessions of 50 minutes
2.3	**Epoxy and Two-Part Chemistry**	3 sessions of 50 minutes
2.4	**Super Glue, Hot Melt, Contact Cement and Construction Adhesives**	3 sessions of 50 minutes
2.5	**Choosing the Joint: Glue, Fasteners or Both**	3 sessions of 50 minutes

Unit 2 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   Define adhesion, cohesion and wetting.

2. **6 pts**
   Water ($\gamma_{LV} = 72.8$ mN/m) sits on a surface where $\gamma_{SV} - \gamma_{SL} = 50$ mN/m. Find the contact angle. Is the surface easy to bond?

3. **6 pts**
   A lap joint 1.0 in wide with a 0.75 in overlap fails at 2,400 lb. Find the average shear stress in psi and MPa.

4. **6 pts**
   Describe the three failure modes and what each tells you.

5. **5 pts**
   List the four steps of good surface preparation.

6. **6 pts**
   Find the clamping force for an edge joint 3/4 in thick and 40 in long at 150 psi, and the number of 750 lb clamps.

7. **6 pts**
   Explain how PVA wood glue sets and why end-grain joints are weak.

8. **6 pts**

   An epoxy mixes 3:1 by volume. How much of each for 60 mL?

9. **6 pts**

   Pot life is 16 minutes at 25 °C. Estimate it at 35 °C and at 15 °C.

10. **7 pts**

    Explain cross-linking and exotherm, and why a deep cup of epoxy can overheat while a thin layer does not.

11. **6 pts**

    What starts the cure of cyanoacrylate, and why is it brittle and poor at filling gaps?

12. **6 pts**

    You are the tradesperson. Choose an adhesive or sealant: (a) laminate on a countertop; (b) a squeaky subfloor; (c) the gap around a bathtub; (d) a small, tight crack in a ceramic figurine.

13. **5 pts**

    A sealant joint 0.60 in wide moves ±0.15 in. What movement rating is needed?

14. **6 pts**

    Joints 25 mm wide fail at 4.8 kN with a 12.5 mm overlap and 6.5 kN with a 25 mm overlap. Find both average shear stresses and explain.

15. **6 pts**

    An adhesive has 3.5 N/mm peel strength. What force peels a 30 mm-wide strip? How does that compare with 30 mm × 25 mm in shear at 12 MPa?

16. **12 pts**

    Short essay. Using Aloha Airlines Flight 243 and one example from your own shop work, explain when a joint should be glued, fastened or both, and what must be true for a hybrid joint to be safe.

ANSWER KEY

1. Adhesion: attraction of the glue to the surface. Cohesion: internal strength of the glue. Wetting: a liquid spreading over and contacting a solid closely.
2. $\cos\theta = 0.687$, $\theta \approx 46.6^\circ$; it is wetted fairly well and is bondable.
3. $2{,}400 / 0.75 = 3{,}200$ psi ≈ 22 MPa.
4. Adhesive (at the interface): poor surface preparation or wrong glue. Cohesive (within the glue): the glue itself is the weak link. Substrate (the material breaks): the bond is stronger than the parts.
5. Clean (degrease), abrade, clean again (remove dust), and bond promptly.
6. $150 \times 30 = 4{,}500$ lb; 6 clamps.
7. PVA is an emulsion; its water soaks into the wood and evaporates, and the polymer particles fuse into a film locked into the wood cells. End grain wicks the glue away and offers only the cut ends of the fibers, so little bond area forms.
8. 45 mL resin and 15 mL hardener.
9. About 8 minutes and 32 minutes.
10. Each resin molecule bonds to several hardener sites, building a three-dimensional network (a thermoset). The reaction gives off heat, and heat speeds the reaction. A deep batch has little surface area per volume to lose heat, so it heats itself and runs away; a thin layer loses heat quickly.
11. Moisture (weak bases) on the surfaces starts a fast chain reaction; it cures from the surfaces inward, so thick gaps cure poorly, and the hard polymer has little toughness in peel or impact.
12. (a) Contact cement. (b) Construction adhesive plus screws. (c) Silicone sealant for kitchen and bath. (d) CA (or a thin epoxy).
13. $0.15 / 0.60 = \pm 25\%$.
14. 15.4 MPa and 10.4 MPa. Stress peaks at the ends of the overlap, so a longer overlap adds mostly lightly loaded area.
15. Peel: 105 N; shear: $12 \times 750 = 9{,}000$ N, about 86 times more.
16. Model answer: the 737's lap joints were bonded and riveted, but the bond degraded from poor durability and moisture, so the rivets carried loads they were not sized for and fatigue cracks linked up. Glue suits shear-loaded, close-fitting joints and thin sheets; fasteners suit concentrated loads, removable joints, heat and inspectable connections; both suit joints that must be strong at once and stiff and sealed for years, like glued-and-screwed subfloors. A hybrid

joint is safe only if the bond is made with proper preparation and durable materials, the fasteners can carry the load alone if the bond fails, and the joint can be inspected.

PORTFOLIO PIECE: A GLUE-TEST REPORT AND ADHESIVE CHART

Combine your Unit 2 experiments into one glue-test report of three to five pages: surface preparation and contact angles, long-grain and end-grain joints, the epoxy ratio and exotherm test, the adhesive-and-material matrix, and the lap-shear, overlap and peel tests. Include data tables, graphs, photos or sketches of failure surfaces, sources of error and conclusions.

Finish a laminated one-page adhesive chart for your shop wall: for each common material pair and job, the recommended adhesive or sealant, surface preparation, clamp and cure times, and safety notes.

LOOK FOR	WHAT IT MEANS
Fair testing	Specimens are identical except for the one variable tested; each condition has at least three trials.
Data and calculation	Loads, areas and stresses are calculated correctly with units; graphs are labeled; averages and spread are reported.
Science	Results are explained with wetting, surface energy, cross-linking, setting mechanisms and loading modes.
Judgment	The chart and recommendations choose glue, fasteners or both sensibly, with surface preparation and safety included.
Presentation	The report and chart are organized, clear and neat enough to use in a real shop.

2.1 How Glue Works

OBJECTIVES

- Explain adhesion and cohesion and the main ways an adhesive holds: wetting and intermolecular forces, mechanical interlock, chemical bonding and diffusion.
- Use surface energy and contact angle (Young's equation) to predict whether a liquid adhesive will wet a surface, and calculate the shear strength of a lap joint.
- Prepare surfaces correctly for bonding and read a broken joint to tell adhesive, cohesive and substrate failure apart.

> **Warm-up.** Put one drop of water on each of these: a clean glass, a plastic grocery bag, a piece of waxed paper and a sheet of aluminum foil you have rubbed with a fingertip. Look at each drop from the side. Sketch the shapes. Which surfaces does water spread on, and which make it bead up?

WATCH

The Stickiest *Non-Sticky* Substance

Veritasium · 13:18

https://www.youtube.com/watch?v=vS0TuIPoeBs

> **WHEN TO WATCH**
> After the story. Listen for why the gecko's tiny hairs need to get within a few billionths of a meter of the surface.

Note: Stanford engineers show how van der Waals forces let geckos and gecko-inspired grippers stick without glue. A sponsor message runs near the end.

BACKUP VIDEO

How Does Glue Work? (feat. VSauce) | James May's Q&A | Earth Science

BBC Earth Science · 6:10

https://www.youtube.com/watch?v=hzFQ6LefGCo

Any time in session 1: a light, quick overview of mechanical and specific adhesion and where old glues came from.

KEY TERMS

adhesion

The attraction that holds an adhesive to the surface of another material (the adherend or substrate).

cohesion

The internal strength that holds the adhesive itself, or any one material, together.

wetting

A liquid spreading over and making intimate contact with a solid surface.

surface energy

The extra energy of molecules at a surface; a liquid wets a solid well when the solid's surface energy is higher than the liquid's surface tension.

contact angle (θ)

The angle a liquid drop makes with a solid at its edge: small angles mean good wetting, angles over 90° mean poor wetting.

failure mode

How a joint breaks: adhesive failure (at the interface), cohesive failure (within the glue) or substrate failure (the material itself breaks).

CORE IDEAS

The story. When Howard Carter opened the tomb of Tutankhamun in 1922, he found chests, chairs and a throne made more than 3,300 years earlier, covered with thin veneers and inlays of ebony, ivory and gold. Many were held on with animal glue, boiled from hides and bones. Egyptian wall paintings show carpenters heating glue pots, and hide glue remained the woodworker's glue for thousands of years: in violins, harpsichords and fine furniture it is still used, because it can be undone with heat and moisture for repair. Yet for most of history nobody knew *why* glue sticks. A modern clue came from an animal. Geckos run up glass and hang from ceilings with no glue at all. In 2000, Kellar Autumn, Robert Full and their colleagues measured the force of a single hair (a *seta*) from a gecko's toe, about one-tenth the width of a human hair, and found it pulled with about 200 micronewtons. Multiplied by the roughly 6.5 million setae on a tokay gecko's feet, that is enough, in principle, to hold over a hundred kilograms.

How they figured it out. Scientists had proposed suction, tiny hooks and sticky secretions for geckos. Autumn's team tested each idea: geckos stick in a vacuum (so not suction), on polished glass (so not hooks), and their feet have no glands. In 2002

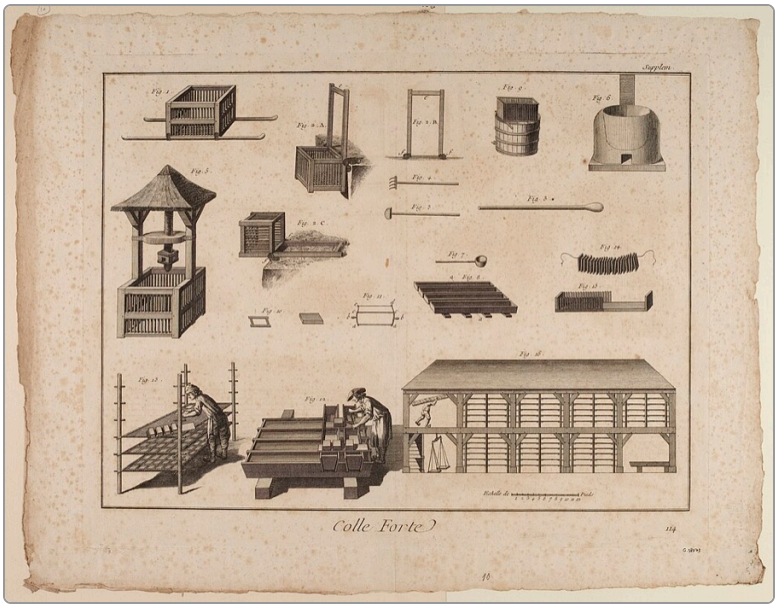
they showed that setae stick about equally to water-loving and water-repelling surfaces, which ruled out water films and pointed to *van der Waals forces*, the weak attraction between all molecules that are very close together. Each seta branches into hundreds of tiny spatulas only about 200 nanometers wide, which bend to get within a few nanometers of the surface everywhere. That is the secret of all adhesion: intermolecular forces are strong only at distances of about a nanometer, and real surfaces are rough. A liquid glue solves the problem by flowing into every valley and making molecular contact over the whole surface; then it hardens so it can carry load.

The science. A bonded joint has three parts: two *adherends* and the adhesive between them. **Adhesion** holds the glue to each surface; **cohesion** holds the glue together. Adhesion comes from several mechanisms acting together: (1) *adsorption*: van der Waals forces and hydrogen bonds once molecules are in contact; (2) *mechanical interlock*: glue flowing into pores and scratches and hardening there, like roots in soil; (3) *chemical bonding*: true covalent bonds, as with some primers and epoxies on metal oxides; (4) *diffusion*: polymer chains mixing across the interface, as when PVC cement softens both pipe and fitting. None of this works without **wetting.** A drop on a solid settles at a contact angle θ given by Young's equation, $\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta$. If the solid's surface energy is higher than the liquid's surface tension, the liquid spreads. Water's surface tension is about 72 mN/m and most liquid adhesives are about 35–45 mN/m, so they wet clean metal, glass and wood readily, but not polyethylene (about 31) or PTFE (Teflon, about 18–20), which is why milk jugs and nonstick pans are so hard to glue.

In the shop. Most bond failures are surface failures. The rule is **clean, abrade, clean, bond.** Remove oil and wax with a solvent such as isopropyl alcohol or acetone on a clean rag. Abrade with 80–120 grit sandpaper or an abrasive pad to remove weak oxide and old finish and to add texture for mechanical interlock. Wipe off the dust, and bond soon, before the surface is contaminated again. A quick test: water should sheet out evenly on a clean surface (the *water-break test*); if it beads, the surface is still dirty. When a joint is tested to destruction, read the break. *Adhesive failure* (glue on one side, bare clean surface on the other) means poor preparation or the wrong glue. *Cohesive failure* (glue on both sides) means the bond was good and the glue itself was the weakest link. *Substrate failure* (torn wood fibers, broken plastic) means the joint was stronger than the material: the best result.

Safety. Solvents for cleaning are flammable and their vapors can ignite; use them outdoors or with good ventilation, away from flames and pilot lights, and wear gloves and eye protection. Read the safety data sheet of every adhesive you use.

PICTURE STUDY



The Glue Maker's Workshop (Colle Forte), Plate from the Supplement to Diderot and d'Alembert's *Encyclopédie*, 1770s · Engraving · *Supplément à l'Encyclopédie*

Image: Wikimedia Commons, public domain

The French *Encyclopédie* set out to describe every trade so clearly that anyone could understand it. This plate shows how "strong glue" (hide glue) was made: scraps of hide were soaked, boiled, strained, set into jelly, cut into thin sheets and dried.

Look closely

- Find the kettles where hides were boiled. What was being extracted from them?
- Find the sheets of glue drying on nets or racks. Why dry glue in thin sheets?
- Look for the tools at the bottom of the plate. Which would you use to strain or cut the glue?
- Follow the steps of the process from left to right. Where does the liquid become a solid?

Talk about it

1. Hide glue gels as it cools and hardens as it dries. Which of the adhesion mechanisms in this lesson does it rely on in wood?
2. Why did a woodworker reheat hide glue in a pot before using it?

3. Why is a clear, step-by-step picture of a trade useful even today?

Safety first. Wear nitrile gloves and safety glasses when using epoxy and solvents, work with good ventilation, and keep solvents away from flames. Aluminum flashing has sharp edges: wear gloves when cutting it and file the cut edges.

SHOP PROJECT

Wetting, Surface Preparation and Failure Modes

You will photograph water drops to estimate contact angles on several surfaces, then bond test strips with the same epoxy but four different surface preparations, break them with a bucket of sand, and read each failure.

You will need

- Surfaces: a glass jar, a piece of acrylic or polycarbonate, a milk-jug panel (HDPE), waxed paper, aluminum flashing
- A dropper, water, a phone camera, a protractor (or a protractor app)
- Aluminum flashing cut into 1 × 4 in strips (16 strips) and milk-jug strips 1 × 4 in (4 strips)
- 5-minute two-part epoxy, mixing sticks and cups; isopropyl alcohol; 120-grit sandpaper; a little cooking oil
- A 5-gallon bucket, sand, a luggage scale, a sturdy hanging support, two small spring clamps
- Nitrile gloves, safety glasses, shop notebook

Steps

1. Place a water drop on each surface. Photograph it from the side at drop level and measure the contact angle on the screen with a protractor. Repeat three times and average.
2. Wipe one area of the aluminum with oil, clean another with alcohol, and sand and clean a third. Measure the contact angle on each. Do the water-break test on each.
3. **Predict.** Rank the four preparations (as received, oily, alcohol-cleaned, sanded and cleaned) from weakest to strongest bond.
4. Prepare four pairs of aluminum strips each way (16 strips), marking a 1/2 in overlap at one end of each strip.
5. Mix the epoxy exactly as directed and bond each pair with a 1 in × 1/2 in overlap. Bond two pairs of milk-jug strips the same way after alcohol cleaning, and two after sanding. Clamp lightly and cure 24 hours.

6. Drill a small hole in the free end of each strip. Hang one end from the support and hang the bucket from the other with a wire hook.
7. Add sand slowly until the joint breaks. Weigh the bucket and sand. Calculate the average shear stress in psi.
8. Examine every break and record its failure mode: adhesive, cohesive or substrate (did the aluminum bend or tear?).
9. Make a table and bar graph of average strength for each preparation, with the contact angles beside them.
10. **Check your work.** Did contact angle predict bond strength? Write a paragraph explaining your results with the words wetting, surface energy and failure mode.

Tips

- Mix epoxy for a full minute and scrape the sides of the cup.
- Handle prepared surfaces by the edges only; a fingerprint is enough to weaken a bond.
- If the aluminum strips bend before the joint breaks, note it: that is a sign of a strong bond.

Check your work

- ☐ I measured contact angles and connected them to wetting and surface energy.
- ☐ My data show how surface preparation changes bond strength, with at least two trials each.
- ☐ I can identify adhesive, cohesive and substrate failures.

SHOP NOTEBOOK

1. Side-view sketches of water drops on each surface with the contact angle marked, and a sketch of Young's equation as three surface-tension arrows at the edge of a drop.
2. A magnified sketch of a glue line: two rough surfaces with glue flowing into the valleys, labeled with the four adhesion mechanisms.
3. Your bond-strength data table, graph and failure-mode photos or sketches.

KEY FORMULAS

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV}\cos\theta \quad \Rightarrow \quad \cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$$

$\tau_{\text{avg}} = \dfrac{F}{b\,L}$ (lap joint of width b and overlap L)

$1\ \text{MPa} = 1\ \text{N/mm}^2 \approx 145\ \text{psi}$

From history. Gecko research has become engineering. Mark Cutkosky's lab at Stanford built a climbing robot, Stickybot, in 2006 with gecko-like feet, and gecko-inspired grippers have been tested on the International Space Station to grab objects in vacuum, where suction cannot work. Industry uses the same science in plasma and flame treatment lines that raise the surface energy of plastic car bumpers so paint and adhesives will stick.

WORKED EXAMPLES

Example 1. A standard lap-shear coupon of aluminum is 1.0 in wide with a 0.50 in overlap. The bonded joint breaks at 1,850 lb. Find the average shear strength in psi and MPa.

Show solution

1. Bonded area: $A = bL = 1.0 \times 0.50 = 0.50\ \text{in}^2$.
2. Average shear stress: $\tau = F/A = 1{,}850/0.50 = 3{,}700\ \text{psi}$.
3. Convert: $3{,}700/145 \approx 25.5\ \text{MPa}$.

Answer: About 3,700 psi (25.5 MPa).

Example 2. Autumn's team measured about 200 μN per seta. A tokay gecko has about 6.5 million setae and a mass of about 70 g. What force could all the setae hold if they all engaged at once, and how many times the gecko's weight is that?

Show solution

1. Total: $(200 \times 10^{-6}\ \text{N})(6.5 \times 10^{6}) = 1{,}300\ \text{N}$.
2. Weight: $0.070\ \text{kg} \times 9.81\ \text{m/s}^2 \approx 0.69\ \text{N}$.
3. Ratio: $1{,}300/0.69 \approx 1{,}900$. A gecko uses only a tiny fraction of its possible grip, which is why it can peel its toes off easily.

Answer: About 1,300 N, nearly 2,000 times its weight.

Example 3. Water ($\gamma_{LV} = 72.8$ mN/m) is placed on two surfaces. On the first, $\gamma_{SV} - \gamma_{SL} = 60$ mN/m; on the second, $\gamma_{SV} - \gamma_{SL} = -6$ mN/m. Find each contact angle and say which surface is easier to bond.

Show solution

1. First: $\cos\theta = 60/72.8 = 0.824$, $\theta \approx 34.5^\circ$.
2. Second: $\cos\theta = -6/72.8 = -0.082$, $\theta \approx 94.7^\circ$.
3. The first is wetted well (like clean glass or metal). The second is a low-energy surface (like polyethylene): liquids bead up, and ordinary glues will not wet it.

Answer: $\approx 34.5^\circ$ and $\approx 94.7^\circ$; the first bonds much more easily.

Example 4. You are the tradesperson. Three broken glue joints come back from a customer. (a) Two pieces of wood with wood fibers torn out and stuck to the glue. (b) A metal bracket whose epoxy stayed entirely on the plastic part; the metal is shiny and bare. (c) Two steel plates with a layer of hardened glue on both faces. Diagnose each.

Show solution

1. (a) Substrate failure: the glue and the bond were stronger than the wood. Nothing to fix in the gluing; the joint design or the load was the problem.
2. (b) Adhesive failure at the metal: the metal was not cleaned and abraded, or it was oily. Degrease, abrade, wipe and rebond.
3. (c) Cohesive failure: the glue held to both surfaces but broke within itself. Use a stronger or tougher adhesive, a thinner bond line, or a larger bonded area.

Answer: (a) substrate; (b) adhesive (poor surface prep); (c) cohesive (glue too weak).

PRACTICE

1. Easy Define adhesion and cohesion in one sentence each.

   Show answer

   Adhesion is the attraction between the glue and the surface it is stuck to; cohesion is the internal strength of the glue (or any material) itself.

2. **Easy** Which failure mode shows the best possible bond, and why?

   Show answer

   Substrate failure: the material broke before the glue or the interface, so the bond was stronger than the parts.

3. **Easy** Convert 3,000 psi to MPa.

   Show answer

   $3{,}000/145 \approx 20.7$ MPa.

4. **Medium** A lap joint 25 mm wide with a 12.5 mm overlap fails at 4.5 kN. Find the average shear strength.

   Show answer

   $4{,}500\ \text{N}/(25 \times 12.5)\ \text{mm}^2 = 14.4$ MPa.

5. **Medium** Water beads up on a plastic part you need to glue. What does that tell you, and what can you do?

   Show answer

   The plastic has low surface energy (likely polyethylene or polypropylene), so ordinary adhesives will not wet it. Abrade it, treat it with a quick flame pass or a primer made for polyolefins, or use an adhesive made for low-energy plastics; or switch to a mechanical fastener.

6. **Medium** Find the contact angle when $\gamma_{LV} = 72.8$ mN/m and $\gamma_{SV} - \gamma_{SL} = 40$ mN/m.

   Show answer

   $\cos\theta = 0.549$, $\theta \approx 56.7^\circ$.

7. **Medium** Give three reasons sanding a surface before gluing improves the bond.

   Show answer

   It removes weak oxide, old finish and contamination; it creates texture for mechanical interlock; and it increases the true surface area in contact with the glue.

8. Hard You are the tradesperson. An epoxy-bonded hook falls off an aluminum boat rail, leaving a perfectly clean, shiny patch on the metal. What happened, and how do you rebond it?

Show answer

Adhesive failure at the aluminum: the surface was oily, or its oxide was weak or contaminated. Degrease with solvent, abrade with an abrasive pad or 80-grit paper, wipe clean, and apply epoxy within the hour; clamp lightly until cured.

9. Hard For two flat surfaces the van der Waals attraction per area falls roughly as $1/d^3$ with gap d. How much weaker is it at a gap of 4 nm than at 0.4 nm? What does this say about why glue must be a liquid when applied?

Show answer

$(0.4/4)^3 = 1/1000$: a thousand times weaker. Only a liquid can flow into the roughness of real surfaces and bring molecules within a nanometer everywhere; then it must harden to carry load.

10. Hard Why do furniture restorers still use hide glue to reglue an antique chair, instead of modern PVA?

Show answer

Hide glue is reversible with heat and moisture, so the chair can be taken apart again later; new hide glue bonds to old hide-glue residue, while PVA does not stick well to it; and it matches the original materials.

11. Challenge A sign bracket must carry 2,000 N in shear with a factor of safety of 4, bonded with an adhesive whose average lap-shear strength is 10 MPa. The overlap is 50 mm wide. Find the overlap length needed by the simple average-stress method, then explain why a real designer would make it longer.

Show answer

Required capacity: 8,000 N; area $8{,}000/10 = 800$ mm^2; length $800/50 = 16$ mm. In real lap joints the shear stress peaks at the ends of the overlap and peel stresses appear, so strength does not grow in proportion to overlap; designers add margin and avoid peel (Lesson 2.5).

COMMON MISTAKES

- Skipping surface preparation, or touching a cleaned surface with bare fingers.

- Thinking more glue makes a stronger joint. A thin, even, complete bond line is strongest.
- Trying to glue polyethylene, polypropylene or PTFE with ordinary glues.
- Blaming the glue for an adhesive failure that was really a dirty surface.

Make it a game · Wet or Bead Up. Put a drop of water on wax paper, plastic wrap, a clean plate and a paper towel. Predict whether each wets or beads, and explain with surface energy and contact angle. Check and score a point per correct call. Then name the failure mode you would expect if a glued joint peeled cleanly off a greasy surface.

Scripture. “From whom the whole body fitly joined together and compacted by that which every joint supplieth” (Ephesians 4:16, KJV)

Paul describes the church as a body fitly joined, held together by what every joint supplies. A good joint is close-fitting and complete, and each part does its share.

2.2 Wood Glues: Hide Glue to PVA

OBJECTIVES

- Explain how hide glue, casein glue, PVA (white glue) and aliphatic resin (yellow glue) set, and compare their strength, water resistance, open time and reversibility.
- Calculate clamping force, bond strength from block-shear tests, and the time budget for a glue-up.
- Explain why long-grain glue joints are stronger than the wood and why end-grain joints are weak, and glue up a joint correctly.

> **Warm-up.** Squeeze a drop of white school glue onto a scrap of wood and another onto a piece of glass. Check them every five minutes during the lesson. Which dries first? Why might wood make a difference?

WATCH

Which Wood Glue is Best? Let's find out! Showdown with Titebond, Flex Glue, Elmer's & Gorilla.

Project Farm · 14:24

https://www.youtube.com/watch?v=k-g3efGa3sI

> **WHEN TO WATCH**
> After the science paragraph. Note how many joints broke in the wood rather than the glue line.

BACKUP VIDEO

Hide Glue! - Primitive Adhesive from the 1700's

Townsends · 9:13

https://www.youtube.com/watch?v=Qwyyi5-Ye7c

With the story: an eighteenth-century trade manual and a demonstration of making and using hide glue over an open fire.

KEY TERMS

hide glue

Animal glue made by boiling collagen from hides and bones; used hot, it gels as it cools and hardens as it dries; reversible with heat and moisture.

casein glue

Glue made from milk protein and lime; it sets chemically and was the first fairly water-resistant woodworking glue.

PVA (polyvinyl acetate)

A synthetic polymer dispersed in water as tiny particles: white glue and, modified, yellow carpenter's glue (aliphatic resin).

open time

How long a spread glue can sit before the parts are assembled and still make a good bond.

clamp time

How long a joint must stay under pressure before it can be handled; full cure takes longer.

long grain and end grain

Long grain is the side of a board, where fibers lie along the surface; end grain is the cut end, where fibers are cut across like a bundle of straws.

CORE IDEAS

The story. For thousands of years, a woodworker's glue pot sat warming near the bench, holding hide glue made from the collagen in animal skins. Violin makers in Cremona, cabinetmakers like Thomas Chippendale, and the Shaker furniture makers all used it. It had real limits: it had to be used hot and fast, and water softened it. During World War I, when airplanes were built of spruce and plywood, the U.S. Forest Products Laboratory in Madison, Wisconsin, tested glues for propellers and wings and developed improved, more water-resistant casein glues made from milk protein. The great change came with synthetic polymers. Polyvinyl acetate was first made in Germany in 1912, and after World War II water-based PVA glues reached every home and shop. In 1947 the Borden Company began selling a white glue called Glue-All, soon named for Elmer, the bull who was a partner of its cow mascot Elsie; it was first made from casein and later from PVA. Yellow "carpenter's glue," an aliphatic resin (a modified PVA that grabs faster and sands cleaner), followed, and water-resistant versions such as Titebond II and III now make outdoor projects possible.

How they figured it out. How do you prove a glue is good? The Forest Products Laboratory and standards bodies developed the *block-shear test* (ASTM D905): two blocks of hard maple are glued face to face, then one is pushed along the glue line in a testing machine. Two things are recorded: the shear stress at failure and the *percent wood failure*, how much of the broken surface is torn wood rather than glue. A good wood glue scores high on both, and modern PVA glues typically test at about 3,600–4,000 psi on maple, according to their makers. Since hard maple itself fails in shear along the grain at only about 2,300 psi, the glue line is stronger than the wood. Other tests soak or boil specimens to rate water resistance: Type II (water resistant) and Type I (waterproof enough for exterior use) under the ANSI/HPVA standard.

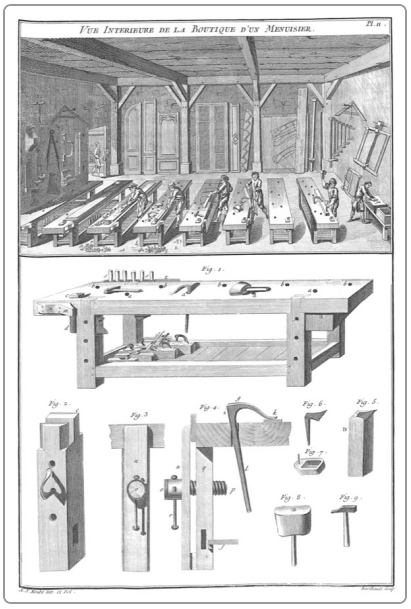
The science. Each wood glue sets in a different way. **Hide glue** is a protein solution: as it cools it gels (the protein chains tangle into a network), then it hardens as water leaves it; heat and moisture reverse both steps. **Casein** sets by chemical reaction with lime. **PVA and yellow glues** are *emulsions*: millions of polymer particles suspended in water. When you clamp a joint, the water soaks into the wood cells and evaporates; the particles crowd together and fuse into a continuous plastic film that has also flowed into the cut cell walls of the wood (mechanical interlock plus hydrogen bonding to the cellulose). That is why PVA sets quickly on wood but slowly on glass. **Long grain to long grain** is the ideal joint: the glue bonds along the sides of the fibers over a large area. **End grain** is a bundle of open tubes that wicks the glue away and offers only the tiny ends of the fibers, so end-grain glue joints have only a small fraction of the strength of long-grain joints and need mechanical help (dowels, tenons, biscuits, or a joint that turns end grain into long grain, as you will learn in Unit 3).

In the shop. Fit first: glue fills only tiny gaps, so joints must close without force. Spread an even, thin film on one or both surfaces (both for end grain or oily woods), assemble within the *open time* (about 5 minutes for Titebond Original, longer for Titebond III, according to the maker), and clamp with moderate pressure: about 100–150 psi for softwoods, 125–175 psi for medium woods and 175–250 psi for hard maple or oak. A thin, even line of small beads of squeeze-out shows the right amount of glue. Clean squeeze-out with a damp rag at once or scrape it when rubbery, because dried glue seals the wood and stain will not take. Keep clamps on for the clamp time (often 30–60 minutes for unstressed joints) and do not stress the joint for

24 hours. PVA glues should not be used below their minimum temperature (often about 50 °F) and are spoiled by freezing.

On the job. Cabinetmakers and finish carpenters glue every day, and furniture restorers still keep a hide-glue pot. Choosing the right glue and clamping it properly is one of the first things a good shop teaches an apprentice.

PICTURE STUDY



Inside a Joiner's Shop, with His Workbench, André-Jacob Roubo, 1769 · Engraving · From Roubo, *L'Art du menuisier*, Plate 11, published by the Académie Royale des Sciences

Image: Wikimedia Commons, public domain

André-Jacob Roubo was a Paris joiner who wrote and engraved the greatest book on woodworking of his century. This plate shows the inside of a joiner's shop and the heavy workbench that is still copied by woodworkers today. Every frame and panel in this shop was glued with hide glue.

Look closely

- Count the workbenches in the shop. Why does each worker need such a heavy bench?
- Find the holdfast (the hooked iron rod) in the lower drawing. How does it clamp a board to the bench?
- Find the vise on the bench's front leg. What could a joiner hold in it while glue sets?
- Look at the finished doors and panels against the back wall. Which joints in them would be glued long grain to long grain?

Talk about it

1. Hide glue gels as it cools. How would that affect how fast these joiners had to assemble a door frame?
2. Why would a joiner make a test joint before gluing up a whole door?

3. What has changed between this shop and a modern one, and what has stayed the same?

Safety first. Wear safety glasses when clamping and loading test joints, and stand to the side of the hanging bucket. If you heat hide glue, use a glue pot, a slow cooker or a double boiler, never an open flame indoors, and keep the temperature below about 150 °F (65 °C).

SHOP PROJECT

Long Grain, End Grain and Glue

You will glue wood strips in long-grain lap joints and end-grain butt joints with two glues, break them with a bucket of sand, and measure both the breaking load and the percent wood failure, just as the standard block-shear test does.

You will need

- Pine or poplar strips about 3/4 × 3/4 in (or 1/4 × 1-1/2 in lattice or paint stirrers), cut to 6 in lengths
- Yellow wood glue (Titebond Original or similar) and one other: liquid hide glue, white school glue or Titebond III
- Small spring clamps or rubber bands; wax paper
- A 5-gallon bucket, sand, a luggage scale, a sturdy support and wire hooks; a drill
- Safety glasses; shop notebook

Steps

1. Cut at least 24 strips the same size. Mark a 1 in overlap on one end of half of them.
2. **Predict.** For each glue, predict the breaking load of a long-grain lap joint and an end-grain butt joint.
3. Make three long-grain lap joints with each glue (1 in overlap on the wide faces), clamped with moderate pressure. Wipe off squeeze-out.
4. Make three end-grain butt joints with each glue: glue two strips end to end. For three more, size the end grain first with a thin coat, wait 5 minutes, then glue.
5. Let all joints cure 24 hours at room temperature on wax paper.
6. Drill a hole near each outer end. Hang each joint from the support and hang the bucket below. Add sand slowly until the joint breaks. Weigh the load.
7. Measure each glue area and compute the stress at failure in psi.
8. Estimate the percent wood failure on each broken surface (look for torn fibers). Photograph each.

9. Tabulate averages: glue, joint type, load, stress, wood failure. Graph them.
10. **Improve it.** Reinforce one end-grain joint with a 1/4 in dowel or a glued-on side splice (long grain over the joint). Test it and compare.

Tips

- Keep the overlap exactly the same on every lap joint; a larger overlap is not a fair test.
- Do not over-clamp; a starved glue line is weak.
- If the wood breaks away from the joint, record the load: the joint was stronger than the wood.

Check your work

- ☐ I measured breaking stress and wood failure for long-grain and end-grain joints with two glues.
- ☐ I can explain why the long-grain joint is stronger than the wood and why end grain is weak.
- ☐ I can plan a glue-up with the right pressure, number of clamps and time.

SHOP NOTEBOOK

1. A magnified sketch of long grain and end grain with glue, showing why one bonds well and the other does not.
2. A comparison table of hide, casein, PVA, yellow, Titebond III, polyurethane and epoxy glues: how each sets, open time, water resistance, reversibility, best uses.
3. Your test data, graph and photos of failure surfaces.

KEY FORMULAS

$$F_{\text{clamp}} = p \times A_{\text{glue}}$$

$$\tau = \frac{F}{A}$$

$$\text{number of clamps} = \left\lceil \frac{F_{\text{clamp}}}{F_{\text{per clamp}}} \right\rceil$$

From history. Hide glue is still preferred by violin makers because a violin must be opened every few decades for repair: the top is glued on with a weaker hide-glue joint so that it lets go before the wood cracks. Some modern guitar makers use it for the same reason, and because they believe it transmits vibration well.

WORKED EXAMPLES

Example 1. You are edge-gluing two oak boards, each 3/4 in thick and 36 in long, into a tabletop. The recommended clamping pressure is 175 psi. Each bar clamp gives about 800 lb. How many clamps do you need?

Show solution

1. Glue area: $A = 0.75 \text{ in} \times 36 \text{ in} = 27 \text{ in}^2$.
2. Force: $F = 175 \text{ psi} \times 27 \text{ in}^2 = 4{,}725 \text{ lb}$.
3. Clamps: $4{,}725 / 800 = 5.9$, so 6 clamps, spaced about 6–7 in apart, alternating above and below the boards to keep them flat.

Answer: 6 clamps.

Example 2. In a block-shear test, maple blocks glued over a 2.0 in^2 area fail at 7,000 lb with 90% wood failure. Find the shear stress, and explain what the wood failure means if maple's shear strength along the grain is about 2,300 psi.

Show solution

1. Stress: $\tau = 7{,}000 / 2.0 = 3{,}500$ psi.
2. Ninety percent of the broken surface is torn wood: the glue line and the adhesion were stronger than the wood near them.
3. The measured stress is above maple's typical shear strength because the test concentrates failure in the glue line and the wood right beside it is supported by the bond; the high wood failure shows the glue is not the weak link.

Answer: 3,500 psi; the joint is stronger than the wood.

Example 3. A test glues pine strips two ways: long grain to long grain with a 2 in × 3/4 in overlap, which fails at 1,100 lb, and end grain to end grain on a 3/4 in × 3/4 in butt, which fails at 60 lb. Compare the bond stresses.

Show solution

1. Long grain: $1{,}100/(2 \times 0.75) = 733$ psi.
2. End grain: $60/(0.75 \times 0.75) = 107$ psi.
3. The end-grain stress is about $107/733 \approx 15\%$ of the long-grain stress, and the end-grain joint must be reinforced or redesigned.

Answer: About 733 psi and 107 psi; end grain is about 15% as strong.

Example 4. You must glue eight boards into a panel. Spreading glue takes about 45 s per board, and assembling and clamping takes 4 minutes more. The glue's open time is 5 minutes and its total assembly time is about 10 minutes. Will it work?

Show solution

1. Spreading: 8×45 s $= 6$ min. The first board's glue has already passed its 5-minute open time.
2. Total: $6 + 4 = 10$ min, right at the limit with no margin.
3. Better plans: glue up in two batches of four boards; use a glue with a longer open time (such as an extended-time formula); or use a roller to spread faster. Always rehearse the clamp-up dry first.

Answer: Too tight; split the glue-up or use a slower glue.

PRACTICE

1. Easy Name two advantages and one disadvantage of hide glue.

Show answer

Advantages: reversible with heat and moisture for repair, bonds to old hide glue, does not creep. Disadvantage: low water resistance (also short open time when used hot).

2. **Easy** Why does PVA glue set faster on wood than on glass?

   Show answer

   PVA sets when its water leaves. Wood absorbs the water quickly; glass absorbs none, so water must evaporate from the edges.

3. **Easy** Which is stronger: a long-grain glue joint or an end-grain one?

   Show answer

   Long grain, by a large margin.

4. **Medium** Find the clamping force for a softwood edge joint 1.5 in thick and 48 in long at 125 psi.

   Show answer

   $125 \times 72 = 9{,}000$ lb.

5. **Medium** A block-shear sample with 1.5 in^2 of glue area fails at 5,100 lb. Find the shear strength.

   Show answer

   $5{,}100 / 1.5 = 3{,}400$ psi.

6. **Medium** Convert 3,600 psi to MPa.

   Show answer

   $3{,}600 / 145 \approx 24.8$ MPa.

7. **Medium** You are building a cutting board that will be washed often, and a bookcase. Which glue for each?

   Show answer

   Cutting board: a waterproof Type I glue rated for indirect food contact, such as Titebond III. Bookcase: ordinary yellow glue (Titebond Original) is strong and inexpensive.

8. Hard You are the tradesperson. A customer's chair joints keep loosening after being reglued with yellow glue over old glue. Diagnose and fix.

Show answer

PVA does not bond to old glue residue, so the new glue only bonded to a film of old glue. Take the joints apart, scrape or sand off all old glue down to clean wood (or use hide glue, which bonds to old hide glue), check that the joints fit snugly, then reglue and clamp.

9. Hard An edge-glued panel has dark lines and gaps after finishing. Name two likely causes in the glue-up.

Show answer

Joints that did not fit, forced closed with excessive clamp pressure and starved of glue; or squeeze-out that dried and sealed the surface so stain could not penetrate. Also uneven clamping that let the boards slip.

10. Hard Conceptual. Explain, using the structure of wood, why end grain makes a weak glue joint and why glue-sizing (a thin first coat allowed to soak in) helps a little.

Show answer

End grain is a bundle of open cell tubes that wick glue away from the joint and offer only the small cut ends of the fibers. Sizing partly fills the tubes so the second coat stays at the surface, but the joint still has little fiber-to-fiber contact and needs mechanical reinforcement.

11. Challenge A tabletop of five 3/4 in oak boards, each 6 in wide and 60 in long, is edge-glued in one go. Find the total clamping force for 175 psi on each of the four glue lines, the number of 800 lb clamps per glue line, and the total clamps if each clamp spans the whole panel.

Show answer

Each line: $0.75 \times 60 = 45$ in^2; $175 \times 45 = 7{,}875$ lb. Clamps spanning the whole panel squeeze all four lines at once, so the force per line equals the clamp force: $7{,}875/800 \approx 9.8$, so about 10 clamps across the panel, about 6 in apart.

COMMON MISTAKES

- Relying on glue alone in end-grain joints.

- Clamping so hard that most of the glue squeezes out (a starved joint), or so lightly that the joint never closes.
- Leaving squeeze-out to dry on wood that will be stained.
- Using glue that has frozen or gone past its shelf life (stringy or lumpy).

> **Make it a game · Glue Chooser Duel.** Your parent names a job: a cutting board, an outdoor bench, a violin repair, a drawer corner. You choose a glue among hide, casein, PVA and aliphatic resin in five seconds and state one strength and one limit. Add open-time math: with a 10-minute window, can you clamp six joints? Keep score.

2.3 Epoxy and Two-Part Chemistry

OBJECTIVES

- Explain how a resin and a hardener react to form a cross-linked thermoset, and why the mix ratio matters.
- Calculate mix ratios by volume and by weight, estimate how temperature changes pot life, and explain exotherm and runaway heating.
- Use epoxy and fillers correctly for bonding, coating and filling, and tell how bonded wooden and metal aircraft (the de Havilland Mosquito) and epoxy-saturated wooden boats (the Gougeon brothers' WEST System) were built.

> **Warm-up.** Look at the label of any two-part product in your garage (epoxy, auto body filler, a two-part paint). Write down the mix ratio, the pot life or working time, and the warnings. What do you think "Part A" and "Part B" are?

WATCH

The Ultimate Epoxy Competition--Which Epoxy is the Best?

Project Farm · 13:07

https://www.youtube.com/watch?v=XObmZIbHOzY

> **WHEN TO WATCH**
> After Worked Example 3. Compare the fast-setting and slow-setting epoxies' results and connect them to cross-linking.

Note: Fair tests of six epoxies in bending, impact and heat. Watch the grinding segment for technique but always wear safety glasses yourself.

BACKUP VIDEO

SAIL Epoxy Basics: Introduction to Epoxy

WEST SYSTEM Epoxy · 4:26

https://www.youtube.com/watch?v=FJbsVS7M0mY

With the story: Ben Gougeon of WEST SYSTEM explains resin, hardeners and fillers.

KEY TERMS

epoxy resin

A liquid whose molecules end in reactive three-membered epoxide rings.

hardener (curing agent)

Usually an amine whose hydrogen atoms open the epoxide rings and link resin molecules together.

cross-linking

Chemical bonds tying polymer chains into one three-dimensional network, so the material can no longer melt.

thermoset

A plastic that cures into a cross-linked network and does not melt when reheated (epoxy, polyurethane foam, phenolic).

exotherm

Heat released by a chemical reaction; in epoxy, the heat speeds the reaction, which releases more heat.

pot life

How long a mixed batch in its container stays usable before it thickens; spreading it thin extends working time.

CORE IDEAS

The story. In 1940, while most warplanes were built of aluminum, the de Havilland company in England built a twin-engine aircraft almost entirely of wood: the DH.98 Mosquito, first flown in November 1940. Its fuselage was two molded half-shells of balsa wood sandwiched between thin birch plywood skins, glued together over curved forms, and its wing was a wooden box of spruce and plywood. Furniture makers, piano factories and boatbuilders could build parts, and aluminum was saved for other aircraft. The whole airplane depended on glue: first casein, then a synthetic urea-formaldehyde glue called Aerolite, developed by Norman de Bruyne's small company, Aero Research, near Cambridge. Glue failures in hot, humid climates, where casein could weaken, taught hard lessons about durability. De Bruyne went on to develop Redux, one of the first adhesives able to bond metal to metal in aircraft structures. Meanwhile, chemists Pierre Castan in Switzerland and Sylvan Greenlee in the United States had independently invented epoxy resins in the late 1930s and 1940s, and by 1946 the Swiss firm Ciba was selling Castan's epoxy as Araldite.

How they figured it out. In the 1960s, the Gougeon brothers of Bay City, Michigan, built iceboats and sailboats of wood and kept fighting the same enemy: water soaking into wood, swelling it and rotting it. They found that epoxy, unlike the glues of the past, could do three jobs at once: glue the joints, fill gaps, and soak into and seal every surface of the wood. They called their method WEST, for Wood Epoxy Saturation Technique, and founded Gougeon Brothers, Inc., in 1969. Their racing trimarans and their book on boat construction taught a generation of builders, and their engineers tested thousands of specimens to learn how epoxy joints behave under repeated loads, work later used for wind-turbine blades. The method is careful engineering: measure the ratio exactly, wet out the surfaces with unthickened epoxy, then thicken more epoxy with fillers to bridge gaps, and never starve a joint.

The science. An epoxy resin molecule has an **epoxide group** at each end: a strained ring of two carbon atoms and one oxygen atom. An amine hardener has nitrogen atoms carrying reactive hydrogens. Each amine hydrogen opens one epoxide ring and bonds to it. Because each resin molecule has two ends and each hardener molecule has several reactive hydrogens, the molecules link in every direction into one giant **cross-linked** network: a **thermoset**, which will not melt when reheated. The mix ratio is set by *stoichiometry*, the count of reactive groups: it is designed so that every epoxide finds an amine hydrogen. Too much of either part leaves unreacted molecules that make the cured epoxy soft, gummy and weak; adding "extra hardener" does not make it cure faster or harder. The reaction is **exothermic**, and like most reactions it speeds up with temperature, roughly doubling for every 10 °C (18 °F). In a deep cup the heat cannot escape, so the batch heats itself, cures faster, heats more, and may smoke, crack or melt the cup. Spread in a thin layer, the same batch stays cool and workable much longer.

In the shop. Measure by the maker's ratio, by volume with calibrated pumps or by weight on a scale. Stir thoroughly for one to two minutes, scraping the sides and bottom, then pour the batch into a shallow tray to extend its working time. For a strong joint, first wet both surfaces with plain epoxy, then add a filler (such as colloidal silica) to the rest until it is about as thick as mayonnaise or peanut butter, and apply it to fill the gap. Clamp only enough to close the joint. Cure at or above the minimum temperature on the label. Fully cured epoxy can be sanded, but the dust

needs a dust mask, and an uncured amine film (“blush”) on the surface should be washed off with water before sanding or recoating.

Safety. Uncured epoxy and especially hardeners are **skin sensitizers**: repeated contact can cause an allergy that lasts for life. Always wear nitrile gloves and safety glasses, work with good ventilation, and wash off any skin contact with soap and water or a waterless hand cleaner, never with solvent. Read the safety data sheet. Let leftover mixed epoxy cure in a thin layer before throwing it away, never in a deep lump in the trash.

PICTURE STUDY



Building Mosquito Aircraft at Hatfield, Ministry of Information Photo Division photographer, 1943 · Photograph · Imperial War Museum (UK government photograph, public domain)

Image: Wikimedia Commons, public domain

This official color photograph was taken at the de Havilland factory in Hatfield in 1943. Behind the worker stand molded wooden fuselage shells: balsa sandwiched between plywood skins, glued, not riveted.

Look closely

- Find the curved fuselage shells behind the worker. What tells you they are wood rather than metal?
- Look at the edges of the shells. Where would one half be glued to the other?
- Look at the worker's tool and bench. Which look like woodworking tools rather than metalworking tools?
- Find the stands holding the shells. Why must a glued shell be supported in its exact shape while the glue sets?

Talk about it

1. Why would building an airplane from glued wood let furniture and piano makers help?
2. What would happen to a glued wooden airframe in a hot, humid climate if its glue absorbed water?

3. How is a balsa-and-plywood sandwich like a modern composite panel?

Safety first. Wear nitrile gloves and safety glasses for every epoxy step, work with ventilation, and keep a cup of mixed epoxy on a non-flammable surface. Never hold a cup that is getting hot; set it down outdoors on concrete and let it cure.

SHOP PROJECT

Ratio, Heat and Cure: An Epoxy Experiment

You will mix small batches of 5-minute epoxy at the correct ratio and at wrong ratios, measure the temperature of a deep batch and a thin one, and test the cured samples for hardness and strength.

You will need

- 5-minute two-part epoxy (dual syringe), small paper cups, a shallow aluminum tray or foil, mixing sticks
- A kitchen scale reading to 0.1 g (or the syringe's markings), a digital kitchen thermometer, a timer
- Craft sticks or wood strips for lap joints; a bucket, sand and luggage scale for testing
- Nitrile gloves, safety glasses, a concrete or tile surface; shop notebook

Steps

1. **Predict.** Which batch will get hottest, the deep cup or the thin tray? Which ratio will cure hardest?
2. Mix a correct 1:1 batch of 10 g in a cup and put the thermometer probe in the center. Record the temperature every 30 seconds for 10 minutes.
3. Mix a second correct 10 g batch and immediately spread it thin on the tray. Measure its temperature (probe flat in the film) on the same schedule.
4. Graph temperature against time for both batches on one graph. Note the peak temperatures and when each became too thick to stir.
5. Mix three small batches by weight: correct ratio, 2:1 resin-rich, and 1:2 hardener-rich. Spread each as a small disk on foil and use each to glue one craft-stick lap joint (1 in overlap).
6. After 24 hours, test each disk's hardness with a fingernail and a pencil (pencil hardness test: which pencil grade scratches it?). Bend each disk and record whether it is brittle, tough or rubbery.
7. Test each lap joint with the bucket of sand and record the breaking load and failure mode.

8. Tabulate and explain the results with the words stoichiometry, cross-linking and exotherm.
9. **Improve it.** Make one more correct-ratio joint with colloidal silica or fine sawdust added as a filler to bridge a 1/16 in gap (use a shim). Compare it with an unfilled joint with the same gap.

Tips

- Use the scale: syringes often dispense unevenly at the end.
- Mix for a full minute; streaks mean uncured spots.
- Label every sample with a marker on the foil before it cures.

Check your work

- ☐ My temperature graph shows the effect of batch shape on exotherm.
- ☐ I can explain why off-ratio epoxy is weaker, using my test data.
- ☐ I can mix, apply and fill with epoxy safely and correctly.

SHOP NOTEBOOK

1. A simple molecular sketch: resin molecules with epoxide rings at both ends, hardener molecules with several reactive hydrogens, and the cross-linked network after cure.
2. Your temperature–time graph for the deep and thin batches, with peak temperatures marked.
3. A cutaway sketch of a Mosquito-style sandwich panel (plywood skin, balsa core, plywood skin) with the glue lines labeled.

KEY FORMULAS

$V_{\text{resin}} = V_{\text{total}} \dfrac{a}{a+b}, \quad V_{\text{hardener}} = V_{\text{total}} \dfrac{b}{a+b}$ for a ratio $a : b$

$m = \rho V$

$t_2 \approx t_1 \cdot 2^{-(T_2 - T_1)/10\,^\circ\text{C}}$

$\dfrac{\text{surface area}}{\text{volume}} = \dfrac{1}{h}$ for a thin layer of thickness h

From history. About 7,800 Mosquitoes were built in Britain, Canada and Australia. Canadian and Australian factories used local woods and glues, and tropical durability problems in 1944 led to stricter glue specifications and inspections. After the war, de Bruyne's bonding methods were used in metal airliners such as the de Havilland Comet and the Fokker F27, and today's airliners use structural adhesives throughout their composite and metal structures.

WORKED EXAMPLES

Example 1. A marine epoxy mixes 5:1 resin to hardener by volume. You need 120 mL of mixed epoxy. How much of each?

Show solution

1. Total parts: $5 + 1 = 6$.
2. Resin: $120 \times \frac{5}{6} = 100$ mL.
3. Hardener: $120 \times \frac{1}{6} = 20$ mL.

Answer: 100 mL resin and 20 mL hardener.

Example 2. Another epoxy mixes 2:1 by volume. The resin's density is 1.16 g/mL and the hardener's 0.96 g/mL. What is the ratio by weight, and how many grams of each make 150 g of mix?

Show solution

1. Masses for 2 mL and 1 mL: $2 \times 1.16 = 2.32$ g and 0.96 g.
2. Ratio by weight: $2.32 : 0.96 = 2.42 : 1$.
3. Resin: $150 \times \dfrac{2.42}{3.42} \approx 106$ g; hardener: $150 - 106 = 44$ g.

Answer: About 2.42:1 by weight; 106 g resin and 44 g hardener.

Example 3. A batch has a pot life of 20 minutes at 22 °C. Estimate the pot life at 32 °C and at 12 °C.

Show solution

1. At 32 °C (10 °C warmer) the rate doubles, so pot life halves: $20/2 = 10$ min.
2. At 12 °C (10 °C cooler) the rate halves: $20 \times 2 = 40$ min. Cure also slows, and below the label minimum the epoxy may never cure fully.

Answer: About 10 minutes at 32 °C and 40 minutes at 12 °C.

Example 4. Compare 100 mL of mixed epoxy in a cup (a cylinder 5.0 cm across and 5.1 cm deep) and the same 100 mL spread 1 mm thick in a tray. Find the area through which each loses heat per milliliter, and explain the difference in pot life.

Show solution

1. Cup surface (sides, bottom and top): $\pi(5.0)(5.1) + 2 \times \frac{\pi}{4}(5.0)^2 \approx 80 + 39 = 119$ cm^2; per mL: about 1.2 cm^2.
2. Thin layer: 100 cm^3 ÷ 0.1 cm = 1,000 cm^2 of top surface alone; per mL: 10 cm^2.
3. The thin layer has about eight times as much cooling area per milliliter, so its heat escapes, it stays near room temperature, and it stays workable far longer. The cup traps its heat, speeds up, and may run away.

Answer: About 1.2 cm^2/mL in the cup and 10 cm^2/mL in the tray; the tray stays cooler and lasts longer.

PRACTICE

1. Easy An epoxy mixes 1:1 by volume. How much of each part for 30 mL?

   Show answer

   15 mL resin and 15 mL hardener.

2. Easy Why can't you melt cured epoxy and reuse it like hot glue?

   Show answer

   It is a thermoset: its molecules are cross-linked into one network, so heating chars it instead of melting it.

3. **Easy** Name two safety precautions for epoxy and the reason for each.

Show answer

Nitrile gloves, because hardeners are skin sensitizers; safety glasses, because a splash can injure the eye; also ventilation for vapors and sanding dust.

4. **Medium** A 4:1 epoxy is needed in a 75 mL batch. How much of each part?

Show answer

Resin 60 mL; hardener 15 mL.

5. **Medium** A product mixes 100:45 by weight. You have 80 g of resin. How much hardener?

Show answer

$80 \times 45/100 = 36$ g.

6. **Medium** A pot life is 30 minutes at 25 °C. Estimate it at 35 °C and at 15 °C.

Show answer

About 15 minutes and 60 minutes.

7. **Medium** Conceptual. Why does adding extra hardener not make epoxy cure harder?

Show answer

The ratio matches reactive groups one for one. Extra hardener has nothing to react with and stays in the network as soft, unreacted material, so the cured epoxy is weaker and may stay tacky.

8. **Hard** You are the tradesperson. A customer’s epoxy repair is still tacky after three days in a cold garage. Give two likely causes and a fix.

Show answer

The mix was off-ratio or poorly stirred, or it was too cold to cure. Scrape off the uncured material, clean with the solvent the maker recommends, measure and mix correctly, and cure at or above the label minimum temperature (warm the area if needed).

9. Hard A 200 mL batch in a cup starts smoking after 8 minutes. Explain what happened and what you would do next time.

Show answer

Runaway exotherm: the deep batch trapped its own heat, which sped the reaction and released more heat. Next time mix smaller batches, pour the mix into a shallow tray at once, use a slower hardener in warm weather, and set a hot cup outside on a non-flammable surface.

10. Hard Why did the Mosquito's builders and the Gougeons both care so much about moisture?

Show answer

Moisture weakens many glues (casein can soften and decay in damp heat) and swells and rots wood. The Mosquito's glues had to survive humid climates; the Gougeons used epoxy to seal every surface so water could not enter the wood at all.

11. Challenge An epoxy's pot life is 24 minutes at 20 °C. Write a formula for pot life at temperature T (°C) using the doubling rule, and find the temperature at which it falls to 8 minutes.

Show answer

$t = 24 \cdot 2^{-(T-20)/10}$. Set $8 = 24 \cdot 2^{-(T-20)/10}$: $2^{-(T-20)/10} = 1/3$,
$(T-20)/10 = \log_2 3 \approx 1.585$, $T \approx 35.8\ ^\circ\text{C}$.

COMMON MISTAKES

- Guessing the ratio or adding extra hardener to speed it up.
- Mixing too briefly or not scraping the cup.
- Leaving a large batch in a deep cup on a hot day.
- Squeezing a joint so hard that the epoxy is starved, or skipping the wet-out coat on porous wood.

> **Make it a game · Mix Ratio Mental Math.** Your parent names a two-part ratio, such as 2 to 1 by volume, and a total needed, like 90 milliliters. Calculate the volumes in 15 seconds, then say what happens if the ratio is wrong and why a thick mass cures hotter. Play five rounds with new ratios and see how fast you answer.

> **Scripture.** “a threefold cord is not quickly broken.” (Ecclesiastes 4:12, KJV)
>
> Strands twisted together are stronger than any one alone. A composite is the same idea in engineering: fibers, resin and core bonded together carry loads that none could carry by itself.

2.4 Super Glue, Hot Melt, Contact Cement and Construction Adhesives

OBJECTIVES

- Explain how cyanoacrylate, hot melt, contact cement, polyurethane, silicone and construction adhesives set, and tell Harry Coover's story of super glue.
- Choose the right adhesive or sealant for a material and job, and explain the difference between a sealant and an adhesive.
- Estimate adhesive quantities and sealant joint movement, and handle each adhesive safely.

> **Warm-up.** Make a list of every adhesive and caulk you can find in your house and garage. Next to each, write what it says it sticks and what it should not be used for. Which ones warn about fire, skin or eyes?

WATCH

Why Super Glue Is Perfect For Gluing Skin

Veritasium · 26:19

https://www.youtube.com/watch?v=Ni82f1-cAXg

> **WHEN TO WATCH**
> After the story. Watch the chemistry section closely: what starts the chain reaction?

Note: Explains Harry Coover's discovery and the chemistry of cyanoacrylate with experiments. Includes cartoon and real scenes of medical use of skin glues on wounds and a brief surgical scene; a sponsor message near the end. Parents may wish to preview it.

BACKUP VIDEO

Testing construction adhesives as woodworking glue

MatthiasWandel · 6:21

https://www.youtube.com/watch?v=ZvtOSVpcvrk

With the construction-adhesive paragraph: a woodworking engineer tests several construction adhesives on his own testing machine.

KEY TERMS

cyanoacrylate (CA)

"Super glue": a liquid monomer that polymerizes in seconds when it meets traces of moisture on a surface.

contact cement

A rubber (often neoprene) adhesive in solvent or water, spread on both surfaces, allowed to dry, then pressed together for an instant bond.

construction adhesive

A thick, gap-filling adhesive in caulking tubes (synthetic rubber or polyurethane) for subfloors, paneling and framing.

hot melt

A thermoplastic adhesive applied molten and set by cooling; it softens again when heated.

moisture cure

Curing by reaction with water vapor from the air or the surface, as in polyurethane and silicone.

sealant

A flexible material whose main job is to keep water and air out of a moving joint, not to carry load.

CORE IDEAS

The story. In 1942 Harry Coover, a young chemist at Eastman Kodak, was searching for a clear plastic for precision gunsights. One family of compounds he tried, the cyanoacrylates, stuck to everything they touched, which made them useless for lenses, and he set them aside. In 1951, at Tennessee Eastman in Kingsport, Tennessee, he was supervising a project to find a heat-resistant plastic for jet-airplane canopies when his colleague Fred Joyner spread a cyanoacrylate between the two glass prisms of a refractometer to measure it, and could not get them apart. This time Coover saw what he had missed: not a failed plastic but a new kind of adhesive that needed no heat, no pressure and no solvent. Eastman sold it as Eastman 910 in 1958, and Coover famously lifted a television host off the floor with a single drop. Later, medical versions were developed to close wounds. Coover received the National Medal of Technology and Innovation in 2010.

How they figured it out. Coover's two encounters show something every engineer should learn: a result is only a failure for the question you were asking. The second time, he asked a new question (what is this good for?) and tested it on metal, glass, rubber and plastics. The chemistry explained both the stickiness and the limits.

Cyanoacrylate is a small molecule with a very reactive carbon–carbon double bond. A trace of a weak base, such as the hydroxide ions in the thin film of water on almost every surface, starts a chain reaction (anionic polymerization) in which molecules link into long chains in seconds. That is why it cures fast in a thin gap but poorly in a thick blob, why it bonds skin (which is always moist) instantly, why an accelerator spray speeds it, and why the bond is hard and brittle, strong in shear but weak in peel and impact.

The science. Other adhesives set in other ways. **Hot melts** (often ethylene-vinyl acetate) are thermoplastics: melted at about 120–200 °C, they wet the surface, then set as they cool, in seconds; they soften again in a hot car. **Contact cement** is synthetic rubber (polychloroprene, sold as neoprene) dissolved in solvent or dispersed in water. You coat both surfaces, let the solvent evaporate until the film is dry to the touch, then press the parts together: the rubber films bond to each other immediately by chain entanglement, with no repositioning, which is ideal for plastic laminate on countertops and for shoe soles. **Polyurethane glues** (such as Gorilla Glue) and **silicones** are *moisture-cure*: they react with water vapor; polyurethane foams and expands as it cures. **Construction adhesives** are thick, gap-filling synthetic rubber or polyurethane pastes in caulking tubes; a bead under each subfloor panel, combined with screws or nails, makes the floor stiffer and stops squeaks. A **sealant** (silicone, polyurethane or acrylic caulk) has a different job from an adhesive: it must stretch and squeeze as a joint moves with temperature while keeping water and air out. Sealants are rated by the movement they can take, such as ±25% of the joint width.

In the shop. Match the adhesive to the job: CA for small, tight-fitting parts and quick repairs; hot melt for temporary jigs, crafts and tacking; contact cement for sheets of laminate, veneer and leather; polyurethane glue for wet or oily woods and outdoor joints; construction adhesive for subfloors, stair treads and paneling; silicone or polyurethane sealant for joints that move or must keep water out. Read the label for what it will *not* bond (many will not bond polyethylene or polypropylene). Cut the caulking-tube nozzle at an angle to the bead size you need, and tool sealant joints so they bond only to the two sides of the joint, not the back.

Safety. Cyanoacrylate bonds skin in seconds: never pull bonded skin apart; soak it in warm soapy water or acetone (nail-polish remover) and gently roll the skin apart. If it gets in an eye, do not force the eyelid open; rinse with water and get medical care.

Hot melt causes burns: cool a burn under running water. Solvent contact cements give off flammable vapors that can ignite: ventilate well, and put out pilot lights and flames in the room. Polyurethane glue stains skin for days; wear gloves.

PICTURE STUDY



Shoemaker in His Shop, Kenner, Louisiana, Russell Lee (Farm Security Administration), 1938 · Photograph · Library of Congress, FSA/OWI Collection

Image: Wikimedia Commons, public domain

Shoemakers were among the first everyday users of rubber cements: soles and heels were cemented as well as stitched and nailed. Russell Lee photographed small-town tradesmen for the Farm Security Administration, recording their tools and shops in careful detail.

Look closely

- Find the shoemaker's hands and tools. What is he doing to the shoe?
- Look for pots, cans or brushes that might hold cement or glue.
- Find the lasts (wooden foot shapes). Why would a shoemaker need them to glue and stitch a sole?
- Look for nails, thread and other fasteners. How many ways of attaching can you find in this shop?

Talk about it

1. Why is contact cement well suited to joining a flexible sole to a shoe?
2. Why might a shoemaker use cement and stitching together?
3. What makes a small repair trade like this valuable to a town?

> **Safety first.** Work with ventilation and safety glasses. Keep acetone nearby for CA spills on skin, wear gloves for polyurethane, use a low-temperature glue gun if possible, and put out any flames before using solvent contact cement.

SHOP PROJECT

Matching the Adhesive to the Material

You will build a test matrix of five adhesives on six pairs of materials, rate every bond in shear and peel, and produce an adhesive chart for your shop.

You will need

- Adhesives: cyanoacrylate (gel), hot-melt glue gun and sticks, contact cement (water-based preferred), a polyurethane construction adhesive, 100% silicone sealant
- Material coupons about 1 × 4 in: plywood, aluminum flashing, PVC (cut from pipe or sheet), HDPE (milk jug), glazed ceramic tile pieces, rubber (an old inner tube or mat)
- Isopropyl alcohol, 120-grit sandpaper, clamps, a bucket, sand and a luggage scale
- Nitrile gloves, safety glasses, acetone; shop notebook

Steps

1. Make a matrix with adhesives as columns and material pairs as rows: wood–wood, aluminum–aluminum, PVC–PVC, HDPE–HDPE, tile–wood, rubber–wood.
2. **Predict.** Mark each box with your prediction: strong, fair or poor.
3. Prepare every coupon the same way: sand lightly and wipe with alcohol.
4. Bond each pair with a 1 in overlap following each product's directions (let contact cement dry before joining; mist the surfaces for polyurethane if the label says so). Label every joint.
5. Cure all joints for the longest time any label requires (usually 24–72 hours).
6. **Peel test.** Try to peel one end of each joint apart by hand, and rate it 0 (falls apart) to 3 (cannot peel).
7. **Shear test.** For the strongest joint in each row, hang it and load it with the bucket of sand until it fails. Record the load and failure mode.
8. Complete the matrix with ratings and loads. Mark where predictions were wrong.

9. Make a one-page adhesive chart for your shop wall: for each material pair, the best adhesive you found and the one to avoid.
10. **Check your work.** Compare your chart with a manufacturer's adhesive guide and explain any differences.

Tips

- Use the same overlap and the same clamp for every joint so the comparison is fair.
- Hot-melt bonds need to be pressed within a few seconds.
- Silicone is included to show the difference between a sealant and an adhesive; expect low strength.

Check your work

- ☐ My matrix shows peel and shear results for five adhesives on six material pairs.
- ☐ I can explain each result with the way that adhesive sets and the surface energy of the material.
- ☐ My shop chart is clear and correct.

SHOP NOTEBOOK

1. A table of the adhesives in this lesson: how each sets (cooling, solvent loss, moisture, chemical reaction), set time, gap filling, flexibility, best uses and hazards.
2. Your test matrix with predictions and results.
3. A sketch of a properly installed sealant joint with backer rod, showing bonding to two sides only.

KEY FORMULAS

$V_{\text{bead}} = \frac{\pi}{4} d^2 \times \text{length}$

$1 \text{ fl oz} \approx 1.80 \text{ in}^3$

$\text{movement} = \dfrac{\Delta w}{w} \times 100\%$

From history. Cyanoacrylate has unexpected uses. Forensic technicians fume it in a closed chamber to make invisible fingerprints show up as white ridges, because the vapor polymerizes on the moisture and oils of the print. Medical versions with longer side chains (such as 2-octyl cyanoacrylate) are more flexible and less irritating and are used by doctors to close small cuts instead of stitches.

WORKED EXAMPLES

Example 1. A cyanoacrylate has a tensile strength of about 20 MPa on clean steel. Two steel rods 1.0 cm^2 in end area are glued end to end. What load can the joint carry in pure tension? Why is this a dangerous number to rely on?

Show solution

1. Area: $1.0\ \text{cm}^2 = 100\ \text{mm}^2$.
2. Load: $20\ \text{N/mm}^2 \times 100\ \text{mm}^2 = 2{,}000\ \text{N}$, roughly the weight of 200 kg.
3. But CA is brittle: any bending, peel or impact concentrates stress at one edge and the joint can snap at a small fraction of that load. It is also weakened by heat and moisture over time.

Answer: About 2,000 N in perfect tension; much less in peel or impact.

Example 2. You will glue and screw 3/4 in plywood subflooring in a 12 ft × 16 ft room. Panels are 4 ft × 8 ft laid across joists 16 in on center, so each panel crosses 7 joist lines 4 ft long. A 3/8 in bead is recommended. How many 28 fl oz tubes are needed?

Show solution

1. Panels: $192\ \text{ft}^2 \div 32\ \text{ft}^2 = 6$. Bead per panel: $7 \times 4 = 28$ ft; total 168 ft.
2. Bead volume per foot: $\frac{\pi}{4}(0.375)^2 \times 12 = 0.1104 \times 12 \approx 1.33\ \text{in}^3$.
3. Tube volume: $28 \times 1.80 \approx 50.4\ \text{in}^3$, about $50.4/1.33 \approx 38$ ft of bead per tube.
4. Tubes: $168/38 \approx 4.4$, so buy 5 (6 to allow for waste).

Answer: 5 to 6 tubes.

Example 3. A sealant joint between a window frame and siding is 1/2 in wide. Through the year the gap varies by ±1/8 in. What movement rating does the sealant need?

Show solution

1. Movement: $\pm 0.125 / 0.50 = \pm 25\%$.
2. Choose a sealant rated for at least ±25% movement (for example, ASTM C920 Class 25 or better), and install a backer rod so the sealant bonds only to the two sides of the joint.

Answer: At least ±25%.

Example 4. You are the tradesperson. Choose an adhesive or sealant for each job and give a reason: (a) plastic laminate on a plywood countertop; (b) a broken ceramic mug handle; (c) a squeaky new subfloor; (d) the joint between a bathtub and tile; (e) an outdoor oak bench joint.

Show solution

1. (a) Contact cement: instant, full-surface bond of thin sheet; use a water-based type or ventilate well.
2. (b) Two-part epoxy (or CA for a tight break): fills small gaps; CA is brittle and dislikes hot water.
3. (c) Construction adhesive plus screws: the bead fills gaps and stops movement.
4. (d) 100% silicone sealant for kitchen and bath, with mildew inhibitor: flexible and waterproof.
5. (e) Waterproof Type I wood glue or polyurethane glue: rated for outdoor exposure.

Answer: Contact cement; epoxy; construction adhesive and screws; silicone sealant; Type I or polyurethane glue.

PRACTICE

1. Easy What starts the curing of cyanoacrylate?

Show answer

Traces of moisture (weak bases such as hydroxide ions) on the surfaces.

2. Easy How does hot glue set, and what is its main weakness?

Show answer

By cooling (it is a thermoplastic); it softens again when warm and creeps under steady load.

3. Easy What is the difference between a sealant and an adhesive?

Show answer

A sealant's main job is to keep water and air out of a moving joint; it is flexible and not meant to carry load. An adhesive's main job is to carry load between the parts.

4. Medium Why must contact cement be allowed to dry before the parts touch?

Show answer

The solvent (or water) must leave so the two rubber films can bond to each other; trapped solvent leaves a weak, soft bond and blisters.

5. Medium How many feet of 1/4 in bead does a 10 fl oz tube give?

Show answer

Bead: $\frac{\pi}{4}(0.25)^2 \times 12 = 0.589$ in^3/ft; tube 18.0 in^3; about 31 ft.

6. Medium A 3/4 in wide sealant joint moves 3/16 in each way. What movement rating is needed?

Show answer

$0.1875 / 0.75 = \pm 25\%$.

7. Medium Why does super glue cure poorly when you squeeze out a thick blob?

Show answer

The reaction starts at moist surfaces; in a thick blob the middle is far from any surface, so polymerization is slow and incomplete.

8. Hard You are the tradesperson. A customer glued a polypropylene lawn-chair leg with super glue and it fell off at once. Explain and recommend.

Show answer

Polypropylene has very low surface energy, so CA does not wet or bond it. Use a mechanical fix (a bolt or rivet through a reinforcing plate), a plastic-welding repair, or an adhesive system made for polyolefins with its primer.

9. Hard Someone glued a deck stair tread with silicone caulk and it came loose. Explain.

Show answer

Silicone is a sealant: flexible and weak in shear, and paint and wood finishes reduce its grip. A structural connection needs screws or bolts, and if adhesive is used, a construction adhesive rated for exterior wood.

10. Hard Explain why a bead of construction adhesive under a subfloor makes the floor stiffer, not just quieter.

Show answer

Glue makes the plywood and joists act together like a T-beam (composite action), so the floor deflects less; it also fills gaps so the panel cannot move up and down on the nails and squeak.

11. Challenge Coover's first and second encounters with cyanoacrylate were with the same chemical. In a short paragraph, explain what changed, and give one modern example of an engineering "failure" that became a product.

Show answer

Model answer: the first time he wanted a clear plastic for optics, and stickiness meant failure; the second time he asked what the stickiness was good for and tested it as an adhesive. The chemical had not changed; the question had. Example: 3M's Post-it notes came from a weak adhesive that Spencer Silver could not use for a strong tape, until Art Fry used it for repositionable bookmarks.

COMMON MISTAKES

- Using super glue for gap-filling or impact-loaded repairs.
- Pressing contact cement before the solvent has flashed off, or trying to reposition it after contact.
- Using silicone caulk as a structural adhesive, or painting over silicone.
- Using hot glue where the part will get hot (a car interior in summer).

Make it a game · Adhesive Match-Up Cards. Make cards with materials and jobs on one set, adhesives on another: CA, hot melt, contact cement, polyurethane, silicone. Shuffle and pair them in 90 seconds, with a reason for each pair. Then explain the difference between an adhesive and a sealant. Your parent challenges two matches. Beat your pair count.

2.5 Choosing the Joint: Glue, Fasteners or Both

OBJECTIVES

- Identify the four ways a joint is loaded (shear, tension, peel and cleavage) and design bonded joints to carry shear and avoid peel.
- Explain why lap-joint strength does not grow in proportion to overlap length, and compare stress distribution in bolted and bonded joints.
- Decide when to glue, when to fasten and when to do both, using the Aloha Airlines Flight 243 accident, modern car bodies and the shop's own glue-and-screw joints as examples.

> **Warm-up.** Take a strip of masking tape 6 in long. Stick 2 in of it to a table. First pull the free end straight along the table (shear). Then lift the free end straight up and peel. Which takes more force? Write a sentence explaining why.

WATCH

Which glue is strongest? Testing with my computerized tester.

MatthiasWandel · 12:49

https://www.youtube.com/watch?v=xUCB4dhvVlc

> **WHEN TO WATCH**
> Before the shop project. Notice how he designs the test specimen so the glue line is in shear, and how the results differ between softwood and hardwood.

KEY TERMS

shear

Loading that slides the two parts along the glue line; adhesives are strongest this way.

tension (normal) loading

Loading that pulls the parts straight apart across the whole bond area.

cleavage

Prying the parts apart at one edge of a rigid joint, so the stress concentrates along that edge.

peel

Lifting a flexible part away from the bond line by line, as with tape; the weakest way to load an adhesive.

stress concentration

A local peak of stress, much higher than the average, at a hole, notch or the end of an overlap.

hybrid joint

A joint that uses both adhesive and mechanical fasteners, such as glue-and-screw, rivet-bonded or weld-bonded joints.

CORE IDEAS

The story. On April 28, 1988, Aloha Airlines Flight 243, a Boeing 737 flying between Hawaiian islands, was climbing through 24,000 feet when about 18 feet of the upper fuselage behind the cockpit tore away. A flight attendant, Clarabelle Lansing, was swept out and lost; dozens of passengers were injured. The pilots landed the crippled airplane on Maui. The airplane was 19 years old and had made about 89,000 flights, a huge number of pressurization cycles, in warm, salty air.

How they figured it out. The National Transportation Safety Board found that the fuselage skin panels had been joined by lap joints that were both *bonded* (with an epoxy-impregnated tape cured at room temperature) and *riveted*. The bond was meant to carry much of the load, so that the rivets saw lower stresses. But the early cold-bonding process was sensitive to surface preparation and moisture, and on this airplane the bond had let go along the lap joints, while corrosion crept in. With the bond gone, the full load went into the rivets in the upper row, and tiny fatigue cracks grew from many rivet holes at once and joined into one long crack. The joint had been designed as "glue and fasteners together," but the glue had quietly failed and the fasteners alone could not carry the repeated load. The accident led to the FAA's aging-aircraft program, with stricter inspections for disbonding, corrosion and widespread fatigue cracking. Earlier engineers had already shown why bonded joints are subtle: in 1938 Olaf Volkersen calculated that the shear stress in a lap joint is not uniform but peaks at the two ends of the overlap, and in 1944 Goland and Reissner showed that a single lap joint also bends, creating peel stresses at the ends.

The science. A joint can be loaded in four ways. In **shear**, the whole bond area works together, and adhesives are at their best. In **tension**, the load is spread over the area as long as it is pulled perfectly square. In **cleavage**, a rigid part is pried open at one edge, and the stress crowds into that edge. In **peel**, a flexible part is lifted line by line, so only a thin strip of adhesive resists at a time; that is why tape peels off easily but is hard to slide. Even in a shear lap joint, the stiff parts stretch differently along the overlap, so the shear stress is highest at the ends and low in the middle; doubling

the overlap length does not double the strength. Making the joint wider, tapering the ends of the overlap, or using a thicker, tougher adhesive spreads the load better. A **bolted or riveted** joint carries load only at the holes: the hole removes material, and at its edge the stress is two to three times the average (a stress concentration), which is where fatigue cracks start. A **bonded** joint needs no holes, spreads load over the whole area, seals out water, joins thin and different materials, and adds stiffness, but it is sensitive to surface preparation, peel, temperature and moisture, and it is hard to inspect.

In the shop. Design glued joints to carry shear and compression and keep peel and cleavage out: overlap rather than butt; wide rather than very long; add a screw, rivet or clamp at the ends of a bonded overlap as a "peel stopper." Use **both** when the joint must be strong on day one and stay stiff and sealed for years: glue-and-screw subfloors and shelves, rivet-bonded aircraft skins, and the weld-bonded steel of modern car bodies, where many meters of structural adhesive run between spot welds to stiffen the body and absorb crash energy. Use **fasteners alone** when the joint must come apart, carry heavy concentrated loads, or survive heat or fire, or when a failure must be visible and inspectable. Use **glue alone** for close-fitting wood joints in shear, veneers and laminates, and thin sheets where holes would weaken the part.

On the job. Auto-body technicians follow carmakers' repair manuals that specify exactly where to use structural adhesive, rivets and welds when replacing panels; aircraft maintenance technicians inspect bonded joints with tap tests and ultrasonic equipment. Both are respected, certified trades.

PICTURE STUDY



A Riveting Team at the Douglas Aircraft Plant, Alfred T. Palmer (Office of War Information), 1942 · Photograph · Library of Congress, FSA/OWI Collection

Image: Wikimedia Commons, public domain

This U.S. government photograph shows a riveting team building aircraft structure at the Douglas plant in Long Beach in 1942. Aircraft of that time were held together almost entirely by rivets; today's aircraft use rivets, bolts and structural adhesives together.

Look closely

- Find the rivet gun and the bucking bar. Which side of the joint is each worker on?
- Look for rows of rivets. How are they spaced, and how far are they from the edges of the sheet?
- Find the thin aluminum sheet. Why must it be joined at many points instead of a few?
- Look for any sealant or paint in the joints. Why would an airplane need its joints sealed?

Talk about it

1. Where in this riveted structure would fatigue cracks be most likely to start?
2. How would adding adhesive to these joints change the way the load travels?

3. Why does an airplane maker still use rivets even though adhesives spread load better?

Safety first. Wear safety glasses for all loading tests and stand to the side of the hanging bucket. Use the safety rules from Lessons 2.1–2.4 for each adhesive: ventilation, gloves for epoxy and polyurethane, and care with hot glue and CA.

SHOP PROJECT

The Lap-Shear Test and the Overlap Puzzle

You will run a lap-shear test of several glues on identical wood strips, then test one glue at three overlap lengths and in peel, to discover for yourself why bonded joints are designed for shear and why longer overlaps give less than you expect. Finally you will compare glue alone, screws alone and glue plus screws.

You will need

- Hardwood strips (poplar or oak), about 1/4 × 1-1/2 × 8 in, at least 30 (paint stirrers work for a quick version)
- Adhesives: yellow wood glue, 5-minute epoxy, CA gel, hot melt, construction adhesive
- #6 × 1/2 in wood screws and a drill with a 1/16 in bit
- Clamps, a ruler, a bucket, sand, a luggage scale and a sturdy support; a drill for hanging holes
- Safety glasses, nitrile gloves; shop notebook

Steps

1. **Glue comparison.** Make three lap joints with each adhesive, each with exactly a 1 in overlap across the full 1-1/2 in width. Cure as each label requires.
2. **Predict.** Rank the adhesives. Predict how much stronger a 2 in overlap will be than a 1 in overlap.
3. **Overlap puzzle.** With yellow glue only, make three joints each with 1/2 in, 1 in and 2 in overlaps.
4. **Peel test.** With yellow glue, bond three strips to a thin, flexible strip (a 1/8 in veneer or thin plywood) with a 2 in overlap, so it can be peeled.
5. **Hybrid test.** Make three joints each with a 1 in overlap: glue only, two screws only, and glue plus two screws.
6. Drill a hanging hole in each end. Load each joint in shear with the bucket of sand until it fails, adding sand slowly. For peel specimens, hang the bucket from the thin strip so it peels from one end.

7. Record load, average shear stress and failure mode (adhesive, cohesive or wood) for every specimen. For the hybrid joints, note whether they failed suddenly or gradually.
8. Graph failure load against overlap length. Is the line straight? Compare with Worked Example 1.
9. Compare shear and peel strength for the same glue as a ratio.
10. **Check your work.** Write a two-page glue-test report with a recommendation: for a bookshelf, a boat seat and a sign bracket, should you glue, fasten or both, and how should the joint be shaped?

Tips

- Mark overlaps with a square and a pencil before gluing; consistent overlaps make a fair test.
- If the wood breaks before the glue, that is a valid and important result: record it.
- Screws in the hybrid test should go in the same positions in every specimen.

Check your work

- ☐ My graph shows how strength changes with overlap, and I can explain why it is not proportional.
- ☐ I measured the peel-to-shear ratio and can explain it.
- ☐ My report recommends glue, fasteners or both for real joints and justifies each choice.

SHOP NOTEBOOK

1. Sketches of the four loading modes (shear, tension, cleavage, peel) with arrows and a note on where stress concentrates in each.
2. A sketch of the shear-stress distribution along a lap joint (high at the ends, low in the middle), and of the stress around a bolt hole.
3. Your lap-shear, overlap and peel data tables and graphs.

KEY FORMULAS

$$\tau_{\text{avg}} = \frac{F}{bL}$$

$$\sigma_{\text{net}} = \frac{F}{(w - d)\,t}, \qquad \sigma_{\text{peak}} \approx K_t\,\sigma_{\text{net}}$$

$$F_{\text{peel}} = (\text{peel strength per width}) \times b$$

From history. Structural adhesives are now everywhere in transportation. Many modern car bodies combine spot welds with long beads of crash-toughened epoxy adhesive, and composite airliner structures are both bonded and fastened. Engineers learned from Aloha 243 that every bonded joint in a structure must be designed so that if the bond fails, the structure still holds long enough for inspectors to find the damage.

WORKED EXAMPLES

Example 1. Lap joints 25 mm wide are bonded with the same adhesive. With a 12.5 mm overlap the joint fails at 5.0 kN; with a 25 mm overlap it fails at 7.0 kN. Find the average shear stress at failure for each and explain the difference.

Show solution

1. Short overlap: $\tau = \dfrac{5{,}000}{25 \times 12.5} = 16.0$ MPa.
2. Long overlap: $\tau = \dfrac{7{,}000}{25 \times 25} = 11.2$ MPa.
3. Doubling the overlap raised the strength only 40%. The shear stress peaks at the ends of the overlap, and the middle carries little, so the average stress at failure falls as the overlap grows.

Answer: 16.0 MPa and 11.2 MPa; strength is not proportional to overlap.

Example 2. An aluminum strap 50 mm wide and 3.0 mm thick carries 10 kN. Compare (a) a bolted joint with one 6.0 mm hole, stress concentration factor about 2.5 at the hole, and (b) a bonded joint with no hole.

Show solution

1. (a) Net area: $(50 - 6.0) \times 3.0 = 132\ \text{mm}^2$; net stress $10{,}000/132 \approx 75.8$ MPa; peak at the hole edge $\approx 2.5 \times 75.8 \approx 190$ MPa.
2. (b) Full area: $50 \times 3.0 = 150\ \text{mm}^2$; stress $10{,}000/150 \approx 66.7$ MPa, with no hole to concentrate it.
3. The bonded strap's highest stress is about a third of the bolted strap's peak, which is why bonded and composite structures can resist fatigue so well, as long as the bond itself stays sound.

Answer: About 190 MPa peak (bolted) versus about 67 MPa (bonded).

Example 3. An adhesive has an average lap-shear strength of 15 MPa and a peel strength of 3.0 N per mm of width. A joint 25 mm wide with a 25 mm overlap is loaded (a) in shear and (b) in peel. Compare the capacities.

Show solution

1. (a) Shear (using the average, an upper estimate): $15 \times 25 \times 25 = 9{,}375$ N.
2. (b) Peel: $3.0 \times 25 = 75$ N.
3. Ratio: $9{,}375/75 = 125$. The same glue is over a hundred times weaker in peel. Design the joint so it is never peeled.

Answer: About 9,400 N in shear versus 75 N in peel.

Example 4. You are the tradesperson. A homeowner wants to hang a 3/4 in plywood shelf on a wall cleat for heavy tools. Should the shelf be glued to the cleat, screwed, or both? Explain the load on each joint.

Show solution

1. The cleat is screwed into studs: the screws carry the shelf load in shear, which they do well. Glue to drywall paper would add nothing.
2. The shelf rests on the cleat and is glued and screwed to it: the shelf's load is mostly downward (shear on the glue line and bearing on the cleat), but a heavy load at the front edge tries to pry the back of the shelf up (cleavage). The screws act as peel stoppers, and the glue keeps the joint from loosening and creeping.
3. Add a bracket or a front-edge support if the shelf is deep, to keep the screws out of withdrawal.

Answer: Screw the cleat to the studs; glue and screw the shelf to the cleat; add brackets for deep, heavy loads.

PRACTICE

1. Easy Name the four ways a bonded joint can be loaded and rank them from strongest to weakest for a typical adhesive.

   Show answer

   Shear (strongest), tension, cleavage, peel (weakest).

2. Easy Find the average shear stress in a joint 20 mm wide with a 15 mm overlap carrying 3.6 kN.

   Show answer

   $3{,}600/300 = 12$ MPa.

3. Easy Give two advantages of a bonded joint over a riveted one.

   Show answer

   No holes or stress concentrations; load spread over the whole area; sealed against water; joins thin or different materials; lighter and stiffer.

4. **Medium** A strap 40 mm wide and 4 mm thick has an 8 mm bolt hole and carries 8 kN. Find the net-section stress.

   Show answer

   $8{,}000/((40-8)\times 4) = 62.5$ MPa.

5. **Medium** With a stress concentration factor of 2.6 at that hole, what is the peak stress?

   Show answer

   $2.6 \times 62.5 \approx 163$ MPa.

6. **Medium** A tape has a peel strength of 0.4 N/mm. What force peels a 48 mm-wide strip?

   Show answer

   $0.4 \times 48 \approx 19$ N.

7. **Medium** Conceptual. Why does making a lap joint wider help more than making it longer?

   Show answer

   Width adds bond area at the highly stressed ends of the overlap along the whole joint, so strength grows nearly in proportion to width; extra length mostly adds the lightly stressed middle.

8. **Hard** You are the tradesperson. A glued plastic sign keeps peeling off a metal post starting at one corner. Give two design changes and one preparation change.

   Show answer

   Design: add a screw or rivet at each corner as a peel stopper; use a wider, stiffer bracket so the load is shear, not peel; round the corners. Preparation: degrease and abrade both surfaces and use an adhesive suited to the plastic (with primer if needed).

9. Hard Explain how the Aloha Flight 243 lap joints were meant to work, why they failed, and what that teaches about hybrid joints.

Show answer

The bond was supposed to carry much of the load so the rivets saw low stress. Poor bond durability (surface preparation, moisture and corrosion) let the bond fail unnoticed, so the rivets carried the full load and fatigue cracks grew from many holes and linked up. A hybrid joint is only as good as its weakest assumption; bonds must be made durably and inspected.

10. Hard A car-body repair manual calls for spot welds plus structural adhesive on a replacement panel. Give two reasons the carmaker specifies both.

Show answer

The adhesive stiffens the joint along its whole length between welds, seals out water and corrosion, and absorbs crash energy; the welds hold the parts while the adhesive cures and keep the joint together in fire or if peel loads occur. Following the specified method restores the car's crash performance.

11. Challenge A bonded doubler must carry 12 kN in shear. Tests on 25 mm-wide coupons gave 6.0 kN at 12.5 mm overlap and 8.4 kN at 25 mm overlap; longer overlaps gave almost no gain. With a factor of safety of 2, how wide must a 25 mm overlap joint be?

Show answer

Required: 24 kN. Capacity per mm of width at 25 mm overlap: $8.4/25 = 0.336$ kN/mm. Width: $24/0.336 \approx 71$ mm, so make it at least 75 mm wide, with peel stoppers at the ends.

COMMON MISTAKES

- Designing a glued joint that will be peeled or pried.
- Assuming twice the overlap gives twice the strength.
- Assuming glue and fasteners always add their strengths together; a stiff bond carries load first, and fasteners take over only after it fails.
- Forgetting that bonded joints must be inspected and that their strength depends on surface preparation and environment.

Make it a game · Loaded Four Ways. Your parent holds up a joint example: a shelf bracket, a pulled label, a peeling tape. Name how it is loaded among shear, tension, peel and cleavage in three seconds, and one design fix. Then explain why doubling a lap joint's overlap does not double strength. Parent plants a wrong fact each round.

UNIT 2

Adhesives: The Chemistry of Sticking

Glue is one of the oldest building materials and one of the most advanced. In this unit you will learn why anything sticks at all, how traditional and modern wood glues work, how a resin and a hardener cross-link into epoxy, how super glue, hot melt, contact cement and construction adhesives each set, and how to decide between glue, fasteners or both.

The stories run from the glued furniture of Tutankhamun's tomb and the gecko's foot to the wooden de Havilland Mosquito, the Gougeon brothers' epoxy boats, Harry Coover's accidental super glue and the hard lessons of Aloha Airlines Flight 243. You will measure contact angles, test surface preparation, break glue joints with a bucket of sand, measure the heat of curing epoxy, build an adhesive chart for your shop, and discover why bonded joints must be designed for shear.

PREREQUISITES

- Unit 1: stress $\sigma = F/A$, shear, factor of safety and the bucket-of-sand test method
- Algebra I: ratios and proportions, solving formulas, exponents
- Basic chemistry vocabulary: molecule, polymer, reaction (helpful but taught where needed)

MASTERY CHECKLIST

- ☐ I can explain adhesion, cohesion and wetting, and use contact angle to predict bonding.
- ☐ I can prepare surfaces for bonding and diagnose adhesive, cohesive and substrate failures.
- ☐ I can choose and use hide glue, PVA, yellow and waterproof wood glues, and plan a glue-up with the right pressure and time.
- ☐ I can mix epoxy by volume or weight, explain cross-linking and exotherm, and use epoxy safely.
- ☐ I can explain how CA, hot melt, contact cement, polyurethane, silicone and construction adhesives set, and choose among them.
- ☐ I can design joints for shear rather than peel and decide when to glue, fasten or both.

OPTIONAL KITS FOR THIS UNIT

- **WEST SYSTEM epoxy (user manual and product guide)**: The Gougeon brothers' company publishes free, detailed guides to epoxy use, fillers and safety; useful for Lesson 2.3. Epoxy from any maker works for the projects.
- **Titebond glue guides**: Free technical data (open time, clamp time, water resistance, strength) for wood glues and construction adhesives; useful for Lessons 2.2 and 2.4.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

2.1 How Glue Works

3 sessions of 50 minutes

2.2	**Wood Glues: Hide Glue to PVA**	3 sessions of 50 minutes
2.3	**Epoxy and Two-Part Chemistry**	3 sessions of 50 minutes
2.4	**Super Glue, Hot Melt, Contact Cement and Construction Adhesives**	3 sessions of 50 minutes
2.5	**Choosing the Joint: Glue, Fasteners or Both**	3 sessions of 50 minutes

Unit 2 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   Define adhesion, cohesion and wetting.

2. **6 pts**
   Water ($\gamma_{LV} = 72.8$ mN/m) sits on a surface where $\gamma_{SV} - \gamma_{SL} = 50$ mN/m. Find the contact angle. Is the surface easy to bond?

3. **6 pts**
   A lap joint 1.0 in wide with a 0.75 in overlap fails at 2,400 lb. Find the average shear stress in psi and MPa.

4. **6 pts**
   Describe the three failure modes and what each tells you.

5. **5 pts**
   List the four steps of good surface preparation.

6. **6 pts**
   Find the clamping force for an edge joint 3/4 in thick and 40 in long at 150 psi, and the number of 750 lb clamps.

7. **6 pts**
   Explain how PVA wood glue sets and why end-grain joints are weak.

8. **6 pts**

   An epoxy mixes 3:1 by volume. How much of each for 60 mL?

9. **6 pts**

   Pot life is 16 minutes at 25 °C. Estimate it at 35 °C and at 15 °C.

10. **7 pts**

    Explain cross-linking and exotherm, and why a deep cup of epoxy can overheat while a thin layer does not.

11. **6 pts**

    What starts the cure of cyanoacrylate, and why is it brittle and poor at filling gaps?

12. **6 pts**

    You are the tradesperson. Choose an adhesive or sealant: (a) laminate on a countertop; (b) a squeaky subfloor; (c) the gap around a bathtub; (d) a small, tight crack in a ceramic figurine.

13. **5 pts**

    A sealant joint 0.60 in wide moves ±0.15 in. What movement rating is needed?

14. **6 pts**

    Joints 25 mm wide fail at 4.8 kN with a 12.5 mm overlap and 6.5 kN with a 25 mm overlap. Find both average shear stresses and explain.

15. **6 pts**

    An adhesive has 3.5 N/mm peel strength. What force peels a 30 mm-wide strip? How does that compare with 30 mm × 25 mm in shear at 12 MPa?

16. **12 pts**

    Short essay. Using Aloha Airlines Flight 243 and one example from your own shop work, explain when a joint should be glued, fastened or both, and what must be true for a hybrid joint to be safe.

ANSWER KEY

1. Adhesion: attraction of the glue to the surface. Cohesion: internal strength of the glue. Wetting: a liquid spreading over and contacting a solid closely.
2. $\cos\theta = 0.687$, $\theta \approx 46.6°$; it is wetted fairly well and is bondable.
3. $2{,}400 / 0.75 = 3{,}200$ psi ≈ 22 MPa.
4. Adhesive (at the interface): poor surface preparation or wrong glue. Cohesive (within the glue): the glue itself is the weak link. Substrate (the material breaks): the bond is stronger than the parts.
5. Clean (degrease), abrade, clean again (remove dust), and bond promptly.
6. $150 \times 30 = 4{,}500$ lb; 6 clamps.
7. PVA is an emulsion; its water soaks into the wood and evaporates, and the polymer particles fuse into a film locked into the wood cells. End grain wicks the glue away and offers only the cut ends of the fibers, so little bond area forms.
8. 45 mL resin and 15 mL hardener.
9. About 8 minutes and 32 minutes.
10. Each resin molecule bonds to several hardener sites, building a three-dimensional network (a thermoset). The reaction gives off heat, and heat speeds the reaction. A deep batch has little surface area per volume to lose heat, so it heats itself and runs away; a thin layer loses heat quickly.
11. Moisture (weak bases) on the surfaces starts a fast chain reaction; it cures from the surfaces inward, so thick gaps cure poorly, and the hard polymer has little toughness in peel or impact.
12. (a) Contact cement. (b) Construction adhesive plus screws. (c) Silicone sealant for kitchen and bath. (d) CA (or a thin epoxy).
13. $0.15 / 0.60 = \pm 25\%$.
14. 15.4 MPa and 10.4 MPa. Stress peaks at the ends of the overlap, so a longer overlap adds mostly lightly loaded area.
15. Peel: 105 N; shear: $12 \times 750 = 9{,}000$ N, about 86 times more.
16. Model answer: the 737's lap joints were bonded and riveted, but the bond degraded from poor durability and moisture, so the rivets carried loads they were not sized for and fatigue cracks linked up. Glue suits shear-loaded, close-fitting joints and thin sheets; fasteners suit concentrated loads, removable joints, heat and inspectable connections; both suit joints that must be strong at once and stiff and sealed for years, like glued-and-screwed subfloors. A hybrid

joint is safe only if the bond is made with proper preparation and durable materials, the fasteners can carry the load alone if the bond fails, and the joint can be inspected.

PORTFOLIO PIECE: A GLUE-TEST REPORT AND ADHESIVE CHART

Combine your Unit 2 experiments into one glue-test report of three to five pages: surface preparation and contact angles, long-grain and end-grain joints, the epoxy ratio and exotherm test, the adhesive-and-material matrix, and the lap-shear, overlap and peel tests. Include data tables, graphs, photos or sketches of failure surfaces, sources of error and conclusions.

Finish a laminated one-page adhesive chart for your shop wall: for each common material pair and job, the recommended adhesive or sealant, surface preparation, clamp and cure times, and safety notes.

LOOK FOR	WHAT IT MEANS
Fair testing	Specimens are identical except for the one variable tested; each condition has at least three trials.
Data and calculation	Loads, areas and stresses are calculated correctly with units; graphs are labeled; averages and spread are reported.
Science	Results are explained with wetting, surface energy, cross-linking, setting mechanisms and loading modes.
Judgment	The chart and recommendations choose glue, fasteners or both sensibly, with surface preparation and safety included.
Presentation	The report and chart are organized, clear and neat enough to use in a real shop.

UNIT 3

Woodworking

Wood is the oldest building material in the house and the first one most tradespeople learn to work. In this unit you will study wood the way a scientist and a craftsman do together: as a bundle of hollow cells that is strong along the grain, weak across it, and always moving with the seasons. You will learn to measure and mark to a knife line, how saw teeth and sharp edges actually cut, and how to sharpen a chisel until it pares end grain cleanly.

Then you will learn to use power tools safely, starting with the physics of kickback and the story of the flesh-sensing saw brake; how joints from the butt joint to the dovetail carry load, tested to failure in your own shop; and how finishes cure. The unit ends with a capstone: a step stool (or toolbox) that you design, build, finish and proof-test, the first piece of real shop work in your portfolio.

PREREQUISITES

- Algebra I: formulas, proportions, rearranging equations
- Right-triangle basics: the Pythagorean theorem and tangent
- Unit 1 (screws and fasteners) and Unit 2 (adhesives) of this course
- Access to basic hand tools and an adult who can supervise power-tool work

MASTERY CHECKLIST

- ☐ I can explain wood's cell structure, calculate moisture content and predict seasonal movement across the grain.
- ☐ I can calculate board feet and the cost of a lumber order using nominal and actual sizes correctly.
- ☐ I can measure and mark to a knife line, check a square, plan for kerf and sharpen a chisel.
- ☐ I can explain kickback and the riving knife, calculate rim speed and safe noise time, and follow a shop safety plan.
- ☐ I can choose and cut a joint for a load, calculate glue area and screw withdrawal, and test joints to failure.
- ☐ I can sand, choose and apply a finish, and build, finish and proof-test a step stool or toolbox.

OPTIONAL KITS FOR THIS UNIT

- **Stanley hand tools**: Tape measures, combination squares, chisels, block planes and handsaws from the company that made Leonard Bailey's plane design standard (Lessons 3.2–3.5). A few good basic tools are all this unit needs; secondhand older tools work well once sharpened.
- **Kreg pocket-hole jigs**: Optional for Lesson 3.4 (joint D in the strength test) and the step stool. A small single-hole jig is enough; dowels or a half-lap work without one.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

3.1	**Wood as a Material: Cells, Grain and Movement**	3 sessions of 50 minutes
3.2	**Measuring, Marking and Hand Tools**	3 sessions of 50 minutes
3.3	**Power Tools and Shop Safety**	3 sessions of 50 minutes
3.4	**Joinery: Fitly Joined Together**	3 sessions of 50 minutes
3.5	**Finishing and a Finished Piece: The Step Stool**	3 sessions of 50 minutes

Unit 3 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Write explanations in complete sentences. The test is worth 100 points.

1. **5 pts**
   Explain why wood shrinks and swells much more across the grain than along it, and why it moves more tangentially than radially.

2. **6 pts**
   A sample weighs 82.5 g as cut and 70.0 g oven-dry. Find its moisture content. Is it ready for indoor furniture?

3. **8 pts**
   A 30-in-wide flat-sawn red oak tabletop ($C_T = 0.00369$) goes from 6% to 11% MC. How much does it widen? How should it be fastened to its base?

4. **6 pts**
   Find the board feet and cost of four 1 in × 6 in × 10 ft poplar boards at $4.80 per board foot.

5. **5 pts**
   Give the actual dimensions of a 2×4 and a 1×12 and explain the difference from the name.

6. **6 pts**

   A 72-in board is cut into five equal parts with a 1/8-in kerf. How long is each part?

7. **6 pts**

   Explain the difference between rip and crosscut teeth and why Japanese saws cut on the pull stroke.

8. **7 pts**

   A 1-in chisel is pushed with 15 lb. Compare the pressure at a sharp edge 0.00004 in wide and a dull edge 0.001 in wide. Connect your answer to Ecclesiastes 10:10.

9. **7 pts**

   A 10-in blade turns at 4,500 rpm. Find the rim speed in m/s (10 in = 0.254 m). If it is stopped in 4 ms, find the average deceleration.

10. **6 pts**

    Describe kickback on a table saw and three practices that prevent it.

11. **5 pts**

    A planer runs at 103 dBA. Find the NIOSH safe time without hearing protection.

12. **6 pts**

    A tenon in red oak (shear strength 1,780 psi) has two cheeks each 1.75 in × 1.25 in. Find its glue area and ideal shear capacity. Why is this joint stronger than a glued end-grain butt joint of the same parts?

13. **6 pts**

    Using $p = 15{,}700\,G^{2}DL$, find the withdrawal strength of a #8 screw (D = 0.164 in) penetrating 1.25 in into side grain of poplar (G = 0.42).

14. **5 pts**

    Name the curing type of shellac, oil-based polyurethane and water-based polyurethane, and one safety rule for oil finishes.

15. **6 pts**

    You are the cabinetmaker. A customer's new cherry tabletop has split down the middle after its first winter. It was screwed tightly through round holes into the apron. Diagnose the problem and explain your repair.

16. **10 pts**

    Short essay. Describe the step stool you built (or would build): its requirements, joints, finish and test. Explain how you prevented tipping, how wood movement and finishing affected your design, and what you would change in a second version.

ANSWER KEY

1. Wood is made of long hollow cells aligned with the grain. Water enters and leaves the cell walls, which thicken and thin, so the board changes in width and thickness but barely in length. Tangential shrinkage is about twice radial, partly because the rays running radially restrain movement in that direction and because of how the cell walls are arranged in the growth rings.
2. $MC = 12.5/70.0 = 17.9\%$. No; indoor furniture should be about 6–8%.
3. $30 \times 0.00369 \times 5 \approx 0.55$ in. With slotted cleats, figure-8 or Z-clips, or screws in slotted holes, so it can move.
4. Each 5 BF; total 20 BF; $96.00.
5. 1½ × 3½ in and ¾ × 11¼ in. The names are the rough sawn sizes before drying and planing.
6. $(72 - 4 \times 0.125)/5 = 14.3$ in
7. Rip teeth are filed square to chisel out fibers along the grain; crosscut teeth are beveled to slice fibers on both sides of the kerf. A pull saw's blade is in tension, so it can be thin without buckling, giving a fine kerf.
8. Sharp: $15/(4 \times 10^{-5}) = 375{,}000$ psi; dull: $15/0.001 = 15{,}000$ psi, 25 times less. A blunt iron needs more force for the same cutting pressure, as Solomon wrote.
9. $v = \pi(0.254)(75) \approx 59.8$ m/s; $a = 59.8/0.004 \approx 15{,}000$ m/s^2.
10. The rising back teeth catch a board that pinches the blade or drifts from the fence and throw it toward the operator. Prevent it with a riving knife, a straight fence parallel to the blade, never using the fence and miter gauge together, keeping the board flat and against the fence with push sticks, and a sharp blade.
11. $8/2^6 = 0.125$ h $= 7.5$ min
12. $A = 4.375$ in^2; $F \approx 7{,}800$ lb. The tenon gives long-grain glue surfaces and shoulders that resist racking; end grain holds glue poorly.
13. $15{,}700(0.42)^2(0.164)(1.25) \approx 568$ lb
14. Evaporative; reactive (oxidation); coalescing. Oily rags must be laid flat to dry or sealed in a water-filled metal can because they can self-heat and ignite.
15. The top shrank across its width in dry winter air but the screws held it rigidly, so it split. Repair: remove the screws, glue the split (clamped flat), and reattach with slotted cleats or clips so it can move; finish both faces equally.
16. A good answer: states measurable requirements (height, top size, proof load, weight); names the joints and why (dados and glue-and-screws for long-grain

surfaces and shoulders); shows the base at least as wide as the top, with a tipping calculation; mentions finishing both sides and choosing a durable finish; reports the proof-test data; and lists specific improvements.

PORTFOLIO PIECE: A FINISHED, TESTED STEP STOOL OR TOOLBOX

Present the step stool or toolbox from Lesson 3.5 together with its documentation: requirements; a three-view drawing with dimensions; a cut list with board feet and cost; the joints you used and why; a finishing log; the proof-load test and tipping calculation; photographs of the build; and a one-page reflection on what you would change. Include your sharpened chisel test, your wood-movement graph and your joint-test results from earlier lessons as supporting evidence.

LOOK FOR	WHAT IT MEANS
Requirements and design	Measurable requirements and a clear, dimensioned drawing and cut list; the design keeps the base under the whole top.
Craftsmanship	Accurate parts, tight joints, square assembly, no rocking; edges eased and surfaces smooth.
Finish	Appropriate finish applied in thin even coats on all faces, with a finishing log; safe handling of rags and solvents.
Testing and data	Proof load and tipping check done safely and recorded with numbers and photographs.
Reflection	Honest, specific improvements based on the test and on what was learned in the unit.

3.1 Wood as a Material: Cells, Grain and Movement

OBJECTIVES

- Describe the cell structure of wood and explain grain, growth rings, hardwood and softwood.
- Calculate moisture content and predict seasonal wood movement across and along the grain.
- Tell flat-sawn from quartersawn boards and explain why quartersawn wood is more stable.
- Calculate board feet and the cost of a lumber order, using nominal and actual sizes correctly.

> **Warm-up.** Find three wooden things at home: a piece of furniture, a cutting board or spoon, and a board from the garage. On each, look at the end grain and the face. Sketch the growth rings you see on the end of each piece. Are the rings curved across the end, or do they run straight up and down? Predict which piece would change shape most if you left it in a damp basement for a month.

WATCH

Why wood moisture content matters

MatthiasWandel · 11:02

https://www.youtube.com/watch?v=KCcKmVJ2hKo

> **WHEN TO WATCH**
> After the story, before the science. Matthias Wandel, an engineer and woodworker, measures real boards with a moisture meter and shows a tabletop that moved with the seasons. Note every number he reads off the meter.

BACKUP VIDEO

Allowing for Wood Expansion on Solid Wood Tops

WoodWorkers Guild Of America · 3:36

https://www.youtube.com/watch?v=kMR4oU1E8P4

After the In the shop section: how furniture makers fasten a solid top so it can move.

KEY TERMS

grain

The direction of the long wood cells (fibers) in a board. Wood is strong and stable along the grain and weaker and much more movable across it.

hardwood and softwood

Hardwoods come from broad-leaved trees (oak, maple, cherry, walnut) and have vessels or pores; softwoods come from conifers (pine, fir, spruce, cedar). The names describe the tree, not the hardness: balsa is a hardwood.

moisture content (MC)

The weight of water in wood as a percentage of the weight of the completely dry wood.

equilibrium moisture content (EMC)

The moisture content wood settles at in a given temperature and humidity; about 6–8% in a heated house in winter and around 12% outdoors in much of the United States.

flat-sawn and quartersawn

A flat-sawn board has growth rings running roughly across its width; a quartersawn board has rings running roughly up and down through its thickness, so it shrinks and swells less across its width.

board foot

A volume of lumber equal to 144 cubic inches: a board 1 inch thick, 12 inches wide and 1 foot long.

CORE IDEAS

The story. About three thousand years ago King Solomon set out to build the temple in Jerusalem, and he wanted the best timber in the known world: the cedars of Lebanon. He wrote to Hiram, king of Tyre, because, as Solomon admitted, none of his own people had the skill "to hew timber like unto the Sidonians." Hiram's men felled the trees in the mountains, floated them down the coast in rafts and delivered them to Solomon's workmen (1 Kings 5). Cedar was prized for good reasons a modern woodworker would recognize: it is straight-grained, light, fragrant, resistant to rot and insects, and stable once dry. Every woodworker since has had to learn the same lesson the Sidonians knew: you cannot build well with wood until you understand what wood is and what it will do.

How they figured it out. In 1665 the English scientist Robert Hooke looked at a thin slice of cork through his microscope and saw that it was made of tiny boxes. He called them *cells*, after the small rooms of a monastery, and his book *Micrographia* printed the drawing you will study today. Later microscopists found that all wood is built the same way: bundles of long, hollow cells glued together. In 1910 the U.S. Forest Service opened the Forest Products Laboratory in Madison, Wisconsin, where scientists spent decades drying, soaking, weighing and breaking thousands of samples. Their findings are collected in the *Wood Handbook*, still the standard reference, which lists for each species its density, strength and how much it shrinks for each percent change in moisture.

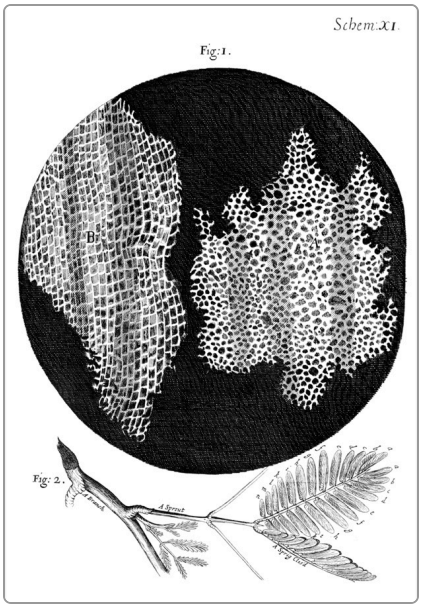
The science. A living tree is mostly water. Each wood cell is a hollow tube whose walls are made of cellulose fibers held in a matrix of lignin, like steel rods in concrete. Water sits in two places: free water in the hollow cell cavities, and bound water soaked into the cell walls themselves. As wood dries, the free water leaves first, and nothing changes size. Below about 28–30% moisture content (the **fiber saturation point**) the cell walls themselves begin to give up water and pull in, and the wood shrinks. Because the cells are long and thin, wood barely shrinks along the grain (about 0.1–0.2% from green to dry), but it shrinks a great deal across the grain, and about twice as much tangentially (along the growth rings) as radially (across the rings). Dry wood never stops responding: it takes on water in humid summer and gives it up in heated winter air, so a wide board is always slowly breathing in and out. Engineers estimate the change in width with $\Delta W = W\, C\, \Delta MC$, where C is the dimensional-change coefficient from the *Wood Handbook*.

In the shop. The craftsman's first rule is *design for movement*. A solid tabletop is fastened with slotted cleats or metal clips so it can slide across its width; a frame-and-panel door lets its panel float in a groove; a breadboard end is pinned only at its center. Wood is bought dry: kiln-dried furniture lumber is around 6–8% MC, and a careful woodworker lets it sit in the shop for a week or two to reach equilibrium before cutting. Choosing the cut matters too. A flat-sawn board shows a cathedral pattern, is cheaper and less wasteful to saw, but cups toward the bark side as it dries and moves more across its width. A quartersawn board, sawn with the rings running through its thickness, shows straight stripes (and in oak, silvery ray fleck), stays flatter and moves about half as much. Lumber is sold by the **board foot**; construction

lumber is named by its rough, **nominal** size, so a 2×4 actually measures 1½ × 3½ inches after drying and planing.

On the job. Carpenters, cabinetmakers, millwrights, flooring installers and furniture makers all read wood the same way. A flooring installer who lays solid oak in August without a gap at the walls will see it buckle; one who lays it in January too tight will see it crush. Many cabinet and millwork shops hire apprentices straight from high school, and a skilled finish carpenter or cabinetmaker is respected and well paid. The knowledge in this lesson is the difference between furniture that cracks in its first winter and furniture that is handed down for a hundred years.

PICTURE STUDY



Cork Cells, from Micrographia, Robert Hooke, 1665 · Engraving from a drawing made at the microscope · Micrographia (London, 1665)

Image: Wikimedia Commons, public domain

Robert Hooke drew this after looking at a thin slice of cork through one of the best microscopes of his day. It was the first time anyone used the word “cell” for the tiny rooms that make up living things. Every board you will cut in this unit is built of cells like these.

Look closely

- Find the two slices. One is cut across the grain and one along it. How do the cells look different in each?
- Look at the walls between the cells. Where would water sit: inside the boxes or in the walls?
- Compare the size and regularity of the rows. Does this look like a material that would be stronger in one direction than another?
- Find the sprig of the plant at the bottom. Why do you think Hooke included it?

Talk about it

1. If the cell walls swell when they take on water, which direction would a board grow most?
2. Hooke found that cork is light and springy. What about its cells explains that?

3. Why might careful drawing at the microscope be just as important to a scientist as careful measuring is to a woodworker?

Safety first. Use the kitchen oven only with an adult, at 103–105 °C (about 220 °F), with small, thin wood samples on a baking sheet; check them often and turn the oven off when you are done. Wear safety glasses when cutting samples, and keep your fingers out of the line of the saw.

SHOP PROJECT

Measure Wood Movement

You will measure the moisture content of real lumber and watch boards change width as they take on and give up water. Then you will compare flat-sawn and quartersawn pieces and test the movement formula against your own data.

You will need

- Two offcuts of the same species (pine or poplar is fine), about 1 × 6 in: one flat-sawn and one with rings running through the thickness (look at the end grain at the lumberyard; ask for a scrap)
- A handsaw, a combination square and a pencil
- A digital caliper (or a steel rule read with a magnifier) and a kitchen scale that reads to 0.1 g
- Two large zip-top bags, a damp (not dripping) paper towel, a small plastic cup
- A kitchen oven (with an adult) and a baking sheet
- An inexpensive pin-type moisture meter (optional)

Steps

1. Cut two strips about 2 in long (along the grain) from each board, so the full width is kept. Label them F1, F2 (flat-sawn) and Q1, Q2 (quartersawn) on the end grain.
2. Mark a measuring line across the face of each strip so you always measure in the same place. Measure and record each width to 0.01 mm (or 1/64 in) and each mass to 0.1 g.
3. Put F1 and Q1 in a bag with the damp paper towel inside a cup (so the wood does not touch the water). Seal it. Leave F2 and Q2 in a dry, warm room (not on a heater).
4. Measure width and mass every day for 5–7 days. Record every reading in a table.
5. At the end, have an adult dry one extra small sliver from each board in the oven at 103 °C until its mass stops changing (about 2–4 hours). Use it to find

the oven-dry mass ratio and calculate the starting moisture content of your boards.

6. Calculate the moisture content of each strip each day, using the dry mass ratio.
7. Calculate the percent change in width of each strip. Graph width change (y) against change in moisture content (x) for flat-sawn and quartersawn pieces on the same axes.
8. Find the slope of each line. This is your measured dimensional-change coefficient C. Compare it with the *Wood Handbook* value for your species.
9. **Check your work.** Use your measured C to predict how much a 30-in-wide tabletop of your wood would move between 6% and 12% MC. Would you fasten it with screws through round holes? Explain.

Tips

- Small strips reach equilibrium faster than whole boards; that is why we cut them short.
- Always measure at the marked line, with the same light pressure on the caliper.
- If you have a moisture meter, compare its readings with your oven-dry numbers. Which do you trust more, and why?

Check your work

- ☐ I calculated moisture content from mass, based on the dry weight.
- ☐ My graph shows which cut moved more, and I compared my slope with a published value.
- ☐ I can explain how a furniture maker designs for wood movement.

SHOP NOTEBOOK

1. A labeled sketch of a log's end showing where a flat-sawn and a quartersawn board come from, with arrows for tangential and radial movement.
2. Your data table and graph from the movement test, with the two best-fit lines and their slopes.
3. A sketch of how you would attach a solid tabletop to its base so it can move, with the movement you calculated written beside it.

KEY FORMULAS

$$MC = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} \times 100\%$$

$$\Delta W = W \cdot C \cdot \Delta MC$$

$$\text{BF} = \frac{T_{\text{in}} \times W_{\text{in}} \times L_{\text{ft}}}{12}$$

$$\rho = \frac{m}{V}$$

From history. Hooke's cork cells were empty walls of dead tissue; it took another two centuries for scientists to understand what cells do in a living plant. Meanwhile, woodworkers learned wood movement by experience. The frame-and-panel door, which lets a thin panel float in grooves, was already common in medieval Europe, and the Forest Products Laboratory's shrinkage tables, first published in the early twentieth century, simply put numbers to what joiners had long known.

WORKED EXAMPLES

Example 1. A small sample of red oak weighs 126.0 g when cut. After drying in a 103 °C oven until its weight stops changing, it weighs 108.0 g. Find its moisture content.

Show solution

1. Mass of water: $126.0 - 108.0 = 18.0$ g.
2. Moisture content is based on the *dry* mass: $MC = \dfrac{18.0}{108.0} \times 100\% = 16.7\%$.
3. This is too wet for indoor furniture (target about 6–8%); it should dry further before use.

Answer: $MC \approx 16.7\%$

Example 2. A 36-inch-wide tabletop is glued up from flat-sawn northern red oak ($C_T = 0.00369$ per percent MC, tangential). It is built in winter at 6% MC and reaches 10% in a humid summer. How much wider does it get? How much would it move if it were quartersawn ($C_R = 0.00158$)?

Show solution

1. Change in moisture content: $\Delta MC = 10 - 6 = 4$ percentage points.
2. Flat-sawn: $\Delta W = 36 \text{ in} \times 0.00369 \times 4 = 0.53 \text{ in}$.
3. Quartersawn: $\Delta W = 36 \text{ in} \times 0.00158 \times 4 = 0.23 \text{ in}$.
4. Over half an inch of movement means the top must be attached with slotted clips or cleats, never glued or screwed tight to the apron.

Answer: About 0.53 in flat-sawn; about 0.23 in quartersawn.

Example 3. You need three 4/4 (1-inch rough) cherry boards, each 6 inches wide and 8 feet long, plus one 8/4 board 7 inches wide and 6 feet long. Cherry costs \$8.50 per board foot. Find the board feet and the cost.

Show solution

1. Each 4/4 board: $\dfrac{1 \times 6 \times 8}{12} = 4.0 \text{ BF}$; three boards $= 12.0 \text{ BF}$.
2. The 8/4 board: $\dfrac{2 \times 7 \times 6}{12} = 7.0 \text{ BF}$.
3. Total 19.0 BF; cost $19.0 \times \$8.50 = \$161.50$.

Answer: $19.0 \text{ BF}, \ \$161.50$

PRACTICE

1. Easy What is the difference between hardwood and softwood? Name one hardwood that is softer than most softwoods.

   Show answer

   Hardwoods come from broad-leaved trees and have vessels (pores); softwoods come from conifers. Balsa is a very soft hardwood.

2. Easy Find the board feet in a board 1 in × 8 in × 10 ft.

   Show answer

   $$\frac{1 \times 8 \times 10}{12} \approx 6.67 \text{ BF}$$

3. Easy What are the actual dimensions of a 2×4 and a 2×6?

Show answer

1½ × 3½ in and 1½ × 5½ in.

4. Medium A pine sample weighs 54.0 g wet and 45.0 g oven-dry. Find its moisture content.

Show answer

$MC = 9.0/45.0 = 20\%$

5. Medium Explain why a board barely changes in length but changes noticeably in width as the seasons change.

Show answer

Wood cells are long, thin tubes aligned with the grain. Water enters and leaves the cell walls, which swell in thickness, so the board grows across the grain; the cells barely lengthen.

6. Medium A 24-in-wide flat-sawn red oak panel ($C_T = 0.00369$) goes from 7% to 11% MC. How much does it widen?

Show answer

$24 \times 0.00369 \times 4 \approx 0.35$ in

7. Medium You are the cabinetmaker. A customer wants a solid-wood door panel glued into its frame on all four sides “so it can’t rattle.” What do you tell them, and what do you build instead?

Show answer

A glued panel cannot move; it will crack or burst the frame when humidity changes. Build a floating panel set in grooves, glued at most at the center of the top and bottom rails, with small rubber spacers to stop rattles.

8. Hard A piece of maple measures 2.00 in × 3.00 in × 12.0 in and has a mass of 1.14 kg. Find its density in g/cm³ (1 in = 2.54 cm).

Show answer

Volume = 72.0 in³ × 16.39 = 1,180 cm³; $\rho = 1140/1180 \approx 0.97$ g/cm³. (This is heavy for maple, so either it is wet or the measurements should be rechecked: dry hard maple is about 0.70 g/cm³.)

9. Hard A flooring installer lays a 15-ft-wide room of flat-sawn oak strips running the long way at 6% MC. Each strip is 2¼ in wide ($C_T = 0.00369$). If summer humidity raises it to 9%, how much does the whole floor try to widen? What gap should she leave?

Show answer

Width 180 in; $180 \times 0.00369 \times 3 \approx 2.0$ in if every strip were flat-sawn and free to move; in practice friction and fastening resist part of it, but she should follow the manufacturer's expansion gap (often ½–¾ in at each wall) and acclimate the wood first.

10. Hard A lumberyard sells 2×10 × 12-ft boards for $18.40 each. Find the price per board foot (use nominal size).

Show answer

BF = 2 × 10 × 12 ÷ 12 = 20 BF; $18.40 ÷ 20 = $0.92 per BF.

11. Challenge Solomon's temple used cedar from Lebanon. Using a density of 0.38 g/cm^3 for dry cedar, estimate the mass of a cedar beam 0.40 m × 0.40 m × 9.0 m, and explain why floating the logs by sea was a sensible engineering choice.

Show answer

Volume = 1.44 m^3; mass ≈ 380 kg/m^3 × 1.44 ≈ 550 kg (more when green). Moving hundreds of such beams overland through mountains would need huge teams of animals; cedar floats (it is less dense than water), so rafts let the sea carry the weight.

COMMON MISTAKES

- Calculating moisture content using the wet mass instead of the dry mass in the denominator.
- Gluing or screwing a wide solid panel tight across its width, so it cracks in the first dry winter.
- Using nominal sizes (2 × 4) in a calculation that needs actual sizes (1½ × 3½).
- Building with lumber straight from a damp yard or garage instead of letting it reach the shop's equilibrium moisture content.

Make it a game · Wood Movement Estimator. Look at a board in your home. Before calculating, predict how much a 10-inch wide flat-sawn board shrinks across its grain if its moisture content drops by 4 points, using a coefficient of about 0.2 percent per point. Compute and compare. Closest estimate wins. Try three different widths and moisture changes.

Scripture. “Now therefore command thou that they hew me cedar trees out of Lebanon; and my servants shall be with thy servants: and unto thee will I give hire for thy servants according to all that thou shalt appoint: for thou knowest that there is not among us any that can skill to hew timber like unto the Sidonians.” (1 Kings 5:6, KJV)

Solomon honored the skill of foreign woodsmen and paid them fairly for it. Knowing your material and doing the work well is a real form of wisdom, and it deserves respect wherever it is found.

3.2 Measuring, Marking and Hand Tools

OBJECTIVES

- Measure and mark accurately with a rule, square, marking gauge and knife, and check a square for accuracy.
- Explain how rip and crosscut saw teeth work, and the difference between Western push saws and Japanese pull saws.
- Explain the physics of a sharp edge and sharpen a chisel to a measurable standard.
- Plan cuts that account for the saw kerf.

> **Warm-up.** Draw a pencil line across a scrap board and then cut a line beside it with a utility knife guided by a square. Look at both with a magnifier. Estimate the width of each line in millimeters. Which line would you rather saw to, and why?

WATCH

How to Sharpen a Chisel | Paul Sellers

Paul Sellers · 7:13

https://www.youtube.com/watch?v=GN4yr7vp4I4

> **WHEN TO WATCH**
> Before the sharpening part of the shop project. Watch how Paul Sellers flattens the back first, then works the bevel through finer and finer abrasives, and how he tests the edge.

BACKUP VIDEO

Woodworking Tips: Measuring and Marking Tools

Woodsmith · 8:47

https://www.youtube.com/watch?v=EBuokmW_iM8

Before the marking part of the shop project: rules, squares, gauges and knives, and how to use them.

KEY TERMS

kerf

The slot a saw blade removes. Its width must be planned for: the cut goes on the waste side of the line.

rip cut and crosscut

A rip cut runs along the grain; a crosscut runs across it. Rip teeth are filed square like little chisels; crosscut teeth are filed with a bevel like little knives that sever the fibers.

set

The alternate bending of saw teeth left and right so the kerf is wider than the blade and the saw does not bind.

TPI / PPI

Teeth (or points) per inch on a saw. Fewer, larger teeth cut fast and rough; more, smaller teeth cut slowly and smoothly.

bevel and back

The two faces that meet at a chisel's or plane iron's edge. The flat back must be truly flat near the edge; the bevel is ground at about 25° and often honed with a slightly steeper secondary bevel.

knife line

A line cut into the wood with a marking knife; it is finer than a pencil line and gives the saw or chisel a crisp starting shoulder.

CORE IDEAS

The story. In 1840 a young English-born saw maker named Henry Disston set up shop in Philadelphia. American carpenters then bought most of their good saws from Sheffield in England. Disston experimented for years with steel, heat-treating, tooth shapes and handles, built his own steel mill so he could control the metal, and by the late 1800s his Keystone Saw Works was the largest saw maker in the world. Meanwhile a Boston plane maker named Leonard Bailey patented, in 1858 and 1867, the iron bench plane with a screw-and-lever blade adjustment, the design the Stanley Rule & Level Company made famous. A Disston D-8 saw or a Stanley-Bailey No. 4 plane from a century ago, sharpened, still works beautifully today.

How they figured it out. Saw makers learned by cutting thousands of boards that one tooth shape cannot do every job. Wood fibers are like a bundle of drinking straws. Cutting *along* the straws (ripping), each tooth should act like a tiny chisel, lifting out a shaving; so rip teeth are filed straight across, about 4–7 per inch. Cutting *across* the

straws (crosscutting), a chisel would tear them, so crosscut teeth are filed with a bevel on alternate sides, making a double row of knife points that slice each fiber on both sides of the kerf before it is removed. Japanese woodworkers took another path: their saws cut on the *pull* stroke, so the thin blade is in tension and cannot buckle, letting it be very thin, with a narrow kerf and very fine teeth.

The science. A cutting edge works by pressure: $p = F/A$. When you push on a chisel, all your force is concentrated on the tiny area of its edge. A freshly honed edge may be about a micrometer (0.001 mm) wide; a dull, rounded one may be twenty times wider, so the same push gives one-twentieth the pressure, and the tool crushes and tears the fibers instead of severing them. That is why a dull tool is more dangerous: you push harder, it skids, and your hand follows it. Sharpening removes metal from both faces until they meet in a clean line; each finer abrasive replaces the scratches of the one before with smaller scratches until the edge reflects no light. Measuring has its own science. A pencil line is about 0.5 mm wide, so “cut on the line” can mean an error of half a millimeter; a knife line is about a fifth of that and gives a physical shoulder for the tool to register against.

In the shop. Good work starts with one reference face and one reference edge on every board; all measurements and square lines come from those. Use the same rule or tape for a whole project. Transfer measurements directly when you can (hold the part in place and mark it) instead of measuring and re-measuring. Check your square: draw a line along it from a straight edge, flip the square over, and draw again; any error shows up doubled. For large frames, use the 3-4-5 rule or compare the diagonals. Saw on the waste side of the knife line. Sharpen chisels and plane irons with a flat back, a primary bevel around 25° and a small honed bevel near 30°; keep them sharp by honing often, rather than letting them become dull.

On the job. A trim carpenter installing crown molding or a cabinetmaker fitting a door lives by these habits. Many professionals still carry a marking knife, a block plane and a set of sharp chisels, because no power tool can pare a joint to a perfect fit. Woodworkers such as Paul Sellers, who trained as an apprentice joiner in England at fifteen, have taught hand-tool methods to thousands of people because the skills are learnable and the tools are affordable.

PICTURE STUDY



Woodwork in the N.Y.A. Shop, Taos, Irving Rusinow, December 1941 · Photograph · U.S. Bureau of Agricultural Economics; National Archives

Image: Wikimedia Commons, public domain

This photograph was taken by a U.S. government photographer in a New Mexico workshop where young people learned trades. The tools are almost all hand tools, and the furniture around them was made with the skills in this lesson.

Look closely

- Find the handsaw. Is the worker ripping or crosscutting? How can you tell from the direction of the board?
- Look at how the work is held. What steadies the board while it is sawn?
- Find the open frame in the foreground. How do you think its corners are joined?
- Look for squares, rules or marking tools anywhere in the shop.

Talk about it

1. What would happen to the frame if one of its pieces were cut 2 mm too short?
2. Why might a school teach hand-tool skills first, even when power tools exist?
3. What safety habit would you add to this picture today?

> **Safety first.** Wear safety glasses. Always cut and pare away from your body, with both hands behind the edge, and clamp the work instead of holding it. Sharp tools cut more safely than dull ones, but treat every edge with respect: store chisels with guards on and never catch a falling tool.

SHOP PROJECT

A Sharp Chisel and an Accurate Cut

You will sharpen a chisel on sandpaper glued to flat glass, measure its sharpness with simple tests, then mark and saw a board to a knife line and measure your accuracy.

You will need

- A bench chisel (an inexpensive ¾-in or 1-in chisel is fine)
- A piece of float glass or a flat tile about 6 × 12 in; wet-or-dry sandpaper in 220, 400, 1,000 and 2,000 grit; a spray bottle of water
- A permanent marker and a magnifier; a honing guide (optional)
- Pine scrap (a 2×4 offcut), a combination square, a marking knife or utility knife, a pencil, a handsaw, clamps
- A digital caliper or steel rule

Steps

1. Check your square with the flip test on a straight-edged board. Record the error over its length.
2. Color the back near the edge and the bevel with marker. Rub the back flat on 220 grit; the marker shows where you are touching. Continue until the last 1 in of the back is evenly scratched, then work it through 400, 1,000 and 2,000.
3. Hone the bevel at a steady angle (about 25–30°) on each grit until the marker is gone and you can feel a tiny burr along the back edge. Remove the burr with a few strokes on the back at 2,000 grit.
4. Test the edge: try to pare a thin shaving from the end grain of the pine. Record whether it cuts cleanly, tears or crushes. Look at the edge under a light: a dull edge reflects a bright line; a sharp one does not.
5. Record the time and the grit at each stage in a table.
6. Square the end of the 2×4 and knife a line all the way around it 3 in from the end, with the square against your reference face and edge.
7. Deepen the knife line on the waste side with a small chisel cut so the saw has a groove to start in. Clamp the work and saw on the waste side.

8. Measure the length of the cut-off piece at four corners. Record the largest error from 3.000 in and how far off square the cut is.
9. **Improve it.** Repeat the marked cut twice more and graph your error. Pare the end to the knife line with your sharpened chisel and measure again.

Tips

- Spray water on the sandpaper so it sticks to the glass and the swarf washes away.
- Most beginners rock the chisel while honing and round the bevel. Lock your wrists and move from the shoulders, or use a honing guide.
- Start the saw cut with a few gentle pull strokes, letting the saw's weight do the work.

Check your work

- ☐ My chisel pares end grain cleanly and shows no bright line at its edge.
- ☐ I measured my sawing error and reduced it on later tries.
- ☐ I can explain why a knife line is more accurate than a pencil line.

SHOP NOTEBOOK

1. Labeled sketches of rip and crosscut teeth seen from the side and from above, showing the set.
2. A table of your sharpening steps: grit, time, what the edge looked like, and the end-grain test result.
3. Your sawing-accuracy data for three tries, with a short note on what you changed each time.

KEY FORMULAS

$$p = \frac{F}{A}$$

$$L_{\text{part}} = \frac{L_{\text{board}} - (n-1)\,k}{n}$$

$$d = \sqrt{a^2 + b^2}$$

$$\theta = \arctan\left(\frac{\text{error}}{\text{length}}\right)$$

From history. Henry Disston's company made saws in Philadelphia for more than a century, and its handsaws were so common that collectors still date them by the shape of their medallions and etchings. Leonard Bailey sold his plane patents to the Stanley Rule & Level Company in 1869, and Stanley made Bailey-pattern planes for over a hundred years; nearly every metal bench plane made today still follows his design.

WORKED EXAMPLES

Example 1. You push a 25 mm wide chisel with a force of 60 N. Compare the pressure at a sharp edge 0.001 mm wide with a dull edge 0.020 mm wide.

Show solution

1. Sharp edge area: $A = 25\ \text{mm} \times 0.001\ \text{mm} = 0.025\ \text{mm}^2$.
2. Sharp pressure: $p = \dfrac{60\ \text{N}}{0.025\ \text{mm}^2} = 2400\ \text{N/mm}^2 = 2400\ \text{MPa}$.
3. Dull edge area: $25 \times 0.020 = 0.50\ \text{mm}^2$; pressure $60 / 0.50 = 120\ \text{MPa}$.
4. The sharp edge gives 20 times the pressure for the same push. Wood fibers that need, say, 500 MPa at the edge to sever cleanly are cut by the sharp chisel but only crushed by the dull one.

Answer: About 2400 MPa versus 120 MPa, a factor of 20.

Example 2. You must cut a 48-inch board into four equal parts. The saw kerf is 1/8 in. How long can each part be?

Show solution

1. Four parts need three cuts: $3 \times 0.125 = 0.375$ in lost to kerf.
2. Remaining wood: $48 - 0.375 = 47.625$ in.
3. Each part: $47.625 / 4 = 11.906$ in, just under 11 29/32 in. (If the ends are rough you must also trim them, so plan for parts of about 11 7/8 in.)

Answer: ≈ 11.91 in each

Example 3. You check a combination square by the flip test on a 300 mm line. The two lines are 0.60 mm apart at the far end. What is the square's error, and how far out of square would the side of a 750 mm tall cabinet be if marked with it?

Show solution

1. The flip doubles the error, so the true error is $0.60/2 = 0.30$ mm in 300 mm.
2. Angle: $\theta = \arctan(0.30/300) \approx 0.057^\circ$.
3. Over 750 mm: $750 \times 0.30/300 = 0.75$ mm out of square, enough to make a door gap visibly tapered.

Answer: Error 0.30 mm in 300 mm; about 0.75 mm over 750 mm.

PRACTICE

1. Easy Why do you saw on the waste side of the line?

   Show answer

   Because the kerf removes wood; if the kerf is centered on the line, the part comes out short by half the kerf.

2. Easy What is the difference between rip and crosscut teeth?

   Show answer

   Rip teeth are filed square, like chisels, to cut along the grain; crosscut teeth are beveled like knives to sever fibers across the grain.

3. Easy Why can a Japanese pull saw have a thinner blade than a Western push saw?

   Show answer

   On the pull stroke the blade is in tension and cannot buckle, so it does not need thickness for stiffness.

4. Medium A frame is 600 mm by 800 mm. What should its diagonal be if it is square?

   Show answer

   $\sqrt{600^2 + 800^2} = 1000$ mm

5. **Medium** A 96-in board is cut into six equal shelves with a 1/8-in kerf. How long is each shelf (ignore end trimming)?

   Show answer

   $(96 - 5 \times 0.125)/6 \approx 15.90$ in

6. **Medium** A plane iron 2 in wide is pushed with 25 lb. Its honed edge is 0.00004 in wide. Find the pressure at the edge in psi.

   Show answer

   $A = 8 \times 10^{-5}$ in^2; $p = 25/(8 \times 10^{-5}) \approx 310{,}000$ psi

7. **Medium** You are the carpenter. A frame's diagonals measure 1,003 mm and 997 mm. Is it square? What do you do?

   Show answer

   No. Push the long-diagonal corners toward each other until the two diagonals are equal (1,000 mm each), then fasten or brace it.

8. **Hard** Explain, using $p = F/A$, why a dull chisel is more dangerous than a sharp one.

   Show answer

   The dull edge has a larger area, so the same force gives much less pressure; you must push harder, the tool resists and then slips suddenly, and the extra force carries your hand into the path of the edge.

9. **Hard** A flip test on a 12-in line shows the two lines 1/32 in apart. What is the angular error of the square?

   Show answer

   Error = 1/64 in in 12 in; $\theta = \arctan(0.015625/12) \approx 0.075^\circ$

10. **Hard** Ecclesiastes 10:10 says that if the iron is blunt one must "put to more strength." Restate this as a physics statement about force, area and pressure.

    Show answer

    To reach the pressure needed to cut, $F = pA$; a blunt edge has larger A, so more force F is needed for the same cutting pressure.

11. **Challenge** You sharpen with abrasive grits of 220, 400, 1,000 and 4,000. Abrasive particle sizes are roughly 68, 35, 15 and 3 micrometers. If each grit leaves scratches about as deep as half its particle size, how deep are the scratches after each step? Why is skipping from 220 to 4,000 a poor plan?

    Show answer

    About 34, 17.5, 7.5 and 1.5 µm. Each grit must remove the scratches of the one before; going straight from 34 µm scratches to a 3 µm abrasive would take a very long time and usually leaves deep scratches at the edge.

COMMON MISTAKES

- Sawing on the line, or on the wrong side of it, so the part is short by half the kerf or more.
- Measuring from the end of a tape with a bent hook, or switching tapes in the middle of a project.
- Sharpening only the bevel and leaving the back of the chisel unflattened, so the edge never becomes keen.
- Taking measurements from a different face or edge each time instead of from one reference face and edge.

Make it a game · Layout Accuracy Duel. With a ruler and pencil, mark ten lines on paper at lengths your parent calls, such as 3 and 5/16 inches. Check against a second ruler and score how many land within a 1/32 inch. Then explain how rip and crosscut teeth differ, and why a pull saw cuts thin. Beat your own accuracy.

Scripture. “If the iron be blunt, and he do not whet the edge, then must he put to more strength: but wisdom is profitable to direct.” (Ecclesiastes 10:10, KJV)

Solomon’s observation is exactly the physics of pressure: a blunt edge needs more force. Taking time to sharpen is the kind of wisdom that makes work easier, safer and better.

3.3 Power Tools and Shop Safety

OBJECTIVES

- Explain what each common power tool does best: drill/driver, circular saw, jigsaw, miter saw and table saw.
- Explain the physics of table-saw kickback and how the riving knife, guard, fence practice and push sticks prevent it.
- Calculate blade rim speed, stopping deceleration and safe noise-exposure time.
- Write and follow a shop safety plan, and make first supervised power-tool cuts.

> **Warm-up.** List every power tool in your home, garage or a relative's shop. For each one, write where its cutting edge or bit is, which way it spins or moves, and where the work or the chips would be thrown if something went wrong. Circle the one you think causes the most injuries.

WATCH

Simple Guide to Table Saw Safety | Ask This Old House

This Old House · 7:54

https://www.youtube.com/watch?v=K77fFwDjRl8

> **WHEN TO WATCH**
> After the story and before the science. General contractor Tom Silva explains the guard, riving knife, fence and push sticks, and shows with the saw switched off why kickback happens. Pause when he points to the back of the blade and predict which way the wood would be thrown.

BACKUP VIDEO

Watch this BEFORE turning on a table saw. The Table Saw Golden Rule.

Steve Ramsey - Woodworking for Mere Mortals · 8:40

https://www.youtube.com/watch?v=IU58UO4O9YA

Before the shop project: Steve Ramsey's checklist to run through every time before you switch on a table saw.

KEY TERMS

kickback

A sudden violent throw of the workpiece back toward the operator, caused when the rising teeth at the back of a spinning blade catch the wood.

push stick / push block

A shop-made or store-bought handle that pushes narrow work past a blade so the hands stay well away from it.

dBA and exchange rate

Sound level in decibels weighted for human hearing. Under the NIOSH guideline, 85 dBA is safe for 8 hours, and every 3 dB louder halves the safe time.

riving knife

A curved steel plate just behind a table-saw blade that rises and falls with the blade, keeping the kerf open so the wood cannot pinch or swing into the back teeth.

rim speed

The speed of the tips of the teeth, $v = \pi D n$; for a 10-in table-saw blade it is well over 100 miles per hour.

flesh-sensing brake

A table-saw safety system (SawStop) that detects skin touching the blade by a change in an electrical signal and stops the blade in a few thousandths of a second.

CORE IDEAS

The story. In 1999 Steve Gass, a physicist and patent attorney who spent his weekends woodworking in Oregon, was looking at his table saw and wondered whether a blade could tell the difference between wood and a finger. Wood conducts electricity poorly; the human body, full of salty water, conducts it well. Gass put a tiny high-frequency electrical signal on the blade and watched it. When skin touched the teeth, the body absorbed part of the signal and the circuit noticed at once. He built a brake: a spring-loaded aluminum block held back by a thin fuse wire. When the signal dropped, a pulse of current melted the wire, the spring drove the block into the teeth, and the spinning blade stopped and dropped below the table in about five milliseconds. To show it, he pushed a hot dog into the blade; it came away with a nick. Gass and two partners founded SawStop, and its first saws went on sale in 2004.

How they figured it out. The harder problem, which saw makers and safety engineers had studied for decades, is **kickback**, which injures far more people than direct contact. Engineers filmed and measured it. A table-saw blade spins toward the

operator at the front, pushing the wood down onto the table. But at the back of the blade, the teeth are *rising* and moving toward the operator. If the cut closes up behind the blade (as wood with internal stress often does) or the board drifts away from the fence, those back teeth grab the wood, lift it and fling it toward the person at nearly the speed of the teeth. The answer was the splitter and then the **riving knife**, a curved plate just behind the blade that holds the kerf open and keeps the board from rotating into the back teeth. Since about 2009 new table saws sold in the United States have been built with riving knives under the UL safety standard.

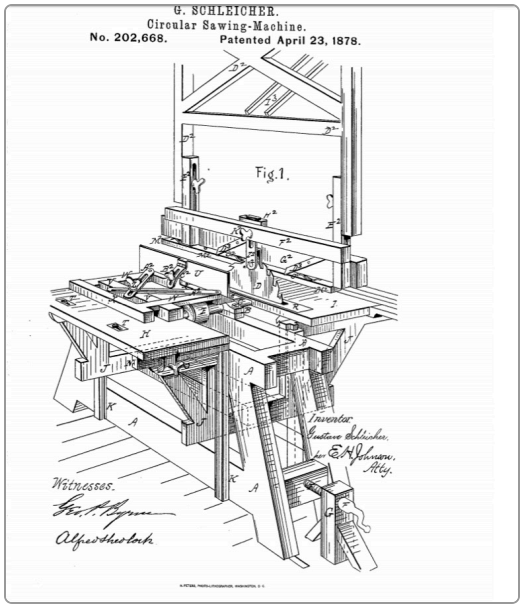
The science. The tip of a 10-inch blade turning at 4,000 turns per minute (rpm) moves at $v = \pi D n \approx 53$ m/s, about 119 mph. A board caught by those teeth can leave the saw at a large fraction of that speed, with kinetic energy $\frac{1}{2}mv^2$ of a couple of hundred joules, enough to cause a serious injury. Your hands are pulled along too: when a board suddenly moves, the hand pushing it falls toward the blade. The SawStop brake must take the blade from 53 m/s to rest in about 5 ms, an average deceleration of roughly 10,000 m/s², over a thousand times gravity, which is why the brake cartridge and often the blade are ruined after it fires. Noise is physics too: a table saw or router often runs at 95–105 dBA. The decibel scale is logarithmic; every 3 dB is twice the sound energy, so the safe exposure time halves.

In the shop. Each tool has a job. A **drill/driver** bores holes and drives screws; its clutch sets the torque at which it slips. A **circular saw** makes rough and straight cuts in big sheets and framing lumber; set the blade only about ¼ in below the work and support the board so the kerf opens rather than pinches. A **jigsaw** cuts curves. A **miter saw** makes accurate crosscuts and angles; keep your hands outside the marked zone and let the blade stop before lifting it. A **table saw** makes accurate rip cuts. Rules that prevent most injuries: guard and riving knife in place; never cut freehand; use the fence for rips and the miter gauge or a sled for crosscuts, never both together; push sticks for anything narrower than about 6 in; stand slightly to the side of the blade; never reach over or behind a spinning blade; unplug before changing blades. Safety glasses always, hearing protection for power tools, a dust mask or respirator for sanding, no loose sleeves, gloves, jewelry or loose long hair near spinning tools. A student's first cuts on any saw are made with an experienced adult right beside them.

On the job. Professional carpenters and cabinetmakers make thousands of cuts a week and keep all ten fingers because they follow the same routine every single

time. Construction employers must follow OSHA rules on guarding and hearing protection, and apprentices are taught that the fastest way to lose a job is to be careless with a saw.

PICTURE STUDY



Circular Sawing-Machine, U.S. Patent 202,668, Gustav Schleicher (inventor), April 23, 1878 · Patent drawing · United States Patent Office

Image: Wikimedia Commons, public domain

Patent drawings are public domain and show exactly how an inventor meant a machine to work. This is a nineteenth-century sawing machine with a table and a circular blade, an ancestor of the table saw in many modern shops.

Look closely

- Find the blade. How high does it stick up above the table?
- Find the pulleys and belts that drive the blade. Where was the power coming from?
- Look for anything that guides the wood, such as a fence or a gauge.
- Look for any guard, splitter or riving knife. Is there one?

Talk about it

1. Which way does the blade spin, and which way would kickback throw a board on this machine?
2. What three safety features would you add to this design today?
3. Why do you think inventors file detailed drawings with a patent?

Safety first. An experienced adult supervises every power-saw cut in this lesson and stands beside you for your first cuts; table-saw work is optional and only with that adult. Safety glasses always, hearing protection for every power tool, close-fitting clothes with sleeves rolled, no gloves near spinning blades, hair tied back and jewelry off. Unplug a tool before changing a blade or bit, and never reach over or behind a spinning blade.

SHOP PROJECT

Safety Plan, Push Stick and First Supervised Cuts

You will measure the noise of real tools, write a one-page shop safety plan, make a push stick from a pattern, and then, with an adult beside you, make straight cuts with a circular saw or jigsaw and measure your accuracy.

You will need

- A free sound-level meter app (for example the NIOSH SLM app) on a phone
- A piece of ½-in or ¾-in plywood about 4 × 14 in for the push stick; a jigsaw or coping saw; sandpaper
- A circular saw or jigsaw, a straight board or level to use as a clamped guide, two clamps
- A 2×4 and a 2 × 2 ft piece of ½-in plywood or OSB to practice on; sawhorses or a foam insulation board under the work
- Safety glasses, earmuffs or earplugs, a dust mask, a tape measure and square

Steps

1. Read the manual for each tool you will use and list its safety features. Write a one-page safety plan: protective gear, clothing, the rule for each tool, where the adult stands, what to do if a tool jams, and where the first-aid kit and phone are.
2. With hearing protection on and an adult running each tool, measure the sound level of a drill, a circular saw, a shop vacuum and (if available) a table saw at the operator's ear position. Record each reading.
3. Calculate the NIOSH safe time for each tool and add it to your plan.
4. Draw a push stick on the plywood: a long handle with a notch at the bottom that hooks the back of a board. Cut it out with a jigsaw (adult beside you) or coping saw and sand the edges.
5. Mark three straight cut lines on the plywood sheet, 6 in apart. Measure the distance from the blade to the edge of the saw's base and clamp a straight guide that far from each line.

6. Support the sheet on sawhorses or a foam board so both pieces are supported and the kerf will not close. Set the blade depth to about ¼ in below the sheet.
7. With the adult beside you, make the cuts, keeping the base against the guide and letting the blade stop before lifting the saw.
8. Measure each strip's width at both ends and the middle. Record your largest error and whether the cut wandered.
9. **Improve it.** Make three crosscuts on the 2×4 using a speed square as a guide. Measure squareness with a combination square and compare your first and last cuts.

Tips

- A clamped guide does more for straightness than a steady hand.
- Let the saw reach full speed before it touches the wood, and do not force it; a laboring motor means a dull blade or a pinching kerf.
- If the blade binds, release the trigger and hold the saw still until the blade stops.

Check your work

- ☐ My safety plan lists the gear, the rules for each tool and the noise times I calculated.
- ☐ I made straight cuts with a guide and measured my accuracy.
- ☐ I can explain kickback and the riving knife to someone else.

SHOP NOTEBOOK

1. A table of sound readings for each tool, with NIOSH safe times.
2. A labeled sketch of a table saw from the side showing blade rotation, the riving knife, the fence, the guard and where to stand.
3. Your measured cut errors, and one sentence on what made the biggest improvement.

KEY FORMULAS

$$v = \pi D n$$

$$a = \frac{\Delta v}{\Delta t}$$

$$KE = \tfrac{1}{2} m v^2$$

$$t_{\text{safe}} = 8\ \text{h} \div 2^{(L-85)/3}$$

$$P = V I$$

From history. Before electric motors, circular saws in mills were driven by water wheels and steam engines through overhead belts. The portable electric circular saw came in the 1920s: Edmond Michel of New Orleans built a worm-drive model in 1923 and with Joseph Sullivan founded the company that made the Skilsaw, still the framer's favorite. Modern shop safety owes much to the National Safety Council and to OSHA, created in 1970, which set rules for guards and noise in workplaces.

WORKED EXAMPLES

Example 1. A 10-in (0.254 m) table-saw blade spins at 4,000 rpm. Find the rim speed in m/s and mph. If a flesh-sensing brake stops it in 5.0 ms, find the average deceleration, and how far a hand moving toward the blade at 0.30 m/s travels during the stop.

Show solution

1. Turns per second: $n = 4000/60 = 66.7\ \text{rev/s}$.
2. Rim speed: $v = \pi D n = \pi(0.254\ \text{m})(66.7\ \text{s}^{-1}) = 53.2\ \text{m/s}$; $53.2 \times 2.237 \approx 119\ \text{mph}$.
3. Deceleration: $a = \dfrac{53.2\ \text{m/s}}{0.0050\ \text{s}} \approx 10{,}600\ \text{m/s}^2$, about $1{,}100\,g$.
4. Hand travel: $d = (0.30\ \text{m/s})(0.0050\ \text{s}) = 0.0015\ \text{m} = 1.5\ \text{mm}$.

Answer: $53\ \text{m/s}\ (119\ \text{mph});\ a \approx 10{,}600\ \text{m/s}^2;\ 1.5\ \text{mm}$

Example 2. A sound meter reads 100 dBA at the table saw. Using the NIOSH guideline (85 dBA for 8 h, 3-dB exchange rate), how long can you work there without hearing protection? With earmuffs that reduce the level to 82 dBA?

Show solution

1. Without protection: $t = \dfrac{8\ \text{h}}{2^{(100-85)/3}} = \dfrac{8}{2^{5}} = 0.25\ \text{h} = 15\ \text{min}$.
2. With earmuffs, 82 dBA is below 85 dBA, so a full 8-hour day is within the guideline.

Answer: 15 minutes unprotected; a full day with earmuffs.

Example 3. A 0.80 kg strip of oak is kicked back at 25 m/s. Find its kinetic energy and compare it with a 0.145 kg baseball thrown at 40 m/s (90 mph).

Show solution

1. Oak strip: $KE = \tfrac{1}{2}(0.80)(25)^2 = 250\ \text{J}$.
2. Baseball: $KE = \tfrac{1}{2}(0.145)(40)^2 = 116\ \text{J}$.
3. The kicked-back strip carries more than twice the energy of a fastball, which is why you stand to the side of the blade line.

Answer: 250 J, about twice a fastball's 116 J.

PRACTICE

1. Easy What does a riving knife do?

   Show answer

   It keeps the kerf open behind the blade so the wood cannot pinch the blade or swing into the rising back teeth, preventing kickback.

2. Easy Why should you never use the rip fence and the miter gauge together to crosscut a short piece?

   Show answer

   The offcut gets trapped between the blade and the fence and can be caught by the back teeth and thrown.

3. **Easy** Name four items of protective gear for a woodshop and what each protects.

Show answer

Safety glasses (eyes from chips), hearing protection (ears from noise), dust mask or respirator (lungs from fine dust), close-fitting clothes with no jewelry or loose hair (prevents entanglement).

4. **Medium** A 7¼-in circular saw blade turns at 5,800 rpm. Find its rim speed in m/s (1 in = 0.0254 m).

Show answer

$\pi(0.184)(96.7) \approx 56 \text{ m/s}$

5. **Medium** A router runs at 97 dBA. What is the NIOSH safe time without protection?

Show answer

$8/2^{4} = 0.5 \text{ h} = 30 \text{ min}$

6. **Medium** A table saw motor draws 13 A at 120 V. Find its electrical power in watts and horsepower (1 hp = 746 W).

Show answer

$P = 1560 \text{ W} \approx 2.1 \text{ hp}$ input; the output is less because of motor losses.

7. **Medium** You are the shop teacher. A student is ripping a 2-in-wide strip with his fingers between the fence and the blade and no riving knife installed. List, in order, what you do.

Show answer

Have him stop and switch off the saw calmly (do not startle him); wait for the blade to stop; unplug it; install the riving knife and guard; show him a push stick; have him make the cut again with the push stick while you stand beside him.

8. Hard Explain, with a sketch in words, why the back of a table-saw blade causes kickback but the front does not.

Show answer

At the front the teeth move down and toward the operator, pressing the board onto the table. At the back they move up and toward the operator, so if they catch the board they lift it and throw it back.

9. Hard A flesh-sensing brake stops a blade spinning at 60 m/s in 3.5 ms. Find the average deceleration in m/s^2 and in g.

Show answer

$a = 60 / 0.0035 \approx 17{,}000 \text{ m/s}^2 \approx 1{,}750\, g$

10. Hard Sound intensity doubles every 3 dB. How many times more sound energy reaches your ears at 100 dBA than at 85 dBA?

Show answer

$2^{15/3} = 2^5 = 32$ times.

11. Challenge Kickback throws a 1.2 kg board straight back at 20 m/s. A worker standing directly behind it is 1.0 m away. Estimate the time before it reaches him and compare with a typical human reaction time of about 0.25 s. What does this tell you about where to stand?

Show answer

$t = 1.0 / 20 = 0.05$ s, five times faster than anyone can react. You cannot dodge kickback; you must prevent it (riving knife, fence technique) and stand out of the line of the blade.

COMMON MISTAKES

- Removing the guard or riving knife “just for this cut” and forgetting to put it back.
- Standing directly behind a table-saw blade instead of slightly to the side.
- Setting a circular saw blade far deeper than the board, which increases kickback and exposure.
- Thinking hearing loss only comes from very loud bangs; long exposure to ordinary shop noise causes it too, slowly and permanently.

> **Make it a game · Name That Hazard.** Study a shop photo or a drawing of a table saw, circular saw or drill. In 90 seconds, list every safety feature and each reason for it: guard, riving knife, fence rules, push stick, eye and ear protection. No tools run in this game. Your parent counts your correct items. Beat the tally.

3.4 Joinery: Fitly Joined Together

OBJECTIVES

- Identify the butt, rabbet, dado, lap, mortise-and-tenon, dovetail and pocket-screw joints and explain where each is used.
- Explain why long-grain glue joints are strong and end-grain glue joints are weak, and how joint shape adds mechanical strength.
- Calculate glue area, the shear capacity of a joint and the withdrawal strength of screws.
- Build several joints and test them to failure in a fair test.

> **Warm-up.** Look at the corners of a drawer, a cabinet door, a chair and a bookcase in your home. For each, sketch how you think the two pieces are joined. Can you see pegs, screws, interlocking “tails”, or nothing at all? Which one do you think is strongest?

WATCH

Paul Sellers | Mortise and tenon joint by hand, in oak

Paul Sellers · 10:31

https://www.youtube.com/watch?v=LPBkO2chZxk

> **WHEN TO WATCH**
> After the science paragraph. Watch the order of operations: layout with a knife and gauge, the mortise chopped first, then the tenon sawn and pared to fit it. Notice how little force a sharp chisel needs.

KEY TERMS

long grain and end grain

Long grain is the side of a board, where fibers run along the surface; end grain is the cut end, where the open ends of the cells show. Glue holds very well on long grain and poorly on end grain, which soaks it up like a bundle of straws.

mortise and tenon

A joint in which a tongue (tenon) on the end of one piece fits a matching hole (mortise) in the other; the classic frame joint for chairs, tables, doors and timber frames.

dovetail

Interlocking flared “tails” and “pins” that cannot be pulled apart in one direction even without glue; the traditional drawer and box joint.

dado and rabbet

A dado is a square-bottomed groove across the grain that a shelf fits into; a rabbet is a step cut along the edge or end of a board.

pocket screw

A screw driven at a steep angle (about 15°) through a pocket drilled in one board into the edge of another; fast and strong enough for face frames and cabinets.

draw-bore

Pegging a mortise and tenon through holes deliberately offset by about 1/16–1/8 in, so the peg pulls the joint tight and holds it even if the glue fails.

CORE IDEAS

The story. Joinery is one of the oldest engineering arts. Furniture from the tombs of ancient Egypt, more than three thousand years old, is held together with mortises, tenons and dovetails that still fit. The Gospel of Mark calls Jesus “the carpenter” (Mark 6:3); the Greek word, *tekton*, means a builder in wood and stone, the sort of man who made doors, yokes, plows and roof beams. In early America the Shakers, a religious community famous for plain, honest furniture, built chairs, tables and cabinets with carefully fitted joints and almost no ornament, on the idea that a thing made well and simply is made rightly. Their pieces sell today for more than many antiques covered with carving, because the joints have never failed.

How they figured it out. Woodworkers learned by experience which joints lasted. A timber framer raising a barn learned that a mortise and tenon pinned with an oak peg would carry a heavy beam for centuries, and that offsetting the peg holes a little (draw-boring) pulled the shoulders tight forever. Cabinetmakers learned that glue alone on end grain fails, so they gave every joint long-grain glue surfaces or interlocking shapes. In the twentieth century the U.S. Forest Products Laboratory and glue makers put numbers to this, testing glued blocks in shear (ASTM D905). They found that a good modern glue joint on long grain is stronger than the wood beside it: the wood tears before the glue lets go.

The science. A joint can fail in three ways: the glue lets go (adhesive failure), the glue itself breaks (cohesive failure), or the wood breaks beside it. Yellow PVA wood glue has a shear strength around 3,600–4,000 psi on maple in standard tests, while the

wood itself fails in shear parallel to the grain at about 900 psi (eastern white pine) to about 1,800 psi (red oak). So a long-grain joint, made well, fails in the wood. End grain is different: the open cells wick the glue away and offer almost no surface for it to grip, so a glued end-grain butt joint can fail at a small fraction of that strength. The joints that last therefore do two things: they put *long grain against long grain* over a large area (the cheeks of a tenon, the faces of a half-lap), and they add a *mechanical lock* that carries load even without glue (the shoulders of a tenon resist racking; the flare of a dovetail resists pulling; a dado's shoulders carry a shelf's weight in bearing). Screws hold by friction and the shear of wood fibers along the threads; their withdrawal strength in side grain is estimated by the *Wood Handbook* formula $p = 15{,}700\, G^{2} D L$.

In the shop. Choose the joint for the load. A **butt joint** with screws or nails is quick and fine for rough work. A **rabbet** or **dado** locates parts and carries shelves. A **half-lap** is simple and strong for frames. A **mortise and tenon** is the joint for chairs, tables and doors; the usual rule is a tenon about one-third the thickness of the stock, with shoulders all around. **Dovetails** are for drawers and boxes; their slope is about 1:6 in softwood and 1:8 in hardwood. **Pocket screws** (popularized by the Kreg jig in the 1980s) are fast and strong for face frames and cabinet boxes. **Dowels** and **biscuits** align parts and add some glue area. Whatever the joint, fit matters: a tenon should slide in with hand pressure, and glue cannot fill gaps in a loose joint.

On the job. Cabinetmakers, furniture makers, stair builders, timber framers and boatbuilders are joiners first. A good cabinet shop can tell you how many pounds a shelf in a dado will carry and why a face frame is pocket-screwed but a door is cope-and-stick or mortise-and-tenon. These trades are learned by apprenticeship, and a fine joiner is never short of work.

PICTURE STUDY



Saint Joseph the Carpenter, Georges de La Tour, about 1642 · Oil on canvas · Musée du Louvre, Paris

Image: Wikimedia Commons, public domain

Georges de La Tour painted the carpenter Joseph at work at night, with the boy Jesus holding the candle. The painter cared about the tools and the work as well as the light: Joseph is boring a hole in a beam, the first step of many joints.

Look closely

- Find the auger. How is Joseph turning it, and how does he steady the beam?
- Look at the beam on the floor. What kind of joint might this hole be for?
- Find the shavings or chips. What do they tell you about how the auger cuts?
- Notice where the light falls. How does the painter make you look at the work?

Talk about it

1. If this hole is for a peg, what is the peg's job in the joint?
2. Why would a carpenter in Joseph's day choose pegged joints instead of nails?
3. What does it say about honest work that the painter shows such an ordinary task with such care?

> **Safety first.** Wear safety glasses while sawing, chopping and especially during the load test, when joints can snap and parts or sandbags can drop. Clamp work to the bench; keep both hands behind the chisel edge. Place the test bucket low over a padded floor with feet well clear.

SHOP PROJECT

Joint Strength Test

You will make four kinds of corner joint from the same pine and test each to failure by hanging a bucket of sand from it. You will calculate the bending moment each joint carried and identify how it failed.

You will need

- An 8-ft 1×3 pine board (actual ¾ × 2½ in), straight and clear of knots
- Yellow wood glue, #8 × 1¼-in wood screws, a drill/driver, clamps
- A handsaw, chisel, marking knife, square and marking gauge
- A pocket-hole jig or a dowel jig (optional, for joint D)
- A 5-gallon bucket, play sand, a sturdy rope loop, a luggage scale (or bathroom scale), a padded mat

Steps

1. Cut eight pieces 10 in long. Pair them into four L-shaped corner joints: A, a glued butt joint (end grain glued to side grain); B, a butt joint with two screws and no glue; C, a glued half-lap; D, a pocket-screw joint, or a glued dowel joint, or a glued bridle (open mortise and tenon) if you can cut one.
2. Lay out every joint with a knife and gauge from reference faces. Cut and fit them. Record how long each took to make.
3. Glue and clamp; let all glued joints cure 24 hours.
4. Clamp one leg of a joint flat to the edge of a sturdy bench so the other leg sticks out horizontally. Mark a point 8 in from the joint on the free leg and drill a small hole for the rope loop.
5. Hang the empty bucket and add sand a scoop at a time, waiting a few seconds between scoops, until the joint fails. Weigh the bucket with the luggage scale.
6. Calculate the bending moment at failure: $M = W \times d$ (pounds × 8 in).
7. Look at each broken joint. Record whether the glue let go, the wood tore beside the glue, or the screws pulled out. Photograph or sketch each.
8. Rank the joints by strength and by strength per minute of work.

9. **Improve it.** Choose the weakest joint and redesign it (more glue area, a better fit, a peg or screw). Build and test the improved version.

Tips

- Make all joints from the same board so wood quality is the same: that is your fair test.
- If a joint holds more sand than the bucket will take, move the rope farther out and recalculate the moment.
- Do not stand under the bucket; reach in from the side when adding sand.

Check your work

- ☐ I tested four joints the same way and calculated the failure moment of each.
- ☐ I identified how each joint failed and explained why.
- ☐ I improved one joint and measured the difference.

SHOP NOTEBOOK

1. Exploded drawings of a mortise-and-tenon joint and a through dovetail, with the long-grain glue surfaces shaded.
2. A results table: joint, minutes to make, failure load, failure moment, failure mode.
3. A short paragraph: which joint would you use for a step stool, and why?

KEY FORMULAS

$$A_{\text{glue}} = (\text{number of surfaces}) \times w \times \ell$$

$$F_{\max} \approx \tau_{\text{wood}} \cdot A_{\text{glue}}$$

$$\theta = \arctan\left(\frac{1}{n}\right) \text{ for a } 1{:}n \text{ slope}$$

$$p = 15{,}700\, G^2 D L \ \ (\text{lb; in})$$

From history. The Shakers founded their largest community at Mount Lebanon, New York, in the 1780s, and by the 1870s were selling chairs from that village across the country, each with a gold Shaker trademark decal. Their ladder-back chairs used round mortise-and-tenon joints and woven seats and weighed only a few pounds. Craig Sommerfeld's Kreg Tool Company, founded in Iowa in 1986, made the pocket-hole jig a common tool in home shops.

Example 1. A tenon is 3/8 in thick, 2 in wide and 1¼ in long, in red oak (shear strength parallel to grain about 1,780 psi). Find the long-grain glue area of its two cheeks and the ideal shear capacity. Why would a designer use only a fraction of this?

Show solution

1. Area of one cheek: $2 \text{ in} \times 1.25 \text{ in} = 2.5 \text{ in}^2$; two cheeks $A = 5.0 \text{ in}^2$.
2. If the glue is stronger than the wood, the wood fails in shear: $F \approx 1780 \text{ psi} \times 5.0 \text{ in}^2 \approx 8{,}900 \text{ lb}$.
3. Real joints have imperfect fit, uneven glue, knots and long-term creep and moisture cycles, so designers apply a large factor of safety (often 4 or more).

Answer: About 5.0 in^2 and 8,900 lb ideal; much less in design.

Example 2. Find the angle of a dovetail laid out at 1:6 and at 1:8.

Show solution

1. 1:6 means 1 unit across for every 6 along: $\theta = \arctan(1/6) \approx 9.5^\circ$.
2. 1:8: $\theta = \arctan(1/8) \approx 7.1^\circ$.

Answer: 9.5° and 7.1°

Example 3. A cabinet back is screwed on with #8 screws (diameter 0.164 in) that penetrate 1.0 in into the side grain of pine (specific gravity G = 0.40). Using $p = 15{,}700\, G^2 D L$, find the ultimate withdrawal load of one screw, and the number of screws needed to hold a 120 lb pull with a factor of safety of 4.

Show solution

1. One screw: $p = 15{,}700(0.40)^2(0.164)(1.0) \approx 412 \text{ lb}$.
2. Design load with safety factor 4: $120 \times 4 = 480 \text{ lb}$.
3. Screws: $480/412 \approx 1.2$, so at least 2 screws; in practice a back gets many more, spaced every 6–8 in, so loads spread evenly.

Answer: ≈ 412 lb each; at least 2 screws for this load.

PRACTICE

1. **Easy** Name the joint: (a) a groove across a bookcase side that holds a shelf; (b) the interlocking corner of a drawer; (c) the joint between a table leg and its apron.

   Show answer

   (a) dado; (b) dovetail; (c) mortise and tenon.

2. **Easy** Why is a glued end-grain butt joint weak?

   Show answer

   End grain soaks up glue and gives little surface for it to grip; the open cell ends are like straws.

3. **Easy** What is the usual thickness of a tenon for ¾-in stock?

   Show answer

   About one-third: ¼ in.

4. **Medium** A half-lap joint joins two 2×4s (1½ × 3½ in) at a corner. Find the glue area.

   Show answer

   $3.5 \times 3.5 = 12.25 \text{ in}^2$

5. **Medium** Find the angle of a 1:7 dovetail.

   Show answer

   $\arctan(1/7) \approx 8.1^\circ$

6. **Medium** A tenon in white pine (shear strength 900 psi) has two cheeks each 1.5 in × 1.0 in. Find the ideal shear capacity.

   Show answer

   $900 \times 3.0 = 2{,}700 \text{ lb}$

7. Medium You are the furniture repairer. A chair's leg wobbles; when you pull it out you find a smooth, shiny, glue-coated tenon that never stuck. What went wrong and how do you fix it?

Show answer

The tenon was loose or the glue was starved or spread on old glue. Scrape and clean both surfaces to bare wood, build up the tenon with glued veneer if it is loose, refit to a snug hand-pressure fit, and reglue with fresh glue; consider a draw-bored peg.

8. Hard Using $p = 15{,}700\,G^2 D L$, compare the withdrawal strength of a #10 screw (D = 0.19 in, L = 1.25 in) in oak (G = 0.63) and in pine (G = 0.40).

Show answer

Oak: about 1,480 lb; pine: about 600 lb. Oak holds about 2½ times as well, because withdrawal strength rises with the square of specific gravity: $(0.63/0.40)^2 \approx 2.5$.

9. Hard Explain why a dovetail drawer front cannot be pulled off even if the glue fails, but the drawer can still slide apart in one direction.

Show answer

The flared tails lock behind the pins against the pull of opening the drawer; but the tails can slide out in the direction they were assembled (along the pins), which is why that direction faces the back of the drawer where no force pulls.

10. Hard A pocket-hole jig drills at 15°. If a pocket screw must travel 1¼ in along its axis, how far does it advance perpendicular to the face of the board it starts in?

Show answer

$1.25 \sin 15^\circ \approx 0.32$ in

11. **Challenge** A timber framer offsets the draw-bore holes in a tenon by 3/32 in toward the shoulder. A 3/4-in oak peg is driven through. Explain what force pulls the shoulder tight, and why this joint can hold for centuries with no glue at all.

Show answer

The peg must bend to pass through the offset holes; its stiffness pushes the tenon deeper, pressing the shoulders together with a lasting spring force. The joint is held by wood bearing on wood and the peg's shear strength, not by glue, so it does not depend on an adhesive that might age or fail.

COMMON MISTAKES

- Relying on glue in an end-grain butt joint for a load-bearing part.
- Cutting a tenon too thin or too loose and expecting the glue to fill the gap.
- Clamping so hard that most of the glue is squeezed out, leaving a starved joint.
- Testing joints made from different boards and then crediting the joint for a difference caused by the wood.

Make it a game · Joint Sketch and Name. Your parent names a joint: butt, rabbet, dado, lap, mortise-and-tenon, dovetail or pocket screw. Sketch it in 20 seconds and say where you would use it and why it is strong. Swap: your parent sketches and you name it. Score a point per correct pair, and list long-grain versus end-grain glue facts.

Scripture. "Is not this the carpenter, the son of Mary" (Mark 6:3, KJV)

The Son of God spent most of His earthly life as a builder in wood and stone. Skilled manual work is not beneath anyone; Christ Himself honored it.

3.5 Finishing and a Finished Piece: The Step Stool

OBJECTIVES

- Plan a sanding sequence and explain why each grit must remove the scratches of the one before.
- Compare evaporative, reactive and coalescing finishes (shellac, lacquer, oil, varnish, polyurethane, water-based) by chemistry, durability and use.
- Calculate finish quantity, dry film thickness and the tipping stability of a step stool.
- Design, build, finish and proof-test a step stool (or toolbox) from a cut list.

> **Warm-up.** Find two wooden surfaces at home: a tabletop and something oiled or unfinished (a cutting board or a garden bench). Put a single drop of water on each and time how long it beads before soaking in. Then look at each surface at a low angle toward a window. What do you see that tells you a finish is there?

WATCH

What Kind of Finish Should You Use? | WOOD FINISHING BASICS

Steve Ramsey - Woodworking for Mere Mortals · 16:27

https://www.youtube.com/watch?v=bbiXJd_1l8Y

> **WHEN TO WATCH**
> After the science paragraph. Steve Ramsey sorts finishes into penetrating oils and film-building finishes and applies each. Make a two-column table as you watch.

Note: The description contains shopping links; nothing needs to be bought from them.

BACKUP VIDEO

No-Fuss Finishing for Wood.

Rex Krueger · 13:43

https://www.youtube.com/watch?v=JQA-EbQ2EGk

Before you finish your stool: a simple shellac-and-wax and wipe-on approach that works without a spray booth.

KEY TERMS

film finish and penetrating finish

A film finish (shellac, lacquer, varnish, polyurethane) builds a hard layer on top of the wood; a penetrating finish (linseed or tung oil, oil-varnish blends) soaks into the surface and leaves little or no film.

evaporative finish

A finish that cures only by its solvent evaporating, such as shellac (alcohol) and lacquer; later coats redissolve earlier ones, so they melt together and are easy to repair.

reactive finish

A finish that cures by a chemical reaction, usually with oxygen from the air (linseed oil, varnish, oil-based polyurethane), forming cross-linked molecules that do not redissolve.

grit

A number describing abrasive particle size; higher grit means finer particles. P120 particles are about 0.12 mm across.

solids content

The fraction of a liquid finish that remains as dry film after the solvent leaves; it sets how thick each coat ends up.

raising the grain

Wiping wood with water so loose fibers swell and stand up, then sanding them off lightly before a water-based finish, so the first coat stays smooth.

CORE IDEAS

The story. In 1754 a Yorkshire-born London cabinetmaker named Thomas Chippendale published *The Gentleman and Cabinet-Maker's Director*, a book of 160 engraved plates showing chairs, tables, bookcases and beds with measurements. It was the first book of its kind devoted entirely to furniture, and cabinetmakers all over Britain and the American colonies bought it and built from it; that is why "Chippendale" chairs were made in Philadelphia, Newport and Charleston as well as London. Chippendale's workshop knew that a design is not finished when the last joint is glued. The surface had to be scraped smooth and protected with oil, wax or a varnish, or the piece would stain, dry out and grime over in a few years.

How they figured it out. For centuries finishers worked by trial: linseed oil from flax seed, beeswax, and resins dissolved in oil or alcohol. One of the best was **shellac**, made from a resin secreted by the lac insect on trees in India and Thailand, dissolved in alcohol. By the 1820s French polishers were rubbing on dozens of very

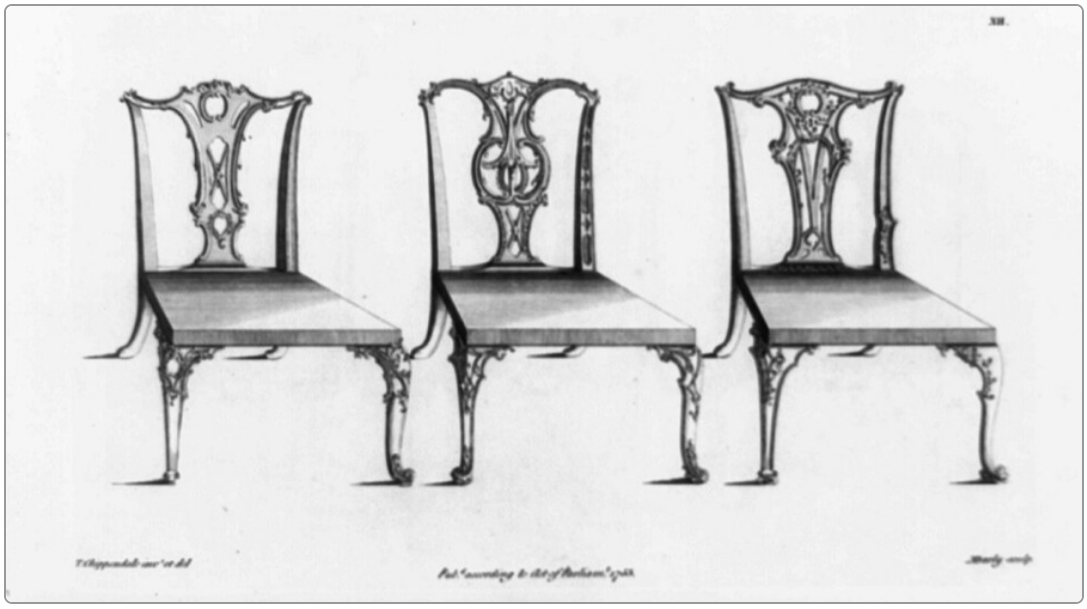
thin coats of shellac with a cloth pad to make a deep, glassy shine. In the twentieth century chemists took over. Nitrocellulose lacquer, sprayed in factories, became standard for furniture in the 1920s; and in 1937 the German chemist Otto Bayer discovered polyurethane chemistry, which led to the tough, water-resistant polyurethane varnishes now sold in every hardware store. Finish makers now test their products for hardness, abrasion, water and heat resistance in standard laboratory tests.

The science. Finishes cure in three ways. *Evaporative* finishes (shellac, lacquer) are long molecules dissolved in a solvent; when the solvent leaves, the molecules tangle into a film, and a new coat partly redissolves the last one. *Reactive* finishes (linseed and tung oil, varnish, oil-based polyurethane) contain molecules with double bonds that react with oxygen and link into a three-dimensional network, hard and insoluble. That reaction gives off heat, which is why oily rags wadded in a pile can heat themselves until they catch fire. *Coalescing* finishes (water-based polyurethane and acrylic) are tiny droplets of resin in water that fuse together as the water evaporates. Sanding is geometry: each abrasive grain plows a scratch about as deep as a fraction of its size, so you must work up through the grits, each removing the scratches of the last. No finish stops wood from exchanging moisture completely; it only slows it down, so both sides of a panel should be finished alike, or it will cup.

In the shop. Sand before assembly where you can, typically 120 then 150 then 180 grit for a film finish (skip no more than one step in the sequence), sanding with the grain for the last grit. Break sharp edges with a light pass of sandpaper. Remove dust with a vacuum and a slightly damp cloth. On blotch-prone woods like pine and cherry, test a stain on scrap first or use a washcoat of thin shellac. Apply thin coats; let each dry fully, scuff it lightly with 320 grit and remove the dust before the next. Wipe-on polyurethane (thinned) is forgiving for a beginner; three to four coats make a durable surface for a stool. Lay oily rags flat outdoors to dry, or put them in a closed metal can filled with water.

The capstone. Your finished piece is a step stool (or a toolbox). Like a real product it has requirements: it must hold a heavy adult with a large margin, must not tip when someone steps near its edge, must be comfortable to carry and must look good. You will turn the skills of this unit into a cut list, joints, a finish and a test. In this course “done” means tested and documented, not just built.

PICTURE STUDY



Three Chairs from the Director, Thomas Chippendale (designer); Matthias Darly (engraver), 1754 · Engraving · The Gentleman and Cabinet-Maker's Director; Library of Congress

Image: Wikimedia Commons, public domain

This plate comes from Chippendale's pattern book of 1754. Cabinetmakers used drawings like these the way you use a plan and cut list: they show proportions, details and choices for the customer.

Look closely

- Compare the three back splats. What stays the same and what changes?
- Find where the back legs, the seat rails and the front legs must meet. What joints would hold them?
- Look at the curved front legs. Which way does the grain need to run in them to be strong?
- Find the scale or measurements on the plate, if any. How would a craftsman get dimensions from it?

Talk about it

1. Which parts of these chairs carry the most load when someone leans back?
2. Why would a designer show three choices on one page?
3. How is this plate like the plan you will draw for your step stool?

> **Safety first.** Finish in a well-ventilated space away from flames, wearing nitrile gloves and safety glasses; read the label and safety data sheet. Lay oily rags flat outdoors to dry or seal them in a water-filled metal can. Wear a dust mask when sanding, and have an adult supervise every power-saw cut in the build.

SHOP PROJECT

Capstone: Build and Proof-Test a Step Stool

You will design, build, finish and test a step stool about 9 in high, using a cut list, at least two kinds of joints from Lesson 3.4, and a three-coat finish. (If your family would rather have a toolbox, design one to carry 40 lb of tools by its handle and test it to 80 lb.)

You will need

- One 6-ft 1×12 (actual ¾ × 11¼ in) and one 4-ft 1×4 (¾ × 3½ in) of pine or poplar, straight and dry
- Wood glue, #8 × 1¼-in screws, a drill/driver with countersink bit, clamps
- A handsaw or circular saw, jigsaw, chisel, square, marking gauge, tape
- Sandpaper in 120, 150, 180 and 320 grit; a sanding block
- Wipe-on polyurethane or shellac, lint-free rags, nitrile gloves
- Bags of sand or concrete mix of known weight (for the proof test), a ruler and a phone camera

Steps

1. Write requirements: height, top size, the heaviest expected user, a proof load of 1.5 times that user (placed gently), no tipping when stepped on at any edge, and a weight under 10 lb.
2. Draw the stool in three views at 1:4 scale (front, side, top) with dimensions. Show the legs splayed or the feet reaching out at least as far as the top.
3. Make a cut list with every part, its final size and its board feet, and lay the parts out on your boards around knots before cutting.
4. Cut the parts. Cut the joints: for example, housed dados in the legs for the aprons and screws and glue through the top into the legs.
5. Dry-fit everything without glue. Check that the legs are equal and the stool sits without rocking on a flat floor; fix any rocking now.
6. Sand all parts to 180 grit, then glue and screw them together. Check diagonals for square while the glue is wet.

7. Ease the edges, remove dust and apply three thin coats of finish, scuff-sanding between coats. Finish the underside too.
8. Weigh the stool. Calculate its tipping margin at the worst edge using your measured weight and dimensions.
9. **Proof test.** On a flat floor, with an adult, place bags gently on the top until you reach your proof load. Measure any sag of the top with a ruler and a straightedge, then remove the load and check that the stool returns to its shape and the joints are tight.
10. **Improve it.** Write what you would change in a second version, and why.

Tips

- Make one leg first and use it as a pattern for the other, so they come out identical.
- Pre-drill and countersink every screw near an end to avoid splitting.
- Apply the finish thin. Two drips on a vertical face come from one heavy coat.

Check your work

- ☐ My stool meets my written requirements, including the proof load and the tipping check.
- ☐ My finish is smooth, with no visible cross-grain scratches or drips.
- ☐ My notebook has the drawing, cut list, cost, test data and a list of improvements.

SHOP NOTEBOOK

1. Your three-view drawing and cut list with board feet and cost.
2. A finishing log: date, grit or coat number, drying time, notes.
3. Your test results: weight, tipping margin, proof load, sag, and photographs.

KEY FORMULAS

$$V_{\text{finish}} = \frac{A \times n_{\text{coats}}}{\text{coverage}}$$

$$t_{\text{dry}} = t_{\text{wet}} \times (\text{solids fraction})$$

$$\text{tips if } W_p\, x > W_s\, b$$

$$\sigma = \frac{F}{A}$$

From history. Chippendale's *Director* went through three editions by 1762, and many American cabinetmakers owned a copy. The Philadelphia makers who followed it, such as Thomas Affleck and Benjamin Randolph, were among the finest woodworkers of the eighteenth century; their pieces are now in museums, and their joints still hold.

WORKED EXAMPLES

Example 1. Your stool has a top 11¼ × 18 in, two legs 11¼ × 9 in and two aprons 3½ × 16½ in. You will finish both faces of every part (ignore edges) with three coats of wipe-on polyurethane that covers about 400 ft² per gallon per coat. How much finish do you need?

Show solution

1. Top: $2 \times 11.25 \times 18 = 405$ in²; legs: $2 \times 2 \times 11.25 \times 9 = 405$ in²; aprons: $2 \times 2 \times 3.5 \times 16.5 = 231$ in².
2. Total 1,041 in² ÷ 144 = 7.23 ft²; three coats = 21.7 ft².
3. Volume: $21.7 / 400 = 0.054$ gal ≈ 6.9 fl oz (1 gal = 128 fl oz).
4. A half-pint (8 fl oz) is just enough; buy a quart to allow for waste and the edges.

Answer: About 7 fl oz; buy at least a half-pint, better a quart.

Example 2. A brushed polyurethane goes on 3.0 mils (0.003 in) wet and has 35% solids by volume. How thick is each dry coat, and how many coats give at least 3 mils of dry film?

Show solution

1. Dry thickness per coat: $3.0 \times 0.35 = 1.05$ mils.
2. Coats: $3 / 1.05 = 2.86$, so 3 coats (about 3.2 mils).

Answer: 1.05 mils per coat; 3 coats.

Example 3. A stool weighs 9 lb, with its weight acting at the center of the top, 5.6 in in from the line of its feet. A 160-lb person steps with their full weight 0.5 in outside the foot line (because the top overhangs the legs). Does the stool tip?

Show solution

1. Take moments about the foot edge. Overturning: $160\ \text{lb} \times 0.5\ \text{in} = 80\ \text{lb·in}$.
2. Resisting: $9\ \text{lb} \times 5.6\ \text{in} = 50\ \text{lb·in}$.
3. Since $80 > 50$, the stool tips. The fix is geometric, not more wood: the feet must reach out at least as far as the top (or splay outward), so that a person standing anywhere on the top is inside the base.

Answer: Yes, it tips; make the base at least as wide as the top.

PRACTICE

1. Easy Name one evaporative, one reactive and one coalescing finish.

   Show answer

   Shellac or lacquer; linseed oil, varnish or oil-based polyurethane; water-based polyurethane.

2. Easy Why must you not jump from 80 grit straight to 220 grit?

   Show answer

   The 220 grit would take a very long time to remove the deep 80-grit scratches, which will show under the finish; each grit should remove the previous grit's scratches.

3. Easy How should oily finishing rags be handled, and why?

   Show answer

   Laid flat outdoors to dry or sealed in a metal can full of water, because the oil's curing reaction gives off heat and a wadded pile can ignite itself.

4. Medium A toolbox has 6.5 ft² of surface. How many fluid ounces of finish are needed for three coats if one gallon covers 450 ft² per coat?

   Show answer

   $6.5 \times 3/450 = 0.0433\ \text{gal} \approx 5.5\ \text{fl oz}$

5. **Medium** A finish has 25% solids. A coat is applied 4 mils wet. How thick is it dry?

Show answer

1.0 mil

6. **Medium** Why should the underside of a tabletop be finished as well as the top?

Show answer

So both faces exchange moisture at the same rate; otherwise one face swells or shrinks more and the top cups.

7. **Medium** You are the finisher. A customer's new pine shelf, stained dark, came out blotchy with dark patches. Explain the cause and how you would avoid it next time.

Show answer

Pine absorbs stain unevenly (soft earlywood and resin areas soak up more). Test on scrap first; use a washcoat of thin shellac or a pre-stain conditioner, or a gel stain, or skip the stain and use a clear finish.

8. **Hard** A step stool's two legs are each ¾ × 11¼ in in cross section. A 250-lb person stands on it and you allow a factor of 2 for stepping down hard. Find the compressive stress in each leg and compare it with pine's compressive strength parallel to grain (about 4,800 psi).

Show answer

Load per leg 250 lb; $\sigma = 250/8.44 \approx 30$ psi, over 150 times less than the strength. The legs are not the weak point; joints and tipping are.

9. **Hard** Explain why a second coat of shellac bonds to the first chemically, but a second coat of polyurethane needs light sanding first.

Show answer

Shellac's alcohol partly redissolves the coat below, so they fuse. Cured polyurethane is cross-linked and does not redissolve, so the new coat bonds mainly mechanically to scratches; scuff-sanding provides them.

10. Hard In the tipping example, how far outside the foot line could a 160-lb person stand before the 9-lb stool tips?

    Show answer

    $x = 9 \times 5.6/160 \approx 0.32$ in. Practically, any overhang beyond the feet is unsafe.

11. Challenge Design check: your stool top is 11¼ in deep and 18 in long, 9 in high. The legs are set 1 in in from each end and splay outward at 10° from vertical. How far beyond the top's ends do the feet reach? Is the stool safe against tipping endwise?

    Show answer

    Each foot moves out $9 \tan 10^\circ \approx 1.6$ in; starting 1 in inside the end, the feet end up about 0.6 in beyond the top's end. Every point on the top is inside the base, so a person standing on it cannot tip it endwise (front-to-back must be checked separately).

COMMON MISTAKES

- Letting the top overhang the feet so the stool tips when someone steps near the edge.
- Gluing up before a dry fit and discovering a wrong-length part with glue setting.
- Applying finish over sanding dust or in thick coats, leaving a rough or runny surface.
- Finishing only the visible faces, so the top cups as the seasons change.

> **Make it a game · Grit Sequence Puzzle.** Shuffle cards labeled 80, 120, 180, 220 grit and a finish type: shellac, oil, varnish, water-based. Put the grits in order in ten seconds and explain why skipping a grit leaves scratches. Then your parent names a project and you choose a finish with one durability reason. Five points wins the round.

UNIT 3

Woodworking

Wood is the oldest building material in the house and the first one most tradespeople learn to work. In this unit you will study wood the way a scientist and a craftsman do together: as a bundle of hollow cells that is strong along the grain, weak across it, and always moving with the seasons. You will learn to measure and mark to a knife line, how saw teeth and sharp edges actually cut, and how to sharpen a chisel until it pares end grain cleanly.

Then you will learn to use power tools safely, starting with the physics of kickback and the story of the flesh-sensing saw brake; how joints from the butt joint to the dovetail carry load, tested to failure in your own shop; and how finishes cure. The unit ends with a capstone: a step stool (or toolbox) that you design, build, finish and proof-test, the first piece of real shop work in your portfolio.

PREREQUISITES

- Algebra I: formulas, proportions, rearranging equations
- Right-triangle basics: the Pythagorean theorem and tangent
- Unit 1 (screws and fasteners) and Unit 2 (adhesives) of this course
- Access to basic hand tools and an adult who can supervise power-tool work

MASTERY CHECKLIST

- ☐ I can explain wood's cell structure, calculate moisture content and predict seasonal movement across the grain.
- ☐ I can calculate board feet and the cost of a lumber order using nominal and actual sizes correctly.
- ☐ I can measure and mark to a knife line, check a square, plan for kerf and sharpen a chisel.
- ☐ I can explain kickback and the riving knife, calculate rim speed and safe noise time, and follow a shop safety plan.
- ☐ I can choose and cut a joint for a load, calculate glue area and screw withdrawal, and test joints to failure.
- ☐ I can sand, choose and apply a finish, and build, finish and proof-test a step stool or toolbox.

OPTIONAL KITS FOR THIS UNIT

- **Stanley hand tools**: Tape measures, combination squares, chisels, block planes and handsaws from the company that made Leonard Bailey's plane design standard (Lessons 3.2–3.5). A few good basic tools are all this unit needs; secondhand older tools work well once sharpened.
- **Kreg pocket-hole jigs**: Optional for Lesson 3.4 (joint D in the strength test) and the step stool. A small single-hole jig is enough; dowels or a half-lap work without one.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

3.1	**Wood as a Material: Cells, Grain and Movement**	3 sessions of 50 minutes
3.2	**Measuring, Marking and Hand Tools**	3 sessions of 50 minutes
3.3	**Power Tools and Shop Safety**	3 sessions of 50 minutes
3.4	**Joinery: Fitly Joined Together**	3 sessions of 50 minutes
3.5	**Finishing and a Finished Piece: The Step Stool**	3 sessions of 50 minutes

Unit 3 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Write explanations in complete sentences. The test is worth 100 points.

1. **5 pts**
   Explain why wood shrinks and swells much more across the grain than along it, and why it moves more tangentially than radially.

2. **6 pts**
   A sample weighs 82.5 g as cut and 70.0 g oven-dry. Find its moisture content. Is it ready for indoor furniture?

3. **8 pts**
   A 30-in-wide flat-sawn red oak tabletop ($C_T = 0.00369$) goes from 6% to 11% MC. How much does it widen? How should it be fastened to its base?

4. **6 pts**
   Find the board feet and cost of four 1 in × 6 in × 10 ft poplar boards at $4.80 per board foot.

5. **5 pts**
   Give the actual dimensions of a 2×4 and a 1×12 and explain the difference from the name.

6. **6 pts**

   A 72-in board is cut into five equal parts with a 1/8-in kerf. How long is each part?

7. **6 pts**

   Explain the difference between rip and crosscut teeth and why Japanese saws cut on the pull stroke.

8. **7 pts**

   A 1-in chisel is pushed with 15 lb. Compare the pressure at a sharp edge 0.00004 in wide and a dull edge 0.001 in wide. Connect your answer to Ecclesiastes 10:10.

9. **7 pts**

   A 10-in blade turns at 4,500 rpm. Find the rim speed in m/s (10 in = 0.254 m). If it is stopped in 4 ms, find the average deceleration.

10. **6 pts**

    Describe kickback on a table saw and three practices that prevent it.

11. **5 pts**

    A planer runs at 103 dBA. Find the NIOSH safe time without hearing protection.

12. **6 pts**

    A tenon in red oak (shear strength 1,780 psi) has two cheeks each 1.75 in × 1.25 in. Find its glue area and ideal shear capacity. Why is this joint stronger than a glued end-grain butt joint of the same parts?

13. **6 pts**

    Using $p = 15{,}700\,G^{2}DL$, find the withdrawal strength of a #8 screw (D = 0.164 in) penetrating 1.25 in into side grain of poplar (G = 0.42).

14. **5 pts**

    Name the curing type of shellac, oil-based polyurethane and water-based polyurethane, and one safety rule for oil finishes.

15. **6 pts**

You are the cabinetmaker. A customer’s new cherry tabletop has split down the middle after its first winter. It was screwed tightly through round holes into the apron. Diagnose the problem and explain your repair.

16. **10 pts**

Short essay. Describe the step stool you built (or would build): its requirements, joints, finish and test. Explain how you prevented tipping, how wood movement and finishing affected your design, and what you would change in a second version.

ANSWER KEY

1. Wood is made of long hollow cells aligned with the grain. Water enters and leaves the cell walls, which thicken and thin, so the board changes in width and thickness but barely in length. Tangential shrinkage is about twice radial, partly because the rays running radially restrain movement in that direction and because of how the cell walls are arranged in the growth rings.
2. $MC = 12.5/70.0 = 17.9\%$. No; indoor furniture should be about 6–8%.
3. $30 \times 0.00369 \times 5 \approx 0.55$ in. With slotted cleats, figure-8 or Z-clips, or screws in slotted holes, so it can move.
4. Each 5 BF; total 20 BF; $\$96.00$.
5. 1½ × 3½ in and ¾ × 11¼ in. The names are the rough sawn sizes before drying and planing.
6. $(72 - 4 \times 0.125)/5 = 14.3$ in
7. Rip teeth are filed square to chisel out fibers along the grain; crosscut teeth are beveled to slice fibers on both sides of the kerf. A pull saw's blade is in tension, so it can be thin without buckling, giving a fine kerf.
8. Sharp: $15/(4 \times 10^{-5}) = 375{,}000$ psi; dull: $15/0.001 = 15{,}000$ psi, 25 times less. A blunt iron needs more force for the same cutting pressure, as Solomon wrote.
9. $v = \pi(0.254)(75) \approx 59.8$ m/s; $a = 59.8/0.004 \approx 15{,}000$ m/s^2.
10. The rising back teeth catch a board that pinches the blade or drifts from the fence and throw it toward the operator. Prevent it with a riving knife, a straight fence parallel to the blade, never using the fence and miter gauge together, keeping the board flat and against the fence with push sticks, and a sharp blade.
11. $8/2^6 = 0.125$ h $= 7.5$ min
12. $A = 4.375$ in^2; $F \approx 7{,}800$ lb. The tenon gives long-grain glue surfaces and shoulders that resist racking; end grain holds glue poorly.
13. $15{,}700(0.42)^2(0.164)(1.25) \approx 568$ lb
14. Evaporative; reactive (oxidation); coalescing. Oily rags must be laid flat to dry or sealed in a water-filled metal can because they can self-heat and ignite.
15. The top shrank across its width in dry winter air but the screws held it rigidly, so it split. Repair: remove the screws, glue the split (clamped flat), and reattach with slotted cleats or clips so it can move; finish both faces equally.
16. A good answer: states measurable requirements (height, top size, proof load, weight); names the joints and why (dados and glue-and-screws for long-grain

surfaces and shoulders); shows the base at least as wide as the top, with a tipping calculation; mentions finishing both sides and choosing a durable finish; reports the proof-test data; and lists specific improvements.

PORTFOLIO PIECE: A FINISHED, TESTED STEP STOOL OR TOOLBOX

Present the step stool or toolbox from Lesson 3.5 together with its documentation: requirements; a three-view drawing with dimensions; a cut list with board feet and cost; the joints you used and why; a finishing log; the proof-load test and tipping calculation; photographs of the build; and a one-page reflection on what you would change. Include your sharpened chisel test, your wood-movement graph and your joint-test results from earlier lessons as supporting evidence.

LOOK FOR	WHAT IT MEANS
Requirements and design	Measurable requirements and a clear, dimensioned drawing and cut list; the design keeps the base under the whole top.
Craftsmanship	Accurate parts, tight joints, square assembly, no rocking; edges eased and surfaces smooth.
Finish	Appropriate finish applied in thin even coats on all faces, with a finishing log; safe handling of rags and solvents.
Testing and data	Proof load and tipping check done safely and recorded with numbers and photographs.
Reflection	Honest, specific improvements based on the test and on what was learned in the unit.

UNIT 4

Home Construction

A house is a system of systems, built in the order you will study them: a foundation that carries everything down to undisturbed soil below the frost line; a frame that carries every load along a continuous path; a roof and walls that shed water; insulation and air sealing that keep the people inside warm, dry and healthy at a reasonable cost; and the plumbing and finishes that make it a home. Each part has a story: Smeaton's underwater mortar and Portland cement, the balloon frame on the Chicago prairie, the asphalt shingle and the factory truss, Rumford's trapped air and the R-value, Cumming's S-trap and Sackett's plasterboard.

You will calculate what tradespeople calculate every day (footing widths and concrete orders, joist stresses and stud counts, rafter lengths and roofing squares, heat loss and heating cost, pressure, drain fall and drywall sheets), and you will build and test models: a soil-bearing test, a framed wall racking test, a shingled roof water test, a heat-loss audit of a real room and a see-through trap and vent. The unit ends with building codes, from Hammurabi and Deuteronomy to today's International Residential Code, and with when to pull a permit and call a licensed professional.

PREREQUISITES

- Algebra I: formulas, unit conversions, square roots
- Right-triangle trigonometry: tangent and the Pythagorean theorem
- Unit 3 (wood as a material, actual lumber sizes, board feet)
- Area and volume of rectangles, prisms and cylinders

MASTERY CHECKLIST

- ☐ I can explain foundation types, frost heave and concrete curing, size a footing from soil bearing capacity and order concrete.
- ☐ I can name the members of a platform frame, trace the load path, and check a joist or header for bending stress and deflection.
- ☐ I can calculate roof pitch, rafter length, squares and roof loads, and explain how roof and wall layers shed water.
- ☐ I can calculate heat loss with $Q = A \cdot \Delta T / R$, combine series and parallel R-values, and estimate yearly heating cost and payback.
- ☐ I can explain supply and drain-waste-vent plumbing, traps and vents, calculate pressure, drain fall and drywall quantities.
- ☐ I can explain why building codes, permits and inspections exist and when a job needs a licensed professional.

OPTIONAL KITS FOR THIS UNIT

- **FLIR thermal imaging cameras**: Optional for Lesson 4.4. A thermal camera that clips onto a phone shows cold spots, missing insulation and air leaks as colors. An inexpensive infrared spot thermometer and a tissue-paper draft finder do the job well enough; many hardware stores and libraries lend or rent thermal cameras.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

4.1	**Foundations: Building upon the Rock**	3 sessions of 50 minutes
4.2	**Framing: From the Balloon Frame to the Platform**	3 sessions of 50 minutes
4.3	**Roofs and the Building Envelope: Shedding Water**	3 sessions of 50 minutes
4.4	**Insulation, Air and Moisture**	3 sessions of 50 minutes
4.5	**Plumbing, Drywall, Codes and Permits**	3 sessions of 50 minutes

Unit 4 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Write explanations in complete sentences. The test is worth 100 points.

1. **5 pts**
   Explain frost heave and how a builder protects a foundation from it.

2. **6 pts**
   A wall load of 2,100 lb per linear foot rests on soil rated 1,500 psf. Find the minimum footing width in inches, and choose a standard width.

3. **6 pts**
   A footing is 150 ft long, 20 in wide and 10 in deep. How many cubic yards of concrete should be ordered with 10% extra?

4. **5 pts**
   Does concrete harden by drying? Explain, and say why it is reinforced with steel.

5. **6 pts**
   Compare balloon and platform framing and give two reasons platform framing replaced the balloon frame.

6. **5 pts**

   How many common studs are needed for an 18-ft wall at 16 in on center?

7. **6 pts**

   Joists of 2×10 (1.5 × 9.25 in) at 16 in on center span 14 ft and carry 50 psf. Find the maximum moment in in·lb and the bending stress.

8. **5 pts**

   By what factor does stiffness increase when a beam's depth doubles? Its strength?

9. **6 pts**

   A 7:12 gable roof has a 13-ft run plus a 1-ft overhang. Find the roof angle and the rafter length.

10. **6 pts**

    A 36 × 26 ft house plan (with overhangs) has a 5:12 roof. Find the roofing squares with 10% waste, and the number of bundles.

11. **5 pts**

    Explain the first rule of the building envelope and give two examples of it.

12. **7 pts**

    A 120 ft^2 exterior wall is R-12 overall and has a 20 ft^2 window with U = 0.32. Find the total heat loss at $\Delta T = 65\ °F$.

13. **6 pts**

    Find the whole-wall R-value of a wall with 25% framing at R-7.0 and 75% cavity at R-16.

14. **6 pts**

    A house has UA = 380 BTU/h·°F in a 6,200 HDD climate. With a 90% furnace and gas at $1.30/therm, estimate the yearly heating cost.

15. **5 pts**

    Water enters a house at 58 psi. Find the static pressure at a fixture 18 ft higher.

16. **5 pts**

You are the plumber. A sink gurgles and the bathroom smells of sewer gas whenever the tub drains. What is wrong and what is the fix?

17. **10 pts**

Short essay. Explain what building codes, permits and inspections are for. Use Deuteronomy 22:8 and at least two examples from this unit (for example frost depth, span tables, flashing, traps and vents, fire-resistant drywall or fire blocking) and say how you would decide whether a home project needs a permit or a licensed professional.

ANSWER KEY

1. Water in the soil freezes and grows ice lenses that lift the ground. Footings are placed below the local frost line on undisturbed soil, and water is drained away from the foundation.
2. $2100/1500 = 1.4$ ft $= 16.8$ in; use an 18-in (or 20-in) footing.
3. $150 \times 1.667 \times 0.833 = 208$ ft^3 $= 7.72$ yd^3; with 10% about 8.5 yd^3.
4. No; it hardens by hydration, a chemical reaction with water, so it is kept moist while curing. It is strong in compression but weak in tension, so steel rebar carries the tension.
5. Balloon framing uses long studs continuous from sill to roof with joists nailed to them; platform framing builds each floor as a deck with walls on top. Platform framing blocks fire at each floor, uses shorter, easier-to-get studs and gives a safe working platform.
6. $216/16 = 13.5 \rightarrow 14$ spaces; 15 studs
7. $w = 66.7$ lb/ft; $M = 66.7(14)^2/8 = 1{,}634$ ft·lb $= 19{,}600$ in·lb; $S = 21.4$ in^3; $f_b \approx 916$ psi
8. Stiffness ($I \propto d^3$) increases 8 times; strength ($S \propto d^2$) 4 times.
9. $\theta = \arctan(7/12) = 30.3^\circ$; slope factor 1.158; $14 \times 1.158 \approx 16.2$ ft.
10. Slope factor 1.083; $936 \times 1.083 = 1{,}014$ ft^2; with 10% 11.2 → 12 squares = 36 bundles.
11. Every layer must lap over the one below it so water runs out: shingles cover the course below; step flashing laps over the piece below and housewrap laps over the flashing; window tape goes sill, sides, head.
12. Wall: $100 \times 65/12 = 542$ BTU/h (net of the window); window: $0.32 \times 20 \times 65 = 416$ BTU/h; total ≈ 958 BTU/h.
13. $U = 0.25/7.0 + 0.75/16 = 0.0357 + 0.0469 = 0.0826$; $R \approx 12.1$
14. $380 \times 6200 \times 24 = 56.5 \times 10^6$ BTU; $\div 0.90 = 62.8 \times 10^6 = 628$ therms; $\approx \$817$
15. $58 - 0.433(18) \approx 50.2$ psi
16. The draining tub is siphoning the sink trap because the vent is blocked or missing (for example, a vent clogged at the roof by debris or ice). Clear or add the vent so the trap stays full.
17. A good answer: codes set minimum requirements so buildings are safe for the people who live in and visit them, learned from past failures; Deuteronomy's battlement is a preventive safety requirement, like modern codes; gives specific

examples and why each exists; explains that permits let the local building department inspect work at key stages; and says the student would check with the town's building department, since rules vary, and call licensed professionals for gas, major electrical, structural and many plumbing jobs.

PORTFOLIO PIECE: A FRAMED WALL MOCK-UP AND A HOUSE-SYSTEMS REPORT

Present your framed wall section from Lesson 4.2 (at 1:4 scale or full size) with its labeled drawing and racking-test results, together with a house-systems report on your own home: its foundation type and drainage, how it is framed (as far as can be seen in the attic, basement or garage), its roof and flashing details, your heat-loss audit of one room with recommended improvements, and your house map and family manual for water shutoff and emergencies. Finish with a page listing which home jobs you can now do safely yourself and which require a permit or a licensed professional in your town.

LOOK FOR	WHAT IT MEANS
Wall mock-up	Correct members and layout (plates, studs at 16 in o.c., king and jack studs, header, sill, cripples, double top plate), square and well built, with racking data.
Calculations	Footing, joist, roofing and heat-loss calculations are correct, with units and stated assumptions.
House-systems report	Accurate observations of the real house in each system, with photographs or sketches and clear explanations.
Recommendations	Specific, ranked improvements with costs and paybacks, and sound judgment about permits and professionals.
Communication	Clear, organized drawings and writing that a family member could follow.

4.1 Foundations: Building upon the Rock

OBJECTIVES

- Describe the main foundation types (footings with stem walls, slab-on-grade, crawlspace and basement) and when each is used.
- Explain soil bearing capacity, frost heave and the frost line, and why water management protects a foundation.
- Explain how concrete gains strength by hydration and why it is reinforced with steel.
- Size a footing from a load and a soil bearing value, and estimate concrete quantities.

> **Warm-up.** Walk around the outside of your house (or school). Find the foundation where it meets the ground. Is it poured concrete, block, brick or stone? Does the ground slope away from it or toward it? Where do the downspouts empty? Note any cracks and sketch where they are.

WATCH

Why Buildings Need Foundations

Practical Engineering · 14:51

https://www.youtube.com/watch?v=0_KhihMIOG8

> **WHEN TO WATCH**
> After the story. Grady Hillhouse, a civil engineer, shows with models and a soil press why soil settles and heaves and how footings spread load. Pause at the frost-depth map and find your state.

Note: The last minute is a sponsor message and can be skipped.

BACKUP VIDEO

All about soil, footings, and codes for residential building | Building Better Homes

Perkins Builder Brothers · 8:26

https://www.youtube.com/watch?v=w3dR9Vs95nw

Before the shop project: a builder probes real soil, measures footings and reads the residential code tables.

KEY TERMS

footing

The widened base of concrete at the bottom of a foundation wall or pier that spreads the building's load over enough soil to carry it.

bearing capacity

The pressure soil can safely carry, in pounds per square foot (psf). The residential code presumes about 1,500 psf for clay and 2,000–3,000 psf for sand and gravel unless a soil test shows otherwise.

frost line

The depth to which the ground freezes in winter in a given place. Footings are set below it so frost cannot heave them.

frost heave

The upward push of soil when water in it freezes into growing ice lenses, which can lift and crack shallow foundations.

hydration

The chemical reaction of cement with water that makes concrete harden. Concrete cures; it does not simply dry, and it needs moisture to keep gaining strength.

rebar

Steel reinforcing bar cast into concrete to carry tension, which concrete alone resists poorly.

CORE IDEAS

The story. Jesus ended the Sermon on the Mount with a builder's parable: the wise man "built his house upon a rock: and the rain descended, and the floods came, and the winds blew, and beat upon that house; and it fell not." Every listener knew what happened to a house on sand when the winter rains came. Builders in every age have had to answer the same question: what will this ground do when it is loaded, wet, dry and frozen? In 1756 the English engineer John Smeaton faced the hardest form of the question when he was asked to build a lighthouse on the Eddystone rocks, about nine miles out in the English Channel, where two earlier lighthouses had been destroyed. He needed a mortar that would set under seawater.

How they figured it out. Smeaton tested limes from all over England, burning them and setting samples in water, and found that the ones made from limestone containing clay hardened under water while pure limes did not. His tower, built of dovetailed granite blocks set in that hydraulic lime, stood for over a century. In 1824

Joseph Aspdin, a bricklayer in Leeds, patented **Portland cement**, made by burning finely ground limestone and clay together; it was improved through the 1800s into the cement used today. Two more inventions finished the modern foundation: steel reinforcement, developed by builders such as Joseph Monier and François Hennebique in France in the late 1800s, and soil mechanics, founded in the 1920s by Karl Terzaghi, who measured how soils carry load, consolidate and hold water.

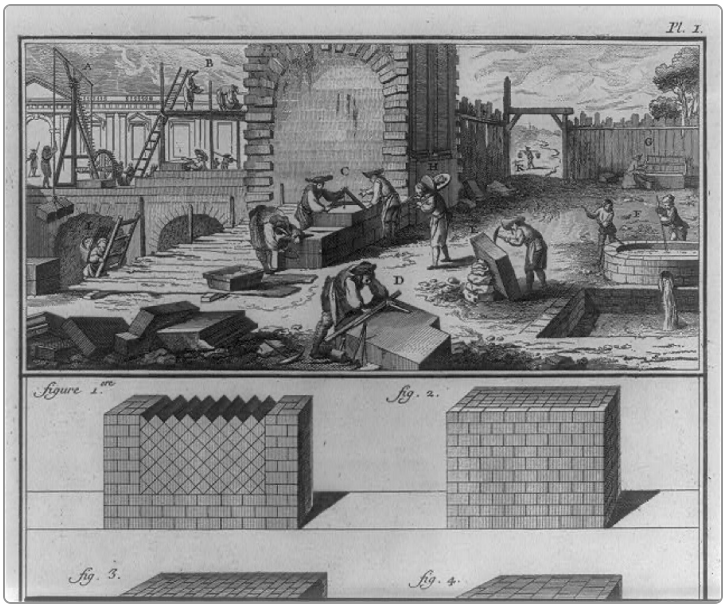
The science. A footing works by spreading load: pressure equals force divided by area, $q = P/A$, so a wider footing puts less pressure on the soil. Soil can fail by shearing out sideways under a footing, or simply by compressing too much over time (settlement); uneven settlement cracks walls. Water is the enemy. When water in the soil freezes, it expands about 9%, and in silty soils it keeps drawing more water up to growing ice lenses, so the ground can heave several inches; footings set below the frost line, which ranges from a few inches in the Gulf states to five feet or more in northern Minnesota, are out of its reach. Concrete gains strength by **hydration**: cement minerals react with water to grow interlocking crystals. It reaches roughly two-thirds of its design strength in a week and its rated strength (often 2,500–4,000 psi for houses) at 28 days, if kept moist. Too much water in the mix makes it easier to place but weaker. Concrete is strong in compression but has only about a tenth as much strength in tension, so steel rebar is placed where the concrete will be pulled.

In the shop. A house foundation starts before any digging, with a phone call to **811**, the national call-before-you-dig number, so utility companies mark buried gas, electric and water lines a few days ahead. The builder clears and lays out the house with batter boards and string lines, digs to undisturbed soil below the frost line, and pours **footings**, typically about 16–24 in wide and 8–12 in thick for a house, sized from the code tables. On them go **stem walls** (for a crawlspace), full **basement walls**, or the thickened edge of a **slab-on-grade**. Anchor bolts are set in the top of the wall to hold the wooden sill plate. Then come drainage and dampproofing: a perforated drain at the footing, dampproofing on the outside of basement walls, and finished ground that slopes away at least 6 inches in the first 10 feet. Most foundation trouble in old houses is water trouble.

On the job. Concrete finishers, form setters, excavator operators and foundation contractors build this part of every house, and inspectors check the footing trench before a single yard of concrete is poured. Geotechnical engineers test soil for larger

buildings. It is hard, outdoor, skilled work, and good concrete crews are always in demand.

PICTURE STUDY



Masonry, Plate I, Plate from Diderot and d'Alembert's Encyclopédie, 1762 · Engraving · Encyclopédie, Recueil de planches, vol. 1; Library of Congress

Image: Wikimedia Commons, public domain

Diderot's great encyclopedia set out to show every trade of its day, drawn from life in the workshops. This plate shows masons building walls from the ground up. Look at how they make a wall carry weight down to the earth.

Look closely

- Find the bottom of the walls. Do they get wider or narrower near the ground?
- Find the stones being shaped and lifted. How are they raised to the top of the wall?
- Look at the drawings at the bottom. How are the stones or bricks overlapped from one course to the next?
- Find the arch. Where does it push its load?

Talk about it

1. Why does overlapping the joints from course to course make a wall stronger?
2. What would happen to this wall if one end sat on soft ground and the other on rock?
3. How does a modern concrete footing do the same job as the wide bottom courses of this wall?

> **Safety first.** Call 811 before anyone digs, even a post hole. Wet concrete and cement are strongly alkaline and can burn skin and eyes: wear gloves, long sleeves and safety glasses, and rinse skin promptly. Never enter a trench deeper than about 4 ft without proper shoring; trench walls collapse without warning.

SHOP PROJECT

Footings, Soil and Frost

You will measure how much a model footing sinks into soil as you load it, compare narrow and wide footings, measure frost heave in a freezer, and cast small concrete samples cured two different ways.

You will need

- A plastic tub at least 8 in deep, filled with damp sand or garden soil, packed in layers
- Two wooden blocks to act as footings: 2 × 2 in and 4 × 4 in (cut from a 2×4 or plywood stack)
- A bathroom scale, a ruler and a straight stick laid across the tub as a reference
- Two clear plastic cups, silty garden soil, water, a freezer and a marker
- A small bag of concrete mix, a bucket, a mixing stick, four paper cups, gloves and safety glasses

Steps

1. Set the 2 × 2 in footing on the soil. Place the bathroom scale on top of it (or stand a board on it) and press down slowly to 10, 20, 30 and 40 lb. At each load, measure how far the footing sank below the reference stick.
2. Repeat with the 4 × 4 in footing in a fresh, equally packed spot.
3. Calculate the pressure under each footing at each load in psi and psf. Graph settlement (y) against pressure (x) for both footings.
4. Fill two cups with silty soil. Saturate one with water and leave the other just damp. Mark the soil surface on each. Freeze overnight and measure the rise of each surface.
5. With gloves and glasses, mix a small batch of concrete with the water on the bag. Fill four paper cups. Cover two with plastic wrap and keep them damp; leave two uncovered in a warm, dry spot.
6. After 7 days peel the cups. Scratch each sample with a nail and drop each from the same height (about 3 ft) onto a hard surface outdoors, with glasses

on. Record the results.

7. Answer: which footing size and which soil condition settled least? Which concrete samples were harder?
8. **Check your work.** Use your settlement graph to estimate the pressure that caused 1/4 in of settlement. If that were the allowable pressure, what width of footing would carry a 1,800 lb/ft wall?

Tips

- Pack the soil the same way for every test: that is your fair test.
- Push slowly and wait a few seconds before reading the settlement.
- Label the concrete cups before filling them.

Check your work

- ☐ I showed with data that a wider footing settles less under the same load.
- ☐ I measured frost heave and explained why saturated soil heaved more.
- ☐ I can explain why concrete must be kept moist while it cures.

SHOP NOTEBOOK

1. A labeled section drawing of a house foundation from the frost line up: footing, rebar, stem or basement wall, anchor bolt, sill plate, drain, dampproofing and sloped grade.
2. Your settlement-versus-pressure graph for both footings, with best-fit lines.
3. A table of your frost-heave and concrete-curing results, with a sentence explaining each.

KEY FORMULAS

$$q = \frac{P}{A}$$

$$b = \frac{w}{q_{\text{allow}}} \quad \text{(footing width for a wall load } w \text{ per foot)}$$

$$V = \ell \times w \times d; \quad 1\ \text{yd}^3 = 27\ \text{ft}^3$$

From history. Smeaton's Eddystone Lighthouse shone from 1759 until the 1870s, when erosion of the rock beneath it, not failure of the tower, forced its replacement. The upper part was taken down and rebuilt on Plymouth Hoe, where visitors can still climb it. Portland cement got its name because Aspdin thought the hardened product looked like the prized building stone quarried on the Isle of Portland.

WORKED EXAMPLES

Example 1. A two-story wood-frame house wall puts a load of 1,900 lb on each linear foot of footing. The soil is silty clay, with a code bearing value of 1,500 psf. How wide must the footing be?

Show solution

1. For one foot of wall, $b = \dfrac{1{,}900 \text{ lb/ft}}{1{,}500 \text{ lb/ft}^2} = 1.27 \text{ ft}$.
2. Convert: $1.27 \times 12 = 15.2$ in.
3. Round up to a standard form width: a 16-in footing (the code's minimum table would give a similar value).

Answer: At least 15.2 in; use a 16 in footing.

Example 2. The house has a 128-ft perimeter footing 16 in wide and 8 in deep. How many cubic yards of concrete should be ordered, with 10% extra for uneven trench bottoms?

Show solution

1. Convert to feet: $16 \text{ in} = 1.333 \text{ ft},\ 8 \text{ in} = 0.667 \text{ ft}$.
2. Volume: $128 \times 1.333 \times 0.667 = 113.8 \text{ ft}^3$.
3. Cubic yards: $113.8 / 27 = 4.21 \text{ yd}^3$; with 10% extra 4.64 yd^3, so order about 4¾ yd^3.

Answer: About 4.75 yd^3.

Example 3. A 24 × 24 ft garage slab is 4 in thick. How many cubic yards is it? If 80-lb bags of concrete mix each yield 0.60 ft^3, how many bags would it take?

Show solution

1. Volume: $24 \times 24 \times 0.333 = 192 \text{ ft}^3 = 7.1 \text{ yd}^3$.
2. Bags: $192 / 0.60 = 320$ bags, about 12.8 tons of bags to mix by hand.
3. This is why slabs are poured from a ready-mix truck (about 8–10 yd^3 per load) and bagged mix is used for posts and small pads.

Answer: 7.1 yd^3; about 320 bags.

PRACTICE

1. Easy Why are footings set below the frost line?

Show answer

So the soil under them never freezes; freezing soil can heave and crack the foundation.

2. Easy What number must you call before digging, and why?

Show answer

811, so utilities mark buried gas, electric, water and communication lines before anyone digs.

3. Easy Does concrete harden by drying out? Explain.

Show answer

No. It hardens by hydration, a chemical reaction with water; it needs to stay moist while it cures.

4. Medium A wall load of 2,400 lb/ft sits on sandy soil rated 2,000 psf. Find the minimum footing width in inches.

Show answer

$2400/2000 = 1.2$ ft $= 14.4$ in; use 16 in.

5. Medium A 10 × 12 ft shed slab is 4 in thick. Find its volume in cubic yards.

Show answer

$40\ \text{ft}^3 = 1.48\ \text{yd}^3$

6. Medium Concrete for footings costs $165 per cubic yard delivered, with a minimum charge for 4 yd³. A footing needs 2.8 yd³. What is the cost?

Show answer

The minimum applies: $4 \times \$165 = \$660$.

7. Medium You are the home inspector. A 1960s house has a wet basement every spring, gutters that overflow and soil that slopes toward the walls. List the fixes in order from cheapest to most expensive.

Show answer

Clean and repair gutters; extend downspouts 5–10 ft from the house; regrade soil to slope away at least 6 in in 10 ft; then, if still wet, install an interior or exterior drain and sump, or excavate and waterproof the walls.

8. Hard A post deck footing must carry 3,200 lb on clay soil rated 1,500 psf. Find the minimum diameter of a round footing.

Show answer

$A = 3200/1500 = 2.13$ ft^2; $d = \sqrt{4A/\pi} \approx 1.65$ ft ≈ 20 in

9. Hard Water expands about 9% when it freezes. If a 1-ft layer of saturated soil is 40% water by volume, estimate how much it would rise just from that expansion. Why can real frost heave be much larger?

Show answer

Water fraction 0.40 ft × 9% ≈ 0.036 ft ≈ 0.43 in. Real heave is larger because ice lenses draw more water up from below as they grow, adding layers of ice.

10. Hard Explain why concrete is reinforced with steel, using the words tension and compression, and say where the rebar goes in a footing.

Show answer

Concrete resists compression well but cracks under tension at about a tenth of that stress. A footing bends upward under soil pressure between loads, putting its bottom in tension, so bars run lengthwise near the bottom (with about 3 in of concrete cover).

11. Challenge A slab-on-grade house in a warm climate has a thickened edge 12 in wide by 12 in deep around a 40 × 30 ft slab 4 in thick. Find the total concrete in cubic yards with 8% extra. (Treat the edge as an extra 8 in of depth around the perimeter.)

Show answer

Slab: $40 \times 30 \times 0.333 = 400$ ft^3. Edge extra: perimeter 140 ft × 1.0 ft × 0.667 ft ≈ 93 ft^3. Total ≈ 493 ft^3 = 18.3 yd^3; with 8% about 19.7 yd^3.

COMMON MISTAKES

- Adding extra water to concrete to make it easier to pour, which weakens it.
- Setting footings on loose fill or topsoil instead of undisturbed soil.
- Letting downspouts dump water right at the foundation.
- Thinking the frost line is the same everywhere; it is set by the local building department.

Make it a game · Foundation Fit. Your parent names a site: a hillside, a flat desert lot, a frozen northern climate, a soft soil. You choose a foundation type in ten seconds and explain frost line, bearing capacity or drainage in one sentence. Parent tries to poke a hole in your answer. Defend or change your pick, then try new sites.

Scripture. "Therefore whosoever heareth these sayings of mine, and doeth them, I will liken him unto a wise man, which built his house upon a rock: And the rain descended, and the floods came, and the winds blew, and beat upon that house; and it fell not: for it was founded upon a rock." (Matthew 7:24-25, KJV)

Every builder knows that what is hidden in the ground decides whether a house stands. Christ used that plain fact to teach that a life must be founded on hearing and doing His words.

4.2 Framing: From the Balloon Frame to the Platform

OBJECTIVES

- Tell the story of the balloon frame and explain why platform framing replaced it.
- Name the members of a framed wall, floor and roof and trace the load path from the roof to the soil.
- Explain why joists stand on edge, using the moment of inertia, and check a joist for bending stress and deflection.
- Lay out and build a framed wall section and measure how sheathing and bracing resist racking.

> **Warm-up.** Find a place where you can see framing: an unfinished garage, attic or basement, a house under construction, or a shed. Count the studs in one wall and measure the spacing between their centers. Look up: which way do the joists or rafters run, and what are they resting on?

WATCH

Framing: The Parts of a Wall

Essential Craftsman · 9:38

https://www.youtube.com/watch?v=ARNrj42sY2M

> **WHEN TO WATCH**
> After the story. Scott Wadsworth, a builder with decades of experience, stands inside a framed house and names every part of a wall. Write down each member he names and draw it as he goes.

BACKUP VIDEO

All House Framing EXPLAINED...In Just 12 MINUTES! (House Construction/Framing Members)

The Honest Carpenter · 12:31

https://www.youtube.com/watch?v=3fP0LZMEV5w

After the In the shop section: a faster tour of the whole frame, from sill plate and joists to rafters, hips and valleys.

KEY TERMS

balloon frame

An early light wood frame in which long studs run continuously from the sill to the roof, with the floor joists nailed to their sides.

platform frame

The modern method: each floor is built as a platform of joists and subfloor, and the walls for the next story stand on it.

stud, plates and on center (o.c.)

Studs are the vertical members of a wall, usually 16 or 24 inches apart center to center; they stand between a bottom (sole) plate and a doubled top plate.

header, king stud and jack stud

A header is the beam over a door or window opening; it rests on short jack (trimmer) studs, which are nailed to full-height king studs.

joist

One of the parallel horizontal members that carry a floor or ceiling, set on edge and spanning between walls or beams.

load path

The continuous route by which every load travels from where it is applied, through each member and connection, down to the soil.

CORE IDEAS

The story. In 1833 Chicago was a muddy frontier town of a few hundred people at the edge of Lake Michigan, growing faster than anyone could find skilled timber framers to build it. That year a carpenter named Augustine Taylor built St. Mary's, the town's first Catholic church, by a new method. Instead of a few heavy hewn timbers joined with mortises, tenons and pegs, he used many light sawn boards, 2 by 4 inches and 2 by 6, nailed together and covered with siding. Older carpenters laughed that a strong wind would carry it off like a balloon, and the name "balloon frame" stuck. But it stood, and within a few years houses, stores and churches across the prairie were built the same way. (Historians also credit Chicago's George Washington Snow, and the method may have had several inventors; it spread because it worked.)

How they figured it out. The balloon frame depended on two things that had just become cheap: lumber sawn to standard sizes by steam-powered mills, and nails made by machine instead of by blacksmiths. A small crew with saws and hammers could frame a house in days. Builders soon learned its weakness. Because the long

studs ran unbroken from the foundation to the roof, the hollow spaces between them were open from the basement to the attic, and a fire starting low could rush up them as up a chimney. The long studs also became hard to find. By the 1930s and 1940s builders had changed to **platform framing**: each floor is built as a deck, the walls for that story are framed flat on it and tilted up, and the next floor is built on top. The platforms block fire at every floor, shorter studs are easy to get, and the crew always has a flat place to work.

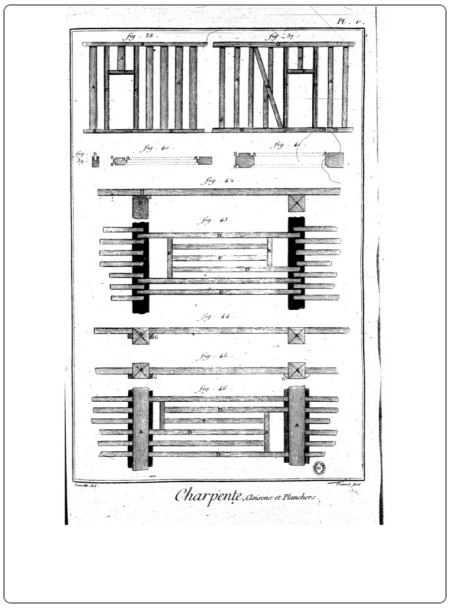
The science. A frame carries load along a **load path**: the roof sheathing to the rafters, rafters to the top plates, through the studs (each one a column) to the bottom plate, the floor platform, the sill and the foundation, and into the soil. A break anywhere, such as a stud cut for a pipe or a missing hanger, interrupts the path. Floors work by bending. When a joist bends, its top is squeezed and its bottom is stretched, and both the stress and the stiffness depend strongly on depth. The stiffness of a rectangular beam is set by its moment of inertia, $I = bd^3/12$; the bending stress is $f_b = M/S$ with section modulus $S = bd^2/6$. A 2×10 on edge is about 38 times stiffer than the same board laid flat, which is why joists stand on edge. Walls must also resist **racking**, the sideways push of wind and earthquakes that turns rectangles into parallelograms; a rectangle of studs alone folds easily, so walls are braced with plywood or OSB sheathing or diagonal bracing, making triangles.

In the shop. Framing lumber's actual sizes are smaller than its names: 2×4 is 1½ × 3½ in, 2×6 is 1½ × 5½, 2×8 is 1½ × 7¼, 2×10 is 1½ × 9¼. Studs are laid out at 16 or 24 in on center so the edges of 4 × 8 ft sheets of sheathing and drywall always land on a stud (48 = 3 × 16 = 2 × 24). The carpenter snaps lines on the deck, cuts the plates, marks every stud, king, jack and cripple on both plates together, nails the wall flat, squares it by measuring diagonals, sheathes it and tilts it up. Headers over openings are sized from code tables (a 6-ft opening in a bearing wall might need two 2×8s or 2×10s on edge). Joists and rafters come from **span tables** in the International Residential Code, which list how far each size, species and grade can span at a given spacing and load; they account for both bending strength and stiffness, since a floor that bounces is a bad floor even if it never breaks.

On the job. Framers are the carpenters who turn a foundation into a house, often in a few weeks. A lead framer reads plans, lays out walls in his head and keeps a crew safe on ladders and roofs. Many framers move on to become superintendents and

builders. Apprenticeships and community-college carpentry programs teach the trade, and good framers are in demand nearly everywhere.

PICTURE STUDY



Carpentry: Partitions and Floors, Plate from Diderot and d'Alembert's Encyclopédie, 1763 · Engraving · Encyclopédie, Recueil de planches, vol. 2 (Charpente)

Image: Wikimedia Commons, public domain

This plate from the carpentry section of Diderot's encyclopedia shows how eighteenth-century carpenters framed partition walls and floors in heavy timber. The members are bigger than ours, but you will find studs, plates, headers and joists you already know.

Look closely

- Find the walls at the top. Which members are like our studs, plates and headers?
- Look for diagonal braces in the walls. What job do they do?
- Find the floors below. Which way do the joists run, and what do they rest on?
- Find an opening framed into a floor, perhaps for a stair or chimney. How are the cut joists supported?

Talk about it

1. How would a modern platform-framed wall do the job of the diagonal braces here?
2. Trace a load from the top of one wall down to the bottom of the plate. Where does it go next?

3. Why might a carpenter of 1760 use fewer, larger timbers than a carpenter of today?

Safety first. Wear safety glasses when nailing and cutting, and keep fingers clear of nails and blades; an adult supervises any power saw. For the scale model, use a sharp utility knife or fine saw with a miter box, cutting away from your hand on a cutting mat.

SHOP PROJECT

A Framed Wall Section and a Racking Test

You will build an 8 × 8 ft wall with a window opening at 1:4 scale (or a full-size 4-ft section of 2×4s if you have the space and an adult), using correct members and layout, then measure how much it racks under a sideways pull before and after sheathing.

You will need

- Wood strips about 3/8 × 7/8 in (1:4 scale of a 2×4), ripped by an adult, or ¼ × ¾-in craft strips (about 1:5 scale); about 30 ft
- Wood glue, brads or small nails, a small hammer, a miter box and fine saw, a square, a ruler
- Thin cardboard or ⅛-in hardboard for scale sheathing
- A base board, two clamps, a luggage scale (or a cup on a string with pennies of known mass) and a ruler for measuring sideways movement

Steps

1. Draw your wall at full scale on paper: 24 in long and 24 in high (8 × 8 ft at 1:4), studs at 4 in on center (16 in at full size), a window 9 in wide (3 ft) with its sill 9 in up.
2. Mark the top and bottom plates together, side by side, with every stud, king stud, jack stud and cripple location, exactly as a framer marks them.
3. Cut all members to length from your drawing. Assemble the wall flat with glue and brads: plates, studs, king and jack studs, a doubled header, a sill and cripples. Add the second top plate.
4. Check square by measuring both diagonals. Adjust until they are equal, and let the glue dry.
5. Clamp the bottom plate to the base board. Fix a ruler beside the top corner. Pull the top plate sideways with the luggage scale at 1, 2, 3 and 4 lb (or hang pennies over a pulley), and record the sideways movement at each.
6. Glue and brad cardboard or hardboard sheathing to one face, nailing every 1 in around the edges (4 in at full size). Let it dry.

7. Repeat the racking test with the same loads. Record the movement.
8. Graph movement against load for both tests. Calculate the stiffness (load per inch of movement) for each.
9. **Improve it.** Build or modify a second wall with a let-in diagonal brace instead of sheathing and test it the same way. Which was stiffer for the material used?

Tips

- Cut all the studs at once with a stop block in the miter box so they are identical.
- Pull exactly sideways along the line of the top plate, not upward.
- If the sheathed wall barely moves, increase the load carefully; note any brads pulling out.

Check your work

- ☐ My wall has correct plates, studs at scale 16 in on center, king and jack studs, a header, a sill and cripples, and a double top plate.
- ☐ I measured and graphed racking with and without sheathing.
- ☐ I can trace the load path through my wall and explain why sheathing stiffens it.

SHOP NOTEBOOK

1. A labeled elevation drawing of your wall with every member named and the stud layout dimensioned.
2. Your racking data table and graph, with stiffness values for each version.
3. A side-by-side sketch of a balloon frame and a platform frame at the second floor, showing where fire could travel in each.

KEY FORMULAS

$$N_{\text{studs}} = \frac{L}{s} + 1 \text{ (rounded up)}$$

$$I = \frac{bd^3}{12}, \quad S = \frac{bd^2}{6}$$

$$M_{\max} = \frac{wL^2}{8}, \quad f_b = \frac{M}{S}$$

$$\Delta_{\max} = \frac{5wL^4}{384\,EI}$$

From history. Balloon-framed houses are still common in older American neighborhoods. Fire codes now require fire-blocking in the stud cavities of any balloon-framed wall that is remodeled. The rapid rebuilding of Chicago after its great fire of 1871 relied on light framing and on new brick and iron construction in the downtown, where wood frames were then forbidden.

WORKED EXAMPLES

Example 1. A wall is 14 ft long with studs at 16 in on center. How many common studs are needed (not counting extra studs at corners and openings)?

Show solution

1. Length in inches: $14 \times 12 = 168$ in.
2. Spaces: $168/16 = 10.5$, so 11 spaces.
3. Studs: $11 + 1 = 12$.

Answer: 12 studs, plus extras for corners and openings.

Example 2. Compare the stiffness (moment of inertia) of a 2×10 (actual 1.5×9.25 in) on edge and laid flat.

Show solution

1. On edge: $I = \dfrac{1.5 \times 9.25^3}{12} = 98.9 \text{ in}^4$.
2. Flat: $I = \dfrac{9.25 \times 1.5^3}{12} = 2.60 \text{ in}^4$.
3. Ratio: $98.9/2.60 \approx 38$.

Answer: On edge it is about 38 times stiffer.

Example 3. Floor joists of 2×8 lumber (1.5 × 7.25 in) are 16 in on center and span 12 ft. The floor carries 40 psf live load plus 10 psf dead load. Find the maximum bending stress in a joist.

Show solution

1. Each joist carries a strip 16 in = 1.333 ft wide: $w = 50 \text{ psf} \times 1.333 \text{ ft} = 66.7 \text{ lb/ft}$.
2. Moment: $M = \dfrac{66.7 \times 12^2}{8} = 1{,}200 \text{ ft·lb} = 14{,}400 \text{ in·lb}$.
3. Section modulus: $S = \dfrac{1.5 \times 7.25^2}{6} = 13.1 \text{ in}^3$.
4. Stress: $f_b = 14{,}400 / 13.1 \approx 1{,}100$ psi. That is close to the allowable bending stress of common No. 2 framing lumber (roughly 1,000–1,300 psi after code adjustments), so a 2×8 at 16 in is near its limit at 12 ft; the span table, which also checks deflection, decides.

Answer: $f_b \approx 1{,}100$ psi, near the limit for No. 2 lumber.

PRACTICE

1. Easy Why was the balloon frame named that way, and what was its main safety weakness?

   Show answer

   Skeptics said it was so light it would blow away like a balloon. Its open stud cavities ran from basement to attic and carried fire upward like chimneys.

2. Easy Give the actual dimensions of a 2×6 and a 2×10.

   Show answer

   1½ × 5½ in; 1½ × 9¼ in.

3. Easy Why are studs placed 16 or 24 in on center?

   Show answer

   So the edges of 4 × 8 ft (48-in) sheets of sheathing and drywall always fall on a stud: 48 = 3 × 16 = 2 × 24.

4. **Medium** How many studs (not counting extras) for a 22-ft wall at 24 in on center?

   Show answer

   $264/24 = 11$ spaces; 12 studs

5. **Medium** Find the moment of inertia of a 2×12 (1.5×11.25 in) on edge.

   Show answer

   $1.5 \times 11.25^3/12 \approx 178 \text{ in}^4$

6. **Medium** Trace the load path of a heavy snowfall on a roof down to the soil.

   Show answer

   Roof sheathing → rafters or trusses → top plates of the walls → studs → bottom plate → floor platform (rim joist and subfloor) → sill plate → foundation wall → footing → soil.

7. **Medium** You are the framer. The plumber wants to cut a 3½-in notch in the bottom edge of a floor joist at mid-span to pass a drain. What do you say, and why?

   Show answer

   No. The bottom edge at mid-span carries the highest tension; a notch there can break the joist. Route the pipe elsewhere, bore a small hole near the joist's center line within code limits, or add framing (a header) designed for it.

8. **Hard** Double a joist's depth while keeping its width. By what factor do its strength (section modulus) and stiffness (moment of inertia) increase?

   Show answer

   Strength by $2^2 = 4$; stiffness by $2^3 = 8$.

9. **Hard** A 2×8 joist (I = 47.6 in⁴, E = 1,400,000 psi) spans 12 ft and carries a live load of 53.3 lb/ft. Find the deflection and compare with the limit L/360.

   Show answer

   $w = 4.44$ lb/in; $\Delta = \dfrac{5(4.44)(144)^4}{384(1.4 \times 10^6)(47.6)} \approx 0.37$ in; limit $144/360 = 0.40$ in, so it just passes.

10. Hard Explain how sheathing makes a wall resist racking, using the idea of triangles.

Show answer

A rectangle of studs with nailed corners can fold into a parallelogram. Sheathing nailed all around each sheet acts like a web of diagonals: the panel cannot change shape without stretching, so the wall becomes a set of rigid triangles that carry sideways loads.

11. Challenge A header over a 6-ft opening carries a roof and ceiling load of 600 lb per linear foot. Treat it as a simple beam spanning 6.0 ft. Two 2×10s on edge are nailed together (b = 3.0 in, d = 9.25 in). Find the bending stress and say whether it is reasonable compared with about 1,000 psi allowable.

Show answer

$M = 600(6)^2/8 = 2{,}700$ ft·lb $= 32{,}400$ in·lb; $S = 3.0(9.25)^2/6 = 42.8$ in^3; $f_b \approx 760$ psi, under 1,000 psi, so it is reasonable (deflection and bearing would also be checked).

COMMON MISTAKES

- Using nominal sizes in calculations instead of actual sizes.
- Laying out studs from the wrong end or not marking both plates together, so the sheathing edges miss the studs.
- Forgetting that a beam's stiffness grows with the cube of its depth, and laying a joist or header flat.
- Cutting or notching joists and studs for pipes and wires without following code limits.

> **Make it a game · Load Path Trace.** Draw a simple house cross-section on paper. Starting at the roof, trace the load path with your finger, naming every member: shingles, rafter, plate, stud, header, joist, footing, soil. Your parent asks 'what if this header were missing?' Time your trace, then beat your time while naming each member correctly.

4.3 Roofs and the Building Envelope: Shedding Water

OBJECTIVES

- Compare rafters and trusses, and explain how a truss uses triangles to carry roof loads.
- Calculate roof pitch, rafter length, roof area in squares and snow and rain loads.
- Explain the layers of a roof and wall (sheathing, underlayment, shingles, flashing, housewrap and siding) and why each lap runs downhill.
- Build and water-test a shingled roof model with flashing, and diagnose a leak.

> **Warm-up.** Go outside on a dry day and look up at your roof. Is it steep or shallow? Find where water would run off, where gutters catch it and where two roof planes meet or a chimney or vent comes through. Sketch the roof and draw arrows showing where water flows. Mark the places you think are most likely to leak.

WATCH

How to Install Roof Shingles | Ask This Old House

This Old House · 6:36

https://www.youtube.com/watch?v=3bQPEEtWGKU

> **WHEN TO WATCH**
> After the science paragraph. Tom Silva builds a roof layer by layer on a mock-up: drip edge, underlayment, starter course and shingles. Notice how every layer laps over the one below it.

BACKUP VIDEO

How to Install Drip Edge and Step Flashing | This Old House

This Old House · 5:04

https://www.youtube.com/watch?v=UvLpM_MZB8M

Before the flashing part of your shop project: step flashing against a wall, shown on a real job with apprentices.

KEY TERMS

pitch

The steepness of a roof, stated as inches of rise per 12 inches of horizontal run (a 6:12 or "6 in 12" roof rises 6 in for every foot).

rafter and truss

A rafter is a single sloped board cut and fitted on site; a truss is a factory-built triangle of lumber joined with toothed steel plates that spans from wall to wall.

square

Roofing's unit of area: 100 square feet of roof surface. Standard asphalt shingles come about three bundles to a square.

underlayment

A water-resistant layer (felt or synthetic) laid over the roof sheathing beneath the shingles, the roof's second line of defense.

flashing

Thin metal (or membrane) pieces that turn water at joints and edges: drip edge at eaves and rakes, step flashing where a roof meets a wall, valley flashing, and boots around pipes.

weather-resistive barrier (housewrap)

A sheet behind the siding that sheds any water getting past the siding while letting water vapor escape; it is lapped like shingles, upper over lower.

CORE IDEAS

The story. For most of history roofs were thatch, wood shingles, slate or clay tile, laid in overlapping rows so that rain runs from one piece onto the next and never through. In 1903 Henry Reynolds, a roofing dealer in Grand Rapids, Michigan, began cutting asphalt-coated felt roofing into individual shingles and selling them, and the asphalt shingle, cheap, light and fire-resistant compared with wood, became the most common roof in America. Half a century later, in the 1950s, inventors in Florida (A. Carroll Sanford and J. Calvin Jureit among them) developed toothed steel plates that could be pressed into the joints of lumber triangles, and factory-built roof **trusses** spread across the country. Today most new American houses have truss roofs covered with asphalt shingles, and almost every one leaks first at a flashing detail.

How they figured it out. Builders learned the first rule of the envelope by experience: *water runs downhill, so every layer must lap over the one below it*. A shingle

that lies under the one below it instead of over it guides water straight into the house. Roofers learned that the joints are where roofs fail, at chimneys, walls, valleys, vents and eaves, and invented flashing to bridge them. Engineers learned from snow-collapse failures to set design snow loads, now mapped by the American Society of Civil Engineers for every part of the country, and building scientists learned in the twentieth century that walls also need a drainage plane behind the siding, because some rain always gets past it.

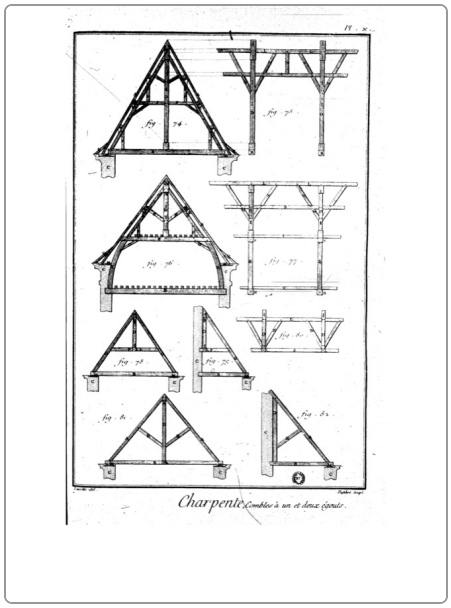
The science. A truss is a set of triangles. A triangle cannot change shape without changing the length of a side, so its members carry load mainly by pulling (tension) and pushing (compression), which lumber does efficiently. In a simple truss the sloped top chords are squeezed, the bottom chord is pulled (it ties the walls together so the roof cannot push them outward), and the webs carry load between. Rafters, by contrast, work in bending, and need a ridge beam or ceiling joists and rafter ties to keep them from spreading the walls apart. Roof loads add up quickly. Water weighs 62.4 lb per cubic foot, so one inch of rain on a roof is about 5.2 lb on every square foot; snow ranges from about 5–10 lb per cubic foot fresh to 20 or more when wet and packed, and design roof snow loads range from zero in Florida to over 100 psf in some mountain towns. Pitch matters for water: steeper roofs shed it faster; asphalt shingles need at least a 2:12 pitch, with extra underlayment below 4:12.

In the shop. A roof goes on in layers from the bottom up. The roofer installs drip edge at the eaves, then ice-and-water membrane at the eaves in cold climates (to stop leaks from ice dams), then underlayment lapped uphill, then drip edge on the rakes over the underlayment, then a starter strip and shingles laid from the eave upward, each course covering the nails of the course below. Standard shingles are about 12 × 36 in, laid with about 5 in exposed. Where the roof meets a wall, each shingle course gets its own piece of **step flashing**, tucked under the housewrap and siding above. On the walls, housewrap is lapped upper over lower and taped, windows are flashed with tape from the bottom up (sill first, then sides, then head), and siding sheds most of the water. A roofer's check: imagine a drop of water on every surface and follow it; it must never find a lap that runs uphill.

On the job. Roofers work at height in heat and weather and must use fall protection: OSHA requires it for construction work six feet or more above a lower level. Skilled roofers and siding installers command good pay, and many go on to run their own companies. Deuteronomy 22:8 commanded a parapet around flat roofs that people

walked on, so no one would fall: fall protection is one of the oldest building rules there is.

PICTURE STUDY



Carpentry: Roofs with One and Two Slopes, Plate from Diderot and d'Alembert's Encyclopédie, 1763 · Engraving · Encyclopédie, Recueil de planches, vol. 2 (Charpente)

Image: Wikimedia Commons, public domain

The carpenters of eighteenth-century France framed roofs from heavy timbers, joined with mortises, tenons and pegs. The shapes on this plate are the ancestors of the factory trusses on a modern house.

Look closely

- Find a tie beam across the bottom of a roof frame. Is it pushed or pulled?
- Find the vertical post in the center of a truss (a king post). What does it hold up?
- Compare the steep and the shallow roofs. Which would shed rain and snow faster?
- Find a single-slope roof leaning against a wall. Where would water collect, and where would flashing be needed?

Talk about it

1. Which members are in compression and which in tension in one of these trusses?
2. Why are all these frames made of triangles?

3. How does a modern truss with toothed steel plates do the same job with much thinner lumber?

Safety first. Do not go onto a real roof for this lesson. Professionals working at height use fall protection, and ladders must be set at a 4:1 angle on firm, level ground, extending 3 ft above the edge, with three points of contact. Use utility knives on a cutting mat, cutting away from your hand, and wear gloves when handling metal flashing, which has sharp edges.

SHOP PROJECT

Shingle, Flash and Water-Test a Roof Model

You will shingle a small model roof that meets a wall, with real or model shingles and step flashing, and water-test it. Then you will deliberately install one detail wrong, measure the leak, and fix it.

You will need

- A 2 × 2 ft piece of ½-in plywood (or stiff corrugated cardboard covered in plastic) for the roof deck, and a 1 × 2 ft board screwed upright along one side as the wall
- Two scrap blocks to prop the deck at a 6:12 and then a 3:12 pitch
- A few real asphalt shingles cut into small pieces with a utility knife (or index cards painted with two coats of exterior paint), roofing nails or staples
- Aluminum flashing or heavy foil cut into 4 × 4 in pieces bent at 90°; a strip of plastic sheet or housewrap for the wall
- A watering can, a tray under the model, a measuring cup, a timer

Steps

1. Set the deck at 6:12 (6 in rise over 12 in run) and measure the angle with a phone level app. Compare with $\arctan(6/12)$.
2. Staple a strip of "underlayment" (plastic sheet) across the deck, starting at the bottom, with each upper strip lapping 2 in over the lower one.
3. Lay a starter course and then courses of shingles from the bottom up, each course offset half a tab and covering the nails of the one below, with a 2–3 in exposure (scaled).
4. Where each course meets the wall, slip a bent step-flashing piece under the shingle, against the wall, lapping over the flashing below. Hang the wall's plastic "housewrap" so it laps over the top of the flashing.
5. Place the model in the tray. Pour 2 cups of water slowly down the wall and over the roof from the top. Collect and measure any water that gets under the deck (it will drip into a cup placed beneath).

6. **Make it wrong.** Reverse one detail: tuck the housewrap behind the flashing, or reverse one row of underlayment. Repeat the water test and measure the leak.
7. Change the pitch to 3:12 and repeat the correct test. Does the slower water find any weakness?
8. Record results in a table: pitch, detail, water poured, water leaked.
9. **Check your work.** Draw a cross-section through your wall-to-roof joint showing every layer and an arrow for water at each lap. Make sure no arrow points into the house.

Tips

- Pour slowly and from the same height each time: that is your fair test.
- Look at the underside of the deck with a flashlight to find where leaks start.
- A drop of food coloring in the water makes leak paths easy to see.

Check your work

- ☐ My correctly built model leaked little or no water at both pitches.
- ☐ I measured how much the deliberately wrong detail leaked and explained why.
- ☐ I can draw the layers of a roof-to-wall joint with every lap running downhill.

SHOP NOTEBOOK

1. A labeled section of a roof from the ceiling joist up: truss or rafter, sheathing, drip edge, ice-and-water membrane, underlayment, shingles, ridge vent.
2. Your water-test table and a short explanation of the leak you created.
3. A sketch of a truss with each member labeled tension or compression.

KEY FORMULAS

$$\text{slope factor} = \sqrt{1 + \left(\tfrac{\text{rise}}{12}\right)^2}$$

$$L_{\text{rafter}} = \text{run} \times \text{slope factor}$$

$$\text{squares} = \frac{A_{\text{plan}} \times \text{slope factor}}{100}$$

$$\theta = \arctan\left(\tfrac{\text{rise}}{12}\right)$$

$$F = p \times A, \;\; p_{\text{rain}} = 62.4\ \text{lb/ft}^3 \times h$$

From history. Slate roofs in Pennsylvania and Vermont and clay-tile roofs in Spain and Italy have lasted more than a century because each piece overlaps the next with plenty of head lap. Modern synthetic underlayments, peel-and-stick membranes and taped housewrap do the same job with thinner layers; the principle has not changed.

WORKED EXAMPLES

Example 1. A gable roof has a 6:12 pitch. Each rafter has a horizontal run of 14 ft to the wall plus a 1-ft overhang. Find the roof angle and the rafter length along its slope.

Show solution

1. Angle: $\theta = \arctan(6/12) = 26.6^\circ$.
2. Slope factor: $\sqrt{1 + 0.5^2} = 1.118$.
3. Total run 15 ft; length $15 \times 1.118 = 16.8$ ft, so buy 18-ft lumber (trimmed to fit at the ridge cut and tail).

Answer: 26.6°; 16.8 ft

Example 2. A house is 40 × 28 ft with a 6:12 gable roof and 1-ft overhangs all around. How many squares of shingles and bundles are needed, with 10% for waste?

Show solution

1. Plan area including overhangs: $42 \times 30 = 1{,}260$ ft^2.
2. Roof surface: $1{,}260 \times 1.118 = 1{,}409$ ft^2 = 14.1 squares.
3. With 10% waste: 15.5 squares; round up to 16 squares = $16 \times 3 = 48$ bundles.

Answer: 16 squares, 48 bundles.

Example 3. The same roof (1,260 ft^2 in plan) receives 1 in of rain in an hour. Find the weight of water that falls on it and how many gallons the gutters must carry that hour (1 ft^3 = 7.48 gal). Then find the snow load if 30 psf of snow lies on it.

Show solution

1. Volume: $1{,}260 \times \frac{1}{12} = 105$ ft^3; weight $105 \times 62.4 = 6{,}552$ lb.
2. Gallons: $105 \times 7.48 \approx 785$ gal.
3. Snow: 30 psf $\times$ 1,260 ft^2 $= 37{,}800$ lb, about 19 tons, which the trusses, walls and foundation must carry.

Answer: 6,550 lb and 785 gal of rain; 37,800 lb of snow.

PRACTICE

1. Easy What is the first rule of the building envelope?

   Show answer

   Shed water: every layer laps over the one below it so water always runs out, never in.

2. Easy What is a square in roofing, and about how many bundles of standard shingles make one?

   Show answer

   100 ft^2 of roof surface; about three bundles.

3. Easy Which member of a simple truss is in tension, and what does it prevent?

   Show answer

   The bottom chord; it ties the two walls together so the roof cannot push them outward.

4. Medium Find the angle and slope factor of an 8:12 roof.

   Show answer

   $\theta = 33.7^\circ$; $\sqrt{1 + (8/12)^2} = 1.202$

5. Medium A 4:12 roof covers a 30 × 50 ft plan area. Find the roof area and squares.

   Show answer

   Slope factor 1.054; $1{,}500 \times 1.054 = 1{,}581$ ft^2 = 15.8 squares.

6. **Medium** Find the rafter length for a 10:12 roof with a 12-ft run plus 1.5-ft overhang.

   Show answer

   Slope factor $\sqrt{1+(10/12)^2} = 1.302$; $13.5 \times 1.302 \approx 17.6$ ft

7. **Medium** You are the roofer. A homeowner reports a ceiling stain directly below where a sloped roof meets a two-story wall. The shingles look fine. What do you check first, and why?

   Show answer

   The step flashing and the siding and housewrap above it: missing, reversed or face-nailed step flashing, or housewrap tucked behind the flashing instead of over it, lets water running down the wall get behind the roofing.

8. **Hard** Wet snow 18 in deep weighs 20 lb/ft^3. Find the load in psf and the total on a 1,200 ft^2 roof.

   Show answer

   $20 \times 1.5 = 30$ psf; $36{,}000$ lb

9. **Hard** Explain how an ice dam forms and two ways to prevent it.

   Show answer

   Heat leaking from the house into the attic melts snow on the upper roof; the water runs down to the cold overhang, refreezes and builds a ridge of ice that backs water up under the shingles. Prevent it by air-sealing and insulating the attic floor and ventilating the roof so the roof deck stays cold, and by installing ice-and-water membrane at the eaves.

10. **Hard** Why are window flashing tapes applied sill first, then sides, then head?

    Show answer

    So each upper piece laps over the lower one; water running down is always directed out over the next lower layer rather than behind it.

11. **Challenge** A roof's design snow load is 40 psf. Trusses are 24 in on center and span 28 ft. Find the snow load on one truss, and the vertical reaction at each wall if the load is uniform.

    Show answer

    Each truss carries a 2-ft strip: $40 \times 2 \times 28 = 2{,}240$ lb; each wall supports 1,120 lb per truss (plus the roof's own dead load).

COMMON MISTAKES

- Lapping any layer uphill, so water runs behind it.
- Nailing shingles too high (above the nailing line), where the next course does not cover the nails.
- Face-nailing step flashing to the wall or tucking the housewrap behind it.
- Cutting or removing a truss web to make attic storage; trusses are engineered as a whole and must not be altered without an engineer.

> **Make it a game · Roof Pitch Estimate.** Your parent gives a run and rise, such as 6 in 12, and a building width. Estimate the rafter length and the roof area in squares by mental math, then calculate. Closest estimate wins the round. Also name flashing locations on a roof drawing within 60 seconds. Five rounds, keep your personal best.

4.4 Insulation, Air and Moisture

OBJECTIVES

- Explain heat flow by conduction, convection and radiation through a building, and how insulation, air sealing and windows slow each one.
- Calculate heat loss with $Q = A\,\Delta T / R$, add R-values in series and estimate a whole wall's R-value including framing.
- Estimate a season's heating cost from UA and heating degree days, and judge whether an upgrade pays for itself.
- Explain why air leaks carry moisture and how vapor, condensation and ventilation are managed in a wall and attic.

> **Warm-up.** On a cold (or very hot) day, hold the back of your hand near a window, an outside wall, an inside wall, an outlet cover on an outside wall and the gap under an exterior door. Rank them from warmest to coldest. Which ones feel like a draft, and which just feel cold? What do you think is different?

WATCH

How to Perform a Whole-House Energy Audit | Ask This Old House

This Old House · 9:10

https://www.youtube.com/watch?v=R_FdTPbgzTs

> **WHEN TO WATCH**
> Before the shop project. An energy auditor uses a blower door and an infrared camera to find air leaks and missing insulation in an old house. Write down each place he finds a problem.

BACKUP VIDEO

How to Choose and Use Insulation | This Old House

This Old House · 5:30

https://www.youtube.com/watch?v=OJ9u3pDQeM4

After the science paragraph: Tom Silva compares fiberglass, mineral wool, cellulose, foam board and spray foam in a wall mock-up.

KEY TERMS

R-value

Resistance to heat flow; in U.S. units, $ft^2 \cdot °F \cdot h/BTU$. A higher R-value insulates better. R-values of layers in series add.

U-factor

The rate of heat flow through an assembly, $U = 1/R$; used for windows (lower is better).

thermal bridge

A path of more conductive material, such as a wood stud or steel beam, that lets heat bypass the insulation.

air barrier

A continuous layer (drywall, sheathing, tape, sealant, foam) that stops air from flowing through the envelope; insulation alone does not stop air.

vapor retarder

A material that slows the diffusion of water vapor, placed according to climate so that moisture does not condense inside a wall.

heating degree days (HDD)

A measure of how cold a heating season is: the sum over the days of how many degrees the daily mean temperature is below 65 °F.

CORE IDEAS

The story. In the 1790s Benjamin Thompson, Count Rumford, an American-born scientist working in Bavaria, was responsible for clothing the Bavarian army, and he wanted to know why some materials kept a person warmer than others. He wrapped thermometers in wool, fur, cotton and down and timed how fast they cooled, and found that the fibers themselves mattered little: what insulated was the still air trapped between them. In the 1930s Games Slayter at the Owens-Illinois glass company found a way to blow molten glass into fine fibers, and "glass wool" insulation, which works on Rumford's principle, went into millions of American attics. In the mid-1940s Everett Shuman of Penn State's Housing Research Institute is credited with suggesting describing every insulating material by a single number, its resistance to heat flow, so that homeowners could compare them. We still call it the **R-value**.

How they figured it out. Engineers measure R-values in a "hot box": a sample wall separates a heated chamber from a cold one, and the electric power needed to keep the hot side steady is exactly the heat flowing through. Field researchers in the 1970s, when energy prices rose sharply, added two instruments that changed how

houses are built. The **blower door**, a calibrated fan sealed into an outside doorway, depressurizes a house so leaks can be measured and found; the **infrared camera** shows warm and cold surfaces as colors. They discovered that many houses lost as much heat through air leaks (around attic hatches, plumbing and wiring holes, rim joists, recessed lights) as through their walls, and that sealing air leaks was often the cheapest improvement of all.

The science. Heat moves from warm to cold by *conduction* (through solids), *convection* (carried by moving air) and *radiation* (infrared, between surfaces). For steady conduction through a wall, the heat flow is $Q = A\,\Delta T / R$, in BTU per hour when A is in square feet and ΔT in °F. Layers in series add their R-values; but parallel paths, such as insulation between studs, combine by their U-factors, because heat takes the easy path through the wood (about R-1.25 per inch, versus R-3 to R-4 per inch for batts). That is why a 2×4 wall with R-13 batts performs closer to R-11 overall. A window is a weak spot: single glass is about R-1 and a good double-pane low-e window about R-3. Air leaks carry heat by convection and also carry moisture: warm indoor air holds more water vapor, and if it leaks into a wall or attic and meets a surface colder than its dew point, the vapor condenses into water, and in time, mold and rot. So the modern rule is: *seal air tight, insulate well, manage vapor for the climate, and ventilate deliberately* (bath and kitchen fans, and in tight houses, mechanical ventilation).

In the shop. Insulation comes as fiberglass or mineral-wool batts (R-13 to R-15 in a 2×4 wall, R-19 to R-21 in a 2×6), blown cellulose or fiberglass for attics (cellulose is about R-3.5 per inch), rigid foam boards (about R-4 to R-5 per inch) and spray foam (open-cell about R-3.6, closed-cell about R-6 to R-7 per inch). Batts work only if they fill the cavity completely, without gaps or compression. Before adding attic insulation, an installer air-seals the attic floor: top plates, wire and pipe holes, the chimney chase (with fire-safe material), the hatch. Codes set minimum R-values by climate zone; in cold zones attics often call for R-49 or more. The homeowner jobs in this lesson are real: weatherstripping doors, sealing gaps with caulk and foam, adding attic insulation over a sealed floor and fixing a damp bathroom by running the fan. All of these are taught here as comfort, cost and durability, the reasons a family cares about.

On the job. Insulation installers, air-sealing contractors and home energy auditors (often certified through organizations such as the Building Performance Institute)

are part of the building trades, and home inspectors check insulation and ventilation in every house they inspect. The skills overlap with HVAC in Unit 6, since a well-sealed house needs a smaller furnace.

PICTURE STUDY



The Hunters in the Snow, Pieter Bruegel the Elder, 1565 · Oil on panel · Kunsthistorisches Museum, Vienna

Image: Wikimedia Commons, public domain

Bruegel painted a Flemish village in the depths of winter, when keeping warm was a matter of life and health. Look at this picture with the eyes of a builder: every house is fighting the cold, and the snow tells you how well.

Look closely

- Find the chimneys and the smoke. Which houses are being heated?
- Look at the snow on the roofs. Is it lying evenly? What would bare patches on a roof tell you about heat leaking from inside?
- Find the windows. How big are they compared with the walls? Why might builders have made them that size?
- Find the inn sign and the fire outside it. Where is that heat going?

Talk about it

1. Which heat-flow processes (conduction, convection, radiation) can you find at work in the painting?
2. How would these villagers have tried to keep their houses warm without modern insulation?

3. If you could add one improvement from this lesson to one of these houses, what would it be and why?

Safety first. Do not enter an attic without an adult: step only on joists or boards (never between them), watch for nails through the roof, and wear a dust mask, gloves, long sleeves and safety glasses near fiberglass. Do not disturb old loose, gray-brown pebbly vermiculite insulation (it may contain asbestos) or any old wiring; leave both to professionals. Use a tissue or ribbon, never a flame, to find drafts.

SHOP PROJECT

Heat-Loss Audit of One Room

You will measure one room with outside walls, estimate the R-value of each surface, calculate its heat loss on a design day, find its air leaks, and recommend improvements with costs and paybacks.

You will need

- A tape measure, graph paper and a calculator
- A strip of tissue paper or a light ribbon taped to a pencil (draft finder)
- An infrared thermometer (optional, about $20) or a thermal camera attachment for a phone (optional)
- Your family's heating bills or the utility's price per therm or kWh, and your town's heating degree days (from a weather service)

Steps

1. Draw a floor plan of the room and measure every exterior wall, window, door and the ceiling (if an attic is above) or floor (if over an unheated space). Calculate each net area.
2. Find out (from the house's age, the wall thickness at an outlet cover viewed with an adult, the attic, or the window labels) what each surface is made of. Estimate each R-value or U-factor from the table in this lesson.
3. Calculate the UA of each surface and the room's total UA.
4. Choose a design temperature difference (for example 70 °F inside and the local winter design temperature outside). Calculate the room's heat loss in BTU/h.
5. On a windy or cold day, move the tissue draft finder slowly around windows, doors, outlets on exterior walls, baseboards and any ceiling fixtures. Mark each leak on your plan.
6. If you have an infrared thermometer, measure the surface temperature of the walls, window glass, the window frame and the corners. Mark cold spots.
7. Estimate the room's share of the yearly heating cost using its UA, your town's heating degree days and your fuel price.

8. List three improvements (for example, weatherstrip the door, seal outlet gaps with foam gaskets, add a storm window or cellular shade). Estimate each one's cost and its savings.
9. **Check your work.** Rank the improvements by simple payback and recommend which to do first. Do one cheap fix with an adult (weatherstripping or outlet gaskets, with the breaker off for outlets) and repeat the draft test.

Tips

- Measure inside dimensions; it is close enough for this audit.
- Air leaks are easiest to find on a windy day or with a bath or kitchen fan running to pull air in.
- Write every assumption down; an audit is only as good as its assumptions.

Check your work

- ☐ I calculated the room's UA and design heat loss from measured areas and stated R-values.
- ☐ I found and marked air leaks and cold spots.
- ☐ I recommended improvements ranked by cost and payback, and tested one fix.

SHOP NOTEBOOK

1. A plan of your room with areas, R-values and leak locations marked.
2. A wall section drawing showing the air barrier, insulation, vapor retarder (if any) and where moisture could condense.
3. Your table of improvements with costs, savings and paybacks.

KEY FORMULAS

$$Q = \frac{A\,\Delta T}{R} = U A\,\Delta T$$

$$R_{\text{series}} = R_1 + R_2 + \cdots$$

$$U_{\text{wall}} = \frac{f_{\text{cavity}}}{R_{\text{cavity}}} + \frac{f_{\text{framing}}}{R_{\text{framing}}}$$

$$Q_{\text{season}} = U A \times \text{HDD} \times 24\ \text{h}$$

From history. Before glass wool, builders insulated with whatever trapped air: sawdust, seaweed, straw, wool, newspaper, cork and, unfortunately, asbestos. The first national energy code for houses in the United States, which grew into today's International Energy Conservation Code, came after the fuel shortages of the 1970s, when families saw their heating bills rise sharply and builders began to measure houses with blower doors.

WORKED EXAMPLES

Example 1. A bedroom has 110 ft² of outside wall (net of window) at an effective R-11 and a 15 ft² window. On a design night it is 70 °F inside and 10 °F outside. Find the heat loss through the wall and through the window if the window is (a) single-pane, R-1, and (b) a double-pane low-e unit, U = 0.30.

Show solution

1. ΔT = 60 °F. Wall: $Q = \dfrac{110 \times 60}{11} = 600\ \text{BTU/h}$.
2. (a) Single-pane: $Q = \dfrac{15 \times 60}{1} = 900\ \text{BTU/h}$, more than the whole wall around it.
3. (b) Low-e: $Q = 0.30 \times 15 \times 60 = 270\ \text{BTU/h}$.

Answer: Wall 600 BTU/h; window 900 (single) or 270 BTU/h (low-e).

Example 2. A 2×4 wall has these layers: inside air film R-0.68, ½-in drywall R-0.45, R-13 batts in the cavity (or 3½ in of wood, R-4.38, at the studs), ½-in OSB R-0.62, siding R-0.62, outside air film R-0.17. Framing covers 25% of the wall. Find the R-value through the cavity, through a stud, and for the whole wall.

Show solution

1. Other layers: $0.68 + 0.45 + 0.62 + 0.62 + 0.17 = 2.54$.
2. Through the cavity: $2.54 + 13 = 15.5$; through a stud: $2.54 + 4.38 = 6.92$.
3. Parallel paths by U: $U = \dfrac{0.75}{15.5} + \dfrac{0.25}{6.92} = 0.0484 + 0.0361 = 0.0845$.
4. Whole wall: $R = 1/0.0845 \approx 11.8$.

Answer: Cavity R-15.5, stud R-6.9, whole wall about R-11.8.

Example 3. A house has a total UA of 450 BTU/h·°F. The town averages 5,500 heating degree days a year. Gas costs $1.40 per therm (100,000 BTU) and the furnace is 95% efficient. Estimate the yearly heating cost.

Show solution

1. Heat lost: $450 \times 5{,}500 \times 24 = 59{,}400{,}000$ BTU.
2. Fuel needed: $59.4 \times 10^6 / 0.95 = 62.5 \times 10^6$ BTU $= 625$ therms.
3. Cost: $625 \times \$1.40 = \$875$.

Answer: About $875 a year.

PRACTICE

1. Easy Name the three ways heat moves and give one example of each in a house.

   Show answer

   Conduction through a wall or window glass; convection by drafts and air leaks; radiation from a warm body to a cold window.

2. Easy Do R-values of layers in series add, or do U-factors add?

   Show answer

   R-values add in series. (U-factors, weighted by area, add for parallel paths.)

3. Easy Why does insulation not stop air leaks?

   Show answer

   Fibrous insulation is mostly air spaces; air can flow through it. Air is stopped by a continuous air barrier of solid materials, tape and sealants.

4. Medium A ceiling of 1,000 ft² is insulated to R-38. Find the heat loss when it is 68 °F inside and 8 °F in the attic.

   Show answer

   $1000 \times 60/38 \approx 1{,}580$ BTU/h

5. Medium An attic is upgraded from R-19 to R-49 over 1,000 ft². With ΔT = 60 °F, how much does the heat loss drop?

   Show answer

   $3{,}160 - 1{,}220 \approx 1{,}930$ BTU/h

6. **Medium** A single-pane window (R-1) of 20 ft² is replaced by one with U = 0.28. Find the heat loss before and after at ΔT = 50 °F.

Show answer

Before $1{,}000\ \text{BTU/h}$; after $0.28 \times 20 \times 50 = 280\ \text{BTU/h}$

7. **Medium** You are the energy auditor. In January a homeowner finds frost on the underside of the roof sheathing above the bathroom and the hallway light fixture. What is happening, and what do you recommend?

Show answer

Warm, moist indoor air is leaking into the cold attic through gaps around the light and the bath fan (or the fan vents into the attic) and condensing as frost. Seal the ceiling penetrations airtight, duct the bath fan outdoors, and check attic ventilation and insulation.

8. **Hard** Using $Q_{\text{season}} = UA \times \text{HDD} \times 24$, find the yearly savings from the R-19 to R-49 attic upgrade above (1,000 ft²) in a 6,000 HDD climate, with gas at $1.40/therm and a 92% furnace. If the upgrade costs $1,500, what is the simple payback?

Show answer

ΔUA = 1000(1/19 − 1/49) = 32.2 BTU/h·°F; savings = 32.2 × 6000 × 24 = 4.64 million BTU = 46.4 therms; ÷ 0.92 ≈ 50.4 therms ≈ $71 a year; payback about 21 years. (Air sealing first usually pays back much faster.)

9. **Hard** Explain why a 2×6 wall with R-21 batts does not perform at R-21.

Show answer

The studs, plates and headers (often 20–25% of the wall) are wood at only about R-1.25 per inch, so heat flows around the insulation through them; this thermal bridging lowers the whole-wall value to roughly R-15 to R-16, before counting any gaps.

10. Hard Warm indoor air at 70 °F and 40% relative humidity has a dew point of about 45 °F. Explain what happens when this air leaks into a wall whose sheathing is at 25 °F, and why air sealing matters more than a vapor retarder in this case.

Show answer

The air cools below its dew point and its vapor condenses (or frosts) on the cold sheathing. Air leaks can carry far more moisture through one small gap than diffusion carries through a whole wall, so stopping the air flow is the most important step.

11. Challenge Derive the effective R-value of a wall with 22% framing at R-6.9 and 78% cavity at R-15.5, then find what cavity R-value would be needed for the whole wall to reach R-15 with the same framing.

Show answer

$U = 0.78/15.5 + 0.22/6.9 = 0.0503 + 0.0319 = 0.0822$; $R \approx 12.2$. For R-15, U = 0.0667, so the cavity part must be 0.0667 − 0.0319 = 0.0348 = 0.78/R, R ≈ 22.4, which a 2×4 cavity cannot hold; that is why builders add continuous foam over the studs.

COMMON MISTAKES

- Adding R-values of parallel paths (studs and insulation) as if they were in series.
- Piling insulation on an attic floor without sealing the air leaks under it first.
- Compressing batts or leaving gaps around wires and boxes, which cuts their real R-value.
- Venting a bath fan into the attic instead of outdoors.

> **Make it a game · R-Value Race.** Your parent names wall layers with R-values, such as drywall 0.5, insulation 13, sheathing 1. Add the series value in 15 seconds, then estimate heat loss for 100 square feet at 40 degrees difference with Q = A dT / R. Race five problems, and discover how a stud lowers the average.

4.5 Plumbing, Drywall, Codes and Permits

OBJECTIVES

- Explain the supply and drain-waste-vent systems of a house, and why traps and vents keep sewer gas out.
- Calculate water pressure from height, drain slope and fall, and drywall quantities.
- Describe how drywall replaced plaster and how it is hung and finished.
- Explain the purpose of building codes from Hammurabi and Deuteronomy to the International Residential Code, and how permits and inspections work.

> **Warm-up.** Find your home's main water shutoff valve, the water heater and the cleanout plug for the main drain (ask an adult to help). Under a sink, find the U-shaped trap. Then go outside and look at the roof: count the pipes sticking up through it. What do you think those pipes are for?

WATCH

How Your Home Plumbing Works (From Start to Finish) | GOT2LEARN

Got2Learn · 7:06

https://www.youtube.com/watch?v=8jxRn-T_LCs

> **WHEN TO WATCH**
> After the story. An animated house shows the supply side, the drains, vents, traps, cleanouts and the sewer or septic system. Sketch the house and add each pipe as it is shown.

Note: The description has shopping links; none are needed.

BACKUP VIDEO

What is a Plumbing Vent? (and Why Do You NEED it?)

Roger Wakefield Plumbing Education · 2:46

https://www.youtube.com/watch?v=_PoycWM_m5A

Before the trap-and-vent part of the shop project: a master plumber explains what vents do.

KEY TERMS

supply and DWV

The supply system brings clean water in under pressure; the drain-waste-vent (DWV) system carries used water out by gravity and lets air in and gases out.

trap

A U-shaped bend in a drain that holds a few inches of water (the trap seal), blocking sewer gas from entering the house.

vent

A pipe connected to the drains and open above the roof, which lets air into the system so draining water cannot siphon traps dry, and carries sewer gases outdoors.

fall (slope)

The downhill pitch of a drain pipe, usually ¼ in per foot for small drains, so waste flows without standing or separating.

drywall (gypsum board)

Panels of gypsum plaster faced with paper, screwed to framing and finished with tape and joint compound; Type X board contains glass fibers for extra fire resistance.

building permit and inspection

Official permission to do construction work, followed by inspections at set stages (footings, framing, rough plumbing and electrical, insulation, final) to confirm the work meets code.

CORE IDEAS

The story. About 1750 BC, King Hammurabi of Babylon had his laws carved on a stone pillar. Several deal with builders: if a builder built a house and did not make it firm, and it fell and caused the death of the owner, the builder was to be put to death; if it destroyed property, he was to replace it and rebuild the house at his own cost. The Law of Moses gave a different and wiser kind of rule: when you build a house, put a parapet (a "battlement") around the flat roof, so that no one falls from it (Deuteronomy 22:8). The first is about punishment after failure; the second is about preventing failure by design. Modern building codes are the second kind. After the Great Fire of London in 1666 destroyed most of the city, Parliament's Rebuilding Act of 1667 required brick and stone walls and set wall thicknesses. American cities wrote codes after their own great fires, and in 1994 the regional code groups joined to form the International Code Council, which published the first *International*

Residential Code in 2000. Most American towns now build houses by it, with local changes.

How they figured it out. Indoor plumbing had its own long lesson. Early drains brought the smell and the dangers of the sewer straight into the house. In 1775 a London watchmaker, Alexander Cumming, patented a water closet with an S-shaped bend in its outlet that always held water, blocking the gas: the first modern **trap**. Plumbers then discovered that a rush of water down a drain could suck a trap dry by siphon, so they added **vents**, pipes open to the air above the roof. Walls changed too. For centuries interior walls were plaster troweled in three coats over wood lath, which took skilled plasterers weeks to dry. In 1894 Augustine Sackett patented "Sackett Board," layers of plaster pressed between sheets of paper, and in 1916 the United States Gypsum Company introduced the improved one-layer panel it named Sheetrock. Gypsum board made walls fast, cheap and fire-resistant, because gypsum holds water chemically and releases it as steam in a fire.

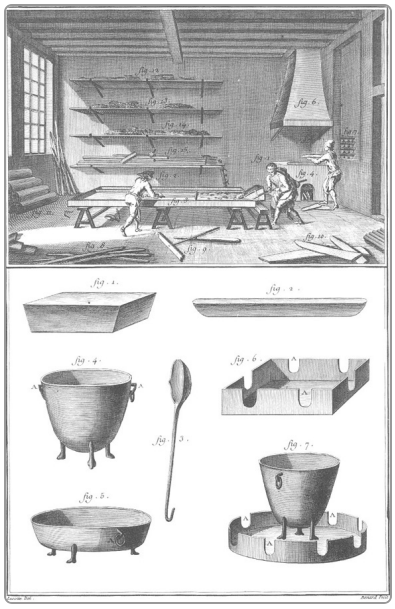
The science. The **supply** side is pressure physics. Water pressure rises with depth, $p = \rho g h$, which in U.S. units is 0.433 psi per foot of height. City water usually arrives at about 40–80 psi; if it is higher, a pressure-reducing valve is installed, since the code limits house pressure to 80 psi. Every foot you go up in a house costs 0.433 psi. The **drain** side is gravity physics: pipes slope about ¼ in per foot (⅛ in for large drains) so that water flows fast enough to carry solids but not so steeply that the water runs ahead and leaves the solids behind. A trap seal is only 2–4 in of water, so a tiny pressure difference, less than a tenth of a psi, can pull it out; vents keep the air pressure in the drains equal to the air outside so the traps stay full. **Drywall** is chemistry: gypsum is calcium sulfate with water locked in its crystals, about 21% by weight; in a fire that water must boil off before the board fails, holding the temperature behind it near 100 °C for a time.

In the shop. A homeowner should know where the **main shutoff** is and how to close it, how to shut off a single fixture at its stop valves, how to clear a sink trap (bucket underneath, unscrew the slip nuts, clean, reassemble with the washers the right way), and how to replace a toilet flapper or a faucet cartridge. Drywall is hung ceilings first, then walls, with sheets running across the framing, screws about 12 in apart on ceilings and 16 in on walls, set just below the paper without tearing it. Joints get paper or mesh tape and three coats of joint compound, each feathered wider and sanded smooth. Before work that changes plumbing, wiring, structure or heating,

check with the local building department: many towns require a **permit** and inspections, and some allow homeowners to do their own work under a permit while others require a licensed contractor. Rules differ from town to town; the building department is the authority.

On the job. Plumbers train through apprenticeships of about four to five years, become licensed journeymen and then master plumbers; their work protects public health, and the trade is well paid. Drywall hangers and finishers, plasterers, building inspectors and code officials are all skilled careers. A building inspector's job, at its best, is the battlement of Deuteronomy: to catch the danger before anyone falls.

PICTURE STUDY



The Plumber's Workshop, Plate I, Plate from Diderot and d'Alembert's Encyclopédie, 1769 · Engraving · Encyclopédie, Recueil de planches, vol. 7 (Plombier)

Image: Wikimedia Commons, public domain

The word "plumber" comes from the Latin *plumbum*, lead, because for two thousand years water pipes, roofs and gutters were made of lead. This plate shows an eighteenth-century plumber's shop casting sheet lead.

Look closely

- Find the furnace and the melting pot. What is being melted?
- Find the long table where the sheet is cast. How do the workers spread the metal evenly?
- Look at the tools at the bottom of the plate. What would each be used for?
- Look for finished sheets or pipes in the shop.

Talk about it

1. Lead is easy to shape and does not rust. Why do we no longer use it for drinking-water pipes?
2. Which parts of this work would a modern plumber still recognize?
3. Why was a plumber's skill once as important for roofs as for water?

> **Safety first.** Know where your main water shutoff is before any plumbing job, and put a bucket under traps and valves. Wear safety glasses when working under sinks and when cutting or sanding drywall, and a dust mask when sanding joint compound. Do not work on gas lines, water heaters' gas or electrical parts, or sewer lines; those jobs belong to licensed professionals, often with permits.

SHOP PROJECT

A Clear-Tube Trap and Vent, and a House-Systems Map

You will build a see-through model of a sink drain with a trap and a removable vent, show how a rush of water siphons a trap dry when there is no vent, and measure the trap seal. Then you will map the main systems of your own home.

You will need

- About 6 ft of clear vinyl tubing (½ to ¾ in inside diameter), a funnel that fits it, a plastic T fitting of the same size
- Tape, zip ties and a board or cardboard panel to fix the tubing in shape; a bucket; a 2-liter bottle; a ruler; food coloring
- A flashlight, graph paper and a notebook for the house map

Steps

1. Fix the funnel at the top of the board as the "sink." Run the tubing down from it and form a U-bend (the trap) about 6 in below, then a horizontal run sloping gently to the bucket.
2. Pour colored water slowly into the funnel until water stands in the U-bend. Measure the trap seal: the height of water from the bottom of the outlet side's top curve down to the lowest water level that still blocks air.
3. Make the drain run downward steeply after the trap (as in a long drop with no vent). Pour a full 2-liter bottle in quickly. Watch the trap. Measure the seal left afterward.
4. Repeat three times and average your results.
5. Insert the T fitting just past the trap, with a short open tube rising from it as a vent above the funnel's rim. Repeat the fast-pour test three times and measure the seal left.
6. Compare the averages and explain the difference using air pressure.
7. **House-systems map.** With an adult, draw a plan of your home and mark the main water shutoff, the water heater, each fixture, the visible drain and vent stacks, the cleanout, the electrical panel and the furnace or air handler. Note any problems you see (drips, missing escutcheons, slow drains).

8. Write a one-page “house manual” for your family: how to shut off the water in an emergency, and which jobs a homeowner can do versus which need a licensed plumber or a permit in your town (call or check the building department’s website).
9. **Check your work.** Have a family member use your manual to find and close the main shutoff (then open it again slowly).

Tips

- Food coloring makes the trap seal easy to see and measure.
- Make all bends gentle; a kinked tube acts like a clog.
- Turn shutoff valves slowly; old valves can leak at the stem when moved and may need a plumber.

Check your work

- ☐ I measured the trap seal left with and without a vent and explained the result.
- ☐ My house map shows the main shutoff and all major systems.
- ☐ My family manual says what to do in a leak and when to call a professional or get a permit.

SHOP NOTEBOOK

1. A labeled diagram of a house’s DWV system: fixtures, traps, branch drains, stack, vent through the roof, cleanout and building sewer, with slopes marked.
2. Your trap-seal data table (with and without vent) and averages.
3. A timeline of building rules: Hammurabi, Deuteronomy, the London Rebuilding Act, the International Residential Code, with one sentence on what each required.

KEY FORMULAS

$p = 0.433\ \frac{\text{psi}}{\text{ft}} \times h$

$\text{fall} = \text{slope} \times \text{run}$

$N_{\text{sheets}} = \dfrac{A_{\text{walls+ceiling}} - A_{\text{openings}}}{32\ \text{ft}^2} \times 1.10$

From history. The Romans piped water in lead and laid stamped lead pipes under their streets, and lead remained common in water service lines into the twentieth century. The United States banned lead pipe and high-lead solder for drinking water in 1986, and many cities are still replacing old lead service lines. Copper, then plastic pipes such as PEX, have replaced it.

WORKED EXAMPLES

Example 1. A bathroom drain runs 22 ft to the main stack at ¼ in per foot. How much lower is its far end?

Show solution

1. Fall: $0.25 \text{ in/ft} \times 22 \text{ ft} = 5.5 \text{ in}$.
2. The joists or the space below must allow for a 5½-in drop over the run, which is why drains are planned before framing is finished.

Answer: 5.5 in

Example 2. Water arrives at the meter in the basement at 62 psi. What is the static pressure at a second-floor shower head 21 ft higher? What is the greatest height that water at 62 psi could rise in a pipe?

Show solution

1. Pressure lost by rising: $0.433 \times 21 = 9.1$ psi.
2. At the shower: $62 - 9.1 = 52.9$ psi (less when water is flowing, because of friction).
3. Maximum height: $h = 62 / 0.433 \approx 143$ ft.

Answer: ≈ 53 psi; 143 ft

Example 3. A bedroom is 12 × 14 ft with 8-ft walls, one 3 × 7 ft door and one 3 × 5 ft window. How many 4 × 8 ft sheets of drywall are needed for the walls and ceiling, with 10% for waste?

Show solution

1. Walls: perimeter $2(12 + 14) = 52$ ft; area $52 \times 8 = 416$ ft^2.
2. Openings: $21 + 15 = 36$ ft^2; net walls 380 ft^2. Ceiling: $12 \times 14 = 168$ ft^2.
3. Total 548 ft^2; sheets $548/32 = 17.1$; with 10%: 18.8, so 19 sheets.

Answer: 19 sheets.

PRACTICE

1. Easy What does a trap do, and how deep is a typical trap seal?

   Show answer

   It holds water that blocks sewer gas from coming into the house; about 2–4 in.

2. Easy Why does a house need vent pipes through the roof?

   Show answer

   To let air into the drains so flowing water cannot siphon the traps dry, and to carry sewer gases safely outdoors.

3. Easy Name three inspections a new house typically receives.

   Show answer

   Any three of: footing, foundation, framing, rough plumbing, rough electrical, mechanical, insulation, final.

4. Medium A kitchen drain runs 14 ft at ¼ in/ft. Find the fall.

   Show answer

   3.5 in

5. Medium A water tower's water level is 120 ft above a house. Find the static pressure at the house.

   Show answer

   $0.433 \times 120 \approx 52$ psi

6. Medium How many 4 × 8 sheets are needed for the walls only of a 10 × 10 ft room with 8-ft walls, no openings, plus 10%?

Show answer

$320/32 = 10;\ \times 1.1 = 11$ sheets

7. Medium You are the plumber. A family smells sewer gas in a guest bathroom that is rarely used. Everything else seems fine. What is the most likely cause and the fix?

Show answer

The trap in the unused shower or floor drain (or sink) has dried out by evaporation. Run water into every fixture to refill the traps; for a seldom-used floor drain, add a trap primer or seal.

8. Hard A trap seal is 2.0 in of water. Find the pressure difference, in psi, that would push or pull it out. Why does this show that vents matter?

Show answer

$p = 0.433 \times (2/12) \approx 0.072$ psi. A very small pressure difference from draining water can empty a trap, so vents must keep the drain air at outdoor pressure.

9. Hard Explain why a drain that is too steep can clog as easily as one that is too flat.

Show answer

Too flat, water moves too slowly to carry solids. Too steep, the water runs ahead and leaves solids behind to dry and build up; the standard slope keeps water and solids moving together.

10. Hard Compare the Code of Hammurabi's builder law with Deuteronomy 22:8 as approaches to safety. Which one does a modern building code resemble more, and why?

Show answer

Hammurabi punished the builder after a failure; Deuteronomy required a safety feature in advance to prevent a fall. Modern codes are mostly preventive: they set requirements and inspect before the house is used, as Deuteronomy did.

11. **Challenge** A two-story house has a shower 24 ft above the meter and the city pressure is only 45 psi. The shower valve needs at least 20 psi while flowing, and friction in the pipes costs about 8 psi at full flow. Will it work? What could be done if not?

    Show answer

    Static at the shower: $45 - 0.433 \times 24 = 34.6$ psi; minus 8 psi friction = 26.6 psi, above 20 psi, so it works, with little margin. If not, use larger pipe to reduce friction or install a booster pump (a plumber's job, often with a permit).

COMMON MISTAKES

- Not knowing where the main shutoff is until water is pouring through a ceiling.
- Installing a drain with too little or too much slope, or with an S-trap that has no vent.
- Driving drywall screws so deep that they tear the paper face, so they hold nothing.
- Assuming a permit is never needed for "small" jobs; the rules depend on your town.

Make it a game · Follow the Water. Draw a house's plumbing on paper from memory, supply on one side and drain-waste-vent on the other, adding a trap and vent. Trace a drain with a finger and say where the water would go and where air enters. Your parent finds one missing part. Then calculate drain fall for a 12-foot run.

Scripture. "When thou buildest a new house, then thou shalt make a battlement for thy roof, that thou bring not blood upon thine house, if any man fall from thence." (Deuteronomy 22:8, KJV)

This is a building code: a required safety feature, written into the house before anyone could be hurt. Following codes is a way of loving the neighbors who will live in and visit what we build.

UNIT 4

Home Construction

A house is a system of systems, built in the order you will study them: a foundation that carries everything down to undisturbed soil below the frost line; a frame that carries every load along a continuous path; a roof and walls that shed water; insulation and air sealing that keep the people inside warm, dry and healthy at a reasonable cost; and the plumbing and finishes that make it a home. Each part has a story: Smeaton's underwater mortar and Portland cement, the balloon frame on the Chicago prairie, the asphalt shingle and the factory truss, Rumford's trapped air and the R-value, Cumming's S-trap and Sackett's plasterboard.

You will calculate what tradespeople calculate every day (footing widths and concrete orders, joist stresses and stud counts, rafter lengths and roofing squares, heat loss and heating cost, pressure, drain fall and drywall sheets), and you will build and test models: a soil-bearing test, a framed wall racking test, a shingled roof water test, a heat-loss audit of a real room and a see-through trap and vent. The unit ends with building codes, from Hammurabi and Deuteronomy to today's International Residential Code, and with when to pull a permit and call a licensed professional.

PREREQUISITES

- Algebra I: formulas, unit conversions, square roots
- Right-triangle trigonometry: tangent and the Pythagorean theorem
- Unit 3 (wood as a material, actual lumber sizes, board feet)
- Area and volume of rectangles, prisms and cylinders

MASTERY CHECKLIST

- ☐ I can explain foundation types, frost heave and concrete curing, size a footing from soil bearing capacity and order concrete.
- ☐ I can name the members of a platform frame, trace the load path, and check a joist or header for bending stress and deflection.
- ☐ I can calculate roof pitch, rafter length, squares and roof loads, and explain how roof and wall layers shed water.
- ☐ I can calculate heat loss with $Q = A \cdot \Delta T / R$, combine series and parallel R-values, and estimate yearly heating cost and payback.
- ☐ I can explain supply and drain-waste-vent plumbing, traps and vents, calculate pressure, drain fall and drywall quantities.
- ☐ I can explain why building codes, permits and inspections exist and when a job needs a licensed professional.

OPTIONAL KITS FOR THIS UNIT

- **FLIR thermal imaging cameras**: Optional for Lesson 4.4. A thermal camera that clips onto a phone shows cold spots, missing insulation and air leaks as colors. An inexpensive infrared spot thermometer and a tissue-paper draft finder do the job well enough; many hardware stores and libraries lend or rent thermal cameras.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

4.1	**Foundations: Building upon the Rock**	3 sessions of 50 minutes
4.2	**Framing: From the Balloon Frame to the Platform**	3 sessions of 50 minutes
4.3	**Roofs and the Building Envelope: Shedding Water**	3 sessions of 50 minutes
4.4	**Insulation, Air and Moisture**	3 sessions of 50 minutes
4.5	**Plumbing, Drywall, Codes and Permits**	3 sessions of 50 minutes

Unit 4 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Write explanations in complete sentences. The test is worth 100 points.

1. **5 pts**
   Explain frost heave and how a builder protects a foundation from it.

2. **6 pts**
   A wall load of 2,100 lb per linear foot rests on soil rated 1,500 psf. Find the minimum footing width in inches, and choose a standard width.

3. **6 pts**
   A footing is 150 ft long, 20 in wide and 10 in deep. How many cubic yards of concrete should be ordered with 10% extra?

4. **5 pts**
   Does concrete harden by drying? Explain, and say why it is reinforced with steel.

5. **6 pts**
   Compare balloon and platform framing and give two reasons platform framing replaced the balloon frame.

6. **5 pts**

   How many common studs are needed for an 18-ft wall at 16 in on center?

7. **6 pts**

   Joists of 2×10 (1.5 × 9.25 in) at 16 in on center span 14 ft and carry 50 psf. Find the maximum moment in in·lb and the bending stress.

8. **5 pts**

   By what factor does stiffness increase when a beam's depth doubles? Its strength?

9. **6 pts**

   A 7:12 gable roof has a 13-ft run plus a 1-ft overhang. Find the roof angle and the rafter length.

10. **6 pts**

    A 36 × 26 ft house plan (with overhangs) has a 5:12 roof. Find the roofing squares with 10% waste, and the number of bundles.

11. **5 pts**

    Explain the first rule of the building envelope and give two examples of it.

12. **7 pts**

    A 120 ft^2 exterior wall is R-12 overall and has a 20 ft^2 window with U = 0.32. Find the total heat loss at $\Delta T = 65\ °F$.

13. **6 pts**

    Find the whole-wall R-value of a wall with 25% framing at R-7.0 and 75% cavity at R-16.

14. **6 pts**

    A house has UA = 380 BTU/h·°F in a 6,200 HDD climate. With a 90% furnace and gas at $1.30/therm, estimate the yearly heating cost.

15. **5 pts**

    Water enters a house at 58 psi. Find the static pressure at a fixture 18 ft higher.

16. **5 pts**

You are the plumber. A sink gurgles and the bathroom smells of sewer gas whenever the tub drains. What is wrong and what is the fix?

17. **10 pts**

Short essay. Explain what building codes, permits and inspections are for. Use Deuteronomy 22:8 and at least two examples from this unit (for example frost depth, span tables, flashing, traps and vents, fire-resistant drywall or fire blocking) and say how you would decide whether a home project needs a permit or a licensed professional.

ANSWER KEY

1. Water in the soil freezes and grows ice lenses that lift the ground. Footings are placed below the local frost line on undisturbed soil, and water is drained away from the foundation.
2. $2100/1500 = 1.4$ ft $= 16.8$ in; use an 18-in (or 20-in) footing.
3. $150 \times 1.667 \times 0.833 = 208$ ft^3 $= 7.72$ yd^3; with 10% about 8.5 yd^3.
4. No; it hardens by hydration, a chemical reaction with water, so it is kept moist while curing. It is strong in compression but weak in tension, so steel rebar carries the tension.
5. Balloon framing uses long studs continuous from sill to roof with joists nailed to them; platform framing builds each floor as a deck with walls on top. Platform framing blocks fire at each floor, uses shorter, easier-to-get studs and gives a safe working platform.
6. $216/16 = 13.5 \rightarrow 14$ spaces; 15 studs
7. $w = 66.7$ lb/ft; $M = 66.7(14)^2/8 = 1{,}634$ ft·lb $= 19{,}600$ in·lb; $S = 21.4$ in^3; $f_b \approx 916$ psi
8. Stiffness ($I \propto d^3$) increases 8 times; strength ($S \propto d^2$) 4 times.
9. $\theta = \arctan(7/12) = 30.3^\circ$; slope factor 1.158; $14 \times 1.158 \approx 16.2$ ft.
10. Slope factor 1.083; $936 \times 1.083 = 1{,}014$ ft^2; with 10% 11.2 → 12 squares = 36 bundles.
11. Every layer must lap over the one below it so water runs out: shingles cover the course below; step flashing laps over the piece below and housewrap laps over the flashing; window tape goes sill, sides, head.
12. Wall: $100 \times 65/12 = 542$ BTU/h (net of the window); window: $0.32 \times 20 \times 65 = 416$ BTU/h; total ≈ 958 BTU/h.
13. $U = 0.25/7.0 + 0.75/16 = 0.0357 + 0.0469 = 0.0826$; $R \approx 12.1$
14. $380 \times 6200 \times 24 = 56.5 \times 10^6$ BTU; $\div 0.90 = 62.8 \times 10^6 = 628$ therms; $\approx \$817$
15. $58 - 0.433(18) \approx 50.2$ psi
16. The draining tub is siphoning the sink trap because the vent is blocked or missing (for example, a vent clogged at the roof by debris or ice). Clear or add the vent so the trap stays full.
17. A good answer: codes set minimum requirements so buildings are safe for the people who live in and visit them, learned from past failures; Deuteronomy's battlement is a preventive safety requirement, like modern codes; gives specific

examples and why each exists; explains that permits let the local building department inspect work at key stages; and says the student would check with the town's building department, since rules vary, and call licensed professionals for gas, major electrical, structural and many plumbing jobs.

PORTFOLIO PIECE: A FRAMED WALL MOCK-UP AND A HOUSE-SYSTEMS REPORT

Present your framed wall section from Lesson 4.2 (at 1:4 scale or full size) with its labeled drawing and racking-test results, together with a house-systems report on your own home: its foundation type and drainage, how it is framed (as far as can be seen in the attic, basement or garage), its roof and flashing details, your heat-loss audit of one room with recommended improvements, and your house map and family manual for water shutoff and emergencies. Finish with a page listing which home jobs you can now do safely yourself and which require a permit or a licensed professional in your town.

LOOK FOR	WHAT IT MEANS
Wall mock-up	Correct members and layout (plates, studs at 16 in o.c., king and jack studs, header, sill, cripples, double top plate), square and well built, with racking data.
Calculations	Footing, joist, roofing and heat-loss calculations are correct, with units and stated assumptions.
House-systems report	Accurate observations of the real house in each system, with photographs or sketches and clear explanations.
Recommendations	Specific, ranked improvements with costs and paybacks, and sound judgment about permits and professionals.
Communication	Clear, organized drawings and writing that a family member could follow.

UNIT 5

Basic Home Electrical

Electricity is the most useful and the least forgiving system in a house. In this unit you will follow it from Edison's Pearl Street Station in 1882 to the panel in your own basement or garage, learn why wire comes in different sizes and how breakers protect it, and learn from Charles Dalziel's measurements why a few thousandths of an ampere matter and how GFCIs and AFCIs protect people and homes.

Then you will learn the electrician's habits before the electrician's tasks: identify the circuit, switch it off, lock and label it, and prove it dead with live–dead–live testing. You will practice wiring a switch, a receptacle, a lamp holder and a pair of 3-way switches on an **unpowered practice board** that is never connected to anything, and you will map which breaker feeds what in your home. The unit ends with lighting, the National Electrical Code, permits and the question every homeowner must answer honestly: when to call a licensed electrician.

Safety rules for the whole unit. You never open the panel cover, never touch the service drop or meter, and never work on anything energized. Any work on a real household circuit is done only with a qualified adult present, after the breaker is switched off, locked or taped, labeled and verified dead live–dead–live. Many jobs need a permit and a licensed electrician; the rules vary by state and town. Never bypass a breaker, a GFCI or a ground pin.

PREREQUISITES

- Algebra I: solving and rearranging formulas, ratios, scientific notation
- Ohm's law and power ($V = IR$, $P = VI$) at the level of a physical science course
- Units 1–4 of this course, especially fasteners and torque (Unit 1) and house framing (Unit 4)

MASTERY CHECKLIST

- ☐ I can trace power from the generating plant to a branch circuit and explain 120/240 V split-phase service.
- ☐ I can explain what is inside a panel without opening one, and which parts belong to the utility.
- ☐ I can match wire gauge to breaker size and calculate circuit current, the 80 percent limit and voltage drop.
- ☐ I can explain how a breaker, a GFCI, an AFCI and the ground wire each protect a house and its people.
- ☐ I can carry out lockout, labeling and live–dead–live verification and explain each step.
- ☐ I can wire a receptacle, a single-pole switch and a 3-way circuit on an unpowered practice board and check them with a meter.
- ☐ I can compare lighting by lumens per watt and calculate lighting cost and payback.
- ☐ I can decide which electrical jobs need a permit and a licensed electrician in my town.

OPTIONAL KITS FOR THIS UNIT

- **Klein Tools electrician's hand tools and testers**: Wire strippers, screwdrivers, non-contact voltage testers and plug-in receptacle testers from a long-established American electricians' toolmaker. Useful for Lessons 5.3–5.5; any brand that is rated for the job will do.
- **Fluke digital multimeters**: Professional meters used by electricians, for continuity checks on the practice board (Lesson 5.4) and for live–dead–live drills. An inexpensive CAT III-rated meter from a reputable brand also works.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

5.1	**From Power Plant to Panel**	3 sessions of 50 minutes
5.2	**Circuits, Wire and Breakers**	3 sessions of 50 minutes
5.3	**Shock, Grounding, GFCI and AFCI**	3 sessions of 50 minutes
5.4	**Working Safely: Switches and Receptacles**	3 sessions of 50 minutes
5.5	**Lighting, Codes and When to Call an Electrician**	3 sessions of 50 minutes

Unit 5 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Use 120 V for single-pole circuits unless told otherwise. For explanations, use complete sentences. The test is worth 100 points.

1. **6 pts**
   Trace electricity from the power plant to a 120 V receptacle in a bedroom, naming at least six parts in order.

2. **6 pts**
   A pole transformer steps 7,200 V down to 240 V. Find the turns ratio and explain how the house gets both 120 V and 240 V.

3. **5 pts**

   Why does switching off the main breaker not make it safe to remove the panel cover?

4. **7 pts**

   A meter reads 18,410 kWh on March 1 and 19,340 kWh on March 31. At $0.16 /kWh, find the energy, the cost and the average power.

5. **6 pts**

   State the usual breaker size for 14 AWG, 12 AWG and 10 AWG copper NM cable, and explain why the breaker must match the wire.

6. **8 pts**

   A 20 A kitchen circuit has a 1,100 W microwave and a 1,200 W coffee maker running. (a) Find the current. (b) Will adding a 900 W toaster trip the breaker? (c) What is the continuous limit under the 80 percent rule?

7. **8 pts**

   A 12 AWG circuit (1.59 Ω/1,000 ft) runs 90 ft to a load of 15 A. Find the voltage drop and percent drop. Is it within 3 percent?

8. **5 pts**

   Distinguish an overload from a short circuit and say which part of a thermal-magnetic breaker responds to each.

9. **8 pts**

   A person with wet hands ($R = 1{,}200\ \Omega$) touches a 120 V hot while grounded. (a) Find the current. (b) Will a 15 A breaker trip? (c) Will a GFCI trip, and why?

10. **6 pts**

    A hot wire touches the grounded metal case of a dryer. The fault loop is 0.40 Ω at 120 V to ground. Find the fault current and explain what the ground wire accomplishes.

11. **5 pts**

    What does an AFCI protect against, and why can a regular breaker miss it?

12. **7 pts**

    List in order the steps for safely replacing a receptacle on a real circuit, including who must be present.

13. **4 pts**

    A box is marked 20.3 in^3. It contains two 14-2 cables with ground, one 14-3 cable with ground, a switch and internal clamps. Does it pass box fill?

14. **5 pts**

    Explain how two 3-way switches control one light; give the truth table.

15. **4 pts**

    Replacing 15 incandescent bulbs of 75 W (1,100 lm) with 11 W LEDs, used 4 h a day at $0.15/kWh: find the yearly savings and the efficacies.

16. **10 pts**

    Short essay (one or two paragraphs): A neighbor says, “Permits are just paperwork; I can wire my new workshop myself, and if the breaker keeps tripping I’ll put in a bigger one.” Respond as a knowledgeable, respectful young tradesperson, using what you learned about wire heating, breakers, codes, inspection and when to call a licensed electrician.

ANSWER KEY

1. Generator, step-up transformer, transmission line, substation, distribution line, pole or pad transformer (center-tapped), service drop or lateral, meter, main breaker, bus bar, branch breaker, NM cable, receptacle.
2. 30 : 1. The secondary is center-tapped and grounded (the neutral): each end to center is 120 V, and end to end is 240 V.
3. The service conductors and lugs feeding the main breaker remain energized from the meter; only the utility can de-energize them, and the cover is never removed by students.
4. 930 kWh; \$148.80; $930/720 \approx 1.29$ kW.
5. 15 A, 20 A, 30 A. The breaker protects the wire from overheating; a larger breaker would allow current that overheats the wire without tripping.
6. (a) $2300/120 = 19.2$ A. (b) $3200/120 = 26.7$ A, so yes, it will trip. (c) 16 A (1,920 W).
7. $R = 1.59 \times 180/1000 = 0.286\ \Omega$; drop $= 4.3$ V $= 3.6\%$; no, slightly over; 10 AWG would bring it to about 2.3 percent.
8. Overload: moderate excess current, slow heating, bimetal strip trips. Short: huge sudden current, magnetic coil trips instantly.
9. (a) 100 mA. (b) No, it is far below 15 A. (c) Yes: 100 mA leaves through the person, so hot and neutral currents differ by far more than the 4–6 mA trip level.
10. 300 A; the ground wire makes the fault a near short so the breaker trips immediately, instead of leaving the case energized.
11. Arcing faults from damaged cords or loose connections that can start fires; an arc can draw less current than the breaker's rating while still producing intense heat.
12. Qualified adult present; identify circuit; breaker off; lock or tape and label; test tester on known live; test both slots of the receptacle and confirm dead; test tester again; remove plate, check every conductor in the box with a non-contact tester; photograph wiring; replace device; test finished work.
13. Conductors 7, grounds 1, device 2, clamps 1 = 11; $11 \times 2.00 = 22.0$ in$^3 > 20.3$; it fails; use a larger box.
14. Each common connects to one of two travelers; the light is on when both switches select the same traveler ((1,1),(2,2)) and off otherwise ((1,2),(2,1)), so either switch toggles it.

15. Savings: $15 \times 64 \times 4 \times 365/1000 = 1{,}402$ kWh $= \$210$. Efficacy: 14.7 lm/W versus 100 lm/W.
16. A strong answer explains that the breaker protects the wire, so a bigger breaker on the same wire lets it overheat inside walls (I^2R heating) and can start a fire; that tripping means the circuit is overloaded or faulty and needs a new circuit or a repair; that codes such as the NEC came from studying fires and injuries; that a permit brings an inspector's check before walls are closed and protects future occupants and insurance; that rules vary by town; and that new circuits and panel work are normally for a licensed electrician. Tone is respectful and offers help (a load list, a call to the building department, a recommended electrician).

PORTFOLIO PIECE: A WIRED PRACTICE BOARD AND A HOME ELECTRICAL MAP

Hand in your finished **unpowered practice board** (single-pole and 3-way versions, photographed at each stage) with its wiring diagrams, box-fill calculations and continuity tables, and your **home electrical map**: a floor plan showing which breaker feeds every light and receptacle, the load audit with the 80 percent check for each circuit, the GFCI and receptacle survey, the corrected panel directory approved by your parents, and your call-or-do-it decision table. Finish with a one-page safety plan for your household: monthly GFCI tests, smoke-alarm and tester checks, and the name of an electrician to call.

LOOK FOR	WHAT IT MEANS
Practice board workmanship	Correct terminal colors, clockwise hooks, tight screws, no nicked or exposed copper, cables secured, board labeled and never connected to power.
Verification	Continuity tables prove the switching works; live–dead–live card is complete and correct.
Home electrical map	Every light and receptacle assigned to a breaker; loads, currents and 80 percent checks calculated correctly.
Safety survey and judgment	GFCI and receptacle results recorded; every fault referred to a qualified electrician; decision table reflects local rules.
Communication	Clear diagrams, neat tables and a household safety plan a family member can follow.

5.1 From Power Plant to Panel

OBJECTIVES

- Trace electricity from the generating plant through transmission, the distribution transformer, the service drop and the meter to the main panel.
- Explain 120/240-volt split-phase service and the jobs of the hot, neutral and grounding conductors.
- Name the parts inside a main panel (seen in a photo or video, never opened) and say which parts belong to the utility.
- Calculate power, current and the monthly cost of electricity from a meter reading.

> **Warm-up.** Walk outside with a parent and, from a few steps away, find where electricity enters your house: an overhead service drop from a pole, or an underground line rising to the meter. Do not touch anything. Sketch what you see and write down the numbers on the meter display. Then find your main panel indoors (often in a garage, basement or utility room) and look only at the closed door. Where do you think the wires go between the meter and the panel?

WATCH

Main electrical panel explained - Load center - service panel

The Engineering Mindset · 10:18

https://www.youtube.com/watch?v=UBERduCp3Wo

> **WHEN TO WATCH**
> After the science paragraph. It shows the inside of a panel in animation so that you never need to open one: bus bars, neutral bar, main breaker, branch breakers, 120 V and 240 V circuits.

BACKUP VIDEO

120V 240V Electricity explained - Split phase 3 wire electrician

The Engineering Mindset · 12:24

https://www.youtube.com/watch?v=fJeRabV5hNU

Optional, before the worked examples: how one center-tapped transformer gives both 120 V and 240 V.

KEY TERMS

service drop

The overhead cables from the utility pole to the house (an underground supply is a *service lateral*). They belong to the utility and are always energized.

meter

The utility's instrument that measures energy used, in kilowatt-hours (kWh). Only the utility removes or replaces it.

split-phase service

The usual North American home supply: two 120 V hot legs from a center-tapped transformer, 240 V between them, with the grounded center tap as the neutral.

hot, neutral and ground

The hot (black or red) carries current at 120 V to the load; the neutral (white) is the grounded return path; the equipment grounding conductor (bare or green) carries current only during a fault.

main breaker

The large breaker at the top of the panel that can switch off all the branch circuits. The wires and lugs feeding it stay live even when it is off.

kilowatt-hour

The unit of energy on your bill: 1,000 watts for one hour, $1\ \text{kWh} = 3.6\ \text{MJ}$.

CORE IDEAS

The story. At 3 p.m. on September 4, 1882, Thomas Edison's Pearl Street Station in lower Manhattan began sending electricity through copper conductors buried under the streets. The first day it lit about 400 lamps for 82 customers, including the offices of the *New York Times*. Steam engines in the old brick building turned enormous direct-current generators the workers called "Jumbos," each weighing about 27 tons. Within two years the station served more than 500 customers and 10,000 lamps. Pearl Street was not the first electric light, but it was the first central station built as a complete *system*: generator, distribution lines, meters, fuses, switches, sockets and lamps all designed to work together.

How they figured it out. Edison's hardest problem was not the bulb but the copper. His calculations showed that feeding thousands of low-resistance lamps would need conductors so thick the system could never pay. So he chose high-resistance lamp filaments wired in parallel, which needed less current, and in 1883 he patented the

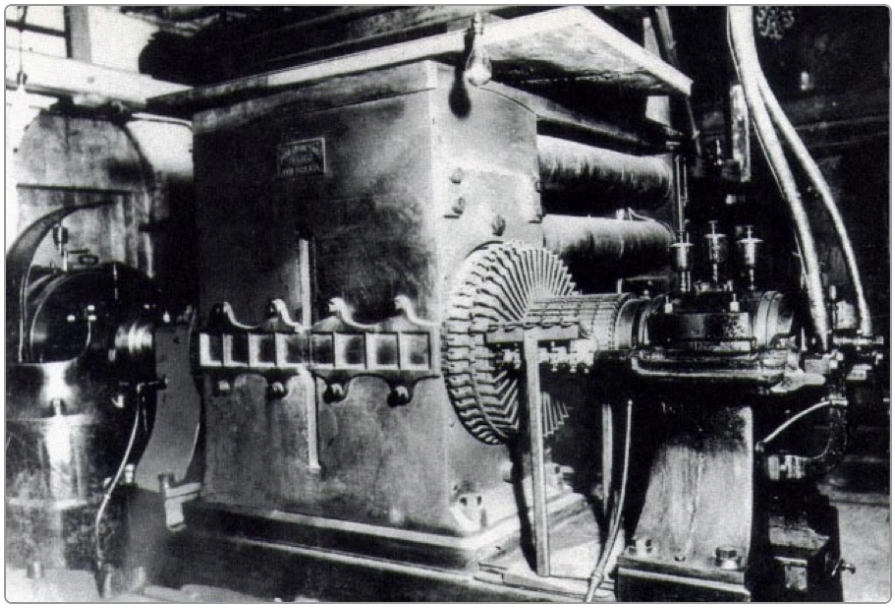
three-wire system: two generators in series gave +110 V and −110 V on two outer conductors with a shared middle conductor between them. Lamps connected between either outer wire and the middle got 110 V, but much of the current cancelled in the middle wire, cutting the copper needed by more than half. He also built the first electric meter, which plated zinc onto small plates that were weighed each month, and lead-wire "safety catches" (fuses) to protect each line. Direct current could not travel far, and within a few years alternating current with transformers, championed by George Westinghouse and Nikola Tesla, won for long distances. Yet your house still uses Edison's three-wire idea.

The science. Power plants generate alternating current that is stepped up by transformers to hundreds of thousands of volts for transmission, because for the same power $P = VI$, a higher voltage means a smaller current and far smaller heating losses I^2R in the lines. Substations step it down to distribution voltages (often 7,200 V on the line along your street). The transformer on the pole or the green pad-mounted box in the yard steps it down again to 240 V. Its secondary coil has a **center tap** that is connected to the earth and becomes the **neutral**. Between either end of the coil and the center you measure 120 V; between the two ends, 240 V. That is **split-phase** service: three wires, just like Edison's, but alternating 60 times a second. Lights and ordinary receptacles use one hot leg and the neutral (120 V); a range, dryer, water heater or air conditioner uses both hot legs (240 V), which halves the current for the same power.

In the shop. The service drop lands on the house, runs down to the meter base, and then to the **main panel** (load center). Inside, behind a screwed-on metal cover called the dead front, two hot **bus bars** are fed through the main breaker; each branch breaker clips onto a bus bar, a single-pole breaker onto one (120 V), a double-pole breaker onto both (240 V). The white neutrals land on a **neutral bar** and the bare grounds on a ground bar; at the main panel only, the neutral and ground are bonded together and connected to a grounding electrode (a rod driven into the earth, and the metal water pipe). The panel door, with its circuit directory, may be opened to read labels and reset a breaker; the cover behind it is never removed by a student or an untrained homeowner. Even with the main breaker off, the conductors that enter the top of the panel from the meter stay energized and can deliver enormous fault currents.

Safety. The service drop and the meter belong to the utility. Never touch them, never climb near them and never try to pull a meter: only the utility does that. Everything you study in this lesson you study from photographs, video and the outside of a closed panel.

PICTURE STUDY



Edison's Jumbo Dynamo at Pearl Street, Unknown photographer, c. 1882–1889 · Photograph · Pearl Street Station, New York

Image: Wikimedia Commons, public domain

This photograph shows one of the Pearl Street "Jumbos" in the station's first years, before the 1890 fire. Each Jumbo was coupled directly to a steam engine, and together they fed the first central electric system in New York.

Look closely

- Find the steam engine and the generator. How is the motion passed from one to the other?
- Find the long horizontal cylinders: the field-magnet coils. What do they do in a generator?
- Look for the brushes and commutator, where the current is collected. Why did Edison's machines produce direct current?
- Find the heavy cables leaving the machine at the upper right. Why must they be so thick?

Talk about it

1. This machine was built to supply a whole neighborhood. Where is the equivalent machine that serves your house today, and how far away is it?
2. Why do you think Edison's system could serve only about a square mile, while modern AC systems send power hundreds of miles?

3. What would happen to the steam engine's speed if many customers turned lamps on at once, and how might the operators respond?

Safety first. Study the service, meter and panel only from outside, from photographs and from video: never touch the service drop or meter, and never remove the panel cover. If you see a damaged service drop, a wire on the ground or a burned meter, stay back and tell an adult to call the utility.

SHOP PROJECT

A Service and Meter Survey

You will survey your home's electrical service from the outside and from the panel door, read the meter over a week, and work out your household's daily energy use, average power and cost. This begins the home electrical map you will finish in Lesson 5.2 and hand in with the unit portfolio.

You will need

- Shop notebook and pencil
- Phone camera
- A recent electric bill (ask a parent)
- Calculator
- Flashlight

Steps

1. With a parent, photograph the service from a safe distance: the pole or pad transformer, the service drop or underground riser, the weatherhead (if overhead) and the meter. Do not touch anything or stand under the service drop on a ladder.
2. Copy the meter's kWh reading and the time. If it is a digital meter that cycles through screens, wait until the kWh total appears.
3. At the panel, open the door only (not the screwed-on cover). Record the main breaker's rating (for example 100, 150 or 200 A), the panel brand, and how many single-pole and double-pole breakers there are.
4. Copy the circuit directory exactly as written, including any blank or unclear labels.
5. Read the meter again at the same time each day for seven days. Make a table of date, reading and kWh used that day.
6. Calculate the average daily energy, the average power in kW, and the cost per day and per month using the rate on the bill.
7. Compare your monthly estimate with the bill. Find on the bill the customer charge, the energy charge and any delivery charges.

8. **Check your work.** Turn off one large load for a day (for example, no clothes dryer) and see whether you can detect the change in the daily reading. Explain any difference from what you expected.

Tips

- Some smart meters let the utility show hourly data online; compare it with your own readings if your parents have an account.
- Do not use a ladder near the service drop for photos; zoom instead.

Check your work

- ☐ I can draw the path from the transformer to a branch breaker and label each part.
- ☐ I can explain why the main breaker does not de-energize the whole panel.
- ☐ I calculated daily kWh, average kW and cost correctly.

SHOP NOTEBOOK

1. A labeled one-line diagram of your service: transformer, service drop or lateral, meter, main breaker, two hot buses, neutral bar, ground bar, grounding electrode.
2. A sketch of the center-tapped transformer secondary with 120 V, 120 V and 240 V marked.
3. Your seven-day meter table and a bar graph of daily kWh.
4. The panel directory as you found it, with a note of labels that are missing or unclear.

KEY FORMULAS

$P = VI$

$E = Pt$ (energy in kWh when P is in kW and t in hours)

$\frac{V_p}{V_s} = \frac{N_p}{N_s}$

$P_{\text{loss}} = I^2 R$

From history. Pearl Street ran until a fire damaged it in 1890; it was rebuilt and the system kept growing. The Edison company's DC networks in Manhattan were gradually replaced by AC, and Consolidated Edison finally shut off its last direct-current service in 2007.

Example 1. A pole transformer has a primary of 7,200 V and a center-tapped secondary of 240 V. Find the turns ratio and the voltage from each end of the secondary to the center tap.

Show solution

1. Turns ratio: $N_p/N_s = V_p/V_s = 7200/240 = 30$, so 30 primary turns for every secondary turn.
2. The center tap divides the secondary in half: $240\ \text{V}/2 = 120\ \text{V}$ from each end to the center (neutral).
3. Between the two ends (the two hot legs) the voltages are opposite in direction at each instant, so they add: 240 V.

Answer: 30 : 1; 120 V from each hot to neutral and 240 V between the hots.

Example 2. An electric clothes dryer is rated 5,600 W. Find its current on a 240 V circuit. What current would the same dryer draw if it were built for 120 V, and why do builders choose 240 V?

Show solution

1. At 240 V: $I = P/V = 5600\ \text{W}/240\ \text{V} = 23.3\ \text{A}$.
2. At 120 V: $I = 5600/120 = 46.7\ \text{A}$, twice as much.
3. Heating in the wire is I^2R: doubling the current would make four times the heat in the same wire, so 120 V would need much thicker, costlier copper.

Answer: $23.3\ \text{A}$ at 240 V versus $46.7\ \text{A}$ at 120 V; the higher voltage halves the current and cuts wire heating to a quarter.

Example 3. Last month the meter read 41,250 kWh; this month it reads 42,180 kWh. Electricity costs \$0.15 per kWh plus a \$12.00 monthly customer charge. Find the energy used, the bill and the average power.

Show solution

1. Energy: $42{,}180 - 41{,}250 = 930$ kWh.
2. Energy charge: $930 \times \$0.15 = \$139.50$; bill $= \$139.50 + \$12.00 = \$151.50$.
3. Average power over a 30-day month: $P = E/t = 930\ \text{kWh}/720\ \text{h} = 1.29\ \text{kW}$.

Answer: 930 kWh, \$151.50, and an average draw of about 1.3 kW.

Example 4. A 200 A, 120/240 V service: what is the largest power it can supply, and what would a 100 A service supply?

Show solution

1. The 200 A rating applies to each hot leg, and the full load is fed at 240 V: $P = VI = 240 \times 200 = 48{,}000\ \text{W} = 48\ \text{kW}$.
2. For 100 A: $P = 240 \times 100 = 24\ \text{kW}$.

Answer: 48 kW for 200 A and 24 kW for 100 A (in practice an electrician sizes a service by a code load calculation, not by adding nameplates).

PRACTICE

1. Easy Name, in order, five things electricity passes through between the generating plant and a branch breaker in your panel.

   Show answer

   For example: step-up transformer and transmission lines, substation, distribution line, pole or pad transformer, service drop, meter, main breaker, bus bar, branch breaker.

2. Easy What colors are normally used for hot, neutral and equipment grounding conductors in house wiring?

   Show answer

   Hot: black (or red); neutral: white (or gray); ground: bare copper or green.

3. Easy Who owns the meter and the service drop, and what should a homeowner do if a service drop is damaged by a fallen tree limb?

Show answer

The utility. Stay well away, keep others away, and call the utility (or 911 if it is down or sparking).

4. Medium A microwave oven draws 10.0 A at 120 V. Find its power.

Show answer

$P = VI = 120 \times 10.0 = 1{,}200$ W.

5. Medium A water heater is rated 4,500 W at 240 V. Find its current and its energy use if it runs 3.0 hours a day for 30 days.

Show answer

$I = 4500/240 = 18.75$ A; $E = 4.5$ kW $\times$ 90 h $= 405$ kWh.

6. Medium Explain why the panel's main breaker being off does not make the whole panel safe to touch.

Show answer

The service conductors and the lugs on the line side of the main breaker come straight from the meter and are still energized; only the utility can de-energize them.

7. Medium Explain why Edison's three-wire system needed less copper than a simple two-wire system at 110 V.

Show answer

Loads on the two sides share the middle conductor and their currents largely cancel there, while the outer wires carry the load at what is effectively 220 V; less current per unit of power means thinner conductors.

8. Hard A feeder has a resistance of 0.050 Ω. Compare the power lost in it when it carries 10 kW at 120 V and at 240 V.

Show answer

At 120 V: $I = 83.3$ A, $P = I^2R = 347$ W. At 240 V: $I = 41.7$ A, $P = 86.8$ W, one quarter as much.

9. Hard A transmission line carries 300 MW. Find the current at 345 kV and at 34.5 kV, and the ratio of the line losses.

Show answer

$I = 870$ A and 8,700 A; losses scale with I^2, so the lower voltage would lose 100 times as much.

10. Hard You are the tradesperson. A homeowner says, “Half my house is dead, but the other half works, and the main breaker is on.” Using split-phase service, give a likely explanation and say who must fix it.

Show answer

One of the two hot legs has been lost, often at a failed connection in the service drop, the meter base or the main lugs. Every 120 V circuit on that leg and every 240 V load is out. The homeowner should call the utility first (their side) and then a licensed electrician; it is never homeowner work.

11. Challenge Pearl Street’s first day served about 400 lamps. If each carbon-filament lamp used about 100 W at 110 V DC, find the total current and the current per lamp. Why did Edison want high-resistance filaments?

Show answer

Per lamp: $I = 100/110 \approx 0.91$ A; total ≈ 364 A for 40 kW. Each lamp’s resistance is $R = V^2/P = 121\ \Omega$. High resistance meant less current for the same voltage, so the copper conductors could be thinner and cheaper; low-resistance lamps would have needed huge currents.

COMMON MISTAKES

- Thinking the main breaker makes the panel dead; the incoming conductors stay live.
- Confusing power (kW) with energy (kWh): the bill charges for energy.
- Thinking neutral is “safe” because it is grounded; it carries the full return current of the circuit and can shock you if opened under load.
- Calling the panel door the cover: the door may be opened to read labels; the dead-front cover is never removed by students.

> **Make it a game · Power Path Relay.** Name, in order and from memory, every step electricity takes from plant to your wall outlet: generator, transmission, substation transformer, service drop, meter, main panel, breaker. You have 30 seconds. Your parent counts correct steps. Then say the jobs of hot, neutral and ground. Beat your count next round.

5.2 Circuits, Wire and Breakers

OBJECTIVES

- Explain how resistance and current heat a wire, and match wire gauge to breaker size (14 AWG on 15 A, 12 AWG on 20 A, 10 AWG on 30 A).
- Distinguish an overload from a short circuit and explain how a fuse and a thermal-magnetic breaker each respond.
- Use Ohm's law, P = VI, the 80 percent rule and voltage drop to judge whether a household circuit is properly loaded.
- Read the printing on NM cable and identify its conductors.

> **Warm-up.** Look at three cords in your house: a phone charger cord, a lamp cord and a heavy extension cord or a space-heater cord. Feel their thickness (unplugged). Read any printing on them (for example "18 AWG" or "14/3"). Predict: which carries the most current, and why would a maker spend more copper on it?

WATCH

Electrical Current Explained - AC DC, fuses, circuit breakers, multimeter, GFCI, ampere

The Engineering Mindset · 18:45

https://www.youtube.com/watch?v=kcL2_D33k3o

> **WHEN TO WATCH**
> After the story. Watch the sections on current, resistance, fuses and breakers; the closing GFCI part previews Lesson 5.3.

BACKUP VIDEO

Understanding Wire Gauges | Ask This Old House

This Old House · 4:52

https://www.youtube.com/watch?v=O2XOCy2zHG0

Before the shop project: a master electrician compares gauges and explains matching wire to breaker size.

KEY TERMS

AWG

American Wire Gauge. A smaller number means a thicker wire: 14 AWG is thinner than 12 AWG, which is thinner than 10 AWG.

ampacity

The current a conductor can carry continuously without exceeding its insulation's temperature rating. In homes, 14 AWG copper is protected at 15 A, 12 AWG at 20 A and 10 AWG at 30 A.

overload

More current than the circuit is rated for, flowing through the normal path (too many appliances). It heats the wire slowly.

short circuit

A fault in which hot touches neutral or ground with almost no resistance in between; the current jumps to hundreds or thousands of amperes almost instantly.

thermal-magnetic breaker

A breaker with a bimetal strip that bends and trips on a sustained overload and an electromagnet that trips instantly on a short circuit.

NM cable

Nonmetallic-sheathed cable (often called by the brand name Romex): insulated conductors and a bare ground inside a plastic jacket, printed with size and type, e.g. "12-2 WITH GROUND TYPE NM-B."

CORE IDEAS

The story. Edison's first circuits were protected by a short piece of lead wire, the "safety catch," that melted before the copper behind it could overheat. Screw-in plug fuses, with the same base as a light bulb, filled American fuse boxes for half a century. Their weakness was human: when a 15 A fuse kept blowing, some people screwed in a 30 A fuse, or even put a copper penny behind it, and the overloaded wiring inside the walls overheated with nothing left to stop it. Inspectors answered with Type S fuses, whose rejection adapters accept only the correct size. Meanwhile, in 1924, the German engineer Hugo Stotz patented a compact **miniature circuit breaker** that could be reset with a switch instead of replaced. Its descendants line every modern panel.

How they figured it out. Engineers and insurance inspectors in the 1890s found that most electrical fires began where a conductor ran hotter than its insulation could stand. Underwriters Laboratories and the electrical code committees measured how hot each size of wire became at each current, in open air and buried in walls, and published **ampacity tables**. The rule that grew from them is simple: the breaker must protect the *smallest wire* on the circuit. A 20 A breaker on 14 AWG wire is a code violation, because the wire could carry 19 A for hours, getting dangerously hot, and the breaker would never trip.

The science. A wire's resistance is $R = \rho L / A$; copper has $\rho = 1.72 \times 10^{-8}\ \Omega \cdot \text{m}$. Real house wire is about $2.5\ \Omega$ per 1,000 ft for 14 AWG, $1.6\ \Omega$ for 12 AWG and $1.0\ \Omega$ for 10 AWG. Current heats it at $P = I^2 R$: double the current and the heat goes up four times. Current also drops voltage along the wire, $V_{\text{drop}} = IR$, counting the length out *and* back. Every receptacle on a branch circuit is in parallel, so the currents of everything plugged in add up. An **overload** (a space heater, a hair dryer and a vacuum on one circuit) slowly warms the breaker's bimetal strip until it bends and trips, in seconds to minutes. A **short circuit** lets thousands of amperes flow; the breaker's magnetic coil yanks the latch open in less than a sixtieth of a second.

In the shop. Read NM cable like a sentence: "12-2 WITH GROUND TYPE NM-B 600V" means two insulated 12 AWG conductors (black and white) plus a bare ground; "12-3" adds a red. By common industry practice the jacket is white for 14 AWG, yellow for 12 AWG and orange for 10 AWG. Electricians apply the **80 percent rule** for continuous loads (three hours or more): a 15 A circuit should carry no more than 12 A (1,440 W) continuously and a 20 A circuit 16 A (1,920 W). Kitchens need at least two 20 A small-appliance circuits because toasters, kettles and microwaves are each 900 to 1,500 W. On long runs they upsize the wire to keep voltage drop to about 3 percent.

Safety. A breaker that trips is doing its job. Unplug some loads before resetting it once; if it trips again with little plugged in, or if a breaker, cover plate or cord is warm, smells hot or is discolored, stop and call a licensed electrician. Never replace a breaker or fuse with a larger one, and never tape or hold a breaker on.

PICTURE STUDY



A Lineman at Work, Arthur Rothstein, July 1942 · Photograph · Library of Congress, Farm Security Administration / Office of War Information collection

Image: Wikimedia Commons, public domain

In 1935 most American farms had no electricity. The Rural Electrification Administration lent money to farmers' cooperatives, and lineworkers like this one strung thousands of miles of line. Every circuit in your panel begins on a line like this.

Look closely

- Find the insulators. What are they made of, and why must the wire not touch the wooden crossarm or pole?
- Find the lineman's safety belt and climbing spurs. How does he keep both hands free?
- Count the conductors on the pole. Which might be the neutral?
- Look at the thickness of the wires. Why can a distribution line be thin compared with the current it delivers?

Talk about it

1. Why does the line along a country road run at thousands of volts, while your house circuits run at 120 V?
2. Lineworkers treat every wire as energized until proved otherwise. How does that habit carry over to your own work in Lesson 5.4?

3. What would it have meant for a farm family in 1940 to have its first electric circuits?

Safety first. An adult switches breakers on and off; you observe and test receptacles only with a plug-in tester or a lamp. Do not remove the panel cover or touch any wire. If a breaker trips again right after being reset, or anything is warm, smells hot or is discolored, stop and have a licensed electrician check it.

SHOP PROJECT

A Home Circuit Map and Load Audit

You will find out which breaker feeds which lights and receptacles in your house, list what is plugged into each circuit, and test whether any circuit is overloaded by the 80 percent rule. The map becomes part of your unit portfolio.

You will need

- Shop notebook or a floor-plan sketch on graph paper
- A plug-in receptacle tester (three-light type) or a small lamp
- Masking tape and a marker
- A helper with a phone (to call out what goes dark)
- Calculator; appliance nameplates or manuals

Steps

1. Draw a floor plan of the house and mark every receptacle, switch and light fixture with a symbol.
2. With a parent at the panel, choose a quiet time and warn the household (computers, freezer). The parent switches off one branch breaker at a time.
3. Walk the house with the plug-in tester or lamp. Mark every receptacle and light that went dead with that breaker's number. Check both halves of duplex receptacles; they are occasionally on different circuits.
4. The parent switches the breaker back on, and you repeat for every breaker. Record 240 V double-pole breakers by the appliance they feed (range, dryer, water heater, air conditioner).
5. For each 120 V circuit, list the appliances normally used on it and their wattage from nameplates (or amps × 120).
6. Calculate the total current on each circuit for a realistic busy moment and compare it with the breaker rating and with 80 percent of it.
7. Write a corrected, typed or neatly printed panel directory for your parents to approve and tape inside the panel door.
8. **Improve it.** Identify the most heavily loaded circuit and propose a simple change of habits (for example moving the space heater to a different circuit).

Note anything that should be checked by an electrician.

Tips

- Older houses often have surprises: a bathroom on the same circuit as a bedroom, or a dead receptacle. Note them; do not try to fix them.
- Keep the freezer and refrigerator circuits off for only a minute or two.

Check your work

- ☐ Every receptacle and light on my plan has a circuit number.
- ☐ I calculated the busy-moment current for each 120 V circuit and compared it with the 80 percent limit.
- ☐ I can explain why the breaker protects the wire, not the appliance.

SHOP NOTEBOOK

1. Your floor plan with circuit numbers, and a table of circuit, breaker size, wire gauge (from the breaker size), loads and busy-moment current.
2. A labeled sketch of a thermal-magnetic breaker: bimetal strip, magnetic coil, latch, contacts, arc chute.
3. A graph of wire heating $P = I^2R$ against current for 50 ft of 14 AWG from 0 to 20 A. Mark 15 A.
4. A label from a piece of NM cable (photograph at a hardware store), with each part of the printing explained.

KEY FORMULAS

$$V = IR$$
$$P = VI = I^2R$$
$$R = \frac{\rho L}{A}$$
$$V_{\text{drop}} = I \cdot R_{\text{per ft}} \cdot 2L$$
$$I_{\text{continuous}} \le 0.80\, I_{\text{breaker}}$$

From history. Before NM cable, houses from about 1880 to 1930 were often wired with “knob and tube”: single conductors run through porcelain knobs and tubes, with hot and neutral apart in the wall cavity. It is still found in old homes; it has no ground and its insulation is now brittle, and insurers and electricians treat it with care.

Example 1. A 20 A, 120 V kitchen circuit has a 1,200 W microwave, a 900 W toaster and a 1,500 W kettle plugged into it at the same time. Will the breaker trip?

Show solution

1. Add the powers, since the loads are in parallel: $1200 + 900 + 1500 = 3600$ W.
2. Current: $I = P/V = 3600/120 = 30$ A.
3. 30 A is 150 percent of the breaker rating; the thermal element will trip within seconds to a minute.

Answer: Yes. It draws 30 A on a 20 A circuit; spread the appliances over the two small-appliance circuits.

Example 2. A 1,500 W space heater will run all evening on a 15 A bedroom circuit that also has a 100 W lamp and a 150 W computer. Check the 80 percent rule.

Show solution

1. Continuous limit: 0.80×15 A $= 12$ A, or $12 \times 120 = 1{,}440$ W.
2. Load: $1500 + 100 + 150 = 1750$ W, so $I = 1750/120 = 14.6$ A.
3. 14.6 A > 12 A. The heater alone is 12.5 A, already over the continuous limit.

Answer: Too much. A 1,500 W heater should have a lightly loaded 20 A circuit, or be set on its 750 W low setting.

Example 3. A 12 AWG circuit (1.59 Ω per 1,000 ft) runs 75 ft from the panel to a shop receptacle and feeds a 16 A load. Find the voltage drop and the percent drop at 120 V.

Show solution

1. Round-trip length: $2 \times 75 = 150$ ft.
2. Resistance: $R = 1.59 \times 150/1000 = 0.239\ \Omega$.
3. Drop: $V = IR = 16 \times 0.239 = 3.8$ V; percent: $3.8/120 = 3.2\%$.

Answer: About 3.8 V, or 3.2%: just over the 3 percent guideline; an electrician might run 10 AWG for a heavy-use shop circuit.

Example 4. Why is 14 AWG wire on a 20 A breaker dangerous? Compare the heat in 50 ft of cable (100 ft of conductor) at 15 A and at 20 A. Use 2.53 Ω per 1,000 ft.

Show solution

1. Resistance: $R = 2.53 \times 100/1000 = 0.253\ \Omega$.
2. At 15 A: $P = I^2R = 15^2 \times 0.253 = 56.9$ W.
3. At 20 A: $P = 20^2 \times 0.253 = 101$ W, 78 percent more heat, inside insulation in a wall cavity, and the breaker would allow it indefinitely.

Answer: About 57 W versus 101 W; the larger breaker lets the small wire run far hotter than its rating.

PRACTICE

1. Easy Which is thicker, 10 AWG or 14 AWG? Which breaker size goes with each in ordinary house wiring?

   Show answer

   10 AWG is thicker. 14 AWG: 15 A; 10 AWG: 30 A (12 AWG: 20 A).

2. Easy Decode “14-3 WITH GROUND TYPE NM-B.”

   Show answer

   Three insulated 14 AWG conductors (black, white, red) plus a bare ground, in nonmetallic sheathed cable rated 90 °C (used at the 60 °C ampacity).

3. **Easy** What is the difference between an overload and a short circuit?

Show answer

An overload is too much current through the normal path, heating the wire slowly; a short is a near-zero-resistance fault with a huge, sudden current.

4. **Medium** A hair dryer is 1,875 W at 120 V. Find its current and its resistance when running.

Show answer

$I = 15.6$ A; $R = V/I = 7.7\ \Omega$.

5. **Medium** How many 60 W-equivalent LED bulbs (9 W each) can a 15 A lighting circuit run continuously under the 80 percent rule?

Show answer

$1440/9 = 160$ bulbs; lighting circuits are almost never limited by LED load.

6. **Medium** Find the resistance of 1,000 ft of 12 AWG copper (diameter 2.05 mm). Use $\rho = 1.72 \times 10^{-8}\ \Omega \cdot \text{m}$.

Show answer

$A = \pi(1.025 \times 10^{-3})^2 = 3.30 \times 10^{-6}\ \text{m}^2$; $L = 304.8$ m;
$R = 1.72 \times 10^{-8} \times 304.8 / 3.30 \times 10^{-6} \approx 1.59\ \Omega$.

7. **Medium** Conceptual: why must the breaker match the smallest wire on the circuit, not the largest appliance?

Show answer

The breaker protects the wire from overheating. If it is larger than the wire's ampacity, the wire can carry an unsafe current without the breaker tripping.

8. **Hard** A 100 ft extension cord of 16 AWG (4.02 Ω per 1,000 ft) feeds a 12 A circular saw. Find the voltage drop and the voltage at the saw. Why do saw makers recommend 12 AWG cords for long runs?

Show answer

$R = 4.02 \times 200/1000 = 0.804\ \Omega$; drop $= 9.6$ V; saw gets about 110 V. Low voltage makes the motor draw more current, overheat and lose power; heavier cords drop less.

9. Hard A short circuit occurs at the end of a 40 ft run of 12 AWG. Ignoring the transformer and service resistance, estimate the fault current. Why does the breaker trip magnetically?

Show answer

$R = 1.59 \times 80/1000 = 0.127\ \Omega$; $I \approx 120/0.127 \approx 940$ A (less in reality). That is far above the magnetic trip level (several times the rating), so the coil opens the breaker in about one cycle.

10. Hard You are the tradesperson. A receptacle cover plate is warm and slightly brown, though nothing plugged in is unusual. What is likely wrong, and what is the right response?

Show answer

A loose or high-resistance connection (often a push-in “backstab” terminal) is heating under load. Turn off the circuit, stop using it and have it repaired by a qualified person; it is a fire hazard that a breaker will not detect.

11. Challenge A detached workshop 120 ft from the panel needs a 240 V, 20 A feeder for a table saw. Compare 12 AWG (1.59 Ω/1,000 ft) and 10 AWG (1.00 Ω/1,000 ft) for voltage drop at 20 A. Which would you choose?

Show answer

Round trip 240 ft. 12 AWG: $R = 0.382\ \Omega$, drop $7.6\ \text{V} = 3.2\%$. 10 AWG: $R = 0.240\ \Omega$, drop $4.8\ \text{V} = 2.0\%$. Choose 10 AWG on the 20 A breaker (allowed: larger wire is always permitted), installed by or under a licensed electrician with a permit.

COMMON MISTAKES

- Using one-way length for voltage drop; the current goes out and back, so use twice the run.
- Adding amps from different circuits together; only loads on the same circuit add up against that breaker.
- Thinking a bigger breaker fixes nuisance tripping; it removes the protection of the wire.
- Forgetting that the 80 percent rule applies to continuous loads such as heaters, not to a brief toaster cycle.

Make it a game · Wire and Breaker Match. Your parent names a breaker size, 15, 20 or 30 amps. You name the correct wire gauge in three seconds: 14, 12 or 10 AWG. Then name what happens in an overload versus a short. Then reverse: your parent names a gauge, you name the breaker. Play 12 rounds with no hesitation, aiming for no misses.

5.3 Shock, Grounding, GFCI and AFCI

OBJECTIVES

- Explain what current through the body does at different levels and use Ohm's law to show why wet skin is so dangerous.
- Explain how the equipment ground makes a breaker trip when a hot wire touches a metal case.
- Explain how a GFCI compares hot and neutral currents and trips at about 5 mA, and how an AFCI detects arcing.
- Explain the purpose of the ground pin and the polarized plug, and why neither may ever be defeated.

> **Warm-up.** Find a GFCI receptacle in your house (it has TEST and RESET buttons; look in a bathroom, the kitchen, the garage or outdoors). Without pressing anything yet, list every place in the house where water and electricity could meet. Predict which receptacles near those places are protected by that GFCI.

WATCH

Why Circuit Breakers DON'T Protect People (electric shocks)

The Engineering Mindset · 18:23

https://www.youtube.com/watch?v=gqEu9t8HwW0

> **WHEN TO WATCH**
> After the science paragraph. It opens a breaker to show its bimetal strip and magnetic coil, then explains why only a residual-current device protects a person.

Note: Filmed with British 230 V equipment: an “RCD” is the same idea as an American GFCI, and an “MCB” is a circuit breaker. Skip the short sponsor segment early in the video. The presenter is a trained engineer working on a test board; students never test live circuits.

BACKUP VIDEO

Everything to Know About GFCI Receptacles | Ask This Old House

This Old House · 5:41

https://www.youtube.com/watch?v=oZWsk2sH6t8

Before the shop project: a master electrician explains line and load terminals and how one GFCI protects the receptacles downstream.

KEY TERMS

equipment grounding conductor

The bare or green wire that bonds metal boxes, appliance cases and the receptacle ground pin back to the panel. It carries current only during a fault, so that the breaker trips fast.

ground fault

Current leaving the circuit by an unintended path to ground: through a metal case, water, or a person.

GFCI

Ground-fault circuit interrupter. It compares the current going out on the hot with the current returning on the neutral and opens the circuit if they differ by about 4–6 mA.

AFCI

Arc-fault circuit interrupter. Its electronics recognize the ragged current signature of an arc (a damaged cord, a loose connection) and open the circuit before the arc starts a fire.

let-go current

The current at which muscles clamp onto a conductor so that a person cannot release it; roughly 6 to 16 mA at 60 Hz for adults.

polarized plug

A plug with one wide blade (neutral) so that it fits only one way, keeping a lamp's screw shell or an appliance's switch on the correct side.

CORE IDEAS

The story. In the 1940s and 1950s Charles Dalziel, a professor of electrical engineering at the University of California, Berkeley, set out to answer a question no one had measured carefully: how much current can a person survive? With volunteers holding electrodes, he slowly raised small currents and recorded where they could still feel it, where it hurt, and where their muscles locked so they could not let go. From his data and from animal studies he estimated the currents that could disturb the heart. He then designed a device to act before that happened: a transistorized **ground-fault interrupter**, patented in 1965. The electrical code began requiring GFCIs near swimming pools in 1968, then outdoors, in bathrooms, garages, kitchens and many other places over the following decades. Electrocutions from household wiring in the United States have fallen sharply since.

How they figured it out. Dalziel's insight was that a breaker cannot protect a person. A 15 A breaker trips at 15 A or more, but a few hundredths of an ampere across the chest can be fatal. The human body is simply too high a resistance to draw enough current to trip a breaker. The only signal of a shock is that some current is going somewhere it should not. In a healthy circuit, every electron that goes out on the hot comes back on the neutral. So the GFCI passes both conductors through a small magnetic ring (a differential current transformer). If the currents are equal, their magnetic fields cancel; if some current leaks away through a person, the imbalance induces a signal, and the device opens the circuit in about a fortieth of a second.

The science. Current through the body depends on voltage and resistance, $I = V/R$. Dry skin may have a resistance near 100,000 Ω; wet skin or a cut can fall to about 1,000 Ω. At 120 V that is the difference between about 1 mA (a tingle) and about 120 mA (enough to send the heart into ventricular fibrillation). Roughly: 1 mA is felt; above about 5 mA it hurts; 10 to 20 mA can freeze the muscles so you cannot let go; 50 to 100 mA or more through the chest can stop the heart's rhythm. This is why the GFCI trip level is set near 5 mA. The **ground wire** works differently: if a loose hot wire touches the metal case of a drill or washer, the ground gives a path of almost

zero resistance back to the panel, so hundreds of amperes flow and the breaker trips at once instead of leaving the case at 120 V waiting for someone to touch it. Arcs are a third hazard: a crushed extension cord or a loose terminal can arc at thousands of degrees while drawing too little current to trip a breaker. The **AFCI**, required in bedrooms by the 1999 code and now in most living areas, watches for the arc's signature.

In the shop. Electricians sum it up: breakers protect the *wire*, GFCIs protect *people*, AFCIs protect against *fire*. One GFCI receptacle wired through its LOAD terminals protects every receptacle downstream, which should be labeled "GFCI protected." Press TEST monthly; the RESET should pop out and power should go off. The ground pin on a plug is the case's connection to that safety path, and the wide neutral blade of a polarized plug keeps the switch and fuse of an appliance on the hot side. Cutting off a ground pin, filing a wide blade narrow, or using a three-to-two adapter on an ungrounded receptacle removes protection that was designed in on purpose.

Safety. Never bypass a breaker, a GFCI or a ground pin, and never touch a person who is being shocked: cut the power first at the breaker or by pulling the plug by its cord, then call 911. Treat any shock, even a mild one, as a reason to stop and have the circuit checked.

PICTURE STUDY



Franklin's Experiment, June 1752, Currier and Ives, 1876 · Hand-colored lithograph · Currier and Ives, New York (copies in the Library of Congress and the Metropolitan Museum of Art)

Image: Wikimedia Commons, public domain

Currier and Ives made this popular print more than a century after the event. Franklin's kite experiment showed that lightning is electricity, and it led him to the lightning rod: a deliberate, low-resistance path to ground. That same idea protects you every time you plug in a three-prong tool.

Look closely

- Find the key and the string. Where would the charge go if someone touched the key?
- Franklin's account says he held a silk ribbon and stayed under shelter so the silk stayed dry. Why would dry silk matter?
- Find the ground under their feet. In a shock, what path does current take?
- Look at the clouds and the sky. Why is this a dangerous experiment no one should repeat?

Talk about it

1. How is a lightning rod like the ground wire in your house circuits?
2. Why does wet skin, or wet silk, change everything about the danger?

3. Several people who tried similar experiments were badly hurt. What does that teach about respecting electricity?

Safety first. Test GFCIs only with their own TEST button or a plug-in GFCI tester; never make a deliberate fault with a wire or your body. Never bypass a breaker, GFCI or ground pin. If someone is being shocked, do not touch them: cut the power first, then call 911.

SHOP PROJECT

A Receptacle and GFCI Safety Survey

You will test every receptacle in the wet and outdoor areas of your home with a plug-in receptacle tester and the GFCI buttons, map which receptacles each GFCI protects, and write a short safety report for your parents. This is the same check a home inspector makes.

You will need

- A three-light plug-in receptacle tester with a GFCI test button (about $10–15 at a hardware store)
- Your floor plan from Lesson 5.2
- Masking tape and a marker
- Shop notebook
- A parent

Steps

1. Learn the tester's light code from its label (correct, open ground, open neutral, open hot, hot/ground reversed, hot/neutral reversed). Test it first in a receptacle you know works.
2. With a parent, plug the tester into each receptacle in the kitchen, bathrooms, laundry, garage, basement and outdoors. Record the result on your floor plan.
3. Find each GFCI receptacle (or GFCI breaker, which an adult can identify from the panel door). Press TEST: the power should go off and the RESET button should pop out. Press RESET.
4. With the GFCI tripped, use the tester to find every other receptacle that went dead. Those are downstream and protected; mark them and label them with tape ("GFCI protected").
5. Use the tester's GFCI button on protected receptacles to confirm the upstream GFCI trips. Count how long it takes to trip (it should be instant to the eye).

6. Look, but do not touch inside, for warning signs: cracked or loose receptacles, scorch marks, warm cover plates, two-slot receptacles in wet areas.
7. Write a one-page report listing every problem found and the recommended action. Anything other than correct wiring is a job for a qualified electrician.
8. **Check your work.** Make a monthly GFCI test reminder on the family calendar and repeat the TEST and RESET a month later. Did any GFCI fail to trip? (A GFCI that will not trip must be replaced.)

Tips

- A dead bathroom receptacle is often protected by a tripped GFCI in another room or in the garage; this survey usually finds it.
- Plug-in testers cannot detect every fault (for example, a reversed hot and ground in some cases); they are a screening tool, not a final word.

Check your work

- ☐ Every wet-area and outdoor receptacle on my plan is marked with its test result and protection.
- ☐ I can explain how a GFCI senses a fault and why it trips at about 5 mA.
- ☐ My report recommends a licensed electrician for every wiring fault found.

SHOP NOTEBOOK

1. A labeled diagram of a GFCI: hot and neutral through the sensing ring, sensing coil, electronics, trip solenoid, contacts, TEST button and its resistor.
2. A table of current versus effect on the body (1, 5, 10–20, 50–100 mA and above) and the resistance that gives each at 120 V.
3. A circuit sketch of a hot-to-case fault with and without the ground wire, showing the current path each time.
4. Your receptacle survey plan and safety report.

KEY FORMULAS

$$I_{\text{body}} = \frac{V}{R_{\text{body}}}$$

$$I_{\text{leak}} = I_{\text{hot}} - I_{\text{neutral}}$$

$$I_{\text{fault}} = \frac{V}{R_{\text{loop}}}$$

From history. Dalziel also helped set the safety limits for electric fences and studied how much current a person could survive from an accidental contact. Modern GFCIs test themselves and refuse to reset if their electronics fail.

WORKED EXAMPLES

Example 1. A person touches a 120 V conductor with one hand while standing on ground. Find the body current with dry skin ($R = 100{,}000\ \Omega$) and with wet skin ($R = 1{,}000\ \Omega$), and describe the effect.

Show solution

1. Dry: $I = 120/100{,}000 = 0.0012\ \text{A} = 1.2\ \text{mA}$, a noticeable tingle.
2. Wet: $I = 120/1{,}000 = 0.12\ \text{A} = 120\ \text{mA}$.
3. 120 mA is far above the let-go level and in the range that can cause ventricular fibrillation; a 15 A breaker would never trip on it.

Answer: About 1.2 mA dry (felt) versus 120 mA wet (life-threatening). Water lowers resistance a hundredfold; that is why bathrooms and kitchens need GFCIs.

Example 2. A GFCI measures 8.000 A on the hot and 7.994 A returning on the neutral. Does it trip?

Show solution

1. Leakage: $I_{\text{leak}} = 8.000 - 7.994 = 0.006\ \text{A} = 6\ \text{mA}$.
2. Class A GFCIs must trip at 6 mA and may trip at 4 mA or more.
3. The 6 mA is leaving by some other path, perhaps through a person or wet equipment.

Answer: Yes: a 6 mA imbalance trips the GFCI, even though 8 A is well under the breaker rating.

Example 3. A loose hot wire touches the metal case of a washing machine. The fault path (hot conductor, case, ground wire back to the panel) has a total resistance of $0.30\ \Omega$. Find the fault current. What would happen if the ground wire had been cut?

Show solution

1. With ground: $I = V/R = 120/0.30 = 400$ A.
2. 400 A is more than 20 times a 15 or 20 A rating, so the breaker's magnetic trip opens in about one cycle.
3. Without ground, no current flows, the breaker stays on, and the case sits at 120 V until someone touches it and the case and a water pipe at the same time.

Answer: About 400 A, tripping the breaker instantly; without the ground the case would stay energized and silent.

PRACTICE

1. Easy State the job of a breaker, a GFCI and an AFCI in one sentence each.

   Show answer

   A breaker protects the wire from overcurrent; a GFCI protects people from shock by detecting leakage; an AFCI protects against fire by detecting arcing.

2. Easy Why does a GFCI trip at about 5 mA rather than at 15 A?

   Show answer

   Currents of tens of milliamperes can be fatal; 5 mA is just above the level that is painful but below the let-go and heart-danger levels.

3. Easy Name four locations in a house where GFCI protection is required by modern codes.

   Show answer

   For example: bathrooms, kitchen countertops, garages, outdoors, unfinished basements, crawl spaces, laundry areas, near sinks.

4. **Medium** A person with wet hands has a hand-to-hand resistance of $1{,}500\ \Omega$. Find the current at 120 V and at 240 V.

Show answer

80 mA and 160 mA; both dangerous.

5. **Medium** Conceptual: a GFCI protects a person who touches hot and ground, but not a person who holds the hot in one hand and the neutral in the other while standing on a rubber mat. Explain.

Show answer

In the second case, current leaves on the hot and returns on the neutral through the person; the GFCI sees no imbalance, so the person looks like an ordinary load.

6. **Medium** A receptacle tester shows "open ground" on a three-slot receptacle. What does that mean, and why is a three-prong appliance plugged there not truly grounded?

Show answer

No equipment ground is connected to the ground slot; the pin connects to nothing, so a fault would leave the case energized. A GFCI with a "No equipment ground" label is one code-approved remedy, installed by a qualified person.

7. **Medium** Why must you never cut the ground pin off a plug to fit a two-slot receptacle?

Show answer

The pin is the appliance's path for fault current; without it a fault leaves the metal case live and the breaker never trips.

8. **Hard** The ground-fault loop of a circuit is $0.50\ \Omega$. Will a 20 A breaker with a magnetic trip at 10 times its rating trip instantly on a hot-to-case fault?

Show answer

$I = 120/0.50 = 240$ A, above $10 \times 20 = 200$ A, so yes.

9. Hard Dalziel's estimate of the current likely to cause fibrillation for a short shock is about $I = 116/\sqrt{t}$ mA for a 50 kg person (t in seconds). Find the current for 1.0 s and for 0.025 s. Why does a fast GFCI matter?

Show answer

116 mA at 1 s; $116/\sqrt{0.025} = 734$ mA at 0.025 s. The shorter the shock, the more current the heart can tolerate, so tripping in about a fortieth of a second gives a large margin.

10. Hard You are the tradesperson. A bathroom GFCI trips every time the hair dryer is used, but a new hair dryer does the same. List checks in order.

Show answer

Check whether other loads or wet devices share the circuit; inspect the receptacle and downstream receptacles for moisture or damaged wiring; test with a different GFCI receptacle; have an electrician look for a neutral shared with another circuit or a ground fault in the wiring. Never replace the GFCI with an ordinary receptacle.

11. Challenge Explain, with magnetic fields, why a GFCI's sensing ring sees no signal when 10 A goes out and 10 A comes back, but does when 10.006 A goes out and 10.000 A returns.

Show answer

Both conductors pass through the same ring in opposite directions; equal currents make equal and opposite fields that cancel, so the net flux and induced voltage are zero. A 6 mA difference leaves a small net alternating flux, which induces a voltage in the sensing coil; the electronics amplify it and fire the trip solenoid.

COMMON MISTAKES

- Thinking a breaker protects people from shock; it trips at amperes, far above deadly milliamperes.
- Thinking the ground wire and the neutral are the same; the neutral carries current all the time, the ground only in a fault.
- Assuming a three-slot receptacle is grounded; older houses often have three-slot receptacles with no ground wire.
- Never pressing TEST; GFCIs can fail, and the monthly test is how you know.

Make it a game · Ohm's Law Danger Math. Your parent gives you body resistance, 1000 ohms for wet skin and 100000 for dry, with 120 volts. Calculate current in each case in 20 seconds and compare with the let-go threshold of about 10 milliamps. Say what a GFCI does about it. Score a point per correct calculation and explanation.

Scripture. “A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished.” (Proverbs 22:3, KJV)

A GFCI, a ground pin and a monthly test are foresight built into the house. The prudent tradesperson expects the fault before it happens.

5.4 Working Safely: Switches and Receptacles

OBJECTIVES

- Describe the full live–dead–live verification procedure and lockout and labeling, and explain why each step is there.
- Wire a duplex receptacle and a single-pole switch correctly on an unpowered practice board, and explain hot, neutral and ground terminal colors.
- Explain how two 3-way switches control one light, and trace both switch positions.
- Calculate box fill and choose an adequate box.

> **Warm-up.** Turn a light on and off from a single switch, then find a stairway or hallway light that can be switched from two places. Predict how two switches can each turn the same light both on and off. Sketch your best guess with a battery, a bulb and wires.

WATCH

How Receptacles Work - The basic working principle explained grounding

The Engineering Mindset · 7:20

https://www.youtube.com/watch?v=eTGkvddOtFc

> **WHEN TO WATCH**
> Before the shop project: an animated look inside a duplex receptacle, its brass and silver terminals, the tab between the halves, and switched receptacles.

BACKUP VIDEO

How to Repair a Three-Way Light Switch | Ask This Old House

This Old House · 7:01

https://www.youtube.com/watch?v=P0tA45TEfqE

After the 3-way paragraph: a licensed electrician explains common and traveler terminals with an animation and shows the breaker turned off before any work.

KEY TERMS

live–dead–live

The verification method: test your tester on a known live source, test the circuit you will work on, then test the tester again on the known live source, to be sure a dead reading was not a dead tester.

lockout and labeling

Holding the breaker off with a breaker lock (or at least tape) and a label saying who is working on it, so that no one can switch it on while you work.

non-contact voltage tester

A pen-shaped tester that beeps or lights near an energized conductor without touching it. Useful for a first check, but not proof of dead by itself.

terminal colors

Brass screw: hot (black). Silver screw: neutral (white). Green screw: equipment ground (bare or green).

3-way switch

A switch with one common terminal and two traveler terminals. Two of them, joined by two traveler wires, control one light from two places.

box fill

The code limit on how many conductors and devices a box may hold, based on its volume: 2.00 in^3 per 14 AWG conductor and 2.25 in^3 per 12 AWG conductor.

CORE IDEAS

The story. In 1890s America, electricity came into homes for light, and nothing else. If you wanted to run a fan or an iron, you unscrewed a light bulb and screwed the appliance's cord into the lamp socket. Harvey Hubbell, a Connecticut manufacturer who had already invented the pull-chain lamp socket, saw how awkward and dangerous that was. In 1904 he patented the **separable attachment plug**: a plug with two flat blades that slid into a matching receptacle. Within a few decades his idea, refined into the polarized and then the grounded plug, was in every American home. In the same years engineers replaced rotary and push-button wall switches with the quick-acting toggle switch, whose spring snaps the contacts apart to break the arc fast.

How they figured it out. Industry learned the procedure for working on equipment the hard way. Workers were hurt when someone else turned a machine or circuit back on while they were inside it, or when they trusted a switch label that was

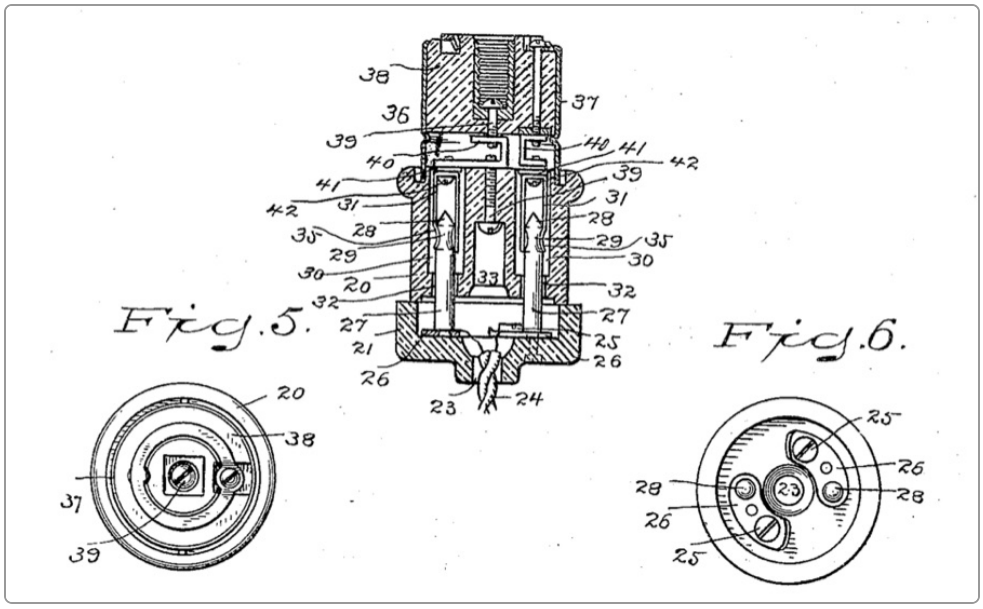
wrong. The result, in the United States, was the OSHA lockout/tagout standard (1989) and the electrical safety practices of NFPA 70E: de-energize, lock and tag, and then **prove** the circuit is dead with a tester that is itself proved to work. Electricians repeat a saying: “Test before you touch.” Every step of the live–dead–live method answers a real failure: a wrong breaker label, a dead tester battery, two circuits in one box, or a wire fed from another panel.

The science. A switch must interrupt the **hot**, so that the fixture is dead when the switch is off; a switch on the neutral would leave the light’s socket live. A duplex receptacle is two receptacles joined by metal tabs; breaking the brass-side tab lets one half be switched for a lamp. In a **3-way** circuit, power goes into the common terminal of the first switch, which connects it to one of two travelers; the second switch’s common feeds the light and connects to one of the same two travelers. The light is on when both switches choose the same traveler, and off when they choose different ones, so either switch can change the state. Box fill comes from heat and crowding: too many conductors in a small box trap heat and get nicked or loosened when the device is pushed in.

In the shop. The procedure on a real circuit, done only with a qualified adult present: (1) identify the circuit from your Lesson 5.2 map; (2) switch the breaker off, lock it or tape it, and label it; (3) test your tester on a known live receptacle; (4) test the device you will work on (both slots of a receptacle, and the switch with the light on); (5) test your tester again on the known live source; (6) remove the cover plate and, before touching, check every wire in the box with the non-contact tester, because a box can hold more than one circuit. When replacing a device, photograph the wiring first, strip about 3/4 inch, form a clockwise hook around the screw so tightening draws it in, tighten to the torque marked on the device, and prefer screw terminals to push-in “backstab” holes. Fold the wires neatly, mount the device square, and test the finished work with the plug-in tester.

Safety. You will build and practice everything in this lesson on an **unpowered practice board** that is never plugged in or connected to anything. Work on a real household circuit only with a qualified adult present, with the breaker off, locked or taped and labeled, and verified dead by live–dead–live testing. Never work on anything energized, and never open the panel cover.

PICTURE STUDY



Hubbell's Separable Attachment Plug, Harvey Hubbell, 1904 · Patent drawing · U.S. Patent 774,250

Image: Wikimedia Commons, public domain

Harvey Hubbell's 1904 patent drawing shows the ancestor of every plug you use. Patent drawings must be precise enough that a skilled mechanic could build the invention from them.

Look closely

- Find the two flat blades and the parts that receive them. How do the blades make contact?
- Look for the springs or clips that hold the blades. Why must they grip firmly?
- Find where the cord's wires attach inside the plug. How are they kept apart?
- Compare the drawing with a modern plug. What has been added since 1904?

Talk about it

1. Why did Hubbell use flat blades rather than round pins? (Think about contact area and holding force.)
2. What problem did the third, round ground pin and the wide neutral blade later solve?
3. Why must a good plug and receptacle make low-resistance contact? What happens when they wear loose?

> **Safety first.** Build and practice only on the unpowered practice board, which is never plugged in or connected to any source; there is no cord on it at all. Any work on a real household circuit needs a qualified adult present, the breaker off, locked or taped and labeled, and live–dead–live verification; never work on anything energized and never open the panel cover. Wear safety glasses when cutting and stripping wire.

SHOP PROJECT

The Unpowered Practice Board

You will build a practice board: a switch and a receptacle in real electrical boxes on plywood, joined with short lengths of NM cable, controlling a porcelain lamp holder. The board is **never plugged in, never given a cord and never connected to anything.** You will check your work with a multimeter on its continuity (resistance) setting, which runs on the meter's own small battery. Then you will rewire it with two 3-way switches.

You will need

- A piece of 3/4-inch plywood about 16 × 24 inches
- Two or three single-gang plastic "new work" boxes and one round ceiling box, with screws
- A porcelain keyless lamp holder (no bulb needed)
- A 15 A duplex receptacle, a 15 A single-pole switch, two 15 A 3-way switches, cover plates
- About 6 feet each of 14-2 and 14-3 NM cable with ground
- Wire nuts and green grounding wire nuts
- Wire strippers with a gauge chart, a cable ripper or utility knife (adult help), screwdrivers, needle-nose pliers
- A digital multimeter with continuity or ohms setting
- Safety glasses; shop notebook

Steps

1. Write PRACTICE BOARD: NEVER CONNECT TO POWER in large letters on the plywood. Mount the boxes in a row and the lamp holder box at the top.
2. Plan the single-pole circuit on paper: an imaginary "source" cable enters the receptacle box; the hot and neutral continue to the switch box and lamp holder; the switch interrupts the black on its way to the lamp.
3. With an adult, strip the cable jackets (leave 1/4 inch of jacket inside the box), strip 3/4 inch of each conductor using the strip gauge, and secure the cables in the boxes.

4. Wire the receptacle (black to brass, white to silver, bare to green), the switch (hot in and hot out on the two brass screws, ground to green) and the lamp holder (switched black to the brass screw, white to the silver shell screw). Splice and pigtail grounds.
5. Count your box fill for each box and compare with the volume stamped inside it.
6. Test with the multimeter set to continuity or ohms, with nothing connected to the board but the meter: across the lamp holder's screws, flip the switch and record open (OL) and closed (near 0 Ω). Check that the receptacle's hot slot connects to the source black, the neutral slot to the white, and the ground hole to the bare wire.
7. Have a parent or mentor inspect every connection: tight, clockwise, no nicked copper, no bare copper showing past a screw, jacket inside the box.
8. **Improve it.** Replace the single-pole switch with two 3-way switches joined by 14-3 cable. Make a truth table of the lamp holder's continuity for all four switch combinations and confirm it matches the worked example.
9. **Check your work.** Write the live–dead–live steps on a card and practice them on the board as a drill, using a non-contact tester and the meter on its voltage setting, so the order becomes habit. (The board will, correctly, always read dead.)

Tips

- Use screw terminals, not the push-in holes; it is good practice and teaches torque.
- Do not cut cables so short that the conductors cannot reach out of the box 6 inches; code requires that much free length.
- Keep the finished board as part of your portfolio; photograph each stage.

Check your work

- ☐ My board has no cord and is labeled never to be connected to power.
- ☐ My continuity readings prove the switch interrupts the hot to the lamp and the 3-way truth table is correct.
- ☐ I can recite and explain every step of live–dead–live and lockout.

SHOP NOTEBOOK

1. A wiring diagram of your single-pole board and a second diagram of the 3-way version, with conductor colors.
2. Box-fill calculations for each box.
3. The continuity table for the 3-way switches.
4. A step-by-step lockout and live–dead–live checklist card you will keep with your tools.

KEY FORMULAS

$V_{\text{required}} = \sum(\text{counts}) \times v_{\text{per conductor}}$
$v = 2.00\ \text{in}^3$ (14 AWG), $2.25\ \text{in}^3$ (12 AWG)

From history. Hubbell's company, still in business, also introduced locking plugs for industry. The three-prong grounding plug spread in the United States after the 1950s, and the electrical code required grounding-type receptacles in new homes from 1962. The tamper-resistant receptacle, with shutters that open only when both blades push at once, has been required in new homes since the 2008 code to protect small children.

Example 1. A receptacle is dead, but the breaker is on. List, in order, the checks you would make and why.

Show solution

1. Check whether the receptacle is switched (a wall switch may control half of it).
2. Look for a tripped GFCI upstream in a bathroom, kitchen, garage or outdoors and press RESET.
3. Check whether the breaker is actually tripped: a tripped breaker may sit in the middle; an adult switches it fully off, then on.
4. Test other receptacles on the same circuit from your map. If the ones beyond it are dead too, a loose connection upstream is likely.
5. Stop there. Finding and repairing a loose connection means opening boxes on a de-energized circuit, a job for a qualified person.

Answer: Switch, GFCI, breaker, neighbors, then a qualified repair: the cheapest and safest explanations first.

Example 2. A single-gang box is marked 18.0 in^3. It will hold two 12-2 NM cables with ground and one duplex receptacle, with an internal cable clamp. Does it pass box fill?

Show solution

1. Count: 4 insulated conductors (2 per cable) count 4; all grounds together count 1; the device counts 2 (double the largest wire on it); internal clamps count 1. Total $= 8$.
2. Volume required: $8 \times 2.25\ \text{in}^3 = 18.0\ \text{in}^3$.
3. $18.0 \leq 18.0$: it just passes.

Answer: Yes, exactly 18.0 in^3; with one more cable it would need a larger box.

Example 3. Two 3-way switches, A and B, each have positions 1 and 2. Make a truth table for the light, and explain why flipping either switch always changes the light.

Show solution

1. The light is on when both commons connect to the same traveler: (1,1) and (2,2).
2. It is off when they connect to different travelers: (1,2) and (2,1).
3. Flipping either switch changes whether they match, so it toggles the light from any starting state. Logically, the light is the XNOR of the two switch positions.

Answer: On for (1,1) and (2,2), off for (1,2) and (2,1); every single flip toggles the light.

PRACTICE

1. Easy Which screw color gets the black wire, the white wire and the bare wire on a receptacle?

   Show answer

   Brass: black (hot). Silver: white (neutral). Green: bare (ground).

2. Easy List the three tests in live–dead–live and say what each guards against.

   Show answer

   Test the tester on a known live source (it works); test the circuit (it is dead); test the tester again (it did not fail during the test).

3. Easy Why must a switch interrupt the hot rather than the neutral?

   Show answer

   So the fixture and its socket are de-energized when the switch is off; a switched neutral leaves the socket live.

4. Medium Why is a non-contact tester alone not enough to prove a circuit dead?

   Show answer

   It can miss a conductor that is shielded or deep in a box, give false readings with a weak battery, and cannot prove the absence of voltage; a contact tester or meter checked live–dead–live is needed.

5. **Medium** A 14 AWG circuit box has three 14-2 cables with ground and a switch. Find the required volume (no internal clamps).

Show answer

6 conductors + 1 (grounds) + 2 (device) = 9; $9 \times 2.00 = 18.0$ in^3.

6. **Medium** A duplex receptacle's brass-side tab is broken off. What is that used for, and what wires would you expect?

Show answer

A split or switched receptacle: one half switched for a lamp, the other always on (or two circuits). Expect two hot conductors (e.g. black and red) and a shared neutral.

7. **Medium** Why should a wire hook wrap clockwise around a terminal screw?

Show answer

Tightening a clockwise screw pulls a clockwise hook tighter around it; a counterclockwise hook is pushed out and loosens.

8. **Hard** You are the tradesperson. You switch off the breaker labeled "Living Room," test the receptacle and get zero, but when you open the box the non-contact tester beeps on a red wire. What is happening and what do you do?

Show answer

The box holds a second circuit (or a multi-wire circuit) still energized. Stop, find and switch off and lock the other breaker, retest every conductor live–dead–live, and correct the panel directory.

9. **Hard** Explain why push-in backstab connections fail more often than screw terminals.

Show answer

The spring contact touches the wire over a tiny area; heating cycles and movement loosen it, raising resistance and heat at the connection; a screw clamps with much more force and area.

10. Hard Draw (describe) the wiring of a 3-way circuit with power entering at switch A, 14-3 cable between the switches, and 14-2 from switch B to the light.

Show answer

Hot to A's common; red and black of the 14-3 as travelers between A and B; B's common to the light's black; neutrals spliced through from the source to the light (white in the 14-3 used as neutral); grounds bonded at every box and device.

11. Challenge Why did Hubbell's separable plug make electrical appliances practical? Give two reasons, one of safety and one of convenience.

Show answer

Safety: the user no longer handled a lamp socket or exposed screw base to connect a device. Convenience: appliances could be plugged and unplugged in seconds anywhere a receptacle was installed, without removing bulbs, so houses could be wired with receptacles for appliances separate from lights.

COMMON MISTAKES

- Trusting the panel directory without testing; labels are often wrong.
- Testing only one slot of a receptacle; test hot-to-neutral and hot-to-ground.
- Connecting the switch to the white neutral; the switch must break the hot.
- Stripping too much insulation, leaving bare copper outside the screw head.

> **Make it a game · Live Dead Live Memory.** From memory, recite every step of the live-dead-live procedure, plus lockout and labeling, in order, and say why each step exists. Your parent holds the textbook list and marks misses. Then match terminal colors to wires: brass hot, silver neutral, green ground. This is a spoken drill only, with no wiring. Repeat for a perfect run.

5.5 Lighting, Codes and When to Call an Electrician

OBJECTIVES

- Compare incandescent, halogen, fluorescent and LED lighting by efficacy (lumens per watt), life and color temperature, and calculate the cost of lighting.
- Explain how an LED makes light and why it needs a driver.
- Explain the origin and purpose of the National Electrical Code, Underwriters Laboratories, permits and inspections.
- Decide which electrical jobs a homeowner may do and which need a licensed electrician, and describe the electrician's apprenticeship and license.

> **Warm-up.** Collect three light-bulb packages or bulbs from around the house. Read the Lighting Facts label or printing on each: lumens, watts, color temperature (K) and life. Rank them by lumens per watt before you calculate anything. Which would you put in a reading lamp, and which in a garage?

WATCH

How LED Works - Unravel the Mysteries of How LEDs Work!

The Engineering Mindset · 19:06

https://www.youtube.com/watch?v=O8M2z2hIbag

> **WHEN TO WATCH**
> After the science paragraph: how a semiconductor junction makes light, why color depends on the material, and why LEDs need current limiting.

Note: There is a sponsor segment about a third of the way through; skip it. The bench demonstrations use small batteries and a lab supply, not household voltage.

BACKUP VIDEO

LED Light Bulbs 101 | Ask This Old House

This Old House · 3:54

https://www.youtube.com/watch?v=z7ZiLgiuw5Y

Before the lighting audit: lumens, watts and color temperature on a real bulb package.

KEY TERMS

lumen

The unit of visible light output. A traditional 60 W incandescent bulb gives about 800 lumens.

efficacy

Light output per electrical power, in lumens per watt (lm/W): about 14 for incandescent, 60–70 for compact fluorescent, 80–150 for LED.

color temperature

How warm or cool white light looks, in kelvins: 2700 K is warm like incandescent, 5000 K is bluish daylight.

LED driver

The electronics inside an LED bulb that turn 120 V AC into the low, steady DC current the LEDs need.

National Electrical Code (NEC)

NFPA 70, the model code for safe electrical installation, first published in 1897 and revised every three years; states and towns adopt it, sometimes with changes.

permit and inspection

Official permission to do electrical work and a check by an inspector that the finished work meets code, before walls are closed and again at the end.

CORE IDEAS

The story. At the 1893 World's Columbian Exposition in Chicago, a whole palace was lit by electricity and visitors marveled. The insurance men did not. Fire insurers worried about the hastily installed wiring, and a young electrical engineer named William Henry Merrill was sent to inspect it. In 1894 he founded what became **Underwriters Laboratories** to test electrical products for fire and shock hazards. Three years earlier, in 1897, insurance, electrical and architectural groups agreed on the first national set of wiring rules, the forerunner of today's **National Electrical Code**. Since 1911 the National Fire Protection Association has published it; it is rewritten every three years from proposals by electricians, engineers, inspectors and manufacturers who study the fires and injuries of the years before.

How they figured it out. Lighting changed as completely as wiring. Edison's 1879–1880 carbon-filament lamp turned only about 2 percent of its energy into light; the rest was heat. Tungsten filaments, gas-filled bulbs, halogen bulbs and fluorescent tubes each improved on it. The great leap came from semiconductors. In 1962 Nick Holonyak Jr., at General Electric, made the first practical visible-light LED, a dim red

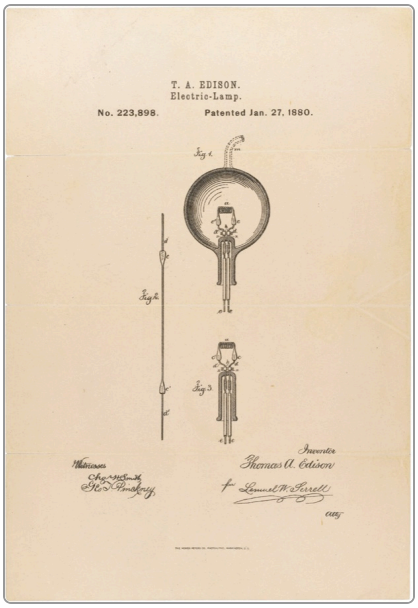
one. Bright blue LEDs eluded researchers for thirty years until Isamu Akasaki, Hiroshi Amano and Shuji Nakamura learned to grow high-quality gallium nitride crystals in the late 1980s and early 1990s, work that won the 2014 Nobel Prize in Physics. A blue LED coated with a yellow phosphor makes white light, and that is the LED bulb in your lamp.

The science. An incandescent filament glows because it is hot, near 2,700 K; most of its radiation is invisible infrared. An LED is a diode: electrons crossing a junction between two kinds of semiconductor drop into lower energy states and release photons whose color depends on the energy gap of the material. Little heat is wasted as infrared, so a 9 W LED bulb can produce the same 800 lumens as a 60 W incandescent. LEDs still make some heat, which their aluminum bases must carry away, and their life (often 15,000–25,000 hours) depends on keeping the LEDs and driver cool. Because an LED needs a controlled current, each bulb carries a small **driver**; that is why some LEDs flicker on old dimmers designed for incandescent loads.

In the shop. Codes are written by trade and adopted by law, and the rules for who may do electrical work vary by state and even by town. Many places allow a homeowner to replace a receptacle, switch or light fixture like-for-like in their own home; some require a permit even for that, and some require all work to be done by a licensed electrician. Adding circuits, extending wiring, installing new receptacles in walls, working in or near the panel, and anything on the service always require a permit and inspection, and panel and service work belong to a licensed electrician. Rental property and other people's homes are always licensed work. Before any job, check with your local building department. The **meter, service drop and anything on the utility side belong to the utility**; no one but the utility touches them.

On the job. Electricians are among the most needed tradespeople in the country. A typical path is a four- or five-year apprenticeship with about 8,000 hours of paid on-the-job training and several hundred hours of classroom study (code, theory, blueprints), followed by a state or local journeyman exam; a master electrician's license, which allows pulling permits and running a business, comes after more years of experience. The U.S. Bureau of Labor Statistics reported a median pay for electricians of about $61,000 in 2023, with many earning far more. Specialties include residential, commercial, industrial, solar and controls work, and lineworkers for the utility.

PICTURE STUDY



Edison's Electric Lamp, Patent Drawing, Thomas A. Edison, January 27, 1880 · Patent drawing · U.S. National Archives

Image: Wikimedia Commons, public domain

This drawing accompanied U.S. Patent 223,898 for Edison's "Electric-Lamp." The real achievement was a filament of high resistance that could glow for hundreds of hours in a vacuum, which made Edison's whole system of wiring practical.

Look closely

- Find the filament. What is its shape, and why would a long, thin filament have high resistance?
- Find where the wires pass through the glass. Why must the seal be airtight?
- Look for the vacuum bulb. What would happen to a hot carbon filament in air?
- Compare this drawing with an LED bulb. What part of the modern bulb has no equivalent here?

Talk about it

1. Why did Edison want a high-resistance filament? (Remember Lesson 5.1 and the cost of copper.)
2. Only about 2 percent of this lamp's energy became light. Where did the rest go?

3. What would Edison find most surprising about an LED bulb?

Safety first. Replace a bulb only with the lamp switched off and cool, and never exceed a fixture's marked maximum wattage. Do not open LED bulbs or drivers. Any fixture replacement is done only with a qualified adult present, the breaker off, locked or taped and labeled, and live–dead–live verification; check local rules about permits first.

SHOP PROJECT

A Home Lighting Audit and a Call-or-Do-It Plan

You will audit every light in your home, calculate its yearly energy and cost, plan an upgrade and its payback, measure light levels at work surfaces, and build a decision table for which electrical jobs your family may do and which need a licensed electrician in your town.

You will need

- Shop notebook or spreadsheet
- A step stool (adult present) to read bulb markings
- A phone light-meter app (the free phyphox app has one) or a handheld light meter
- Your electric bill (rate per kWh)
- Your town or county building department's website or phone number

Steps

1. List every fixture room by room with the number of bulbs, the bulb type, watts and lumens (from the bulb or package), color temperature, and an estimate of hours used per day.
2. Calculate each fixture's yearly kWh and cost, and the house total for lighting.
3. Identify the five fixtures with the highest yearly cost. Price LED replacements (lumens and color temperature matched) and calculate savings and payback.
4. Measure light levels with the app at the kitchen counter, a desk, a stairway and the garage workbench, at night with lights on. Convert lux to footcandles (1 fc = 10.76 lux) and compare with typical targets (stairs 5–10 fc, kitchen counter and desk 30–50 fc, workbench 50–100 fc).
5. Find your local rules: Does your town allow homeowners to do electrical work on their own home? Which jobs need a permit? Record the source and date.
6. Make a decision table of at least ten jobs (bulb change, cover plate, like-for-like receptacle, GFCI, fixture swap, dimmer, new circuit, new receptacle,

panel work, service upgrade, outdoor wiring, EV charger) with columns: homeowner allowed here?, permit?, who should do it, why.

7. Present the upgrade plan and the decision table to your parents.
8. **Check your work.** After any bulbs are changed, measure the light levels again and read the meter for a week to compare with Lesson 5.1.

Tips

- Phone light meters are only approximate; compare readings with each other rather than trusting absolute values.
- Ask an electrician at church or in your neighborhood about his apprenticeship; it is a good start on a career interview.

Check your work

- ☐ My audit totals the lighting energy and cost correctly.
- ☐ My upgrade plan matches lumens and color temperature and has a payback calculation.
- ☐ My decision table cites local rules and sends panel, service and new-circuit work to a licensed electrician.

SHOP NOTEBOOK

1. A table of bulb types with lumens, watts, efficacy, life and cost per year.
2. A labeled diagram of an LED bulb: LED chips, phosphor, heat sink, driver, base.
3. Your measured light levels on a floor plan.
4. Your call-or-do-it decision table.

KEY FORMULAS

$$\text{efficacy} = \frac{\text{lumens}}{\text{watts}}$$

$$E\ (\text{kWh}) = \frac{P\ (\text{W}) \times t\ (\text{h})}{1000}$$

$$\text{illuminance (fc)} = \frac{\text{lumens reaching the surface}}{\text{area (ft}^2\text{)}}$$

From history. Nick Holonyak Jr. predicted in 1963 that LEDs would one day replace the incandescent lamp; it took about fifty years. Underwriters Laboratories' mark on a product means a sample of it was tested to a published safety standard; electrical inspectors look for such listing marks on every device they approve.

WORKED EXAMPLES

Example 1. A house has 20 bulbs of 60 W incandescent used an average of 3.0 hours a day. Find the yearly savings from replacing them with 9 W LEDs at \$0.15 per kWh, and the payback time if LEDs cost \$2.00 each.

Show solution

1. Power saved per bulb: $60 - 9 = 51$ W; for 20 bulbs: 1,020 W.
2. Energy saved per year: $1.020 \text{ kW} \times 3.0 \text{ h/day} \times 365 = 1{,}117$ kWh.
3. Money saved: $1{,}117 \times \$0.15 = \$167.54$ per year.
4. Payback: $\$40.00 / \$167.54 \approx 0.24$ year ≈ 3 months.

Answer: About \$168 per year, paid back in about three months.

Example 2. Compare the efficacy of an 800 lm, 60 W incandescent, an 800 lm, 13 W compact fluorescent and an 800 lm, 8.5 W LED.

Show solution

1. Incandescent: $800/60 = 13.3$ lm/W.
2. CFL: $800/13 = 61.5$ lm/W.
3. LED: $800/8.5 = 94.1$ lm/W, about 7 times the incandescent.

Answer: 13.3, 61.5 and 94.1 lm/W.

Example 3. A 10 ft × 12 ft workshop bench area needs about 50 footcandles. If about 60 percent of the bulbs' lumens reach the work surface, how many 1,600-lumen LED bulbs are needed?

Show solution

1. Area: $10 \times 12 = 120$ ft^2.
2. Lumens needed on the surface: $50 \times 120 = 6{,}000$ lm.
3. Lumens from the bulbs: $6{,}000 / 0.60 = 10{,}000$ lm; number: $10{,}000 / 1{,}600 = 6.25$, so 7 bulbs.

Answer: Seven 1,600-lumen bulbs (about 7 × 15 W = 105 W of LED).

Example 4. A homeowner lists four jobs: (a) replace a cracked receptacle like-for-like; (b) add a new 20 A circuit for a garage workshop; (c) replace the main panel; (d) swap a ceiling fixture for a new one in the same box. Sort them by who should do them, assuming a town that allows homeowner work with permits.

Show solution

1. (a) and (d): homeowner-possible like-for-like replacements, with the breaker off and verified dead; check whether a permit is needed locally; the fixture must be supported by a box rated for its weight.
2. (b): new circuit means work in the panel and new wiring: permit and inspection; best done by a licensed electrician (and required in many places).
3. (c): panel replacement involves the service and utility coordination: licensed electrician with permit, always.

Answer: (a) and (d) possible for a careful homeowner where allowed; (b) permit and normally an electrician; (c) licensed electrician only.

PRACTICE

1. Easy Define lumen and efficacy.

   Show answer

   A lumen measures visible light output; efficacy is lumens per watt of electrical input.

2. Easy What is the National Electrical Code, and when was the first national wiring code written?

   Show answer

   NFPA 70, the model code for safe electrical installation, adopted by states and towns; the first national rules date from 1897.

3. Easy Which part of the electrical system belongs to the utility, and who may work on it?

   Show answer

   The service drop or lateral and the meter (and everything upstream); only the utility.

4. **Medium** A 100 W incandescent (1,600 lm) runs 5 h a day. Find its yearly energy and cost at \$0.14/kWh, and the same for a 15 W LED.

Show answer

Incandescent: 182.5 kWh, \$25.55. LED: 27.4 kWh, \$3.83.

5. **Medium** Why does an LED bulb need a driver while an incandescent bulb does not?

Show answer

An LED needs a limited DC current; its current rises steeply with voltage, so electronics regulate it from 120 V AC. A filament is a simple resistor that limits its own current.

6. **Medium** Why might an LED bulb flicker or buzz on an old dimmer?

Show answer

Older dimmers were designed for resistive incandescent loads and need a minimum load; the LED driver's low, electronic load can confuse them. Use an LED-rated dimmer and dimmable bulbs.

7. **Medium** A room needs 30 footcandles over 200 ft^2 and 50 percent of the light reaches the work plane. How many lumens of bulbs are needed?

Show answer

$30 \times 200 / 0.50 = 12{,}000$ lm.

8. **Hard** An LED bulb rated 25,000 hours runs 4 hours a day. How many years should it last? Why might it fail sooner in a closed glass fixture?

Show answer

About 17 years. Heat trapped in a closed fixture raises LED and driver temperature, shortening their life; use bulbs rated for enclosed fixtures.

9. Hard You are the tradesperson. A homeowner wants to add three receptacles to a basement and asks if he can just run an extension cord through the wall instead. Answer him.

Show answer

No: cords may not run through walls, ceilings or doorways or substitute for permanent wiring; they overheat, get damaged and hide from inspection. New receptacles need a permit, the right cable and GFCI protection in an unfinished basement; recommend a licensed electrician or a permitted job.

10. Hard Why is the NEC revised every three years, and who proposes the changes?

Show answer

So that it can respond to new technology and to the causes of fires and injuries found since the last edition; anyone may propose changes, and committees of electricians, inspectors, engineers, manufacturers and insurers decide.

11. Challenge An electrician apprentice works 2,000 hours a year for 4 years at an average of $22/h, and a journeyman then earns $32/h for 2,000 hours a year. Find total apprenticeship earnings and journeyman yearly earnings. Compare this with a four-year degree that costs money instead of paying it.

Show answer

Apprenticeship: $8{,}000 \times \$22 = \$176{,}000$ earned while learning. Journeyman: $64,000 per year. The apprentice finishes trained, licensed-eligible and without tuition debt; the comparison should weigh calling, aptitude and the type of work, not money alone.

COMMON MISTAKES

- Buying bulbs by watts instead of lumens; LED watts are much smaller for the same light.
- Assuming any rule you read online applies in your town; electrical rules vary by state and locality.
- Thinking a permit is only red tape; the inspection is a second pair of trained eyes on work that will be hidden in walls.
- Ignoring color temperature, so one room has mismatched warm and cool light.

Make it a game · Lumens per Watt Duel. Find three light bulbs, or their box labels, in your home. Predict which one has the highest efficacy in lumens per watt, then calculate each. Next, estimate the yearly cost of the least efficient one at 3 hours a day. Closest guess wins. Also decide which jobs are for an electrician instead.

Scripture. “Neither do men light a candle, and put it under a bushel, but on a candlestick; and it giveth light unto all that are in the house.” (Matthew 5:15, KJV)

A light is placed to serve the whole house. Good lighting, like good work, is placed where it helps others, and the craftsman who wires it safely serves everyone who lives there.

UNIT 5

Basic Home Electrical

Electricity is the most useful and the least forgiving system in a house. In this unit you will follow it from Edison's Pearl Street Station in 1882 to the panel in your own basement or garage, learn why wire comes in different sizes and how breakers protect it, and learn from Charles Dalziel's measurements why a few thousandths of an ampere matter and how GFCIs and AFCIs protect people and homes.

Then you will learn the electrician's habits before the electrician's tasks: identify the circuit, switch it off, lock and label it, and prove it dead with live–dead–live testing. You will practice wiring a switch, a receptacle, a lamp holder and a pair of 3-way switches on an **unpowered practice board** that is never connected to anything, and you will map which breaker feeds what in your home. The unit ends with lighting, the National Electrical Code, permits and the question every homeowner must answer honestly: when to call a licensed electrician.

Safety rules for the whole unit. You never open the panel cover, never touch the service drop or meter, and never work on anything energized. Any work on a real household circuit is done only with a qualified adult present, after the breaker is switched off, locked or taped, labeled and verified dead live–dead–live. Many jobs need a permit and a licensed electrician; the rules vary by state and town. Never bypass a breaker, a GFCI or a ground pin.

PREREQUISITES

- Algebra I: solving and rearranging formulas, ratios, scientific notation
- Ohm's law and power ($V = IR$, $P = VI$) at the level of a physical science course
- Units 1–4 of this course, especially fasteners and torque (Unit 1) and house framing (Unit 4)

MASTERY CHECKLIST

- ☐ I can trace power from the generating plant to a branch circuit and explain 120/240 V split-phase service.
- ☐ I can explain what is inside a panel without opening one, and which parts belong to the utility.
- ☐ I can match wire gauge to breaker size and calculate circuit current, the 80 percent limit and voltage drop.
- ☐ I can explain how a breaker, a GFCI, an AFCI and the ground wire each protect a house and its people.
- ☐ I can carry out lockout, labeling and live–dead–live verification and explain each step.
- ☐ I can wire a receptacle, a single-pole switch and a 3-way circuit on an unpowered practice board and check them with a meter.
- ☐ I can compare lighting by lumens per watt and calculate lighting cost and payback.
- ☐ I can decide which electrical jobs need a permit and a licensed electrician in my town.

OPTIONAL KITS FOR THIS UNIT

- **Klein Tools electrician's hand tools and testers**: Wire strippers, screwdrivers, non-contact voltage testers and plug-in receptacle testers from a long-established American electricians' toolmaker. Useful for Lessons 5.3–5.5; any brand that is rated for the job will do.
- **Fluke digital multimeters**: Professional meters used by electricians, for continuity checks on the practice board (Lesson 5.4) and for live–dead–live drills. An inexpensive CAT III-rated meter from a reputable brand also works.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

5.1	**From Power Plant to Panel**	3 sessions of 50 minutes
5.2	**Circuits, Wire and Breakers**	3 sessions of 50 minutes
5.3	**Shock, Grounding, GFCI and AFCI**	3 sessions of 50 minutes
5.4	**Working Safely: Switches and Receptacles**	3 sessions of 50 minutes
5.5	**Lighting, Codes and When to Call an Electrician**	3 sessions of 50 minutes

Unit 5 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Use 120 V for single-pole circuits unless told otherwise. For explanations, use complete sentences. The test is worth 100 points.

1. **6 pts**
   Trace electricity from the power plant to a 120 V receptacle in a bedroom, naming at least six parts in order.

2. **6 pts**
   A pole transformer steps 7,200 V down to 240 V. Find the turns ratio and explain how the house gets both 120 V and 240 V.

3. **5 pts**

   Why does switching off the main breaker not make it safe to remove the panel cover?

4. **7 pts**

   A meter reads 18,410 kWh on March 1 and 19,340 kWh on March 31. At \$0.16 /kWh, find the energy, the cost and the average power.

5. **6 pts**

   State the usual breaker size for 14 AWG, 12 AWG and 10 AWG copper NM cable, and explain why the breaker must match the wire.

6. **8 pts**

   A 20 A kitchen circuit has a 1,100 W microwave and a 1,200 W coffee maker running. (a) Find the current. (b) Will adding a 900 W toaster trip the breaker? (c) What is the continuous limit under the 80 percent rule?

7. **8 pts**

   A 12 AWG circuit (1.59 Ω/1,000 ft) runs 90 ft to a load of 15 A. Find the voltage drop and percent drop. Is it within 3 percent?

8. **5 pts**

   Distinguish an overload from a short circuit and say which part of a thermal-magnetic breaker responds to each.

9. **8 pts**

   A person with wet hands ($R = 1{,}200\ \Omega$) touches a 120 V hot while grounded. (a) Find the current. (b) Will a 15 A breaker trip? (c) Will a GFCI trip, and why?

10. **6 pts**

    A hot wire touches the grounded metal case of a dryer. The fault loop is 0.40 Ω at 120 V to ground. Find the fault current and explain what the ground wire accomplishes.

11. **5 pts**

    What does an AFCI protect against, and why can a regular breaker miss it?

12. **7 pts**

    List in order the steps for safely replacing a receptacle on a real circuit, including who must be present.

13. **4 pts**

    A box is marked 20.3 in^3. It contains two 14-2 cables with ground, one 14-3 cable with ground, a switch and internal clamps. Does it pass box fill?

14. **5 pts**

    Explain how two 3-way switches control one light; give the truth table.

15. **4 pts**

    Replacing 15 incandescent bulbs of 75 W (1,100 lm) with 11 W LEDs, used 4 h a day at $0.15/kWh: find the yearly savings and the efficacies.

16. **10 pts**

    Short essay (one or two paragraphs): A neighbor says, “Permits are just paperwork; I can wire my new workshop myself, and if the breaker keeps tripping I’ll put in a bigger one.” Respond as a knowledgeable, respectful young tradesperson, using what you learned about wire heating, breakers, codes, inspection and when to call a licensed electrician.

ANSWER KEY

1. Generator, step-up transformer, transmission line, substation, distribution line, pole or pad transformer (center-tapped), service drop or lateral, meter, main breaker, bus bar, branch breaker, NM cable, receptacle.
2. 30 : 1. The secondary is center-tapped and grounded (the neutral): each end to center is 120 V, and end to end is 240 V.
3. The service conductors and lugs feeding the main breaker remain energized from the meter; only the utility can de-energize them, and the cover is never removed by students.
4. 930 kWh; \$148.80; $930/720 \approx 1.29$ kW.
5. 15 A, 20 A, 30 A. The breaker protects the wire from overheating; a larger breaker would allow current that overheats the wire without tripping.
6. (a) $2300/120 = 19.2$ A. (b) $3200/120 = 26.7$ A, so yes, it will trip. (c) 16 A (1,920 W).
7. $R = 1.59 \times 180/1000 = 0.286\ \Omega$; drop $= 4.3$ V $= 3.6\%$; no, slightly over; 10 AWG would bring it to about 2.3 percent.
8. Overload: moderate excess current, slow heating, bimetal strip trips. Short: huge sudden current, magnetic coil trips instantly.
9. (a) 100 mA. (b) No, it is far below 15 A. (c) Yes: 100 mA leaves through the person, so hot and neutral currents differ by far more than the 4–6 mA trip level.
10. 300 A; the ground wire makes the fault a near short so the breaker trips immediately, instead of leaving the case energized.
11. Arcing faults from damaged cords or loose connections that can start fires; an arc can draw less current than the breaker's rating while still producing intense heat.
12. Qualified adult present; identify circuit; breaker off; lock or tape and label; test tester on known live; test both slots of the receptacle and confirm dead; test tester again; remove plate, check every conductor in the box with a non-contact tester; photograph wiring; replace device; test finished work.
13. Conductors 7, grounds 1, device 2, clamps 1 = 11; $11 \times 2.00 = 22.0\ \text{in}^3 > 20.3$; it fails; use a larger box.
14. Each common connects to one of two travelers; the light is on when both switches select the same traveler ((1,1),(2,2)) and off otherwise ((1,2),(2,1)), so either switch toggles it.

15. Savings: $15 \times 64 \times 4 \times 365/1000 = 1{,}402$ kWh $= \$210$. Efficacy: 14.7 lm/W versus 100 lm/W.
16. A strong answer explains that the breaker protects the wire, so a bigger breaker on the same wire lets it overheat inside walls (I^2R heating) and can start a fire; that tripping means the circuit is overloaded or faulty and needs a new circuit or a repair; that codes such as the NEC came from studying fires and injuries; that a permit brings an inspector's check before walls are closed and protects future occupants and insurance; that rules vary by town; and that new circuits and panel work are normally for a licensed electrician. Tone is respectful and offers help (a load list, a call to the building department, a recommended electrician).

PORTFOLIO PIECE: A WIRED PRACTICE BOARD AND A HOME ELECTRICAL MAP

Hand in your finished **unpowered practice board** (single-pole and 3-way versions, photographed at each stage) with its wiring diagrams, box-fill calculations and continuity tables, and your **home electrical map**: a floor plan showing which breaker feeds every light and receptacle, the load audit with the 80 percent check for each circuit, the GFCI and receptacle survey, the corrected panel directory approved by your parents, and your call-or-do-it decision table. Finish with a one-page safety plan for your household: monthly GFCI tests, smoke-alarm and tester checks, and the name of an electrician to call.

LOOK FOR	WHAT IT MEANS
Practice board workmanship	Correct terminal colors, clockwise hooks, tight screws, no nicked or exposed copper, cables secured, board labeled and never connected to power.
Verification	Continuity tables prove the switching works; live–dead–live card is complete and correct.
Home electrical map	Every light and receptacle assigned to a breaker; loads, currents and 80 percent checks calculated correctly.
Safety survey and judgment	GFCI and receptacle results recorded; every fault referred to a qualified electrician; decision table reflects local rules.
Communication	Clear diagrams, neat tables and a household safety plan a family member can follow.

UNIT 6

HVAC: Heating, Cooling and Air

Heating, ventilation and air conditioning keep a house comfortable, dry and safe. In this unit you will start with the physics of heat and humidity, from the Roman hypocaust and Franklin's fireplace to the dew point on your windows; follow fuel and fire through the modern furnace and boiler, with the carbon monoxide safety every household needs; trace the refrigeration cycle from Jacob Perkins and Willis Carrier to the air conditioner outside your house; see how a heat pump moves heat in both directions; and finish with the airflow, filters, ducts and controls that make it all work, and with the HVAC technician's trade.

You will measure temperatures, humidity, airflow and run times in your own home, calculate loads, capacities and costs, and leave the unit with a home HVAC inspection and a maintenance log you can keep using.

Safety rules for the whole unit. Refrigerant handling legally requires EPA Section 608 certification in the United States; students never open refrigerant lines. Turn off power at the thermostat and at the furnace or air-handler switch (and the outdoor disconnect) before changing a filter, clearing a drain or cleaning around equipment. No work on gas lines, burners or vents. If you smell gas, leave the house and call the gas company from outside. Keep working carbon monoxide alarms on every level and outside sleeping areas.

PREREQUISITES

- Algebra I: formulas, proportions, graphing lines and finding where two lines cross
- Unit 4 of this course: R-value and heat loss, $Q = A \cdot \Delta T / R$
- Unit 5 of this course: power, $P = VI$, and electrical safety

MASTERY CHECKLIST

- ☐ I can explain conduction, convection, radiation, relative humidity and dew point, and use $Q = mc\Delta T$ and BTU conversions.
- ☐ I can explain how a furnace and a boiler work, calculate output from AFUE and hydronic heat from flow, and explain CO and gas safety.
- ☐ I can trace the refrigeration cycle and calculate tons, EER and COP.
- ☐ I can explain how a heat pump heats and cools, compare costs per million BTU and find a balance point.
- ☐ I can calculate CFM and air-side heat, choose a filter sensibly, and explain duct leakage and static pressure.
- ☐ I can safely change a filter, inspect my home's system and keep a maintenance log, and I know which work belongs to a certified or licensed technician.

OPTIONAL KITS FOR THIS UNIT

- **First Alert carbon monoxide and smoke alarms**: Maker of UL-listed CO and combination alarms with end-of-life dates printed on each unit (Lesson 6.2). Kidde and other listed brands are equally good; the important thing is working alarms in the right places.
- **Fluke infrared thermometers**: Optional for the comfort survey (Lesson 6.1) and register temperatures (Lesson 6.5). An inexpensive digital probe thermometer and hygrometer are enough.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

6.1	**Heat, Humidity and Comfort**	3 sessions of 50 minutes
6.2	**Furnaces, Boilers and Combustion Safety**	3 sessions of 50 minutes
6.3	**The Refrigeration Cycle**	3 sessions of 50 minutes
6.4	**Heat Pumps and Efficiency**	3 sessions of 50 minutes
6.5	**Air Flow, Ducts, Filters and Maintenance**	3 sessions of 50 minutes

Unit 6 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Use 1 W = 3.412 BTU/h and 1 ton = 12,000 BTU/h. For explanations, use complete sentences. The test is worth 100 points.

1. **5 pts**
   Name the three modes of heat transfer and give a household example of each.

2. **6 pts**
   How much heat raises 50 gallons of water (8.34 lb/gal) from 50 °F to 120 °F? Give the answer in BTU and kWh.

3. **5 pts**
   Explain why a cold window fogs on a winter morning, using the terms relative humidity and dew point.

4. **6 pts**
   A furnace has an input of 100,000 BTU/h and an AFUE of 95%. Find its output in BTU/h and kW.

5. **5 pts**
   A boiler loop carries 6.0 gpm with a 20 °F drop. Find the heat delivered.

6. **10 pts**

   List the symptoms of carbon monoxide poisoning, three ways CO can enter a home, and what to do if a CO alarm sounds.

7. **4 pts**

   What should you do if you smell gas in the house?

8. **8 pts**

   Trace the refrigerant through the four main parts of an air conditioner, giving its phase and whether it is gaining or losing heat in each coil.

9. **6 pts**

   A 2.5-ton air conditioner draws 2,400 W. Find its capacity in BTU/h, its EER and its COP.

10. **4 pts**

    Why may students and homeowners not open refrigerant lines or add refrigerant?

11. **6 pts**

    Compare the cost per million BTU delivered for electric resistance heat and a heat pump with COP 3.0 at $0.13/kWh.

12. **6 pts**

    Find the Carnot heating COP for moving heat from 30 °F outdoor air into a 100 °F coil. Why is a real heat pump's COP lower?

13. **6 pts**

    A house loses 30,000 BTU/h at 10 °F and nothing at 65 °F. A heat pump delivers 24,000 BTU/h at 47 °F and 14,000 BTU/h at 17 °F (straight lines). Find the balance point.

14. **6 pts**

    A furnace blower moves 1,000 CFM with a 45 °F temperature rise. Find the heat delivered. A 14 × 20 inch filter serves it; find the face velocity.

15. **5 pts**

You are the technician. In July the indoor coil is iced and the filter is black with dust. Explain the chain of cause and effect and the first fix.

16. **12 pts**

Short essay (one or two paragraphs): Explain to a family why an air conditioner or heat pump is said to “move heat, not make cold,” and why the right size, a clean filter and yearly service matter more than buying the biggest unit. Mention one thing they can do themselves and one thing that requires a certified technician.

ANSWER KEY

1. Conduction (bare feet on tile), convection (warm air rising from a register), radiation (feeling the cold of a window or the warmth of sunlight).
2. $417 \times 70 = 29{,}190$ BTU; $29{,}190 / 3{,}412 = 8.6$ kWh.
3. Room air near the glass cools; when the glass is below the air's dew point, the air there reaches 100% RH and water vapor condenses on it.
4. 95,000 BTU/h; 27.8 kW.
5. $500 \times 6.0 \times 20 = 60{,}000$ BTU/h.
6. Headache, dizziness, nausea, confusion, flu-like illness in several people that improves away from home. Sources: cracked heat exchanger, blocked or disconnected flue, backdrafting water heater, car or generator running in or near the house, misuse of a range or grill. Get everyone into fresh air and call 911; do not go back in until the fire department says it is safe.
7. Leave at once with everyone; do not use switches, phones or flames inside; call the gas company or 911 from outside.
8. Compressor: low-pressure vapor compressed to hot high-pressure vapor. Condenser (outdoor): vapor loses heat and condenses to liquid. Metering device: pressure drops, liquid partly flashes, becomes cold. Evaporator (indoor): liquid boils to vapor, gaining heat from house air. Back to the compressor.
9. 30,000 BTU/h; EER 12.5; COP 3.66.
10. Federal law (EPA Section 608) requires certification to handle refrigerant; it is under pressure, can cause frostbite, and must not be vented.
11. Resistance: $293 \times 0.13 = \$38.09$. Heat pump: \$12.70.
12. $T_c = 272.0$ K, $T_h = 310.9$ K; $\text{COP}_{\max} = 310.9 / 38.9 = 8.0$. Real machines have friction, pressure drops, finite temperature differences in the coils, fan power and defrost losses.
13. Load $= 545.5(65 - T)$; capacity $= 14{,}000 + 333.3(T - 17)$.
    $35{,}455 - 545.5T = 8{,}333 + 333.3T$; $T = 30.9\ ^\circ\text{F}$.
14. $1.08 \times 1{,}000 \times 45 = 48{,}600$ BTU/h. Area $= 280 / 144 = 1.94$ ft^2; velocity $= 514$ ft/min, high; a larger filter would help.
15. The clogged filter cuts airflow; too little warm air crosses the evaporator, so the refrigerant stays very cold and the coil drops below freezing; moisture freezes and blocks airflow further. Turn the system off to thaw (fan on), replace the filter, and call a technician if it recurs.

16. A strong answer explains that refrigerant absorbs heat indoors by boiling at low pressure and rejects it outdoors by condensing at high pressure, driven by the compressor; that an oversized unit short-cycles, dehumidifies poorly and costs more, while a correctly sized unit from a load calculation runs long, steady cycles; that a clean filter keeps airflow and prevents iced coils or overheating; and that yearly service catches problems early. Homeowner: filter changes, clearing around the outdoor unit with power off, keeping registers open. Technician: anything involving refrigerant (EPA 608), gas, burners or electrical repairs.

PORTFOLIO PIECE: A HOME HVAC INSPECTION AND MAINTENANCE LOG

Assemble a complete record of your home's heating, cooling and air system: the comfort survey (Lesson 6.1); the heating-system and CO inspection with your family's emergency plan (6.2); your air conditioner or refrigerator measurements (6.3); your heat-pump sizing and cost study (6.4); and the filter-and-airflow inspection with register temperatures and CFM (6.5). End with a one-year maintenance log that your family will use, listing each task, how often, who does it (family or certified technician), and the date it was last done, plus a one-page summary of the three most valuable improvements you found.

LOOK FOR	WHAT IT MEANS
Measurements	Temperatures, humidity, airflow and run times measured carefully at the stated places and times, with units.
Calculations	Output from AFUE, CFM and air-side heat, COP and cost comparisons and the balance point are correct.
Safety	CO alarms checked and mapped, emergency plan written, power turned off before filter work, and every gas, burner or refrigerant issue referred to a qualified technician.
Maintenance log	Complete, realistic, dated and actually started.
Recommendations	Three improvements justified with your data and with cost, comfort and safety trade-offs.

6.1 Heat, Humidity and Comfort

OBJECTIVES

- Explain conduction, convection and radiation in a house and identify each in your own rooms.
- Use the BTU, specific heat and Q = mcΔT, and convert between watts and BTU per hour.
- Explain relative humidity, dew point, sensible and latent heat, and why comfort depends on more than air temperature.
- Measure temperature and humidity around a house and interpret the results.

> **Warm-up.** Stand barefoot on a rug and then on a tile or wood floor in the same room. Both are at nearly the same temperature, yet one feels colder. Then stand near a large window on a cold day (or a hot one) and notice how your face feels. Write down two explanations before you read on.

WATCH

We Fired Up A Roman Hypocaust - For 8 Days Straight!

Butser Ancient Farm · 14:28

https://www.youtube.com/watch?v=l-ppMOPE-hE

> **WHEN TO WATCH**
> After the story. Archaeologists at a reconstructed Roman villa fire its hypocaust for eight days and measure floor, wall and air temperatures and humidity with modern instruments.

Note: From an experimental archaeology farm in England, a reputable educational channel. The thermal-camera and hygrometer readings are an excellent model for your own shop project.

KEY TERMS

BTU

British thermal unit: the heat needed to raise 1 pound of water by 1 °F, about 1,055 J. Furnaces and air conditioners are rated in BTU per hour; 1 W = 3.412 BTU/h.

specific heat

The heat needed to raise one unit of mass by one degree: 1.0 BTU/(lb·°F) for water and about 0.24 BTU/(lb·°F) for air.

conduction, convection, radiation

Heat moving through solids by contact; heat carried by moving air or water; heat traveling as infrared light from warm surfaces to cooler ones.

relative humidity

The water vapor in the air as a percentage of the most the air could hold at that temperature.

dew point

The temperature at which air becomes saturated and water condenses: the temperature of a surface that will just begin to fog or sweat.

sensible and latent heat

Sensible heat changes temperature; latent heat changes phase (evaporating or condensing water) without changing temperature.

CORE IDEAS

The story. The Romans heated their public baths and the floors of wealthy villas with the **hypocaust** ("heat from below"). A fire in a small furnace room, the *praefurnium*, sent hot gases under a floor raised on short stacks of tiles called *pilae*, and often up through hollow flue tiles in the walls to vents near the roof. The architect Vitruvius described how to build one: the floor of two-foot tiles laid on columns of eight-inch bricks, sloped so that the hot gases would flow toward the vent. Seventeen centuries later, in 1744, Benjamin Franklin published a pamphlet describing his "Pennsylvanian Fire-Place," an iron box set into the hearth that warmed the room with an air chamber heated by the fire. He refused a patent, saying that since we enjoy the inventions of others, we should be glad to serve others by ours.

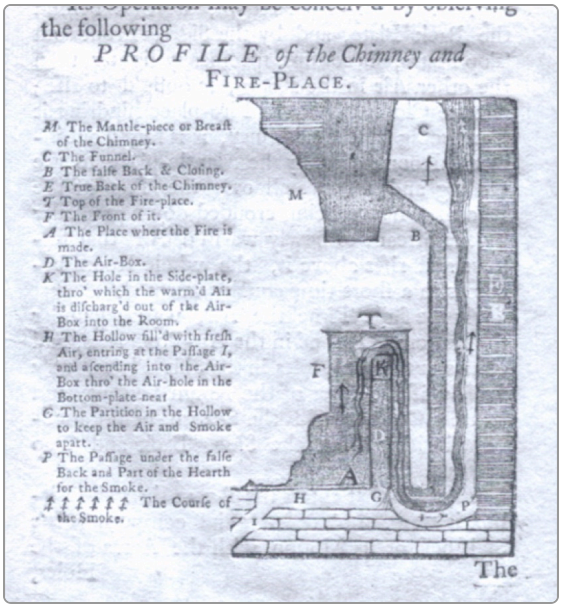
How they figured it out. Both inventors were fighting the same enemy: an open fire sends most of its heat up the chimney. The Roman builders learned that a massive floor, slowly heated, would warm people in the baths by contact and by radiation for hours and that the gases needed a draft to keep moving. Franklin experimented with the airflow, letting cold room air pass over hot iron plates and come out warm, and he wrote about where people felt drafts, cold backs and smoky rooms. His first design smoked when the draft was poor, and later stove makers improved the flue. Each step came from the same method you will use: measure how warm a room and its surfaces are, find where the heat is going, and change one thing at a time.

The science. Heat always flows from warmer to cooler, by **conduction** (a cold tile floor drawing heat from your feet faster than a rug, because tile conducts better), **convection** (warm air rising off a radiator and cool air sliding down a window) and

radiation (your face losing infrared to a cold window, or gaining it from a sunny wall). The heat to warm something is $Q = mc\Delta T$. Air holds surprisingly little heat: the air in a whole bedroom has a mass of about 100 pounds and needs only a few hundred BTU to warm it 10 °F, while the walls, floor and furniture store far more. Air also carries water vapor. **Relative humidity** compares the vapor present with the most the air can hold at that temperature; warm air can hold much more than cold. When air touches a surface below its **dew point**, water condenses, as on a cold glass or a winter window. Evaporating or condensing water moves large amounts of **latent heat** (about 1,000 BTU per pound) without changing temperature.

In the shop. HVAC technicians think about **comfort**, not just air temperature. ASHRAE Standard 55 describes comfort in terms of air temperature, the mean radiant temperature of the surfaces around you, humidity, air speed, clothing and activity. A room at 70 °F with cold windows and a draft can feel colder than a room at 67 °F with warm walls and still air. Indoor relative humidity between roughly 30 and 50 percent is usually comfortable and discourages mold and dust mites; higher humidity in summer makes the same temperature feel sticky, which is why air conditioners must remove moisture as well as heat. Technicians measure with a thermometer, a hygrometer and often an infrared thermometer or thermal camera, the same tools you will use.

PICTURE STUDY



Franklin's Pennsylvanian Fire-Place, Benjamin Franklin, 1744 · Engraving · *An Account of the New Invented Pennsylvanian Fire-Places*, Philadelphia

Image: Wikimedia Commons, public domain

Franklin published this diagram so that any skilled ironworker could build his fireplace. It shows his attempt to capture heat that an open fireplace sends up the chimney.

Look closely

- Find the fire chamber and the passage the smoke follows. Where does it reach the chimney?
- Find the air box or chamber behind the fire. Where does room air enter, and where does warm air come out?
- Look for the plates and how they fit together. Why use thin iron plates rather than thick brick?
- Find the labels or letters. How does a labeled drawing help a builder?

Talk about it

1. Which of the three heat-transfer modes does this fireplace use to warm the room?
2. Why would a stronger draft reduce smoke in the room, and how could the design have made the draft weaker?

3. Franklin gave this design away. What does that say about his idea of a tradesman's or inventor's duty to others?

Safety first. Use only a thermometer, a hygrometer and (if you have one) an infrared thermometer; never point an infrared thermometer's laser at anyone's eyes. Do not open stoves, fireplaces, furnaces or wall heaters to take readings, and stay well away from any flame or hot surface.

SHOP PROJECT

A Home Comfort Survey

You will map air temperature, surface temperature and relative humidity through your home over one day, find the coldest and warmest surfaces and any risk of condensation, and recommend changes for comfort and cost.

You will need

- A digital thermometer-hygrometer (about $10–15)
- An infrared thermometer (optional; a library or neighbor may lend one)
- Your floor plan from Unit 5
- A watch or phone
- A dew-point chart or online calculator
- Shop notebook

Steps

1. Choose six locations: three rooms, a bathroom, near a large window, and the basement or a closet on an outside wall.
2. At each location, place the hygrometer at about chest height for 10 minutes and record air temperature and RH.
3. With the infrared thermometer (or by careful touch comparison), record the temperature of the floor, an inside wall, an outside wall and the window glass.
4. Repeat the readings at three times of day: early morning, afternoon and evening. Record the outdoor temperature each time (a weather app is fine).
5. For each reading, find the dew point. Mark every surface that is within 5 °F of the dew point: those are condensation and mold risks.
6. Calculate the difference between air and coldest-surface temperature in each room. Rank rooms by comfort as you experienced them and see whether the surface temperatures explain your ranking.
7. Recommend three low-cost changes (for example, a bathroom fan run longer, insulated curtains, a door sweep) and predict their effect.

8. **Check your work.** Try one change for a day and measure again. Did the numbers change as you predicted?

Tips

- Hygrometers need time to settle; always wait the same time before recording.
- Do not hold the thermometer in your hand; your body heat changes the reading.

Check your work

- ☐ I recorded air and surface temperatures and RH at six places and three times.
- ☐ I can explain which surfaces risk condensation using the dew point.
- ☐ I can explain why a room at the same air temperature can feel different.

SHOP NOTEBOOK

1. A floor plan with air temperature, surface temperatures and RH written at each location.
2. A labeled cross-section of a Roman hypocaust showing furnace, pilae, floor, wall flues and the path of hot gases.
3. A graph of indoor RH against time of day for two rooms.
4. A short list: what I would change first and why.

KEY FORMULAS

$$Q = mc\Delta T$$

$$1\ \text{W} = 3.412\ \text{BTU/h}$$

$$\text{RH} = \frac{\text{vapor present}}{\text{vapor at saturation}} \times 100\%$$

$$\dot{Q} = \frac{A\,\Delta T}{R}$$

From history. Count Rumford (Benjamin Thompson), an American-born scientist working in Europe, redesigned fireplaces in the 1790s with shallow, angled sides and a narrow throat, sending more radiant heat into the room and less up the chimney. Many old houses still have “Rumford fireplaces.” Thompson also showed, by boring cannon, that heat is a form of motion rather than a fluid.

WORKED EXAMPLES

Example 1. A bedroom is 12 ft × 15 ft × 8 ft. Air has a density of about $0.075\ \text{lb}/\text{ft}^3$ and a specific heat of $0.24\ \text{BTU}/(\text{lb}\cdot{}^\circ\text{F})$. How much heat warms the air from 60 °F to 70 °F?

Show solution

1. Volume: $12 \times 15 \times 8 = 1{,}440\ \text{ft}^3$.
2. Mass: $m = 1{,}440 \times 0.075 = 108\ \text{lb}$.
3. Heat: $Q = mc\Delta T = 108 \times 0.24 \times 10 = 259\ \text{BTU}$.

Answer: About 260 BTU, less than the heat in a cup of hot coffee cooling down. The walls and furniture, not the air, take most of the heat and time.

Example 2. A 1,500 W space heater runs for 2.0 hours. Find its output in BTU/h and the total heat delivered. How much water could that heat raise from 50 °F to 120 °F?

Show solution

1. Rate: $1{,}500 \times 3.412 = 5{,}118\ \text{BTU}/\text{h}$.
2. Heat in 2.0 h: $5{,}118 \times 2.0 = 10{,}236\ \text{BTU}$.
3. Water: $m = Q/(c\Delta T) = 10{,}236/(1.0 \times 70) = 146\ \text{lb}$, about 17.5 gallons (8.34 lb/gal).

Answer: $5{,}118\ \text{BTU}/\text{h}$; $10{,}236\ \text{BTU}$; enough to heat about 146 lb (17.5 gal) of water by 70 °F.

Example 3. A single-pane window of 15 ft^2 has $R = 0.9$ ($\text{ft}^2\cdot{}^\circ\text{F}\cdot\text{h/BTU}$). Inside is 70 °F and outside 20 °F. Find the heat loss, then repeat for a double-pane window with $R = 2.0$.

Show solution

1. Single pane: $\dot{Q} = A\Delta T / R = 15 \times 50 / 0.9 = 833$ BTU/h.
2. Double pane: $15 \times 50 / 2.0 = 375$ BTU/h.
3. Surface temperature matters too: the single pane's inner surface is much colder, so it radiates and causes condensation and drafts.

Answer: 833 BTU/h versus 375 BTU/h, less than half.

Example 4. Indoor air at 70 °F and 40% RH has a dew point of about 45 °F. On a 10 °F night the inside surface of a single-pane window is about 35 °F. Will it fog? What can be changed?

Show solution

1. Compare the surface with the dew point: $35\ ^\circ\text{F} < 45\ ^\circ\text{F}$.
2. The window glass is below the dew point, so water vapor condenses (and may freeze).
3. Remedies: lower indoor humidity (run bath and kitchen fans, cover pots), or raise the glass temperature (storm window, better glazing, open curtains so room air reaches it).

Answer: Yes, it will fog or frost; lower the humidity or warm the glass.

PRACTICE

1. Easy Name the three ways heat moves and give one household example of each.

   Show answer

   Conduction: feet on a cold tile floor. Convection: warm air rising from a register. Radiation: feeling cold near a window or warm in sunlight.

2. Easy Convert a 12,000 W electric furnace to BTU/h.

   Show answer

   $12{,}000 \times 3.412 = 40{,}944$ BTU/h.

3. **Easy** What is the dew point, and where do you see it at work in a house?

   Show answer

   The temperature at which air saturates and water condenses: a sweating cold-water pipe, fogged windows, a sweating toilet tank.

4. **Medium** How many BTU does it take to heat 40 gallons of water (8.34 lb/gal) from 55 °F to 125 °F?

   Show answer

   $Q = 333.6 \times 1.0 \times 70 = 23{,}352$ BTU.

5. **Medium** A natural-gas furnace burns 60 cubic feet of gas per hour at 1,030 BTU per cubic foot. Find the input in BTU/h and in kW.

   Show answer

   $61{,}800$ BTU/h; $61{,}800/3{,}412 = 18.1$ kW.

6. **Medium** Conceptual: why does a room at 70 °F feel cooler with a ceiling fan running, though the fan does not lower the air temperature?

   Show answer

   Moving air speeds convection and evaporation of moisture from skin, so the body loses heat faster.

7. **Medium** A wall of 120 ft^2 has $R = 13$. Find its heat loss when $\Delta T = 50$ °F.

   Show answer

   $120 \times 50/13 = 462$ BTU/h.

8. **Hard** Air at 70 °F can hold about 0.0158 lb of water per lb of dry air at saturation. If it holds 0.0063 lb, find the RH. If the air is cooled to 50 °F (saturation 0.0077), what is the new RH?

   Show answer

   $0.0063/0.0158 = 40\%$; at 50 °F, $0.0063/0.0077 = 82\%$. Cooling raises RH without adding water.

9. Hard A family adds 2.0 gallons (16.7 lb) of water vapor to the house air each day from cooking, showers and breathing. How much latent heat does it take to remove that water by condensing it on an air-conditioner coil (about 1,060 BTU/lb)?

Show answer

$16.7 \times 1{,}060 \approx 17{,}700$ BTU per day.

10. Hard You are the technician. A homeowner says the thermostat reads 70 °F but the living room feels cold, especially by the large windows. Give two likely reasons and two remedies that do not involve raising the thermostat.

Show answer

Low mean radiant temperature from cold glass, and drafts from air leaks or cold air falling off the glass. Remedies: insulating curtains or storm windows, air sealing, placing seating away from the glass, supply registers under windows.

11. Challenge The Butser hypocaust took days to bring its floor to a steady temperature. A concrete floor of 200 ft^2, 4 in thick (density 140 lb/ft^3, specific heat 0.21 BTU/(lb·°F)) must rise 25 °F. How much heat is needed, and how long would a 20,000 BTU/h fire take if 40% of its heat reached the floor?

Show answer

Volume 66.7 ft^3, mass 9,333 lb; $Q = 9{,}333 \times 0.21 \times 25 = 49{,}000$ BTU. Useful heat 8,000 BTU/h, so about 6 hours, ignoring losses to the ground and room, which make it much longer.

COMMON MISTAKES

- Thinking cold air is the only cause of discomfort; cold surfaces and drafts matter as much.
- Confusing relative humidity with the amount of water in the air; cooling air raises RH without adding water.
- Forgetting that 1 W is 3.412 BTU/h, not 1 BTU/h.
- Using °C in a formula with BTU, which is defined in °F.

Make it a game · Heat Flow Spotter. Walk a room and point out five examples of conduction, convection and radiation: a window, a heater, a warm wall, a mug. Name the type for each in five seconds and your parent challenges one. Then convert 3000 watts to BTU per hour by multiplying by 3.41. Beat your count in round two.

Scripture. “Now the king sat in the winterhouse in the ninth month: and there was a fire on the hearth burning before him.” (Jeremiah 36:22, KJV)

Even a king in ancient Judah needed a winter house and a fire on the hearth. People have always worked to keep their homes warm, and the HVAC trade is the modern form of that old service.

6.2 Furnaces, Boilers and Combustion Safety

OBJECTIVES

- Explain combustion in a gas furnace, the role of the heat exchanger, the flue and draft, and why incomplete combustion makes carbon monoxide.
- Compare forced-air furnaces and hydronic boilers and calculate output from input and AFUE, and boiler heat from flow and temperature drop.
- Explain what carbon monoxide does to the body, where CO alarms belong, and what to do if you smell gas.
- Inspect a home heating system safely from the outside and keep a record of its data and safety devices.

> **Warm-up.** With a parent, find your home's heating system and read its nameplate from where you stand (do not open any panel). What fuel does it use: natural gas, propane, oil, electricity, or wood? Then find every carbon monoxide alarm in the house. Write down where they are and the date printed on the back of one (a parent can take it down).

WATCH

Furnace Parts and Functions Explained

Word of Advice TV · 15:00

https://www.youtube.com/watch?v=gN-UIr6824w

> **WHEN TO WATCH**
> After the science paragraph: a walk through a real high-efficiency gas furnace, from the inducer motor and pressure switch to the burners, flame sensor, limit switches and both heat exchangers.

Note: The presenter works with the furnace's front panel removed, which is a technician's job. Students never open a furnace, touch burners or gas valves, or remove safety switches; you watch to understand, not to copy.

BACKUP VIDEO

Understanding Smoke and Carbon Monoxide Detectors | Ask This Old House

This Old House · 6:51

https://www.youtube.com/watch?v=LKmhqdq1YnI

Before the shop project: the difference between smoke and CO alarms, where to put them and when to replace them.

KEY TERMS

heat exchanger

The sealed metal passages inside a furnace that keep the combustion gases apart from the house air while passing their heat through the metal.

flue and draft

The flue (vent) carries combustion gases outdoors; draft is the pressure difference that moves them, from rising hot gases (natural draft) or a fan (induced draft).

AFUE

Annual Fuel Utilization Efficiency: the percentage of the fuel's heat that reaches the house over a season. Standard gas furnaces are about 80%; condensing furnaces 90–98%.

condensing furnace

A furnace with a second heat exchanger that cools the exhaust enough to condense its water vapor, recovering latent heat; it vents through plastic pipe and drains condensate.

hydronic heating

Heating with hot water from a boiler pumped through radiators, baseboards or tubing in floors.

carbon monoxide (CO)

A colorless, odorless gas from incomplete combustion that binds to the blood's hemoglobin about 200 times more strongly than oxygen.

CORE IDEAS

The story. A century ago many American houses were heated by a coal-burning "gravity" furnace in the basement, its round ducts spreading out like the arms of an octopus. Someone, usually the father of the family, shoveled coal and carried out ashes every day. In 1919 Alice H. Parker of Morristown, New Jersey, patented a furnace that burned natural gas and sent heated air through ducts to separate parts of the house, with separate burners and controls. Her design was not built as drawn, but it pointed the way: gas or oil fuel delivered automatically, an electric blower to push air through ducts, and a thermostat in control. By the 1950s that was the American standard. In 1982 Lennox introduced its Pulse furnace, one of the first high-efficiency condensing furnaces, which captured heat that older furnaces had sent up the chimney.

How they figured it out. Furnace makers measured the temperature and makeup of the flue gases. A standard furnace sends its exhaust out hot, around 350 °F or more, with the water vapor from combustion still a gas. Engineers realized that this vapor holds a large amount of latent heat. By adding a second heat exchanger that cools the exhaust below its dew point (about 130 °F), they could condense the water and recover that heat. The cool exhaust could no longer rise up a chimney by itself, so they added a fan and switched to plastic vent pipe, and the slightly acidic condensate needed a drain. Every part of a modern condensing furnace answers a problem found by measuring.

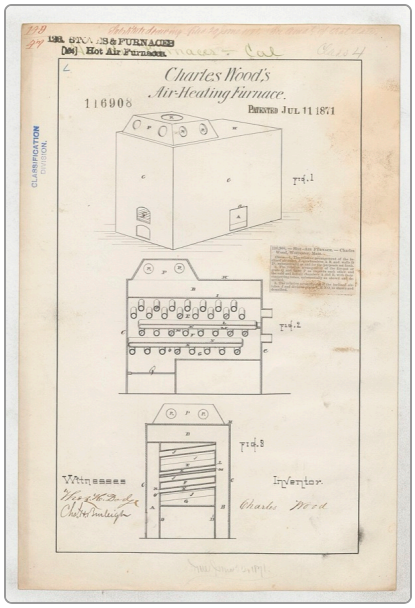
The science. Natural gas is mostly methane: $\mathrm{CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + \text{heat}}$, releasing about 1,030 BTU per cubic foot. Each cubic foot of gas needs two cubic feet of oxygen, or about 10 cubic feet of air. With too little air, a flame that is cooled, or a burner that is dirty, combustion is **incomplete** and makes **carbon monoxide**. CO crowds oxygen out of the blood. Early symptoms are like the flu, headache, dizziness and nausea, often in several family members at once and improving when they leave the house; high levels cause confusion, unconsciousness and death. The **heat exchanger** keeps combustion gases out of the air you breathe; a cracked exchanger, a

blocked or disconnected flue, or a backdrafting water heater can let CO into the house. In a **hydronic** system, a boiler heats water and a pump moves it; the heat delivered is $\dot{Q} \approx 500 \times \text{gpm} \times \Delta T$ in BTU/h, because one gallon per minute of water is about 500 lb per hour and each pound carries 1 BTU per °F.

In the shop. The homeowner's jobs are simple and important: change the filter (Lesson 6.5), keep three feet clear around the furnace and water heater, keep combustion-air openings and outdoor vent pipes clear of snow, leaves and nests, and have the system inspected each year by a qualified technician, who checks the flame, the heat exchanger, the draft and the safety switches and measures CO in the flue. Install CO alarms (listed to UL 2034) outside every sleeping area and on every level, test them monthly and replace them at the end of their life, often 7 to 10 years. Burners, gas valves, gas lines and venting are licensed work.

Safety. Natural gas has no smell of its own; a sulfur odorant (mercaptan) is added so you can smell a leak. **If you smell gas, leave the house at once**, taking everyone with you. Do not flip switches, use a phone, start a car in the garage or light anything inside. Call the gas company or 911 from outside or from a neighbor's house. If a CO alarm sounds, get everyone into fresh air and call 911. Never use a range, oven, grill or generator to heat a house.

PICTURE STUDY



Charles Wood's Air-Heating Furnace, Charles Wood (inventor); U.S. Patent Office drawing, July 11, 1871 · Patent drawing · U.S. Patent 116,908; U.S. National Archives

Image: Wikimedia Commons, public domain

Charles Wood of Worcester, Massachusetts, patented this basement hot-air furnace in 1871, a generation before electric blowers. Fire below heated rows of iron air tubes; house air passed through the tubes, never mixing with the smoke, and rose by its own buoyancy to the rooms. It is a heat exchanger you can see.

Look closely

- In Fig. 1, find the fire door near the bottom and the opening marked A. Which do you think feeds the fire, and which lets cool house air in?
- In Figs. 2 and 3, find the many tubes marked J running across the fire chamber. Air flows inside them; hot fire gases flow around them. Why use many small tubes instead of one large pipe?
- Find the plates that divide the fire chamber into levels (K, L, M, N). How might they make the hot gases pass back and forth across the tubes before leaving?
- Find the hood P on top with its round outlets R. Where would those outlets lead, and what moves the warm air up to the rooms without a fan?
- Find the fire-pot at the bottom and the pipes on the side of Fig. 2. Which one might be the flue to the chimney?

Talk about it

1. Which surfaces in this furnace are the heat exchanger? What would happen if one of the air tubes cracked?
2. Why must the air path and the smoke path stay completely separate? Connect your answer to carbon monoxide.
3. A modern furnace adds a blower, a filter and an induced-draft fan. What problem does each solve that Wood's gravity furnace could not?

Safety first. Never open a furnace, boiler or water heater, touch burners, pilot lights or gas valves, or work on gas lines; those are licensed jobs. If you smell gas, leave the house and call the gas company from outside. Inspect only from outside the equipment with an adult present, and test CO alarms with their own test button.

SHOP PROJECT

A Heating System and Carbon Monoxide Safety Inspection

You will identify your home's heating system, read its data, calculate its output, inspect its surroundings and venting from the outside, check every CO and smoke alarm, and make a household gas-and-CO emergency plan.

You will need

- Flashlight
- Phone camera
- Tape measure
- Shop notebook
- Your floor plan
- A parent

Steps

1. Identify the system type (forced-air furnace, boiler, heat pump, electric baseboard, or other) and the fuel. Photograph the nameplate and record make, model, input BTU/h, output or AFUE, and the year if shown.
2. Calculate the output from input and AFUE, and convert it to kW.
3. Measure clearances around the furnace and water heater. Note anything stored within 3 feet, especially paint, gasoline, cleaners or boxes.
4. Without touching, follow the vent from the appliance to where it leaves the house. Note whether it is metal (standard) or plastic (condensing), and look for rust, gaps, sagging or disconnected joints. Outside, check that the vent and intake are clear of snow, leaves and nests.
5. With a parent, find the furnace's service switch and the gas shutoff valve near the appliance and the gas meter outside. Only learn where they are; do not operate the gas valves.
6. Check every CO and smoke alarm: location, test button, manufacture date and end-of-life date. Mark them on your floor plan and list any that are missing or expired.

7. Write a household emergency plan: what to do if you smell gas, if a CO alarm sounds, and if a smoke alarm sounds; where to meet outside; and the gas company's phone number.
8. **Check your work.** Ask your parents when the system was last professionally serviced. If it has been more than a year, add a service visit to your maintenance log and recommend it.

Tips

- If you see soot, rust streaks below the vent, a yellow or lazy flame through a window in the furnace door, or water under the appliance, tell your parents to call a technician.
- Keep the emergency plan on the refrigerator.

Check your work

- ☐ I recorded the nameplate data and calculated output correctly.
- ☐ Every CO and smoke alarm is on my floor plan with its date and test result.
- ☐ My family has a written plan for gas odor and CO alarms.

SHOP NOTEBOOK

1. A labeled cross-section of a gas furnace: burners, primary and secondary heat exchangers, inducer fan, flue, blower, filter, supply and return plenums.
2. A sketch of a hydronic loop: boiler, pump, expansion tank, baseboards, with supply and return temperatures.
3. The balanced equation for methane combustion with a note on what happens when air is short.
4. Your inspection checklist and emergency plan.

KEY FORMULAS

$$\text{output} = \text{input} \times \text{AFUE}$$

$\dot{Q} \approx 500 \times \text{gpm} \times \Delta T$ (BTU/h, water)

$$\text{CH}_4 + 2\,\text{O}_2 \rightarrow \text{CO}_2 + 2\,\text{H}_2\text{O}$$

$1 \text{ therm} = 100{,}000 \text{ BTU}$

From history. Carbon monoxide alarms were uncommon in homes until the 1990s, after UL published its standard for them in 1992. Today most states require them in homes with fuel-burning appliances or attached garages, and firefighters credit them with saving many families.

WORKED EXAMPLES

Example 1. A furnace nameplate shows an input of 80,000 BTU/h. Find its output at 80% AFUE and at 96% AFUE.

Show solution

1. 80%: $80{,}000 \times 0.80 = 64{,}000$ BTU/h.
2. 96%: $80{,}000 \times 0.96 = 76{,}800$ BTU/h.
3. Difference: 12,800 BTU/h more heat to the house from the same gas.

Answer: 64,000 versus 76,800 BTU/h.

Example 2. A house needs 50 million BTU (500 therms) of delivered heat in a winter. Gas costs $1.40 per therm. Compare the fuel cost with an 80% and a 96% furnace, and find the payback if the condensing furnace costs $1,800 more.

Show solution

1. 80%: $500/0.80 = 625$ therms, $625 \times 1.40 = \$875$.
2. 96%: $500/0.96 = 520.8$ therms, $729.
3. Savings: $146 per year; payback $= 1800/146 \approx 12$ years.

Answer: $875 versus $729; about 12 years to pay back, shorter in colder climates with larger heating loads.

Example 3. A boiler pumps 4.0 gpm through a baseboard loop. Water leaves at 180 °F and returns at 160 °F. Find the heat delivered.

Show solution

1. Temperature drop: $\Delta T = 180 - 160 = 20$ °F.
2. $\dot{Q} = 500 \times 4.0 \times 20 = 40{,}000$ BTU/h.

Answer: 40,000 BTU/h.

Example 4. How much air does a furnace need to burn 75 ft^3 of natural gas per hour completely? Air is 21% oxygen by volume.

Show solution

1. Oxygen: $2 \times 75 = 150$ ft^3 per hour.
2. Air: $150 / 0.21 = 714$ ft^3 per hour; furnaces are set with some excess air, so real values are higher.
3. That air must come from somewhere: combustion-air openings or a sealed intake pipe. Starve the furnace and it makes CO.

Answer: About 710 ft^3 of air per hour (more in practice).

PRACTICE

1. Easy What does the heat exchanger do, and why is a cracked one dangerous?

   Show answer

   It passes heat from the combustion gases to the house air while keeping them apart; a crack can let combustion gases, including CO, into the air you breathe.

2. Easy List what to do, in order, if you smell gas in the house.

   Show answer

   Leave immediately with everyone; do not operate switches, phones or flames inside; call the gas company or 911 from outside; do not go back in until told it is safe.

3. Easy Where should CO alarms be installed?

   Show answer

   Outside each sleeping area and on every level of the home (and as the maker and local code require), tested monthly.

4. Medium A furnace burns 100 ft^3 of gas per hour (1,030 BTU/ft^3) at 92% AFUE. Find input and output.

   Show answer

   Input 103,000 BTU/h; output 94,760 BTU/h.

5. Medium A hydronic floor delivers 24,000 BTU/h with a 10 °F temperature drop. What flow is needed?

Show answer

$\text{gpm} = 24{,}000/(500 \times 10) = 4.8$ gpm.

6. Medium Why does a condensing furnace vent through plastic pipe, while an 80% furnace uses a metal flue?

Show answer

Its exhaust is cool (around 100–120 °F) and wet and slightly acidic; plastic resists the condensate, and the cool gas needs a fan, not a hot chimney draft.

7. Medium Conceptual: why can several family members have "the flu" at once in winter that improves when they are away from home? What should be checked?

Show answer

These are classic CO poisoning signs; leave, call 911 if symptoms are serious, and have the heating appliances, vents and CO alarms checked.

8. Hard Write the balanced equation for complete combustion of propane, C_3H_8, and find the cubic feet of air for 1 ft^3 of propane.

Show answer

$C_3H_8 + 5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O$; 5 ft^3 O_2, so about $5/0.21 = 24$ ft^3 of air.

9. Hard A furnace's 1 lb of methane per hour makes 2.25 lb of water vapor. If a condensing furnace recovers its latent heat at about 1,000 BTU/lb, how much extra heat is captured per hour?

Show answer

About 2,250 BTU/h, which is a large part of the gap between 80% and 95% efficiency.

10. Hard You are the technician. In the spring a homeowner says the furnace "runs a little, shuts off, and tries again." Name two likely causes a homeowner can check, and one that only a technician should handle.

Show answer

Homeowner: a badly clogged filter (overheating trips the high limit), a blocked vent pipe outside (snow, nest) or closed registers. Technician: a dirty flame sensor, faulty pressure switch or inducer, or a cracked exchanger.

11. **Challenge** A family switches from an 80% propane furnace (propane 91,500 BTU/gal at $2.60/gal) to a 96% furnace. Their delivered load is 40 million BTU per year. Find annual savings.

    Show answer

    80%: $40{,}000{,}000 / 0.80 / 91{,}500 = 546$ gal = $1,421. 96%: 455 gal = $1,184. Savings about $236 per year.

COMMON MISTAKES

- Confusing input with output: the nameplate input is the fuel burned, not the heat delivered.
- Thinking a smoke alarm also detects CO; many do not unless marked as a combination alarm.
- Calling the gas company from inside the house, where a phone or switch could ignite gas.
- Storing gasoline, paint or cleaners next to the furnace or water heater.

> **Make it a game · Safe Furnace Sequence.** Teach your parent the path of combustion air and exhaust through a furnace, from burner to heat exchanger to flue, drawn as a sketch. Then explain why incomplete combustion makes carbon monoxide and where detectors belong. Parent plants one error in a retelling; catch it. Calculate output from 100,000 BTU at 80 percent AFUE.

6.3 The Refrigeration Cycle

OBJECTIVES

- Trace refrigerant through the compressor, condenser, metering device and evaporator, stating its pressure, temperature and phase at each point.
- Explain how boiling point depends on pressure and how latent heat makes the cycle work.
- Define a ton of cooling from melting ice and calculate capacity, EER and COP.
- Explain why refrigerant handling requires EPA Section 608 certification and why homeowners never open refrigerant lines.

> **Warm-up.** Put a drop of water on the back of one hand and a drop of rubbing alcohol on the other (in a ventilated room, away from any flame). Blow gently on both. Which feels colder, and which disappears first? Then pump up a bicycle tire and feel the pump barrel. Write down what evaporation and compression each did to temperature.

WATCH

Air Conditioning System Basics hvacr how does it work

The Engineering Mindset · 7:17

https://www.youtube.com/watch?v=SfuSzBja8QA

> **WHEN TO WATCH**
> After the science paragraph: an animation of the cycle with the bicycle-pump and kettle comparisons used in this lesson.

BACKUP VIDEO

Basic Refrigeration cycle - How it works

The Engineering Mindset · 12:44

https://www.youtube.com/watch?v=Uv3GfEQhtPE

Optional, before the worked examples: a slower walk around the cycle marking pressure and temperature at each point.

KEY TERMS

compressor

The pump that squeezes low-pressure refrigerant vapor into high-pressure, high-temperature vapor and drives it around the circuit.

condenser

The outdoor coil where hot vapor gives off heat to the outside air and condenses to liquid.

metering device

A fixed orifice, capillary tube or thermostatic expansion valve (TXV) that drops the liquid's pressure so it can boil at a low temperature.

evaporator

The indoor coil where the cold, low-pressure refrigerant boils, absorbing heat (and condensing moisture) from house air.

ton of cooling

12,000 BTU/h: the rate of heat absorbed by melting one ton of ice in 24 hours.

EPA Section 608

The U.S. rule under the Clean Air Act that requires technicians who service or dispose of equipment with refrigerant to be certified, and forbids knowingly venting refrigerant.

CORE IDEAS

The story. In 1834 Jacob Perkins, an American inventor working in London, patented a machine in which a hand-cranked pump compressed ether vapor, a cooled coil condensed it, and the liquid boiled again at low pressure inside a vessel surrounded by water, freezing it. It was the first vapor-compression refrigeration machine. In 1851 John Gorrie, a Florida physician trying to cool rooms for fever patients, patented an ice machine of his own. The man who made cooling a trade was Willis Carrier, a 25-year-old engineer at the Buffalo Forge Company. In 1902 the Sackett-Wilhelms printing plant in Brooklyn had a problem: in humid summer weather the paper swelled between color passes, and the colors did not line up. Carrier designed a system that passed air over chilled coils to control both temperature and humidity. In 1906 he patented an "Apparatus for Treating Air," and in 1911 he presented the psychrometric formulas engineers still use.

How they figured it out. Carrier is said to have worked out the key idea on a foggy railroad platform in Pittsburgh: air that is cooled to its dew point and stays saturated

holds a known amount of water. Control the temperature of the saturated air, and you control its moisture. He made careful tables relating temperature, humidity and heat, so that systems could be designed by calculation instead of guesswork. Later engineers improved the refrigerants: early machines used ammonia, sulfur dioxide or methyl chloride, which were toxic or flammable; in 1930 Thomas Midgley and colleagues introduced safer chlorofluorocarbons, which in turn were phased out from the 1990s onward because they damage the ozone layer. Each generation of refrigerant has traded off safety, efficiency, cost and environmental rules.

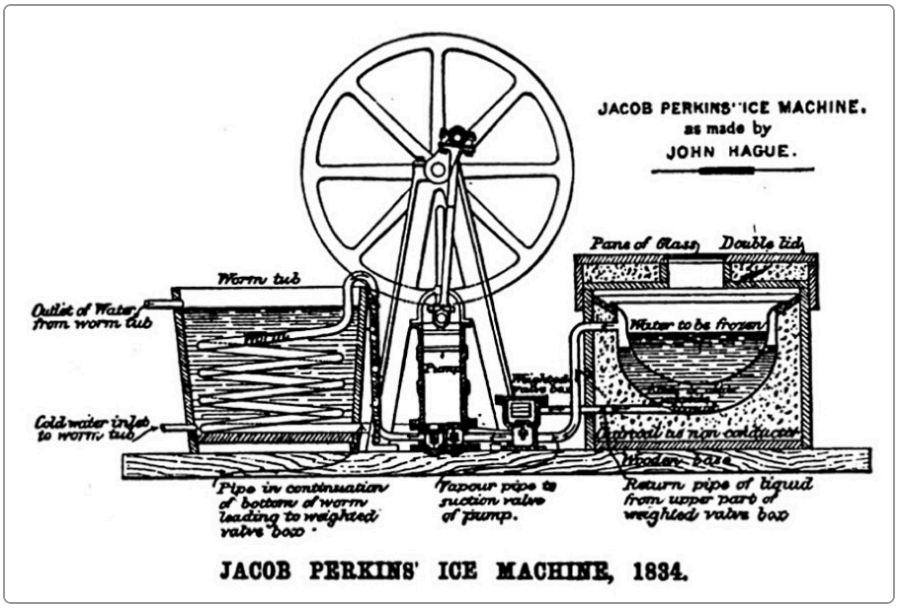
The science. The cycle depends on one fact: **a liquid's boiling point depends on pressure.** Water boils at 212 °F at sea level, near 200 °F on a high mountain, and above 250 °F in a pressure cooker. A refrigerant is chosen to boil far below room temperature at low pressure and to condense well above outdoor temperature at high pressure. (1) The **compressor** takes cool, low-pressure vapor and compresses it, like a bicycle pump, into hot, high-pressure vapor. (2) In the outdoor **condenser**, the vapor, hotter than the outside air, gives off heat and condenses to a warm liquid, releasing its latent heat. (3) The **metering device** drops the pressure suddenly; some liquid flashes to vapor and the mixture becomes very cold. (4) In the indoor **evaporator**, the cold refrigerant boils, absorbing latent heat from the house air blown across the coil, and the cooled air drops below its dew point, so water condenses and drains away. The refrigerant returns to the compressor and the cycle repeats. An air conditioner does not make cold; it **moves heat** from inside to outside.

In the shop. Capacity is rated in **tons**: one ton is 12,000 BTU/h, because melting a ton (2,000 lb) of ice absorbs $2{,}000 \times 144 = 288{,}000$ BTU, and spread over 24 hours that is 12,000 BTU/h. A typical house uses a 2- to 5-ton system; the model number often contains the capacity in thousands of BTU/h (for example "036" for 3 tons). Technicians check a system by measuring the **temperature split** (return air minus supply air, usually about 15–20 °F), pressures and superheat. Refrigerants in the United States have changed by regulation: R-22 was phased out of new equipment in 2010 and of production in 2020; R-410A followed; and since 2025 new systems use lower-impact refrigerants such as R-32 and R-454B, which are mildly flammable and need new practices.

Safety. Refrigerant handling legally requires **EPA Section 608 certification** in the United States. Students and homeowners never open, cut, braze or connect gauges to refrigerant lines. Refrigerant under pressure can cause frostbite and eye injury, and

a large leak indoors can displace oxygen. Turn off power at the thermostat and at the outdoor disconnect (an adult does this) before cleaning around an outdoor unit.

PICTURE STUDY



Jacob Perkins's Ice Machine, Frederick Bramwell (drawing), 1834 machine; drawing published 1883 · Engraving · *Scientific American*

Image: Wikimedia Commons, public domain

The engineer Frederick Bramwell drew this machine from Perkins's patent and the memories of men who saw it work. It contains every essential part of the refrigerator and air conditioner in your house.

Look closely

- Find the pump driven by the big flywheel. Which part of a modern system does it match?
- Find the coil in a tank of water. What is happening to the vapor inside it?
- Find the weighted valve box between the coil and the freezing box. What modern part does it match?
- Find the vessel where the water was frozen. Where is the heat going?

Talk about it

1. Perkins used ether as his refrigerant. Why would ether be a dangerous choice in a house today?
2. Trace the cycle on the drawing and name the phase (liquid or vapor) in each pipe.

3. Why do you think it took nearly seventy years after Perkins for cooling to become a business?

Safety first. Never open, cut, braze or attach gauges to refrigerant lines: that requires EPA Section 608 certification. Use rubbing alcohol for the warm-up only in a ventilated room away from flames. An adult turns off the thermostat and the outdoor disconnect before anyone clears debris around an outdoor unit, and no one touches the fan or fins.

SHOP PROJECT

Modeling and Measuring the Refrigeration Cycle

You will measure the two physical effects that make refrigeration work, evaporation cooling and compression heating, and then measure the performance of your own air conditioner (or refrigerator) from the outside: its temperature split, its nameplate capacity and its run time.

You will need

- Two inexpensive digital probe thermometers or one thermometer used twice
- Cotton balls, rubber bands, water and 70% rubbing alcohol (ventilated area, no flames)
- A small fan
- A bicycle pump and an old tire or ball
- Shop notebook and stopwatch

Steps

1. **Evaporation.** Wrap the thermometer probe tips in cotton; wet one with room-temperature water and one with rubbing alcohol. Place both in front of a fan. Record temperatures every 30 seconds for 5 minutes and graph them.
2. Explain the result using latent heat: which liquid evaporates faster and pulls more heat from the probe?
3. **Compression.** Pump a ball or tire firmly with 30 strokes, then hold a thermometer probe against the pump barrel near the bottom (or feel it). Record the temperature rise and explain where the heat came from.
4. **Your system.** With the air conditioner running for at least 15 minutes, measure the air temperature at a return grille and at the supply register nearest the indoor unit. Calculate the temperature split.
5. From the outdoor unit’s nameplate (read from a step away), record the model number, refrigerant type and electrical data. Find the capacity from the model number or the manual.

6. Time how many minutes per hour the outdoor unit runs on a hot afternoon. Estimate the heat removed per hour: capacity × fraction of time running.
7. If you have no central air conditioning, do steps 4–6 with your refrigerator: measure the air near the condenser coils and inside the box, and time its run cycles.
8. **Check your work.** Compare your split with the normal 15–20 °F range. If it is far outside, note it for a technician; do not adjust anything.

Tips

- Keep the thermometer out of direct sunlight outdoors.
- If the split is low and the filter is dirty, Lesson 6.5's filter change may fix it.

Check your work

- ☐ My evaporation graph shows alcohol cooling more than water, and I can explain why.
- ☐ I measured and interpreted my system's temperature split.
- ☐ I can trace the refrigerant around the cycle and say where heat enters and leaves.

SHOP NOTEBOOK

1. A cycle diagram with the four components, arrows for refrigerant flow, and labels for high and low pressure, hot and cold, liquid and vapor at each point.
2. Your evaporation graph with both curves.
3. Nameplate data and your calculations of capacity, run time and estimated heat removed.
4. A paragraph: "An air conditioner moves heat; it does not make cold," explained in your own words.

KEY FORMULAS

$$1\ \text{ton} = 12{,}000\ \text{BTU/h}$$

$$\text{EER} = \frac{\text{cooling (BTU/h)}}{\text{power (W)}}$$

$$\text{COP} = \frac{\text{heat moved}}{\text{work input}} = \frac{\text{EER}}{3.412}$$

$$\dot{Q}_{\text{cond}} = \dot{Q}_{\text{evap}} + \dot{W}_{\text{comp}}$$

From history. In 1925 Carrier's centrifugal refrigeration machines cooled the Rivoli Theatre in New York, and summer moviegoing became a habit. Carrier designed the first residential air-conditioning units in the late 1920s, but most American homes had no central air until after 1960.

WORKED EXAMPLES

Example 1. Show that one ton of cooling is 12,000 BTU/h. The latent heat of fusion of ice is 144 BTU/lb.

Show solution

1. Heat to melt one ton: $2{,}000\ \text{lb} \times 144\ \text{BTU/lb} = 288{,}000\ \text{BTU}$.
2. Spread over a day: $288{,}000/24\ \text{h} = 12{,}000\ \text{BTU/h}$.

Answer: 12,000 BTU/h: the cooling a ton of ice provided in a day, from the era of ice-house cooling.

Example 2. A 3-ton air conditioner draws 3,000 W. Find its capacity, EER and COP, and the heat rejected at the condenser.

Show solution

1. Capacity: $3 \times 12{,}000 = 36{,}000\ \text{BTU/h}$.
2. EER: $36{,}000/3{,}000 = 12.0\ \text{BTU/(W·h)}$.
3. COP: $12.0/3.412 = 3.5$: it moves 3.5 units of heat per unit of electricity.
4. Condenser: $36{,}000 + 3{,}000 \times 3.412 = 46{,}236\ \text{BTU/h}$ rejected outdoors.

Answer: 36,000 BTU/h; EER 12.0; COP 3.5; about 46,200 BTU/h leaves through the outdoor coil.

Example 3. On a humid day the indoor coil condenses 2.5 lb of water per hour. How much of the system's capacity goes to removing moisture (latent load)? Use 1,060 BTU/lb.

Show solution

1. Latent load: $2.5 \times 1{,}060 = 2{,}650$ BTU/h.
2. For a 2-ton (24,000 BTU/h) system: $2{,}650 / 24{,}000 = 11\%$ of its capacity.

Answer: About 2,650 BTU/h, roughly 11% of a 2-ton system's capacity, spent drying the air rather than cooling it.

PRACTICE

1. Easy Name the four main parts of the vapor-compression cycle in order, starting from the compressor.

   Show answer

   Compressor, condenser, metering device, evaporator.

2. Easy Where in the cycle does the refrigerant absorb heat from the house, and where does it give heat to the outdoors?

   Show answer

   It absorbs heat in the indoor evaporator and rejects it in the outdoor condenser.

3. Easy Why may a homeowner not add refrigerant to an air conditioner?

   Show answer

   Handling refrigerant requires EPA Section 608 certification; a low charge also means a leak that a technician must find and repair.

4. Medium A unit's model number contains "048." What is its likely capacity in BTU/h and tons?

   Show answer

   48,000 BTU/h, 4 tons.

5. Medium Why does water boil below 212 °F in Denver, and how does the same idea let a refrigerant boil cold?

Show answer

Lower pressure lowers the boiling point; the metering device drops the refrigerant's pressure so it boils at a low temperature in the evaporator.

6. Medium An air conditioner has EER 11. How much power does a 30,000 BTU/h unit draw?

Show answer

$30{,}000/11 = 2{,}727$ W.

7. Medium The return air is 76 °F and the supply air is 58 °F. Is the temperature split normal?

Show answer

18 °F, within the usual 15–20 °F range.

8. Hard A refrigerator moves 400 BTU/h out of its box using 75 W. Find its COP and the heat it adds to the kitchen.

Show answer

$75 \times 3.412 = 256$ BTU/h; COP $= 400/256 = 1.56$; kitchen gets 656 BTU/h.

9. Hard Why must the condenser be hotter than the outdoor air, and what happens to efficiency on a 105 °F day?

Show answer

Heat flows only from hot to cold, so the refrigerant must be compressed to a temperature above outdoor air; on a very hot day it must be compressed more, using more work for the same heat moved, so EER and COP fall.

10. Hard You are the technician. The indoor coil is covered with ice and the house is warm. Give two common causes a homeowner can check and two that need a certified technician.

Show answer

Homeowner: a clogged filter or closed or blocked returns and registers (low airflow). Technician: low refrigerant charge from a leak, a failed blower motor, a faulty metering device.

11. **Challenge** Carrier's printing-plant system was rated about 54 tons by some accounts (the cooling of about 108,000 lb of ice a day). Check that figure and convert it to BTU/h.

    Show answer

    $$54 \text{ tons} \times 2{,}000 \text{ lb} = 108{,}000 \text{ lb of ice per day; } 54 \times 12{,}000 = 648{,}000 \text{ BTU/h}.$$

COMMON MISTAKES

- Saying refrigerant is "used up"; it circulates in a sealed loop, and a low charge means a leak.
- Thinking the evaporator is outside; the indoor coil is the evaporator in cooling mode.
- Forgetting that the condenser rejects the house's heat plus the compressor's work.
- Confusing a ton of cooling with the weight of the unit.

> **Make it a game · Refrigerant Role Play.** Act as refrigerant: your parent names a point in the cycle, such as 'after the compressor'. You state the pressure, temperature and phase there (high pressure gas, hot) in five seconds, and then name the next component. Go around the loop twice. Speed up your second lap to beat your time.

6.4 Heat Pumps and Efficiency

OBJECTIVES

- Explain how a heat pump moves heat into a house in winter and out in summer, and the jobs of the reversing valve, defrost and backup heat.
- Calculate COP, compare it with the Carnot limit, and convert SEER and HSPF ratings.
- Compare heating costs per million BTU for different fuels and systems.
- Find a heat pump's balance point from a load line and a capacity line, and explain why sizing by calculation matters.

> **Warm-up.** Put your hand near the grille at the bottom or back of your refrigerator while it runs (not on the coils or fan). The air is warm. Where did that heat come from? Write a sentence explaining how the same machine could heat a house.

WATCH

Heat Pumps Explained - How Heat Pumps Work HVAC

The Engineering Mindset · 9:42

https://www.youtube.com/watch?v=QykwWs3L1W8

> **WHEN TO WATCH**
> After the science paragraph: air-source, water-source and ground-source heat pumps, with an animation of the reversing valve in heating and cooling modes.

Note: The video opens with a short sponsor message; you may skip it.

BACKUP VIDEO

How a Heat Pump Works | This Old House

This Old House · 8:37

https://www.youtube.com/watch?v=-vU9x3dFMrU

Before the worked examples: a technician shows real compressor, coils, reversing valve and expansion valve on a shop bench.

KEY TERMS

heat pump

A refrigeration system that can run in reverse, moving heat from outdoors into the house in winter and from the house to outdoors in summer.

reversing valve

A valve that swaps which coil receives the hot compressed gas, so the indoor coil becomes the condenser (heating) or the evaporator (cooling).

COP

Coefficient of performance: heat delivered divided by electrical energy used. Electric resistance heat has COP 1; heat pumps typically 2–4.

SEER2 and HSPF2

Seasonal ratings (revised in 2023): SEER2 is seasonal cooling BTU per watt-hour; HSPF2 is seasonal heating BTU per watt-hour.

balance point

The outdoor temperature at which a heat pump's capacity exactly equals the house's heat loss; below it, backup heat is needed.

Manual J

The ACCA standard method for calculating a home's heating and cooling loads room by room, used to size equipment.

CORE IDEAS

The story. In 1852 William Thomson, later Lord Kelvin, a devout Christian and one of the founders of thermodynamics, wrote that a machine working backward could warm a building with less fuel than burning the fuel directly; he called it a "heat multiplier." A few years later, in the 1850s, the Austrian engineer Peter von Rittinger built the first practical heat pump to recover heat for evaporating brine at a salt works. Home heat pumps waited for reliable compressors. In the late 1940s Robert C. Webber, an inventor in Indianapolis, is said to have touched the outlet pipe of his deep freezer, burned his hand, and wondered why that heat was wasted; he connected it to his water heater and then built a ground-source heat pump to heat his house. Heat pumps for homes spread in the 1950s and 1960s, and today's cold-climate models keep working below 0 °F.

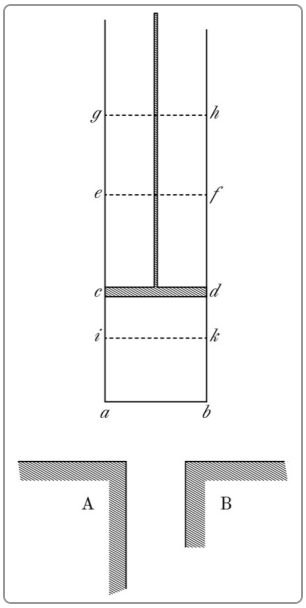
How they figured it out. Kelvin reasoned from Sadi Carnot's 1824 analysis of heat engines. A heat engine lets heat flow from hot to cold and takes some work out; a heat pump puts work in to push heat from cold to hot. Carnot and Kelvin showed that the best possible performance depends only on the two temperatures,

measured from absolute zero. Engineers learned the practical problems by testing: the outdoor coil ices up in winter and needs a **defrost** cycle that briefly runs the system backward; capacity falls as the outdoors gets colder, just when the house needs more heat; and oversized units short-cycle and fail to dehumidify in summer. Each problem led to a design answer: defrost controls, variable-speed "inverter" compressors and careful load calculation.

The science. A heat pump does not create heat; it **moves** it, so it can deliver more heat than the electrical energy it uses. Its performance is $\mathrm{COP} = Q_{\text{delivered}}/W$. The ideal (Carnot) limit for heating is $\mathrm{COP}_{\max} = T_{\text{hot}}/(T_{\text{hot}} - T_{\text{cold}})$ in kelvins. Moving heat from 32 °F (273 K) outdoors into a 95 °F (308 K) indoor coil has a limit of about 8.8; real machines reach roughly a third to a half of that. The colder it is outside, the bigger the temperature lift and the lower the COP. Electric resistance heat always has COP 1: each kWh gives 3,412 BTU. At COP 3, the same kWh delivers about 10,000 BTU. A ground-source heat pump draws heat from the earth a few feet down, which stays roughly between 45 and 75 °F year round depending on the region, so its lift and COP stay better in winter.

In the shop. A heat pump system is sized by a **Manual J load calculation**, not by a rule of thumb such as "one ton per 500 square feet." The technician adds the heat loss through every wall, window, ceiling and floor ($A\Delta T/R$, from Unit 4) plus air leakage, at the local winter design temperature. Plotting the house's heat loss against outdoor temperature (a falling line) and the heat pump's capacity from the maker's table (a rising line) shows the **balance point.** Below it, electric resistance strips or a gas furnace (a "dual-fuel" system) make up the difference. Ratings help compare models: an HSPF2 of 7.5 means a seasonal average COP of about $7.5/3.412 = 2.2$. Whether a heat pump, a furnace or both is the best choice depends on the climate, the price of electricity and fuel, and the house; it is an engineering and cost decision for each family.

PICTURE STUDY



Carnot's Engine, Figure 1, Sadi Carnot, 1824 · Diagram (redrawn from the original engraving) · *Réflexions sur la puissance motrice du feu*, Paris

Image: Wikimedia Commons, public domain

Sadi Carnot was a young French military engineer who wanted to know how much work a steam engine could possibly produce. His little book of 1824, with this plain diagram, founded the science of thermodynamics. Run backward, his ideal engine is an ideal heat pump.

Look closely

- Find the cylinder and piston. What happens to the gas when the piston moves out, and when it moves in?
- Find the hot body and the cold body Carnot imagined touching the cylinder in turn.
- Notice how little detail the drawing has. Why might a simple diagram help a thinker see the essential idea?
- Imagine the steps run in reverse. Where would heat be taken in and where given out?

Talk about it

1. Carnot showed that the best possible engine depends only on the two temperatures. How does that same idea set the limit for a heat pump's COP?
2. Why does a smaller temperature difference make a heat pump work better?

3. What can a few lines on paper accomplish that a real machine cannot?

Safety first. Look at outdoor units only with an adult and from a step away; never put hands or tools near the fan or fins, and never open panels. Before clearing leaves or snow from around an outdoor unit, an adult turns off the thermostat and the outdoor disconnect switch. Refrigerant work requires EPA Section 608 certification.

SHOP PROJECT

Sizing a Heat Pump: Load Line, Capacity Line and Balance Point

You will estimate your house's heat loss at its local winter design temperature, draw its load line, plot a real heat pump's capacity from a manufacturer's published data, find the balance point, and compare yearly heating costs for several systems with your local prices. This is a paper design project; no equipment is touched.

You will need

- Graph paper or a spreadsheet
- Your house measurements (or a floor plan) and insulation estimates (Unit 4)
- Your local winter design temperature (from an HVAC reference or your local building department)
- A heat pump's published performance table (from any manufacturer's website)
- Your local electricity and fuel prices from bills
- Calculator

Steps

1. Measure or estimate the areas of walls, windows, doors, ceiling and floor of your house. Assign each an R-value (Unit 4).
2. Calculate the heat loss at design conditions: $\sum A \Delta T / R$ for each surface plus air leakage using $0.018 \times \text{volume} \times \text{ACH} \times \Delta T$ (use 0.5 air changes per hour for an average house).
3. Draw the load line on a graph of BTU/h versus outdoor temperature, from the design load at the design temperature to zero at 65 °F.
4. Choose a heat pump and copy its heating capacity at 47 °F, 17 °F and 5 °F (if given). Plot its capacity line.
5. Find the balance point where the lines cross, and the backup heat needed at the design temperature.

6. Using your local prices, calculate the cost per million BTU for resistance heat, a heat pump at COP 2.5, and whatever fuel your house uses now (gas, propane or oil, with its efficiency).
7. Write a one-page recommendation: what size of heat pump, whether backup heat or a dual-fuel system would be needed, and what the trade-offs are for your climate and prices.
8. **Check your work.** Compare your load with your existing furnace's output. Older furnaces are often much larger than the load; explain why that might be.

Tips

- Your load will be approximate; a professional Manual J uses room-by-room detail.
- Keep units straight: BTU/h, °F and ft² go together.

Check your work

☐ My load and capacity lines are plotted correctly with labeled axes and units.

☐ I found the balance point and the backup heat at design temperature.

☐ My cost comparison uses real local prices and correct efficiencies.

SHOP NOTEBOOK

1. Diagrams of the heat pump in heating and in cooling mode, showing the reversing valve and which coil is condenser and which evaporator.
2. Your load-line and capacity-line graph with the balance point marked.
3. A table of cost per million BTU for each heating option at your prices.
4. What I would recommend for my house, and why.

KEY FORMULAS

$$\text{COP} = \frac{Q_{\text{delivered}}}{W}$$

$$\text{COP}_{\text{Carnot,heating}} = \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cold}}} \text{ (kelvins)}$$

$$\text{COP}_{\text{seasonal}} = \frac{\text{HSPF}}{3.412}$$

$$\text{cost per MMBTU} = \frac{\text{price per unit}}{\text{BTU per unit} \times \text{efficiency}} \times 10^6$$

From history. The 2023 change from SEER and HSPF to SEER2 and HSPF2 was not a change in machines but in the test: the new procedure uses higher external static pressure in the ducts, closer to real houses, so the new numbers are lower for the same unit. Always compare ratings measured by the same test.

WORKED EXAMPLES

Example 1. Compare the cost of 1 million BTU of delivered heat from (a) electric resistance (COP 1), (b) a heat pump with seasonal COP 2.8, at \$0.15/kWh, and (c) a 95% gas furnace with gas at \$1.40/therm.

Show solution

1. (a) kWh needed: $10^6/3{,}412 = 293$ kWh; cost $= 293 \times 0.15 = \$43.96$.
2. (b) $293/2.8 = 104.7$ kWh; cost $= \$15.70$.
3. (c) therms: $10/0.95 = 10.53$; cost $= 10.53 \times 1.40 = \$14.74$.

Answer: \$43.96, \$15.70 and \$14.74 per million BTU. At these prices the heat pump and the gas furnace are close; resistance heat is about three times as expensive.

Example 2. Find the Carnot heating COP when a heat pump moves heat from outdoor air at 20 °F into an indoor coil at 100 °F. Convert to kelvins: $K = (^\circ F - 32) \times 5/9 + 273.15$.

Show solution

1. $T_{\text{cold}} = (20 - 32) \times 5/9 + 273.15 = 266.5$ K.
2. $T_{\text{hot}} = (100 - 32) \times 5/9 + 273.15 = 310.9$ K.
3. $\text{COP}_{\max} = 310.9/(310.9 - 266.5) = 310.9/44.4 = 7.0$.

Answer: An ideal limit of 7.0; a real unit might reach about 2.5 at these conditions.

Example 3. A house loses 40,000 BTU/h at a design temperature of 5 °F and nothing at 65 °F (assume a straight line). A 3-ton heat pump delivers 36,000 BTU/h at 47 °F and 22,000 BTU/h at 17 °F (assume a straight line). Find the balance point.

Show solution

1. House load: $L = 40{,}000 \times (65 - T)/60 = 666.7\,(65 - T)$.
2. Capacity: slope $= (36{,}000 - 22{,}000)/30 = 466.7$ per °F, so $C = 22{,}000 + 466.7\,(T - 17)$.
3. Set equal: $666.7(65 - T) = 22{,}000 + 466.7(T - 17)$, giving $43{,}333 - 666.7T = 14{,}067 + 466.7T$.
4. $29{,}267 = 1{,}133.3T$, so $T \approx 25.8$ °F. Load there: $666.7 \times 39.2 \approx 26{,}100$ BTU/h.

Answer: A balance point of about 26 °F; below that, backup heat is needed (at 5 °F the heat pump gives about 16,400 BTU/h, so about 23,600 BTU/h of backup).

Example 4. A 36,000 BTU/h cooling system runs an equivalent of 1,200 full-load hours a summer. Compare yearly electricity for SEER2 14 and SEER2 18 at \$0.15/kWh.

Show solution

1. Seasonal cooling: $36{,}000 \times 1{,}200 = 43.2 \times 10^6$ BTU.
2. SEER2 14: $43.2 \times 10^6 / 14 = 3.09 \times 10^6$ Wh $= 3{,}086$ kWh, \$463.
3. SEER2 18: 2,400 kWh, \$360.

Answer: About \$103 a year saved by the higher rating.

PRACTICE

1. Easy What does the reversing valve do?

   Show answer

   It sends the compressor's hot gas to the indoor coil for heating or to the outdoor coil for cooling, swapping the roles of condenser and evaporator.

2. Easy Why can a heat pump deliver more heat energy than the electricity it uses?

Show answer

It moves existing heat from outdoors rather than making it; the electricity only drives the compressor.

3. Easy What is the COP of electric baseboard heat?

Show answer

1: each kWh of electricity becomes 3,412 BTU of heat.

4. Medium A heat pump uses 2.5 kW to deliver 27,000 BTU/h. Find its COP.

Show answer

$27{,}000/(2.5 \times 3{,}412) = 3.2$.

5. Medium Convert HSPF2 8.1 to a seasonal COP.

Show answer

$8.1/3.412 = 2.4$.

6. Medium Why does a heat pump's outdoor coil need a defrost cycle?

Show answer

In heating mode it runs below freezing and below the dew point of outdoor air, so frost builds up and blocks airflow; the system briefly reverses to melt it.

7. Medium Conceptual: why does a heat pump's heating capacity fall as outdoor temperature falls?

Show answer

Colder outdoor air means lower refrigerant pressure and density at the compressor inlet, so less refrigerant is moved per stroke, and the temperature lift is larger.

8. Hard Find the Carnot heating COP for a ground-source heat pump moving heat from 50 °F ground water into a 100 °F coil, and compare with an air-source unit at 0 °F.

Show answer

Ground: $310.9/(310.9 - 283.15) = 11.2$. Air at 0 °F (255.4 K): $310.9/55.5 = 5.6$. The ground source has half the lift and a much higher limit.

9. Hard Oil costs \$3.80/gal (138,500 BTU/gal) in an 85% boiler. Find the cost per million BTU delivered and compare with Worked Example 1.

   Show answer

   $3.80/(138{,}500 \times 0.85) \times 10^6 = \$32.28$ per MMBTU, more than the heat pump or gas, less than resistance.

10. Hard You are the technician. A customer's new heat pump runs nearly nonstop at 10 °F and the auxiliary heat light is on. Is something wrong? Explain.

    Show answer

    Probably not: below the balance point the heat pump cannot meet the load alone, so it runs continuously and the auxiliary strips help. Check that the filter is clean, the outdoor coil is not iced, and the defrost works; if the house cannot stay warm, the system may be undersized.

11. Challenge Using the house and heat pump of Worked Example 3, find the heat pump's capacity and the backup heat needed at 0 °F, and the electricity for backup heat in kW.

    Show answer

    Load: $666.7 \times 65 = 43{,}300$ BTU/h. Capacity: $22{,}000 + 466.7(0 - 17) = 14{,}070$ BTU/h. Backup: $29{,}200$ BTU/h $= 8.6$ kW of resistance heat.

COMMON MISTAKES

- Using °F instead of kelvins in the Carnot formula.
- Thinking COP above 1 breaks conservation of energy; the extra heat comes from outdoors.
- Sizing by square footage alone; insulation, windows, air leakage and the local weather all change the load enormously.
- Comparing fuels by price per unit instead of price per delivered BTU.

> **Make it a game · COP Quick Math.** Your parent supplies heat delivered and electricity used, such as 12,000 BTU per hour and 1000 watts of input. Compute the COP in 30 seconds, then compare it with a Carnot limit for temperatures your parent chooses. Explain why a heat pump gets less efficient in the cold. Five problems; track your accuracy.

6.5 Air Flow, Ducts, Filters and Maintenance

OBJECTIVES

- Calculate airflow (CFM) from velocity and area and heat delivered from Q = 1.08 × CFM × ΔT, and use the guideline of about 400 CFM per ton.
- Explain static pressure, filter resistance and MERV ratings, and why a clogged or overly restrictive filter harms a system.
- Explain duct leakage and how ducts are sealed, and trace the thermostat from Warren Johnson to programmable controls.
- Carry out a safe homeowner filter-and-airflow inspection and start a maintenance log, and describe the HVAC technician's career.

> **Warm-up.** Hold a single tissue in front of a supply register and then in front of a return grille while the system runs. Which way does it move at each? Count the supply registers and the return grilles in your house. Predict what would happen to airflow if half the registers were closed.

WATCH

Ductwork sizing, calculation and design for efficiency - HVAC Basics + full worked example

The Engineering Mindset · 17:39

https://www.youtube.com/watch?v=5y_VBiTiuAY

> **WHEN TO WATCH**
> After the science paragraph: how engineers turn room loads into airflows, size each duct and reduce pressure losses in fittings.

Note: The worked example is in metric units for a small commercial building; follow the method, not the numbers. Skip the sponsor segment about simulation software in the middle.

BACKUP VIDEO

How to Choose the Right Furnace Air Filter | This Old House

This Old House · 3:20

https://www.youtube.com/watch?v=_k6N3g_swog

Before the shop project: filter sizes, the airflow arrow and the trade-off between filtering and airflow.

KEY TERMS

CFM

Cubic feet per minute of airflow. Residential systems move roughly 350–450 CFM per ton of cooling.

static pressure

The pressure the blower must overcome to push air through filters, coils and ducts, measured in inches of water column (in. w.c.); many residential blowers are designed for about 0.5 in. w.c. total.

MERV

Minimum Efficiency Reporting Value (ASHRAE 52.2), from 1 to 16: higher numbers catch smaller particles but may add resistance to airflow.

duct leakage

Air lost through unsealed joints and seams; leaky ducts in attics or crawl spaces can lose 20–30 percent of the air a system moves.

mastic

A thick paste brushed onto duct joints (often over fiberglass mesh) to seal them permanently; ordinary cloth duct tape fails within a few years.

thermostat

The control that switches heating and cooling to hold a set temperature; from bimetal and mercury switches to programmable and connected electronic models.

CORE IDEAS

The story. Warren S. Johnson taught science at the State Normal School in Whitewater, Wisconsin. In the early 1880s the school's classrooms were heated by a steam boiler, and the custodian had to walk from room to room, knocking on doors and opening or closing dampers. Johnson invented an electric "tele-thermoscope" that signaled the boiler room when a classroom was too hot or too cold, and in 1883 he patented an electric heat regulator that controlled the dampers automatically. In 1885 he founded the Johnson Electric Service Company, now Johnson Controls, and in 1895 he patented a multi-zone temperature-control system using compressed air to move valves in each room. In the same years Albert Butz's "damper flapper" led, through several companies, to Honeywell. In 1953 Honeywell's T86 Round thermostat, designed with Henry Dreyfuss, became one of the best-known household objects in America.

How they figured it out. Johnson used the fact that a strip of two different metals bonded together bends when warmed, because one expands more than the other. The bending strip closed a contact and signaled or switched the heat. Engineers who designed forced-air systems later learned, by measuring, that the thermostat is only the brain: if the air cannot get where it is sent, the best control in the world cannot make a room comfortable. Studies by national laboratories and utilities in the 1980s and 1990s, using blower-door and duct-blaster tests, found that many American duct systems leaked a fifth or more of their air into attics and crawl spaces. That led to duct-sealing standards in building codes and to the static-pressure measurements technicians now make.

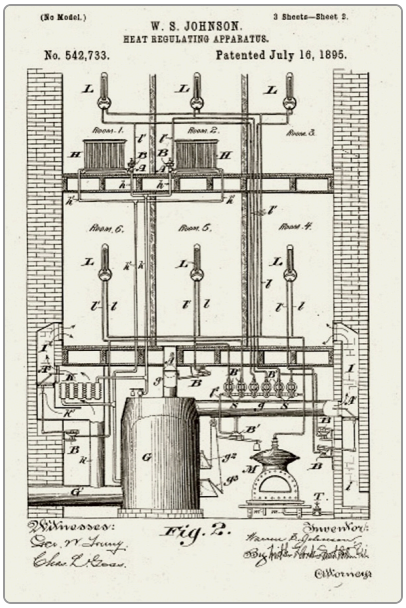
The science. Airflow is velocity times area: $\mathrm{CFM} = v \times A$, with v in feet per minute and A in square feet. The heat carried by air is $\dot{Q} = 1.08 \times \mathrm{CFM} \times \Delta T$ (BTU/h), where 1.08 comes from air's density and specific heat ($0.075 \times 0.24 \times 60$). A blower can move air only against a limited **static pressure**. Every filter, coil, duct and bend adds resistance; when the resistance rises, airflow falls. A clogged or very dense filter starves the system: in cooling, the evaporator gets too cold and ices over; in heating, the heat exchanger overheats and the high-limit switch shuts the burners off. That is why the right filter is a balance between catching dust and letting air through. Pleated filters of about MERV 8 to 11 suit most homes; higher MERV filters should be used only where the system is designed for them, often with a deeper filter cabinet.

In the shop. A homeowner maintenance routine: check the filter monthly and change it every one to three months (sooner with pets or construction dust), with the airflow arrow pointing toward the blower; keep supply registers and return grilles open and unblocked; keep 2 feet clear around the outdoor unit and hose its fins gently from the inside out only with the power off; check that the condensate drain flows and keep its line clear; replace thermostat batteries; test CO alarms; and have a qualified technician service heating and cooling equipment each year. Ducts in unconditioned spaces should be sealed with mastic or foil tape listed for ducts and insulated. A programmable thermostat set back 7–10 °F for 8 hours a day can save around 10 percent of heating and cooling energy in many homes, according to the U.S. Department of Energy.

On the job. HVAC technicians install, maintain and repair heating, cooling, ventilation and refrigeration systems in homes, offices, hospitals, schools and

factories. Most train through a trade-school program (often six months to two years) or an apprenticeship of three to five years, and every technician who handles refrigerant must hold EPA Section 608 certification (Type I, II, III or Universal). Many also earn NATE certification and state licenses. The U.S. Bureau of Labor Statistics reported a median pay of about $57,000 for HVAC mechanics and installers in 2023, with strong demand expected. It is skilled, needed work, and every comfortable, safe room is the result of it.

PICTURE STUDY



Johnson's Temperature Control System, Warren S. Johnson, 1895 · Patent drawing · U.S. Patent 542,733, "Heat Regulating Apparatus"

Image: Wikimedia Commons, public domain

This drawing shows Johnson's system for controlling the temperature of each room separately. The American Society of Mechanical Engineers has named it a historic engineering landmark.

Look closely

- Find the thermostats in the rooms. What do they sense, and what do they control?
- Follow the lines from the thermostats to the valves. What carries the signal?
- Find the radiators or heating units. How does each room get its own control?
- Find the boiler (G) in the basement and the valves near it. Why use one central source and many room controls?

Talk about it

1. How is this system like the zoned systems and smart thermostats in houses today?
2. Why would a school or office building especially benefit from controlling each room?

3. Johnson's problem began with a custodian walking room to room. What problem in your house could a better control solve?

Safety first. Before changing a filter or clearing a condensate drain, turn off power at the thermostat and at the furnace or air-handler service switch, with an adult present. Never open the blower or burner compartments or reach into the outdoor unit; never work on refrigerant lines or gas lines.

SHOP PROJECT

A Home HVAC Filter-and-Airflow Inspection and Maintenance Log

You will carry out the routine maintenance a homeowner can safely do, measure the airflow and temperatures that show how the system is working, and begin a maintenance log for your home. This inspection and log become the core of your unit portfolio.

You will need

- A replacement filter of the correct size (read it from the old filter)
- Flashlight
- Digital thermometer
- Tissue or a strip of light paper (or a vane anemometer if available)
- Tape measure
- Phone camera
- Shop notebook or a printed log sheet

Steps

1. With an adult, set the thermostat to OFF and switch off the furnace or air-handler service switch. Wait for the blower to stop.
2. Remove the filter. Photograph it, record its size, MERV or rating and the date written on it, and note how dirty it is. Install the new one with the arrow toward the blower, write today's date on its frame, and close the filter door.
3. Restore power and set the system to run. Measure the temperature at the return grille and at each supply register after 15 minutes; calculate the temperature rise (heating) or drop (cooling) at each.
4. Measure each register's opening and check airflow with the tissue or anemometer. Calculate CFM where you have velocities. Note any registers that are closed, blocked by furniture or weak.
5. Where ducts are visible (basement or utility room), look without touching for disconnected joints, crushed sections, or old cloth duct tape that has failed.
6. Outdoors, with the power off at the disconnect (adult), clear leaves and debris 2 feet around the unit by hand from the outside; do not reach inside.

7. Find the condensate drain line and check that water flows when the system is cooling; note any standing water or algae.
8. Begin a maintenance log with dates and tasks for the year: filter checks, CO alarm tests, outdoor unit clearing, condensate checks and professional service.
9. **Check your work.** Compare your temperature rise with the range printed on the furnace nameplate (often 35–65 °F). If it is outside the range, or any room is far weaker than others, record it for a technician.

Tips

- Buy filters in a multi-pack and write the next change date on the furnace with a marker.
- Do not use the tissue near the outdoor fan; it is for indoor registers only.

Check your work

☐ I changed the filter with the power off and the arrow pointing the right way.

☐ I measured temperatures and calculated airflow for each register.

☐ My maintenance log lists every task with a date and who does it.

SHOP NOTEBOOK

1. A floor plan with every supply and return marked, with its measured temperature and airflow.
2. A labeled diagram of a forced-air system: return grille, filter, blower, heat exchanger or coil, supply plenum, trunk, branches, registers.
3. Your maintenance log for the year.
4. Notes from a short interview with an HVAC technician (or answers from the BLS Occupational Outlook Handbook): training, certifications, daily work, what they like about the trade.

KEY FORMULAS

$$\text{CFM} = v \times A$$

$$\dot{Q} = 1.08 \times \text{CFM} \times \Delta T$$

$$\text{CFM} \approx 400 \times \text{tons}$$

$$v_{\text{face}} = \frac{\text{CFM}}{A_{\text{filter}}}$$

> **From history.** Johnson also built a tower clock company and experimented with steam automobiles. His firm installed temperature controls in the U.S. Capitol and the Smithsonian; the multi-zone principle in his 1895 patent is still the basis of building controls today.

WORKED EXAMPLES

Example 1. A supply register has a free opening of 0.60 ft^2, and a vane anemometer reads an average of 500 ft/min. Find the airflow.

Show solution

1. $\text{CFM} = v \times A = 500 \times 0.60 = 300$ CFM.

Answer: 300 CFM.

Example 2. A furnace moves 1,200 CFM. Return air is 68 °F and supply air is 118 °F. Find the heat delivered, and compare with a nameplate output of 64,000 BTU/h.

Show solution

1. $\Delta T = 118 - 68 = 50\ ^\circ\text{F}$.
2. $\dot{Q} = 1.08 \times 1{,}200 \times 50 = 64{,}800\ \text{BTU/h}$.
3. That matches the nameplate output within about 1%, a sign the airflow is about right.

Answer: About $64{,}800\ \text{BTU/h}$, consistent with the furnace's rated output.

Example 3. A 3-ton system should move about 400 CFM per ton. Its 16 × 25 inch filter has a face area of how much, and what is the face velocity? Many filters are rated at 300 ft/min.

Show solution

1. Airflow: $3 \times 400 = 1{,}200$ CFM.
2. Area: $16 \times 25 = 400$ in^2 $= 400/144 = 2.78$ ft^2.
3. Face velocity: $1{,}200/2.78 = 432$ ft/min, well above 300 ft/min, so the filter's resistance will be high.
4. A 20 × 25 filter (3.47 ft^2) gives 346 ft/min; two returns or a deeper media filter would do better.

Answer: 2.78 ft^2 and about 430 ft/min: undersized for this system, especially with a high-MERV filter.

Example 4. Ducts in an attic leak 25% of the air from a furnace delivering 64,000 BTU/h. The family pays $900 a year for heating. Estimate the yearly cost of the leaked heat and the value of sealing that cuts leakage to 5%.

Show solution

1. Heat lost now: $0.25 \times 64{,}000 = 16{,}000$ BTU/h; cost share about $0.25 \times \$900 = \$225$ a year.
2. After sealing: $0.05 \times \$900 = \$45$.
3. Savings: about $180 a year, plus better comfort in the rooms at the ends of the ducts.

Answer: About $225 a year lost now, and roughly $180 a year saved by sealing (a rough estimate; the furnace will also run less).

PRACTICE

1. Easy Which way should the arrow on a furnace filter point?

   Show answer

   Toward the blower and furnace, the direction the air flows.

2. Easy Name four homeowner maintenance tasks for a forced-air system.

Show answer

Change the filter, keep registers and returns open, keep the outdoor unit clear, keep the condensate drain clear, test CO alarms, schedule yearly professional service.

3. Easy What certification does every technician who handles refrigerant need?

Show answer

EPA Section 608 certification.

4. Medium A return grille of $2.0\ \text{ft}^2$ has an average velocity of 450 ft/min. Find the CFM.

Show answer

900 CFM.

5. Medium A 2.5-ton air conditioner should move about how many CFM?

Show answer

About 1,000 CFM (400×2.5).

6. Medium An air conditioner moves 1,000 CFM with a 19 °F temperature drop. Find its sensible cooling.

Show answer

$1.08 \times 1{,}000 \times 19 = 20{,}520\ \text{BTU/h}$.

7. Medium Conceptual: why can a MERV 16 filter make a house less comfortable in a system not designed for it?

Show answer

Its higher resistance reduces airflow, lowering capacity, freezing the coil in summer and tripping the high limit in winter.

8. Hard Why is closing the supply registers in unused rooms often a poor way to save energy in a forced-air system?

Show answer

It raises static pressure and lowers total airflow, can freeze coils or overheat the exchanger, and increases leakage from ducts; the furnace does not burn less fuel just because rooms are closed.

9. Hard Show where the 1.08 comes from in $\dot{Q} = 1.08 \times \text{CFM} \times \Delta T$.

Show answer

$0.075\ \text{lb/ft}^3 \times 0.24\ \text{BTU/(lb·°F)} \times 60\ \text{min/h} = 1.08$.

10. Hard You are the technician. A homeowner reports the upstairs bedrooms are hot in summer though the downstairs is cool, and the filter is new. List likely causes in order of what you would check.

Show answer

Closed or blocked registers and returns upstairs; disconnected, crushed or leaky ducts in the attic; undersized or missing return air from upstairs rooms; poor attic insulation; then a system or zoning design problem.

11. Challenge A setback thermostat lowers the heat from 70 °F to 62 °F for 8 hours each night. If heat loss is proportional to the inside–outside difference and the average outdoor temperature is 30 °F, estimate the fractional savings in heating energy.

Show answer

Normal: $40\ ^\circ\text{F} \times 24\ \text{h} = 960$ degree-hours. With setback:
$40 \times 16 + 32 \times 8 = 896$. Savings $\approx 64/960 = 6.7\%$ (more in milder weather).

COMMON MISTAKES

- Installing the filter backward or forgetting to restore power and the thermostat setting.
- Buying the highest-MERV filter on the shelf without checking whether the system can handle it.
- Using cloth duct tape to seal ducts; use mastic or listed foil tape.
- Closing many registers to “save energy,” which raises static pressure and lowers airflow.

> **Make it a game · Airflow Estimate Duel.** Your parent names a system of 3 tons and a temperature drop of 20 degrees. Estimate the airflow with 400 CFM per ton, then the heat moved with 1.08 times CFM times delta T. Closest guess wins before the calculator is out. Then say what a clogged filter does to static pressure and why.

> **Scripture.** “Be thou diligent to know the state of thy flocks, and look well to thy herds.” (Proverbs 27:23, KJV)
>
> A farmer who knew his flocks well caught trouble early; a homeowner who knows the state of the furnace, filters and alarms does the same. A maintenance log is a modern way of looking well to what you have been given.

UNIT 6

HVAC: Heating, Cooling and Air

Heating, ventilation and air conditioning keep a house comfortable, dry and safe. In this unit you will start with the physics of heat and humidity, from the Roman hypocaust and Franklin's fireplace to the dew point on your windows; follow fuel and fire through the modern furnace and boiler, with the carbon monoxide safety every household needs; trace the refrigeration cycle from Jacob Perkins and Willis Carrier to the air conditioner outside your house; see how a heat pump moves heat in both directions; and finish with the airflow, filters, ducts and controls that make it all work, and with the HVAC technician's trade.

You will measure temperatures, humidity, airflow and run times in your own home, calculate loads, capacities and costs, and leave the unit with a home HVAC inspection and a maintenance log you can keep using.

Safety rules for the whole unit. Refrigerant handling legally requires EPA Section 608 certification in the United States; students never open refrigerant lines. Turn off power at the thermostat and at the furnace or air-handler switch (and the outdoor disconnect) before changing a filter, clearing a drain or cleaning around equipment. No work on gas lines, burners or vents. If you smell gas, leave the house and call the gas company from outside. Keep working carbon monoxide alarms on every level and outside sleeping areas.

PREREQUISITES

- Algebra I: formulas, proportions, graphing lines and finding where two lines cross
- Unit 4 of this course: R-value and heat loss, $Q = A \cdot \Delta T / R$
- Unit 5 of this course: power, $P = VI$, and electrical safety

MASTERY CHECKLIST

- ☐ I can explain conduction, convection, radiation, relative humidity and dew point, and use $Q = mc\Delta T$ and BTU conversions.
- ☐ I can explain how a furnace and a boiler work, calculate output from AFUE and hydronic heat from flow, and explain CO and gas safety.
- ☐ I can trace the refrigeration cycle and calculate tons, EER and COP.
- ☐ I can explain how a heat pump heats and cools, compare costs per million BTU and find a balance point.
- ☐ I can calculate CFM and air-side heat, choose a filter sensibly, and explain duct leakage and static pressure.
- ☐ I can safely change a filter, inspect my home's system and keep a maintenance log, and I know which work belongs to a certified or licensed technician.

OPTIONAL KITS FOR THIS UNIT

- **First Alert carbon monoxide and smoke alarms**: Maker of UL-listed CO and combination alarms with end-of-life dates printed on each unit (Lesson 6.2). Kidde and other listed brands are equally good; the important thing is working alarms in the right places.
- **Fluke infrared thermometers**: Optional for the comfort survey (Lesson 6.1) and register temperatures (Lesson 6.5). An inexpensive digital probe thermometer and hygrometer are enough.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

6.1	**Heat, Humidity and Comfort**	3 sessions of 50 minutes
6.2	**Furnaces, Boilers and Combustion Safety**	3 sessions of 50 minutes
6.3	**The Refrigeration Cycle**	3 sessions of 50 minutes
6.4	**Heat Pumps and Efficiency**	3 sessions of 50 minutes
6.5	**Air Flow, Ducts, Filters and Maintenance**	3 sessions of 50 minutes

Unit 6 test

Answer every question. Calculators are allowed. Show your work and write units on every number. Use 1 W = 3.412 BTU/h and 1 ton = 12,000 BTU/h. For explanations, use complete sentences. The test is worth 100 points.

1. **5 pts**
   Name the three modes of heat transfer and give a household example of each.

2. **6 pts**
   How much heat raises 50 gallons of water (8.34 lb/gal) from 50 °F to 120 °F? Give the answer in BTU and kWh.

3. **5 pts**
   Explain why a cold window fogs on a winter morning, using the terms relative humidity and dew point.

4. **6 pts**
   A furnace has an input of 100,000 BTU/h and an AFUE of 95%. Find its output in BTU/h and kW.

5. **5 pts**
   A boiler loop carries 6.0 gpm with a 20 °F drop. Find the heat delivered.

6. **10 pts**

   List the symptoms of carbon monoxide poisoning, three ways CO can enter a home, and what to do if a CO alarm sounds.

7. **4 pts**

   What should you do if you smell gas in the house?

8. **8 pts**

   Trace the refrigerant through the four main parts of an air conditioner, giving its phase and whether it is gaining or losing heat in each coil.

9. **6 pts**

   A 2.5-ton air conditioner draws 2,400 W. Find its capacity in BTU/h, its EER and its COP.

10. **4 pts**

    Why may students and homeowners not open refrigerant lines or add refrigerant?

11. **6 pts**

    Compare the cost per million BTU delivered for electric resistance heat and a heat pump with COP 3.0 at $0.13/kWh.

12. **6 pts**

    Find the Carnot heating COP for moving heat from 30 °F outdoor air into a 100 °F coil. Why is a real heat pump's COP lower?

13. **6 pts**

    A house loses 30,000 BTU/h at 10 °F and nothing at 65 °F. A heat pump delivers 24,000 BTU/h at 47 °F and 14,000 BTU/h at 17 °F (straight lines). Find the balance point.

14. **6 pts**

    A furnace blower moves 1,000 CFM with a 45 °F temperature rise. Find the heat delivered. A 14 × 20 inch filter serves it; find the face velocity.

15. **5 pts**

You are the technician. In July the indoor coil is iced and the filter is black with dust. Explain the chain of cause and effect and the first fix.

16. **12 pts**

Short essay (one or two paragraphs): Explain to a family why an air conditioner or heat pump is said to “move heat, not make cold,” and why the right size, a clean filter and yearly service matter more than buying the biggest unit. Mention one thing they can do themselves and one thing that requires a certified technician.

ANSWER KEY

1. Conduction (bare feet on tile), convection (warm air rising from a register), radiation (feeling the cold of a window or the warmth of sunlight).
2. $417 \times 70 = 29{,}190$ BTU; $29{,}190 / 3{,}412 = 8.6$ kWh.
3. Room air near the glass cools; when the glass is below the air's dew point, the air there reaches 100% RH and water vapor condenses on it.
4. 95,000 BTU/h; 27.8 kW.
5. $500 \times 6.0 \times 20 = 60{,}000$ BTU/h.
6. Headache, dizziness, nausea, confusion, flu-like illness in several people that improves away from home. Sources: cracked heat exchanger, blocked or disconnected flue, backdrafting water heater, car or generator running in or near the house, misuse of a range or grill. Get everyone into fresh air and call 911; do not go back in until the fire department says it is safe.
7. Leave at once with everyone; do not use switches, phones or flames inside; call the gas company or 911 from outside.
8. Compressor: low-pressure vapor compressed to hot high-pressure vapor. Condenser (outdoor): vapor loses heat and condenses to liquid. Metering device: pressure drops, liquid partly flashes, becomes cold. Evaporator (indoor): liquid boils to vapor, gaining heat from house air. Back to the compressor.
9. 30,000 BTU/h; EER 12.5; COP 3.66.
10. Federal law (EPA Section 608) requires certification to handle refrigerant; it is under pressure, can cause frostbite, and must not be vented.
11. Resistance: $293 \times 0.13 = \$38.09$. Heat pump: \$12.70.
12. $T_c = 272.0$ K, $T_h = 310.9$ K; $\text{COP}_{\max} = 310.9 / 38.9 = 8.0$. Real machines have friction, pressure drops, finite temperature differences in the coils, fan power and defrost losses.
13. Load $= 545.5(65 - T)$; capacity $= 14{,}000 + 333.3(T - 17)$.
    $35{,}455 - 545.5T = 8{,}333 + 333.3T$; $T = 30.9\ ^\circ\text{F}$.
14. $1.08 \times 1{,}000 \times 45 = 48{,}600$ BTU/h. Area $= 280 / 144 = 1.94$ ft^2; velocity $= 514$ ft/min, high; a larger filter would help.
15. The clogged filter cuts airflow; too little warm air crosses the evaporator, so the refrigerant stays very cold and the coil drops below freezing; moisture freezes and blocks airflow further. Turn the system off to thaw (fan on), replace the filter, and call a technician if it recurs.

16. A strong answer explains that refrigerant absorbs heat indoors by boiling at low pressure and rejects it outdoors by condensing at high pressure, driven by the compressor; that an oversized unit short-cycles, dehumidifies poorly and costs more, while a correctly sized unit from a load calculation runs long, steady cycles; that a clean filter keeps airflow and prevents iced coils or overheating; and that yearly service catches problems early. Homeowner: filter changes, clearing around the outdoor unit with power off, keeping registers open. Technician: anything involving refrigerant (EPA 608), gas, burners or electrical repairs.

PORTFOLIO PIECE: A HOME HVAC INSPECTION AND MAINTENANCE LOG

Assemble a complete record of your home's heating, cooling and air system: the comfort survey (Lesson 6.1); the heating-system and CO inspection with your family's emergency plan (6.2); your air conditioner or refrigerator measurements (6.3); your heat-pump sizing and cost study (6.4); and the filter-and-airflow inspection with register temperatures and CFM (6.5). End with a one-year maintenance log that your family will use, listing each task, how often, who does it (family or certified technician), and the date it was last done, plus a one-page summary of the three most valuable improvements you found.

LOOK FOR	WHAT IT MEANS
Measurements	Temperatures, humidity, airflow and run times measured carefully at the stated places and times, with units.
Calculations	Output from AFUE, CFM and air-side heat, COP and cost comparisons and the balance point are correct.
Safety	CO alarms checked and mapped, emergency plan written, power turned off before filter work, and every gas, burner or refrigerant issue referred to a qualified technician.
Maintenance log	Complete, realistic, dated and actually started.
Recommendations	Three improvements justified with your data and with cost, comfort and safety trade-offs.

UNIT 7

Welding: Science and Uses

Welding makes two pieces of metal into one. It holds together the ships, bridges, pipelines, skyscraper frames, trailers, tractors and car bodies of the modern world, and it is one of the most needed skilled trades. In this unit you will learn the science underneath it: how an electric arc makes a plasma hotter than the surface of the sun, how heat input and cooling rate change steel's grains, why the weld pool must be shielded from air, and how welds are sized, distorted, inspected and sometimes fail.

The stories run from Tubal-cain and the village forge through Davy's arc, Benardos, Thomson and Kjellberg, to the Liberty ships and Constance Tipper's discovery of brittle fracture. You will not weld in this course unless you are in a supervised school, community-college or professional shop with a qualified instructor. Instead you will survey real welds, heat-treat steel nails, solder a copper pipe joint, load-test model "weld beads," write a hot-work plan and interview a working welder.

PREREQUISITES

- Algebra I: formulas, unit conversions and solving for a variable
- Unit 1: stress $\sigma = F/A$, tension and shear, factor of safety
- Unit 2: joint loads (shear, tension, peel, cleavage)
- Unit 5: $P = VI$ and Ohm's law

MASTERY CHECKLIST

- ☐ I can tell the history of welding from the forge weld to the coated electrode and explain what each step solved.
- ☐ I can calculate arc power and heat input and explain how heat input and cooling rate affect the weld and heat-affected zone.
- ☐ I can describe stick, MIG, flux-core, TIG, oxy-fuel and spot welding, read an electrode code, and choose a process for a job.
- ☐ I can calculate the throat and strength of a fillet weld, estimate shrinkage, and name common defects and inspection methods.
- ☐ I can explain welding hazards and protection, write a hot-work plan, and describe the paths into the welding trade.

OPTIONAL KITS FOR THIS UNIT

- **Miller Electric (welding information and education)**: A major American welding-equipment maker. Its site has free articles and videos on processes, safety and choosing equipment; useful background for Lessons 7.3 and 7.5. No purchase is needed for this unit.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

7.1	**Joining Metal: Forge Welding to the Electric Arc**	3 sessions of 50 minutes
7.2	**The Science of the Arc and the Weld Pool**	3 sessions of 50 minutes

7.3	**Welding Processes: Stick, MIG, Flux-Core, TIG, Oxy-Fuel and Spot**	3 sessions of 50 minutes
7.4	**Joints, Strength, Distortion and Defects**	3 sessions of 50 minutes
7.5	**Welding Safety, Uses and Careers**	3 sessions of 50 minutes

Unit 7 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   Explain the difference between welding, brazing and soldering.

2. **6 pts**
   Tell what each of these people contributed: Humphry Davy, Nikolay Benardos, Elihu Thomson, Oscar Kjellberg.

3. **6 pts**
   An arc runs at 26 V and 160 A for 90 s. Find its power and the energy delivered.

4. **7 pts**
   Find the heat input of a weld at 23 V, 180 A and 9 in/min, and the net heat input for MIG ($\eta = 0.8$).

5. **6 pts**
   A procedure limits heat input to 25 kJ/in. At 25 V and 200 A, what is the slowest allowed travel speed?

6. **6 pts**
   Explain why a small, fast weld on thick, cold, medium-carbon steel can crack, and what a welder does to prevent it.

7. **5 pts**

   Find the carbon equivalent of a steel with 0.25% C and 1.20% Mn (no other alloys).

8. **5 pts**

   Decode E7018 and explain why it is stored in a heated rod oven.

9. **6 pts**

   A spot weld uses 12,000 A for 0.15 s through 120 μΩ. Find the heat.

10. **6 pts**

    Choose a process for each and give a reason: (a) aluminum boat repair, (b) bulldozer bucket repair in a muddy field, (c) car body panel on an assembly line.

11. **7 pts**

    A 5/16-inch E70 fillet weld is 5 inches long. Find its throat and its allowable load at 21 ksi.

12. **7 pts**

    A tab must carry 12 kips through two 1/4-inch E70 fillets (3.71 kips/in each). How long must each be?

13. **5 pts**

    A 1.2 m steel bar is heated 400 °C above its surroundings. How much would it expand freely?

14. **6 pts**

    Name four non-destructive tests for welds and what each finds.

15. **6 pts**

    You are the tradesperson. A friend wants you to weld a bracket onto a galvanized trailer in his garage, next to the lawn mower and gas can. List what you would do before striking an arc.

16. **5 pts**

    An oxygen cylinder holds 244 ft^3 at 2,200 psi. The gauge reads 1,650 psi. How much oxygen is left?

17. **6 pts**

Short essay (one paragraph). Explain what the Liberty ships and Constance Tipper taught engineers about welding, materials and design.

ANSWER KEY

1. Welding melts the base metal (fusion), usually with a filler of the same kind. Brazing and soldering melt only a lower-melting filler that bonds to the unmelted base metal; brazing fillers melt above 450 °C (840 °F), solder below.
2. Davy showed the continuous electric arc (early 1800s); Benardos showed and patented carbon-arc welding (1881–1887); Thomson invented resistance welding (1886); Kjellberg patented the coated electrode (1907), which shielded the weld from air.
3. $P = 4160$ W; $E = 4160 \times 90 \approx 374{,}000$ J $= 374$ kJ.
4. $HI = \dfrac{60(23)(180)}{9000} = 27.6$ kJ/in; net 22.1 kJ/in.
5. $S = \dfrac{60(25)(200)}{1000(25)} = 12$ in/min.
6. The thick cold plate cools the weld and heat-affected zone very fast, forming hard, brittle martensite; hydrogen in that hard zone causes cracking. Preheat the steel, use low-hydrogen rods kept dry, clean the joint, and cool slowly.
7. $CE = 0.25 + 0.20 = 0.45$; preheat is likely needed.
8. Electrode, 70 ksi tensile strength, all positions, low-hydrogen iron-powder coating. The coating absorbs moisture from the air, which would put hydrogen into the weld and cause cracking.
9. $Q = (12{,}000)^2(1.2 \times 10^{-4})(0.15) \approx 2590$ J.
10. (a) TIG or MIG with argon: aluminum needs inert shielding and good heat control. (b) Stick or self-shielded flux-core: portable, works on dirty steel outdoors. (c) Resistance spot welding: fast, automatic, no filler, ideal for thin sheet.
11. Throat $0.707 \times 0.3125 \approx 0.221$ in; load $21 \times 0.221 \times 5 \approx 23.2$ kips.
12. Each carries 6 kips: $6 \div 3.71 \approx 1.6$ in; specify 2 in each.
13. $(12 \times 10^{-6})(1200)(400) = 5.76$ mm.
14. Visual (surface shape and defects), dye penetrant (surface cracks), magnetic particle (surface and near-surface cracks in steel), ultrasonic (internal flaws by echoes), radiography (internal porosity and slag on film).
15. Move the job outdoors or move all fuel and combustibles at least 35 ft away; grind the zinc from the weld area with a respirator and weld with ventilation; have an extinguisher and a fire watch for at least 30 minutes after; wear a helmet

with the correct shade, safety glasses, fire-resistant clothing, gloves and boots; secure cylinders; stand dry.

16. $244 \times \dfrac{1650}{2200} = 183\ \text{ft}^3$.
17. Model answer: The welded Liberty ships cracked, some breaking in two, mostly in cold water. Tipper showed that the ships' steel became brittle below a transition temperature near North Atlantic winter temperatures, and that cracks started at sharp hatch corners and weld notches. Because the welded hull was continuous, a crack could run all the way around. Engineers learned to test steel toughness at service temperature (the Charpy test), round off corners, add crack arrestors, train and inspect welders, and design the whole system, not just the joint.

PORTFOLIO PIECE: A WELD-JOINT TEST REPORT AND A WELDER INTERVIEW

Write a 3–4 page report that combines your work in this unit: the hot-glue joint test (with your data table, chart, throat calculations and failure modes, and how each failure models a real welding defect), your heat-treating results and what they mean for the heat-affected zone, and your hot-work plan for a real repair.

Add a one-page summary of your interview with a working welder, welding instructor or inspector, and finish with a paragraph on whether you would consider the trade and what path you would take into it. If you have the chance to weld in a supervised school or community-college lab, include photos and a description of your test coupons.

LOOK FOR	WHAT IT MEANS
Joint test	Fair test with consistent beads; peak loads, throat areas and strength per inch calculated correctly with units; failure modes identified.
Science	Correct explanation of heat input, cooling and the heat-affected zone, tied to the nail heat-treating results.
Safety plan	Hot-work permit covers radiation, fumes, fire watch, shock, coatings and cylinders, and was reviewed by a welder or instructor.
Interview	At least eight thoughtful questions; a clear summary of how the welder learned, certifications and daily work.
Communication	Organized report with labeled sketches, tables and a clear conclusion.

7.1 Joining Metal: Forge Welding to the Electric Arc

OBJECTIVES

- Explain what welding is and how it differs from bolting, riveting, brazing and soldering.
- Tell the story of welding from the blacksmith's forge weld through Davy's arc, Benardos, Thomson, Kjellberg and the oxy-acetylene torch.
- Calculate arc power and heat energy with $P = VI$, $E = Pt$ and $Q = mc\Delta T$.
- Survey welded objects around you and identify how they were joined.

> **Warm-up.** Look around your house, garage or street for five metal objects that are joined: a bicycle frame, a chair, a gate, a trailer hitch, a car exhaust, a mailbox post. For each, write whether the pieces are bolted, riveted, screwed, glued or welded, and what clue told you. Keep the list; you will use it in the shop project.

WATCH

Introduction to forge welding - basic blacksmithing

Black Bear Forge · 26:28

https://www.youtube.com/watch?v=j814AqiKVvE

> **WHEN TO WATCH**
> After the story. Watch the first 12 minutes closely (the welding heat, the flux and the scarf), and the rest if you have time. Notice the color of the steel when it is ready to weld.

Note: Black Bear Forge is a one-man blacksmith shop in Colorado; the smith wears eye protection and leather. The forge and the hammering are for trained adults only.

BACKUP VIDEO

Oxy-acetylene Welding & Cutting - Linde Air 1920s Instructional Film 41270 HD

PeriscopeFilm · 13:40

https://www.youtube.com/watch?v=lcNv67a2v2o

With the paragraph on the oxy-acetylene torch: a real 1920s instructional film from Linde Air Products, with title cards.

KEY TERMS

welding

Joining two pieces of metal by making them one piece at the joint, usually by melting them together (fusion) and often adding filler metal of the same kind.

forge welding

The oldest kind of welding: heating iron or steel nearly to melting in a forge and hammering the pieces together so the metal bonds in the solid state.

flux

A material (borax, sand, or the coating on a welding rod) that melts over the hot metal, dissolves oxide scale and keeps air away from the joint.

electric arc

A continuous spark: electric current flowing through hot, ionized gas between an electrode and the work, producing intense heat and light.

resistance welding

Welding by passing a large current through metal pieces clamped together; their electrical resistance heats the contact point (Elihu Thomson, 1886).

oxy-fuel welding

Welding with the flame of a fuel gas, usually acetylene, burned with pure oxygen.

CORE IDEAS

The story. For three thousand years the only way to make two pieces of iron into one was the forge weld. A smith heated both ends to a white heat, around 1,300 °C (about 2,400 °F) for wrought iron, sprinkled them with sand or borax, laid one on the other and struck quickly with the hammer. Every link of an anchor chain, every wagon tire and many ship fittings were joined that way. The Bible names the first of these craftsmen: Tubal-cain, “an instructer of every artificer in brass and iron.” Then, in the nineteenth century, electricity gave the smith a new fire. Humphry Davy showed at the Royal Institution in London in the first decade of the 1800s that current from a large battery would jump between two carbon rods in a brilliant, continuous arc. It took eighty years to turn that light into a tool.

How they figured it out. In 1881, at the International Exposition of Electricity in Paris, a Russian inventor, Nikolay Benardos, showed that a carbon-rod arc could melt the edges of two iron plates into a single piece. With his partner Stanisław

Olszewski he patented the process, which they called *Elektrogefest*, in Britain in 1885 and in the United States in 1887. In 1886 Elihu Thomson, an American engineer, found that passing a huge current through two bars pressed end to end heated the joint until they fused: resistance welding. Early arc welds with bare iron wire were brittle and full of holes, because air rushed into the molten metal. In 1907 a Swedish engineer, Oscar Kjellberg, who had been repairing ship boilers in Gothenburg and founded the company ESAB, patented an electrode with a *coating* that melted into a protective slag and gas. At almost the same time the French engineers Edmond Fouché and Charles Picard built a torch that burned acetylene with pure oxygen, the hottest common flame, above 3,000 °C. In Cleveland, John C. Lincoln (who founded Lincoln Electric in 1895) and his brother James built and sold arc welders and trained welders to use them.

The science. Welding works because metal atoms bond to any clean metal atoms they touch, whatever piece they came from. Two things stop that from happening at room temperature: the pieces never touch closely enough, and every metal surface is covered by a thin film of oxide. Heat solves the first problem: at a welding heat the metal is soft or liquid and flows together. Flux, slag or shielding gas solves the second by dissolving the oxide and keeping out oxygen and nitrogen from the air. An arc is a conductor made of gas: once the air between the electrode and the work is ionized, current flows through it and delivers power $P = VI$. A welding arc at 25 volts and 150 amperes delivers about 3,750 watts into a spot the size of a pencil eraser, which is why it melts steel in a moment.

In the shop. Most welding today is **fusion welding**: the edges of the base metal melt, often with a filler wire or rod, into a shared puddle that freezes as one piece. That is different from **brazing** and **soldering** (Lesson 7.3), where only a lower-melting filler melts and the base metal does not, and from bolting and riveting (Unit 1), where the pieces stay separate and are clamped together. A weld is permanent, can be as strong as the parts, makes a watertight or gas-tight joint, and needs no holes to weaken the plates. Its weaknesses are heat (which can warp parts and change the steel near the weld) and hidden flaws that only a trained welder and an inspector can prevent and find.

On the job. The welder you will meet in Lesson 7.5 descends directly from Tubal-cain and the village blacksmith. Blacksmiths still forge-weld today for ornamental

ironwork, tools and chain, and many modern welders learned to love metal at a forge.

PICTURE STUDY



An Iron Forge, Joseph Wright of Derby, 1772 · Oil on canvas · Tate Britain, London

Image: Wikimedia Commons, public domain

Joseph Wright of Derby painted the new industry of the English Midlands by the light it made. Here a bar of iron is being worked under a water-driven hammer, the same white heat a smith needs for a forge weld. Look at it as a metalworker would.

Look closely

- Find the source of all the light in the picture. What color is the hot iron, and what does that color tell a smith about its temperature?
- Find the large hammer. What do you think drives it? (Look at the shaft and the wheel at the edge.)
- Find the tongs. How is the worker holding the hot bar steady under the hammer?
- Look at the people standing back from the anvil. Where are they, and why?

Talk about it

1. Smiths judged temperature by color long before thermometers. Why would that only work in a dim shop?
2. Why does a forge weld need a hammer blow, while an arc weld does not?
3. What hazards in this shop are still hazards in a welding shop today?

> **Safety first.** This lesson involves no welding. If you visit a forge or welding shop, stay behind the line the smith or welder gives you, wear safety glasses, and never look at an arc without a proper welding filter: a few seconds can burn the eyes.

SHOP PROJECT

A Welded-Joint Survey

Engineers learn to read joints the way a doctor reads an X-ray. You will find, photograph and classify at least 15 metal joints in your home and town, decide how each was made, and collect the evidence in a table.

You will need

- Phone camera
- Shop notebook
- A magnifying glass
- A small magnet
- A tape measure or ruler
- Optional: a printed chart of weld bead types from a welding supplier's free guide

Steps

1. Make a table with columns: object, material (steel? aluminum? magnet test), joint type (bolted, riveted, screwed, glued, welded, brazed/soldered, crimped), process guess, evidence, bead length or fastener count.
2. Search the house and garage: chair and table frames, a bicycle, a lawn mower deck, a wheelbarrow, shelving, a grill, a trailer hitch, metal fence posts, plumbing.
3. Search the town (with an adult): playground equipment, a steel railing, a bridge or overpass, a trailer, a farm implement, a light pole base, a dumpster.
4. For each welded joint, look closely with the magnifier. Rippled "stacked coins" with a shine often mean TIG; a smooth, slightly convex bead with spatter dots nearby often means MIG; a rougher bead with chipped slag residue often means stick; round dimples in a row on sheet metal are resistance spot welds.
5. Measure the length of at least five weld beads and count spot welds on one panel.
6. Photograph each joint with a coin or ruler in the frame for scale.

7. Sort the table: which joining method was most common on thin sheet, on thick structural steel, on things that must come apart?
8. **Check your work.** Ask a welder, a shop teacher or a fabricator (or compare with photos in a welding supplier's guide) to check five of your process guesses. Record how many you got right.

Tips

- Spot welds are easiest to see on the inside of a car door jamb or on a metal shelf.
- Paint hides welds; look where paint is chipped.
- Do not climb on anything to see a joint.

Check your work

- ☐ I identified at least 15 joints and the evidence for each.
- ☐ I can explain why spot welds suit sheet metal and full beads suit structural steel.
- ☐ I can tell the story of the arc from Davy to Kjellberg.

SHOP NOTEBOOK

1. A timeline of welding from the forge weld to Kjellberg's coated electrode (1907) and the oxy-acetylene torch, with one sentence on what each inventor solved.
2. Your survey table, with a bar chart of how many joints of each type you found.
3. A labeled sketch of one welded joint from your survey: the two parts, the bead, and the direction of the load on it.

KEY FORMULAS

$P = VI$ (watts = volts × amperes)
$E = Pt$ (joules = watts × seconds)
$Q = mc\,\Delta T$ (heat to warm a mass m by ΔT)

From history. Russia, Sweden, France and America all claim a share of the invention of arc welding, and each is right: Benardos and Olszewski made the carbon arc work, C. L. Coffin in Detroit patented welding with a metal electrode in 1890, and Kjellberg made the electrode reliable. The new process spread quickly during the First World War for ship repair, and by the 1930s welded steel was replacing riveted steel in buildings, bridges and ships.

WORKED EXAMPLES

Example 1. A stick welder runs an arc at 24 V and 140 A. Find the arc power. How much heat energy does it deliver in a 45-second weld?

Show solution

1. Power: $P = VI = 24\ \text{V} \times 140\ \text{A} = 3360\ \text{W}$.
2. Energy: $E = Pt = 3360\ \text{W} \times 45\ \text{s} = 151{,}200\ \text{J} \approx 151\ \text{kJ}$.
3. For comparison, a 1,500 W hair dryer would need about 100 s to use that much energy, but it spreads it over a whole room of air instead of one small puddle of steel.

Answer: About 3.4 kW and 151 kJ.

Example 2. A blacksmith heats the last 10 cm of a 2.5 cm × 1.2 cm wrought-iron bar from 20 °C to a welding heat of 1,300 °C. Iron's density is 7.8 g/cm³; use an average specific heat of $0.60\ \text{J/(g}\cdot^\circ\text{C)}$. How much heat must the forge put into that end?

Show solution

1. Volume: $10 \times 2.5 \times 1.2 = 30\ \text{cm}^3$.
2. Mass: $m = 30\ \text{cm}^3 \times 7.8\ \text{g/cm}^3 = 234\ \text{g}$.
3. Heat: $Q = mc\Delta T = 234 \times 0.60 \times (1300 - 20) \approx 180{,}000\ \text{J} = 180\ \text{kJ}$.
4. A coal forge loses most of its heat to the air, so it burns far more fuel than this. That is one reason the arc, which puts its heat exactly where it is needed, replaced the forge in factories.

Answer: About 180 kJ for each end.

Example 3. Reasoning. A farmer's steel gate hinge has snapped. He can (a) bolt a steel strap across the break, (b) have it arc-welded, or (c) glue it with epoxy. Compare the three and recommend one.

Show solution

1. The hinge is loaded in bending and shear every time the gate swings, outdoors, in heat and cold.
2. (a) Bolting works and can be undone, but the holes weaken the strap and the bolts may loosen with vibration (Unit 1).
3. (b) A good fusion weld makes the hinge one piece again, needs no holes and will not loosen. It must be done by a trained welder, and the paint must be ground off first.
4. (c) Epoxy is weak in peel and cleavage (Unit 2) and softens in hot sun; it is the wrong choice for a working steel hinge.

Answer: Have it welded by a qualified welder; a bolted strap is an acceptable temporary repair.

PRACTICE

1. Easy Name the three main ways metal parts can be held together permanently, and give an everyday example of each.

   Show answer

   Welding (a steel bicycle frame), riveting (an aluminum ladder or aircraft skin), and adhesive bonding (a car panel or a glued trim strip). Bolting is also common but can be taken apart.

2. Easy An arc runs at 20 V and 90 A. Find its power.

   Show answer

   $P = 20 \times 90 = 1800$ W.

3. Easy What two problems must be overcome for two pieces of metal to bond, and how does a forge weld solve each?

Show answer

The surfaces must touch closely, and the oxide film must be removed. Heat softens the metal and the hammer presses it together; flux dissolves the oxide and keeps air out.

4. Medium A MIG welder delivers 4.2 kW to the arc. How much energy goes into a 2-minute weld?

Show answer

$E = 4200 \times 120 = 504{,}000 \text{ J} \approx 504 \text{ kJ}.$

5. Medium Why did Kjellberg's coated electrode make better welds than bare iron wire?

Show answer

The coating melted into slag and gas that shielded the molten metal from oxygen and nitrogen in the air, so the weld had fewer holes and was less brittle; it also steadied the arc.

6. Medium How much heat is needed to raise 500 g of steel from 20 °C to 1,500 °C ($c \approx 0.60 \text{ J/g}\cdot^\circ\text{C}$)?

Show answer

$Q = 500 \times 0.60 \times 1480 = 444{,}000 \text{ J} \approx 444 \text{ kJ}$ (and more to actually melt it).

7. Medium Elihu Thomson's resistance welder heats the joint, not the whole bar. Explain why, using $P = I^2R$.

Show answer

The same current flows through the whole circuit, but the contact between the two bars has the highest resistance, so that is where I^2R heating is greatest and the metal reaches welding heat first.

8. Hard Benardos's arc in 1881 was powered by banks of batteries. If his arc ran at 40 V and 200 A for 10 minutes, how many kilowatt-hours did it use? At 15 cents per kWh today, what would that cost?

Show answer

$P = 8 \text{ kW}$; $E = 8 \times \frac{10}{60} \approx 1.33 \text{ kWh}$; cost about 20 cents.

9. Hard **You are the tradesperson.** A customer brings a cracked cast-iron engine bracket and wants it “welded like steel.” What questions would you ask before deciding?

Show answer

Model answer: Is it really cast iron (spark test, file test)? Cast iron is brittle and cracks with fast heating and cooling, so it needs preheat, special nickel rods or brazing, and slow cooling. Is the part load-bearing or safety-critical? Is a replacement part cheaper and safer than a repair?

10. Hard Conceptual. Why is a weld usually better than a bolted joint for a pressure tank, and why is a bolted joint better for a bridge bearing that may need replacing?

Show answer

A weld is continuous and gas-tight with no holes to leak or weaken the shell. A bolted joint can be inspected, taken apart and replaced, which is valuable for parts that wear out.

11. Challenge A forge burns charcoal that releases about 30 kJ per gram. If only 5% of that heat reaches the iron, how many grams of charcoal are burned to bring the 234 g bar end of Worked Example 2 to welding heat (180 kJ)?

Show answer

Useful heat per gram: $0.05 \times 30 = 1.5$ kJ/g; charcoal needed $180 \div 1.5 = 120$ g. The arc puts most of its energy where it is needed, which is why it is so much more efficient.

COMMON MISTAKES

- Thinking any joint with a bead of metal is a weld; brazed and soldered joints look similar but the base metal never melted.
- Forgetting that the oxide film, not just the cold, is what stops metal from bonding.
- Confusing power (watts) with energy (joules): the arc’s power times the time gives the heat delivered.

Make it a game · Joining Method Sort. Write welding, brazing, soldering, bolting and riveting on cards. Your parent reads descriptions such as 'base metal melts' or 'filler flows by capillary action'. You hold up the correct card in three seconds. Then recite the welding history timeline: forge, Davy, Benardos, oxy-acetylene. This is a spoken game only. Beat your streak.

Scripture. “And Zillah, she also bare Tubal-cain, an instructer of every artificer in brass and iron” (Genesis 4:22, KJV)

Metalworking is among the oldest crafts named in Scripture, and Tubal-cain is remembered as a teacher. Skilled trades have always been passed on from master to apprentice.

7.2 The Science of the Arc and the Weld Pool

OBJECTIVES

- Explain the welding arc as a plasma and describe how electrode polarity changes where the heat goes.
- Calculate weld heat input from volts, amps and travel speed, and explain how it affects the weld.
- Describe the fusion zone and heat-affected zone and what happens to steel's grains when it is heated and cooled.
- Explain why oxygen, nitrogen and hydrogen must be kept out of the weld pool, and how flux and shielding gas do it.

> **Warm-up.** Hold a steel paper clip with pliers and bend it back and forth until it breaks. Feel the bend: it gets warm. Now look at the broken ends with a magnifier. Write down what you see and predict: if you heated one end red-hot and cooled it quickly in water, would it bend more easily or snap sooner?

WATCH

Welding 101 for Hobbyists (and Nerds)

Practical Engineering · 10:18

https://www.youtube.com/watch?v=ZZvMsnSUDqo

> **WHEN TO WATCH**
> Before the science paragraphs. Grady Hillhouse explains what welding is, the types of heat sources and the main arc processes, and shows his first beads.

Note: A sponsor message for an online lecture service runs near the end; you can stop there.

BACKUP VIDEO

How Arc Welding Works

Edison Tech Center · 1:50

https://www.youtube.com/watch?v=TeBX6cKKHWY

With the paragraph on the arc: a short clip from an old General Electric training film with animation of metal droplets crossing the arc.

KEY TERMS

plasma

Gas so hot that some electrons are stripped from their atoms; it conducts electricity. The core of a welding arc is a plasma, thousands of degrees hot.

polarity

Which way current flows in a DC arc. Electrode positive (DCEP) puts more heat into the electrode and gives deep penetration with most stick and MIG; electrode negative (DCEN) is used for TIG to keep the tungsten cool.

heat input

The arc energy delivered per unit length of weld: $HI = \frac{60VI}{1000S}$ kJ/in, with S the travel speed in in/min.

fusion zone

The part of the joint that melted and froze again: weld metal made of filler and melted base metal.

heat-affected zone (HAZ)

The band of base metal next to the weld that did not melt but was heated enough to change its grain structure and properties.

shielding

Keeping air away from the molten pool with flux, slag or a shielding gas such as argon, carbon dioxide or a mix.

CORE IDEAS

The story. In the 1920s welding engineers had a puzzle. Their arc welds looked solid, yet some cracked, some were full of tiny bubbles, and some were as brittle as glass. At General Electric, the chemist Irving Langmuir (who later won the Nobel Prize in Chemistry) studied what gases did in hot arcs and invented atomic-hydrogen welding in 1926. In the 1930s, aircraft builders needed to weld magnesium and aluminum, which burn fiercely and grab oxygen instantly. In 1941 Russell Meredith at Northrop Aircraft developed a way to shield a tungsten arc with helium, a process that became TIG welding. Both stories teach the same lesson: the weld pool is a tiny steel furnace, and its chemistry matters as much as its heat.

How they figured it out. Metallurgists cut welds in half, polished and etched them with acid, and looked under the microscope. They saw three regions: the **weld metal** in the middle, with long grains that had grown inward from the cooler edges as it froze; next to it, a **heat-affected zone** where the base metal never melted but its grains had grown coarse or turned hard; and then the unchanged base metal. They

measured hardness across the weld, found where cracks began, and tested what happened when they changed the current, the speed and the shielding. Those experiments are behind every welding procedure written today.

The science. An arc starts when the electrode touches the work and is drawn back. Current heats the tip, electrons are boiled off it, and they ionize the gas into a **plasma** whose core can reach 6,000 to 20,000 °C, far above steel's melting point of about 1,500 °C. Electrons crash into the positive side and dump their energy there, so with DC the positive pole gets more of the heat. The welder controls the heat with volts (arc length), amps (current) and travel speed. Engineers combine them as the **heat input**, $HI = \dfrac{60\,VI}{1000\,S}$ in kJ per inch, where S is the travel speed in inches per minute. Only part of it reaches the metal: the arc efficiency η is about 0.8 for stick and MIG and about 0.6 for TIG. Too little heat input gives poor fusion and fast cooling that can harden the steel; too much gives a wide, weak heat-affected zone, coarse grains and more warping.

Grains and hardness. Steel is iron with a little carbon. Above about 727 °C its crystal structure changes and the carbon dissolves. If it cools slowly, the carbon comes back out as soft layered pearlite. If it cools very fast, as when cold base metal sucks heat out of a small weld, the carbon is trapped in a hard, brittle structure called martensite. That is exactly what a blacksmith does on purpose when he quenches a chisel, and exactly what a welder must avoid in a structural joint. The more carbon and alloy in the steel, the easier it hardens; engineers measure this with the **carbon equivalent**, $CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$. Above about 0.40–0.45, the steel usually needs **preheat** so it cools more slowly.

Keeping air out. Molten steel dissolves gases. Oxygen forms oxides and makes bubbles; nitrogen makes the weld brittle; hydrogen (from water, oil, rust or damp electrodes) diffuses into the hardened heat-affected zone and causes cracks hours or days later. That is why welders clean joints to bright metal, store low-hydrogen rods such as E7018 in heated ovens, and choose the shielding: the flux coating of a stick rod, the flux inside a flux-cored wire, argon and carbon dioxide for MIG, or pure argon for TIG.

In the shop. A welding procedure specification (WPS) lists every one of these variables: the steel, the filler, the shielding, the volts, amps and travel speed range, the preheat, and the heat input limits. A welder who follows it, and an inspector who

checks it, can promise that a weld will behave like the test welds that were broken in the lab.

PICTURE STUDY



Welder Making Boilers for a Ship, Alfred T. Palmer, U.S. Office of War Information, June 1942 · Color transparency photograph · Library of Congress, Prints and Photographs Division

Image: Wikimedia Commons, public domain

Alfred Palmer took some of the first color photographs of American industry for the government in 1942. This welder is joining thick steel parts for a ship's boiler, a pressure vessel where a bad weld could be deadly. Look at how he controls the heat and protects himself.

Look closely

- Find the arc. Where is the brightest point, and what is the welder holding?
- Look at the sparks and the smoke. Which way is the fume plume rising, and how close is it to his face?
- Find every piece of protective gear the welder is wearing.
- Look at the thickness of the boiler plate. Would it cool a small weld quickly or slowly?

Talk about it

1. A boiler holds steam at high pressure. Why would its welding procedure set strict limits on heat input, preheat and electrode type?
2. Why do you think the welder's face shield has such a dark lens?

3. If this plate were cold, what could happen to the heat-affected zone of a small, fast weld?

Safety first. The heat-treating project uses a propane torch: an adult must run it outdoors on a non-flammable surface (bricks or concrete), with safety glasses, leather gloves, long cotton sleeves, a bucket of water and a fire extinguisher at hand. Hot steel looks exactly like cold steel; handle every sample with pliers until it has cooled in water.

SHOP PROJECT

Heat-Treating a Steel Nail

The steel next to a weld goes through the same heating and cooling a blacksmith uses to harden and soften steel. You will see it happen in nails: an ordinary low-carbon nail and a hardened masonry (concrete) nail, which contains more carbon. You will anneal, quench and temper them, then test them with a file and a bend test.

You will need

- Six hardened masonry nails (about 2 in) and six common steel nails of similar size
- A propane torch (adult only) and a brick or two to rest work on
- Locking pliers or tongs; a bench vise
- A coffee can of water for quenching; a can of dry sand or wood ash for slow cooling
- An old metal file
- Safety glasses, leather gloves, cotton clothing
- A protractor; a magnifier; a marker

Steps

1. Label two of each kind of nail "A – as received." File-test each: draw the file across the shank. Does it bite and leave a mark, or skate across? Bend one in the vise until it cracks or reaches 90° and record the angle.
2. **Predict.** For each treatment below, predict whether each nail will be harder or softer than as received, and which kind of nail will change more.
3. **B – anneal (adult).** Heat two of each nail to a bright cherry red (until a magnet no longer sticks: that is about 770 °C) and push them into the sand or ash to cool slowly over 20 minutes.
4. **C – quench (adult).** Heat two of each to the same nonmagnetic cherry red and plunge them straight down into the water.
5. **D – quench and temper (adult).** Take one quenched nail of each kind, polish one side bright with sandpaper, and heat it gently from the head end until a

light straw color creeps along the polished side (about 220 °C). Let it cool in air.

6. File-test every sample and score hardness from 1 (file bites easily) to 5 (file skates). Bend-test one of each in the vise and record the angle at which it cracks or the angle reached without cracking.
7. Snap a quenched masonry nail in the vise (wrap it in a rag; pieces fly) and look at the broken face with the magnifier. Compare it with the bent, annealed nail.
8. Make a table: nail type × treatment × file score × bend angle × appearance of the break. Which combination was hardest? Which was toughest?
9. **Connect it.** Explain in your notebook what this tells you about a small, fast weld on thick, cold, higher-carbon steel, and why welders preheat such steel.
10. **Improve it.** Repeat the temper at a darker color (purple or blue, about 280–300 °C) and see whether the nail becomes tougher.

Tips

- Use a magnet on a stick to find the nonmagnetic temperature; it keeps your hands back from the flame.
- Quench straight down, not sideways, to reduce warping.
- If you have no torch or adult helper, ask a shop teacher, a blacksmith or a community-college welding lab to run steps 3–5 with you.

Check your work

- ☐ I can explain why the low-carbon nail barely hardened.
- ☐ My table shows hardness and toughness for each treatment.
- ☐ I can connect quenching to hardening in the heat-affected zone of a weld.

SHOP NOTEBOOK

1. A labeled cross-section of a fillet weld showing the weld metal, fusion line, heat-affected zone and unaffected base metal, with arrows for how heat flowed out of the pool.
2. Your heat-treating data table and a short paragraph on what surprised you.
3. A chart of the gases that harm a weld (oxygen, nitrogen, hydrogen), what each does, and how welders keep each out.

KEY FORMULAS

$HI = \dfrac{60\,V I}{1000\,S}$ (kJ/in; V volts, I amps, S in/min)
$HI_{\text{net}} = \eta \cdot HI$ ($\eta \approx 0.8$ stick/MIG, ≈ 0.6 TIG)
$HI = \dfrac{V I}{1000\,v}$ (kJ/mm; v in mm/s)
$CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}$

From history. Irving Langmuir's atomic-hydrogen torch broke hydrogen molecules apart in an arc and let them recombine on the metal, releasing intense heat. It was soon replaced by simpler processes, but the research behind it, and Russell Meredith's helium-shielded "Heliarc" of 1941, led directly to the TIG torches used on aircraft, racing frames and food-grade stainless steel today.

WORKED EXAMPLES

Example 1. A welder runs a MIG bead at 24 V and 200 A with a travel speed of 12 in/min. Find the heat input and the net heat input to the plate ($\eta = 0.8$).

Show solution

1. Heat input: $HI = \dfrac{60(24)(200)}{1000(12)} = \dfrac{288{,}000}{12{,}000} = 24\ \text{kJ/in}.$
2. Net: $0.8 \times 24 = 19.2\ \text{kJ/in}.$

Answer: 24 kJ/in gross, about 19 kJ/in into the plate.

Example 2. The procedure for a bridge girder limits heat input to 30 kJ/in. The welder slows down to 8 in/min to fill a wide joint, keeping 24 V and 200 A. Is he within the limit? What is the slowest speed he may use?

Show solution

1. At 8 in/min: $HI = \dfrac{60(24)(200)}{1000(8)} = 36\ \text{kJ/in}$, over the limit.
2. Set $HI = 30$ and solve for S: $S = \dfrac{60(24)(200)}{1000(30)} = 9.6\ \text{in/min}.$
3. To fill the joint he should run more passes at 9.6 in/min or faster, not one slow, hot pass.

Answer: No (36 kJ/in); he must travel at least 9.6 in/min.

Example 3. A steel has 0.20% C, 1.00% Mn, 0.10% Cr, 0.05% Mo, 0.10% Ni and 0.15% Cu. Find its carbon equivalent. Will it probably need preheat?

Show solution

1. $CE = 0.20 + \frac{1.00}{6} + \frac{0.10+0.05+0}{5} + \frac{0.10+0.15}{15}$
2. $= 0.20 + 0.167 + 0.030 + 0.017 = 0.414.$
3. That is near the 0.40–0.45 range, so thick sections of it would usually need preheat; the welding code and the steel's thickness decide exactly how much.

Answer: $CE \approx 0.41$; preheat is likely for thick parts.

Example 4. In metric: a TIG weld on stainless steel runs at 12 V, 110 A and 2.5 mm/s. Find the heat input in kJ/mm and the net heat input.

Show solution

1. $HI = \dfrac{12 \times 110}{1000 \times 2.5} = \dfrac{1320}{2500} = 0.53 \text{ kJ/mm}.$
2. Net: $0.6 \times 0.53 \approx 0.32 \text{ kJ/mm}.$

Answer: About 0.53 kJ/mm gross, 0.32 kJ/mm net.

PRACTICE

1. Easy Find the heat input for 22 V, 150 A and 10 in/min.

   Show answer

   $$HI = \frac{60(22)(150)}{1000(10)} = 19.8 \text{ kJ/in}.$$

2. Easy What is the difference between the fusion zone and the heat-affected zone?

   Show answer

   The fusion zone melted and froze again (weld metal); the heat-affected zone did not melt but was heated enough to change its grain structure.

3. Easy Why must a welder clean rust, oil and paint off a joint before welding?

Show answer

They release oxygen, hydrogen and other gases into the pool, causing porosity, oxides and hydrogen cracking, and they keep the arc from fusing cleanly.

4. Medium A welder doubles his travel speed and keeps volts and amps the same. What happens to the heat input?

Show answer

It is cut in half, because heat input is inversely proportional to travel speed.

5. Medium Find the net heat input for a stick weld at 25 V, 125 A and 6 in/min ($\eta = 0.8$).

Show answer

$HI = 31.25$ kJ/in; net $0.8 \times 31.25 = 25$ kJ/in.

6. Medium In metric, find the heat input for 28 V, 250 A and 6 mm/s.

Show answer

$\dfrac{28 \times 250}{1000 \times 6} \approx 1.17$ kJ/mm.

7. Medium Why does TIG welding usually use DC electrode negative?

Show answer

With electrode negative, most of the heat goes into the work and less into the tungsten, so the tungsten stays cool and does not melt into the weld.

8. Hard A procedure allows 18–28 kJ/in. At 26 V and 180 A, what range of travel speeds is allowed?

Show answer

Fast limit at 18 kJ/in: $S = \dfrac{60(26)(180)}{18{,}000} = 15.6$ in/min; slow limit at 28 kJ/in: $S \approx 10.0$ in/min. Allowed range about 10.0–15.6 in/min.

9. Hard Find the carbon equivalent of a steel with 0.45% C, 0.75% Mn and no other alloys. Would you expect it to need preheat?

Show answer

$CE = 0.45 + 0.125 = 0.575$; yes: it hardens easily and needs preheat and controlled cooling (this is a medium-carbon steel like many axles and shafts).

10. Hard **You are the tradesperson.** A new welder's stick welds on a cold January morning keep cracking a few hours after he finishes. The rods were stored in an open box in the truck. What is the likely cause, and what would you change?

Show answer

Hydrogen cracking: damp low-hydrogen rods put hydrogen into a fast-cooled, hard heat-affected zone. Use rods from a heated rod oven, clean and dry the joint, preheat the steel, and let it cool slowly.

11. Hard Conceptual. Why can a weld on thin sheet metal and a weld on a thick plate made with the same settings behave so differently?

Show answer

Thick plate draws heat away much faster, so the weld cools quickly and can harden or fail to fuse; thin sheet heats up, so the same settings can burn through or warp it.

12. Challenge A welder must keep heat input under 1.5 kJ/mm. His machine runs at 30 V. If he travels at 5 mm/s, what is the most current he can use? If he needs 280 A for good fusion, how fast must he travel?

Show answer

From $HI = \dfrac{VI}{1000v}$: $I_{\max} = \dfrac{1.5 \times 1000 \times 5}{30} = 250$ A. At 280 A: $v = \dfrac{30 \times 280}{1000 \times 1.5} = 5.6$ mm/s or faster.

COMMON MISTAKES

- Forgetting the 60 in the heat-input formula, which converts minutes to seconds.
- Thinking more heat always makes a stronger weld. Too much heat input coarsens grains, widens the heat-affected zone and causes warping.
- Thinking the heat-affected zone melted. It did not; it was only heated enough to change.
- Storing low-hydrogen electrodes in the open; they pick up moisture from the air.

Make it a game · Heat Input Calculator. Your parent gives volts, amps and travel speed, such as 24 volts, 200 amps and 6 mm per second. Calculate heat input in joules per millimeter in 45 seconds, then say what happens to the heat-affected zone if travel speed doubles. This is paper math only, with no equipment in use. Five rounds, beat your time.

7.3 Welding Processes: Stick, MIG, Flux-Core, TIG, Oxy-Fuel and Spot

OBJECTIVES

- Describe how stick (SMAW), MIG (GMAW), flux-core (FCAW), TIG (GTAW), oxy-fuel and resistance spot welding work, and what each is best for.
- Read an electrode classification such as E7018 and a welder's duty-cycle rating.
- Calculate spot-weld heat with $Q = I^2Rt$ and explain how brazing and soldering differ from welding.
- Choose a joining process for a job and justify the choice.

> **Warm-up.** Make three columns: "thin," "medium," "thick." Sort these jobs into them: a car fender, a farm trailer frame, a bicycle frame, a pipeline, an aluminum boat, a stainless kitchen sink, a bulldozer bucket, a copper water pipe. Next to each, guess whether it should be done indoors or outdoors, and why that might matter.

WATCH

5 Types of Welding Explained: MIG, TIG, Stick, Flux Core & Oxy Acetylene

TimWelds · 14:38

https://www.youtube.com/watch?v=5M9I_bBrnZ0

> **WHEN TO WATCH**
> Before the descriptions of each process. Pause at each chapter and add a line to your process table: heat source, shielding, filler, what it is good for.

Note: A short promotion for the presenter's paid courses appears at the start and end.

BACKUP VIDEO

4 Types of Welding Explained: MIG vs TIG vs Stick vs Flux Core

TimWelds · 11:26

https://www.youtube.com/watch?v=y-OKi8oSNQ4

If you want a second, slower look at the four arc processes, especially the difference between gas-shielded MIG and self-shielded flux-core.

KEY TERMS

SMAW (stick welding)

Shielded metal arc welding: a flux-coated rod is the electrode and the filler; the coating makes gas and slag to shield the weld. Simple, portable and good outdoors and on dirty steel.

GMAW (MIG welding)

Gas metal arc welding: a solid wire fed continuously through a gun is the electrode and filler, shielded by gas such as 75% argon / 25% CO_2. Fast and easy to learn; poor in wind.

FCAW (flux-core)

Flux-cored arc welding: like MIG but the wire is a tube filled with flux. Self-shielded wire needs no gas and works outdoors; it leaves slag.

GTAW (TIG welding)

Gas tungsten arc welding: a non-melting tungsten electrode makes the arc, argon shields it, and the welder adds filler rod by hand. Slow but precise and clean; best for thin metal, stainless and aluminum.

resistance spot welding

Clamping sheets between copper electrodes and passing a very large current for a fraction of a second; the heat I^2Rt melts a small nugget. Used for car bodies.

brazing and soldering

Joining with a filler metal that melts below the base metal, which does not melt. Brazing fillers melt above 450 °C (840 °F); soldering fillers melt below it.

CORE IDEAS

The story. Welding processes multiplied when industry needed them. Stick welding with Kjellberg's coated rods built the welded ships and buildings of the 1930s and 1940s. In 1948, researchers at the Battelle Memorial Institute with the Air Reduction Company introduced gas metal arc welding, feeding a continuous bare wire through a gun under inert gas, first for aluminum; it became MIG welding, which today does most factory welding. Flux-cored wire followed in the 1950s for outdoor construction. Meanwhile car makers adopted Elihu Thomson's resistance welding; a modern car body is held together by several thousand spot welds, most of them made by robots.

How they figured it out. Each process answers the same three questions differently: *Where does the heat come from? What shields the molten metal? Where does the filler come from?* Stick: the arc; the rod's coating; the rod itself. MIG: the arc; a gas from a

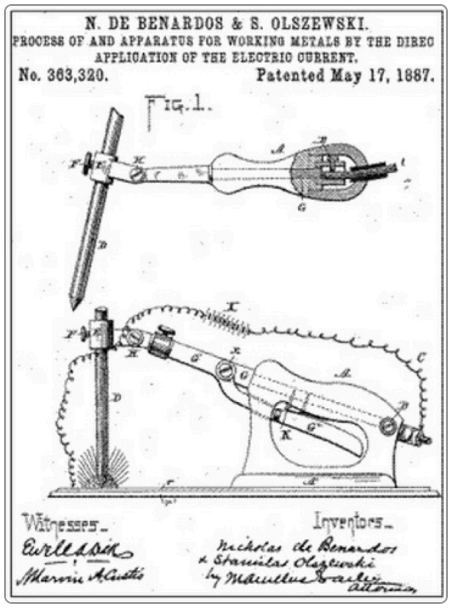
cylinder; the wire. Flux-core: the arc; the flux inside the wire (plus gas, for some wires); the wire. TIG: the arc from a tungsten that does not melt; argon; a separate rod fed by hand. Oxy-fuel: a flame of acetylene and oxygen; the flame's own gases; a rod. Spot welding: electrical resistance; the clamped sheets themselves; no filler at all. Engineers then tested each for speed, quality, cost and how hard it is to learn.

The science. In spot welding, the copper electrodes have very low resistance and are water-cooled, while the contact between the two steel sheets has the highest resistance. The heat $Q = I^2Rt$ is greatest there, so a nugget of molten steel forms between the sheets while the outside stays solid. Because the current is squared, doubling it gives four times the heat, which is why spot welders use currents near 10,000 amperes for about a fifth of a second. In **brazing** and **soldering**, the base metal never melts. The filler is drawn into a thin, tight gap by **capillary action**, the same force that lifts water up a paper towel, and bonds to the clean, fluxed surfaces. A plumber "sweating" a copper joint uses tin-based solder that melts near 220–230 °C, far below copper's 1,085 °C.

In the shop. Electrodes and wires are named by a code. In **E7018**, E means electrode, 70 means the weld metal's tensile strength is at least 70,000 psi (70 ksi), 1 means it can weld in all positions, and 8 describes the coating (low-hydrogen, iron powder) and current. A MIG wire marked **ER70S-6** is a rod or electrode (ER), 70 ksi, solid (S), with extra deoxidizers (6) for slightly dirty steel. Every machine has a **duty cycle**: "30% at 90 A" means it may weld 3 minutes out of every 10 at 90 amperes before it must cool.

Choosing. Thin car sheet metal: MIG or spot welding. A farm repair on rusty steel in the wind: stick or self-shielded flux-core. Aluminum or stainless: MIG with argon, or TIG. Bicycle frames and aircraft tubing: TIG. A pipeline: stick for the root and hot passes, often flux-core or automatic welding for the fill. Copper plumbing: soldering or brazing. A cutting job: an oxy-fuel torch or a plasma cutter. The tradesperson's skill is matching the process to the metal, its thickness, the position, the place and the budget.

PICTURE STUDY



Benardos and Olszewski's Arc-Welding Patent, Nikolay Benardos and Stanisław Olszewski (U.S. Patent Office drawing), May 17, 1887 · Patent drawing · U.S. Patent No. 363,320

Image: Wikimedia Commons, public domain

Every arc process in this lesson descends from this drawing. Benardos and Olszewski's American patent shows a carbon rod held in an insulated handle, with the arc drawn between the rod and the metal. Compare it with the stick electrode holder, MIG gun and TIG torch in the video.

Look closely

- Find the insulated handle in Fig. 1. Why did the inventors put the wooden or rubber grip where they did?
- Find the long rod. In this patent it is carbon and does not melt. Which modern process also uses an electrode that does not melt?
- Look at the lower figure. What do the curly lines represent, and where do they connect?
- Find the tiny lines at the tip of the rod on the stand. What are they showing?

Talk about it

1. If the carbon rod does not melt, where would filler metal come from in a Benardos weld?
2. What problem with this process did Kjellberg's coated electrode solve twenty years later?

3. Which modern process looks most like this drawing, and which looks least like it?

Safety first. Soldering copper pipe uses a propane torch: an adult must supervise, outdoors or in a ventilated shop on a non-flammable surface, with safety glasses, leather gloves, a fire extinguisher and a bucket of water nearby. Use lead-free solder and flux, wash your hands afterward, and remember that soldered pipe stays hot for minutes after it stops glowing or smoking.

SHOP PROJECT

Sweating a Copper Pipe Joint

Soldering a copper water pipe is the most common joining job a homeowner ever does with a torch, and it shows the difference between soldering and welding. You will solder a joint, test it for leaks, then cut it open to see whether the solder filled the joint by capillary action.

You will need

- Two 6-inch pieces of 1/2-inch type M or L copper pipe, a 1/2-inch coupling and a 1/2-inch cap
- Tubing cutter, emery cloth or a fitting brush, and a pipe-reaming tool
- Lead-free plumbing solder and paste flux with a brush
- Propane torch (adult only), striker, bricks or a metal tray, heat shield or wet rag
- Safety glasses, leather gloves
- Hacksaw, vise, a ruler and a magnifier

Steps

1. Cut the pipe square with the tubing cutter and ream the burr from the inside. Measure the gap between the pipe and the fitting with the ruler or estimate it: it should be very small (about 0.004 in), which is what makes capillary action work.
2. Clean the outside of the pipe ends and the inside of the fittings to bright metal with emery cloth and the brush. Do not touch the cleaned surfaces with your fingers.
3. Brush a thin coat of flux on both surfaces and assemble: cap on one pipe, coupling joining the two pipes.
4. **Adult step.** Heat the fitting, not the solder, moving the flame around it. Touch the solder to the joint opposite the flame. When the copper is hot enough the solder melts and is pulled all the way into the joint. Feed about as much solder as the pipe diameter (½ inch) and stop.
5. Let it cool without moving it, then wipe off the extra flux with a damp rag.

6. **Test.** Stand the assembly cap-down in a bucket, fill it with water to the top and leave it for 24 hours on a dry paper towel. Record any drips or damp spots.
7. Cut the assembly lengthwise through the coupling with the hacksaw (adult help with the vise). Look at the cut faces with the magnifier.
8. Measure how far into the joint the solder reached on each side, and whether there are voids. Record the percentage of the joint length that is filled.
9. Compare: the copper did not melt, but the solder bonded to it. Write one sentence explaining how this joint is different from a weld.
10. **Improve it.** Make a second joint on purpose with one surface left uncleaned or unfluxed, test and cut it, and compare the fill.

Tips

- Overheating burns the flux black and the solder will not flow; if that happens, let it cool, clean it and start again.
- Never solder a pipe that has water in it; the water absorbs the heat and turns to steam.
- If you have no torch or adult helper, a plumber, a hardware store's how-to class or a shop class can show you steps 4–5.

Check your work

- ☐ My joint held water for 24 hours, or I can explain why it leaked.
- ☐ I measured the solder fill on the cut joint.
- ☐ I can explain capillary action and why soldering is not welding.

SHOP NOTEBOOK

1. A process table with columns for stick, MIG, flux-core, TIG, oxy-fuel and spot welding: heat source, shielding, filler, metals, thickness, indoor/outdoor, cost and skill.
2. A labeled cross-section of your cut copper joint showing pipe, fitting, solder fill and any voids.
3. A flowchart for choosing a process: start with the metal, then thickness, then location, then appearance.

KEY FORMULAS

$Q = I^2 Rt$ (resistance heating, joules)

$\text{weld time per 10 min} = \text{duty cycle} \times 10 \text{ min}$

E$XXYZ$: XX = tensile strength in ksi, Y = position, Z = coating and current

From history. The plasma cutter, developed from TIG research in the 1950s, forces the arc through a narrow nozzle with fast-flowing gas, making a jet hot enough to cut any metal. Today friction stir welding (invented at TWI in Britain in 1991) joins aluminum without melting it at all, by stirring the softened metal with a spinning tool; it is used on rocket fuel tanks and ship panels.

WORKED EXAMPLES

Example 1. A spot welder passes 9,000 A for 0.25 s through two steel sheets. The resistance at the joint is 150 μΩ. How much heat is produced? What if the current is raised to 11,000 A?

Show solution

1. Convert: $R = 150\ \mu\Omega = 1.5 \times 10^{-4}\ \Omega$.
2. $Q = (9000)^2 (1.5 \times 10^{-4})(0.25) = 8.1 \times 10^{7} \times 3.75 \times 10^{-5} \approx 3040$ J.
3. At 11,000 A: $Q = (11{,}000)^2 (1.5 \times 10^{-4})(0.25) \approx 4540$ J, about 49% more heat for 22% more current.

Answer: About 3.0 kJ; about 4.5 kJ at 11,000 A.

Example 2. Decode the electrode E7018 and the MIG wire ER70S-6. Which would you take to a windy field to repair a trailer?

Show solution

1. E7018: electrode, 70 ksi minimum tensile strength, all-position, low-hydrogen iron-powder coating.
2. ER70S-6: rod or electrode wire, 70 ksi, solid wire with extra deoxidizers; it needs shielding gas from a cylinder.
3. Wind blows shielding gas away, causing porosity. The stick rod makes its own shielding from its coating.

Answer: E7018 stick rods (or self-shielded flux-core wire), not gas-shielded MIG wire.

Example 3. A small welder is rated 20% duty cycle at 140 A. A student needs to lay 30 beads, each taking 50 s of arc time, at 140 A. What is the least total time the job will take?

Show solution

1. Allowed arc time per 10 minutes: $0.20 \times 600\ \text{s} = 120\ \text{s}$.
2. Total arc time: $30 \times 50 = 1500\ \text{s}$.
3. Number of 10-minute periods: $1500 \div 120 = 12.5$, so about 125 minutes.

Answer: About 2 hours; at a lower current the duty cycle rises and the job goes faster.

PRACTICE

1. Easy What does each part of E6011 mean?

   Show answer

   Electrode; 60 ksi minimum tensile strength; 1 = all positions; 1 = a cellulose-type coating that runs on AC or DC and digs deeply.

2. Easy Which process uses a non-melting electrode?

   Show answer

   TIG (GTAW), with a tungsten electrode.

3. Easy What is the difference between brazing and soldering?

Show answer

Both melt only the filler, not the base metal. Brazing fillers melt above 450 °C (840 °F); soldering fillers melt below it.

4. Medium A spot weld uses 10,000 A for 0.2 s through a resistance of 100 μΩ. Find the heat.

Show answer

$Q = (10{,}000)^2(1.0 \times 10^{-4})(0.2) = 2000$ J.

5. Medium If the spot-weld current is cut in half, by what factor does the heat change (same R and t)?

Show answer

It drops to one-fourth, because heat goes as I^2.

6. Medium A welder is rated 60% duty cycle at 200 A. How many minutes of every 10 can it weld at 200 A?

Show answer

6 minutes.

7. Medium Why is MIG welding a poor choice on a windy job site?

Show answer

The wind blows the shielding gas away, letting air reach the molten metal and causing porosity.

8. Hard **You are the tradesperson.** Choose a process for each and give one reason: (a) a stainless-steel dairy tank, (b) a broken steel fence post in a pasture, (c) a car's rusted rocker panel, (d) a copper water line.

Show answer

(a) TIG: clean, precise, sanitary welds on stainless. (b) Stick or self-shielded flux-core: portable, works on dirty steel in wind. (c) MIG with a small wire: controllable on thin sheet. (d) Soldering (or brazing): the standard for copper plumbing.

9. Hard A car body has 4,000 spot welds averaging 2.5 kJ each. How much energy is that in kilowatt-hours?

Show answer

$4000 \times 2.5 = 10{,}000\ \text{kJ} = 10^7\ \text{J}$; $10^7 \div 3.6 \times 10^6 \approx 2.8\ \text{kWh}$.

10. Hard Conceptual. Why does a soldered joint need such a small gap, while a weld joint on thick plate is often beveled to leave a wide V-groove?

Show answer

Solder is drawn in by capillary action, which only works in a narrow gap. A fusion weld must melt through the whole thickness, so the groove opens room for the arc and filler to reach the root.

11. Challenge A TIG welder lays filler at 0.8 lb/h; a MIG welder at 8 lb/h. A job needs 12 lb of weld metal. Welder labor costs $45/h and the welder is actually welding 40% of the time. Find the labor cost of each process.

Show answer

Arc hours: TIG 15 h, MIG 1.5 h. Paid hours: TIG $15 \div 0.4 = 37.5$ h, cost $1,687.50; MIG $1.5 \div 0.4 = 3.75$ h, cost $168.75. TIG is chosen only where its quality is needed.

COMMON MISTAKES

- Calling every wire-fed process “MIG.” Self-shielded flux-core needs no gas and behaves differently.
- Heating the solder instead of the joint; the copper must be hot enough to melt the solder itself.
- Ignoring the duty cycle and overheating a small welder.
- Thinking a brazed or soldered joint has melted the base metal.

> **Make it a game · Process Picker Cards.** Make cards for stick, MIG, flux-core, TIG, oxy-fuel and spot welding, with a best use on another set. Shuffle and match them in 90 seconds, explaining each pair. Then decode a classification such as E7018 digit by digit, aloud. Your parent challenges one match. Beat your pair count in round two.

7.4 Joints, Strength, Distortion and Defects

OBJECTIVES

- Name the five basic weld joints and the main weld types (fillet and groove) and read a simple weld symbol.
- Calculate the throat and strength of a fillet weld and the length of weld a load requires.
- Explain shrinkage and distortion with $\Delta L = \alpha L \Delta T$ and how welders control them.
- Identify common defects, tell the story of the Liberty ships and Constance Tipper, and describe the main non-destructive tests.

Warm-up. Bend a strip of aluminum foil sharply back and forth at one spot, and another strip gently around a pencil. Which breaks first? Now tear a sheet of paper with a small notch cut in the edge, and one without. Write one sentence about what a sharp corner or notch does to a material.

WATCH

The Big Bang - The facts behind brittle fracture

TWI Ltd · 7:59

https://www.youtube.com/watch?v=ru8zXGoVRDk

WHEN TO WATCH

After the Liberty ship story. Watch how a notched test bar breaks differently when it is cold, and the S-shaped graph of energy against temperature.

Note: Produced by TWI, the British welding research institute, for engineers. Short and technical.

BACKUP VIDEO

WELDING DEFECTS!! Porosity, Arc Strikes, Undercut

Weld.com · 8:39

https://www.youtube.com/watch?v=82LQ2cMoE5c

With the paragraph on defects: a welding instructor shows porosity, undercut and arc strikes and their causes.

KEY TERMS

five basic joints

Butt (edge to edge in one plane), lap (overlapping), tee (one piece square to another), corner (an L at the edges) and edge (two edges side by side).

fillet weld

A roughly triangular weld in the corner of a lap, tee or corner joint. Its size is the leg length.

throat

The shortest distance from the root of a fillet weld to its face; for an equal-leg fillet, $t = 0.707\,a$, where a is the leg. The weld breaks through its throat.

distortion

The bending, bowing or shrinking of parts caused by the weld metal shrinking as it cools.

defect

A flaw that makes a weld unacceptable: cracks, porosity, lack of fusion, incomplete penetration, undercut, trapped slag, overlap.

brittle fracture

Sudden cracking with almost no stretching or warning, which happens in some steels below their transition temperature, especially from a sharp notch.

CORE IDEAS

The story. Between 1941 and 1945 American shipyards built 2,710 Liberty ships, plain cargo ships of about 10,800 tons, to carry supplies across the oceans. Rivets were slow, so their hulls were welded, often by workers trained in a few weeks. Henry Kaiser's yards cut the building time from months to weeks; in November 1942 one ship, the *Robert E. Peary*, was assembled in under five days to show what the method could do. Then reports came in of cracks. On January 16, 1943, the new T2 tanker *Schenectady*, built the same way, lay quietly at her fitting-out dock in Portland, Oregon, on a cold night, when she cracked across the deck and down the sides with a sound heard a mile away and broke almost in two. More than a thousand welded ships of the period reported cracks, and a small number broke completely in two, most of them in cold water.

How they figured it out. A board of investigation, and engineers in Britain and America, studied the cracks. Many began at the square corners of the cargo hatches and at notches made by poor welds, where stress was concentrated. A Cambridge

University metallurgist, Constance Tipper, tested notched steel samples from the ships at different temperatures. She showed that ordinary ship steel was tough at room temperature but became brittle below a certain **transition temperature**, and that the ships' steel had a transition temperature close to the temperature of the North Atlantic in winter. Welding had not made the steel weaker; it had made each hull one continuous piece, so a crack that started at a notch could run right around the ship instead of stopping at a riveted seam. Her notched-bar test, now done as the Charpy impact test, became part of steel specifications. The fixes were rounded and reinforced hatch corners, riveted "crack arrester" strips, better welding training and inspection, and steels chosen for toughness in the cold.

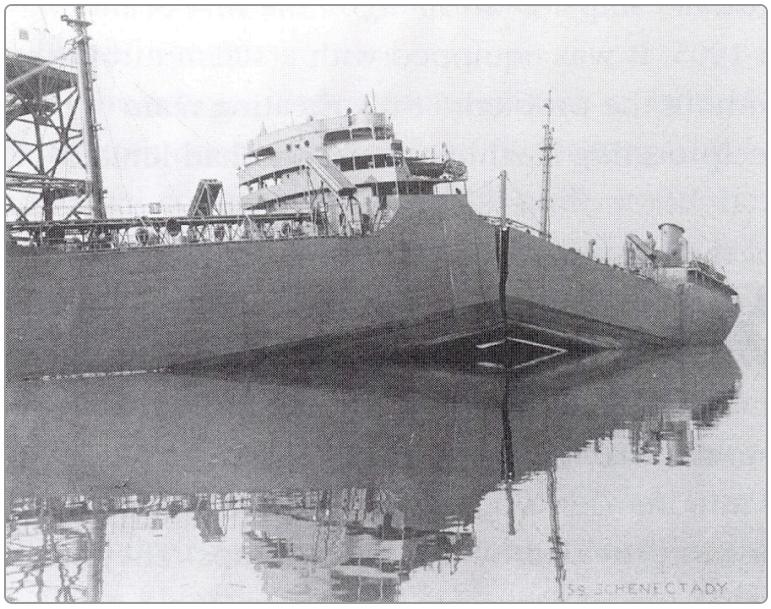
The science. A **fillet weld** fails in shear through its **throat**. For an equal-leg fillet of leg a, the throat is $t = a\cos 45^\circ = 0.707a$. The weld's strength is the shear stress the weld metal can carry times the throat area: $F = \tau_{\text{allow}}\,(0.707a)\,L$. A common allowable shear stress for E70 weld metal is $\tau_{\text{allow}} = 0.30 \times 70 = 21$ ksi, so a 1/4-inch fillet carries about 3.7 kips per inch of length. Welds also shrink. Steel expands about $\alpha = 12 \times 10^{-6}\ /^\circ\text{C}$ (6.5×10^{-6} per °F). The hot weld metal tries to shrink as it cools, but the cold plate around it resists, so the joint pulls itself out of line and locks in residual stress.

In the shop. Welders control distortion by tacking parts in place before welding, welding in short sequences that balance each other (back-stepping and alternating sides), presetting parts slightly out of line so they shrink straight, clamping to a heavy table, and not over-welding: a fillet twice as big has four times the metal and shrinks much more. They prevent **defects** by fitting joints properly and cleaning them, keeping the right arc length, angle and travel speed, and chipping slag between passes. Common defects are **porosity** (gas holes), **undercut** (a groove melted into the plate beside the bead), **lack of fusion** (weld metal lying on the plate without bonding), **incomplete penetration** (the root not reached), trapped **slag**, and above all **cracks**, which are never allowed.

Inspection. A certified welding inspector checks fit-up, procedure and the finished weld by eye with gauges. **Non-destructive testing (NDT)** looks inside without cutting: dye penetrant shows surface cracks in red; magnetic particle testing shows cracks in steel as lines of iron powder; ultrasonic testing sends sound pulses into the steel and listens for echoes from flaws; radiography (X-ray or gamma ray film) shows porosity and slag as dark spots. Some test welds are broken on purpose: a welder's

qualification test bends strips cut from his weld around a mandrel to see if they crack.

PICTURE STUDY



The Tanker Schenectady at Portland, Unknown photographer, U.S. government, January 1943 · Photograph · U.S. government record; Wikimedia Commons

Image: Wikimedia Commons, public domain

The *Schenectady* was only a few weeks old and had not yet gone to sea when she broke at her dock on a cold January night in 1943. No storm, no collision: the crack ran through the steel by itself. We look at her as engineers who learned from her.

Look closely

- Find the crack. Where on the ship is it, near the middle or near the ends?
- Look at how the two halves sag. Which part of the hull was in tension before the crack opened: the deck or the bottom?
- Look at the water and the dock. Is the ship under any obvious load?
- Look for openings or corners in the deck near the crack.

Talk about it

1. A riveted hull is made of separate plates. Why might a crack stop at a riveted seam but keep running through a welded one?
2. Why did the cold night matter?
3. If you had been the investigating engineer, what three things would you have tested first?

> **Safety first.** Hot-glue guns burn: use a low-temperature gun if you have one, keep a bowl of cold water nearby for skin contact, and set the gun on its stand. During the load test, wear safety glasses and keep feet out from under the bucket; joints let go suddenly.

SHOP PROJECT

Hot-Glue “Weld Bead” Joint Test

A bead of hot glue in the corner of two wooden strips behaves much like a fillet weld: it fuses to both parts, has a leg and a throat, and fails through the bead, at the bond line, or in the parts. You will make lap and tee joints with different bead sizes and lengths, load them to failure, and compare strength per inch of bead.

You will need

- Paint stirrers or 3/4-inch wood strips (at least 12 pieces)
- A hot-glue gun and glue sticks
- A luggage scale (digital, with a hold function) and a bucket with sand, or a sturdy hook and a rope
- A drill or screw eye for hanging the bucket
- A ruler and a fine marker; sandpaper
- Safety glasses

Steps

1. Plan six joint types: lap joint with a 1-inch bead, lap with a 2-inch bead, lap with a 2-inch bead on both edges, tee joint with one 2-inch bead, tee with beads on both sides, and a deliberately bad lap joint (glue laid on a dusty, oily surface).
2. Make each joint twice. Lightly sand and wipe the surfaces first (except the bad one). Lay a smooth, even bead in the corner and measure the leg with the ruler after it cools.
3. **Predict.** Using $F \propto tL$, predict the order of strength from weakest to strongest.
4. Hang each joint from a firm support, attach the bucket and luggage scale, and pour sand in slowly (or pull steadily on the scale) until it breaks. Record the peak force.
5. Record the failure mode: through the bead (weld metal), peeling off one surface (lack of fusion), or breaking the wood (base metal).

6. Calculate the throat $t = 0.707a$, the throat area tL and the strength per inch of bead and per square inch of throat for each joint.
7. Make a table and a bar chart. Did doubling the bead length double the strength? Did the double-sided joints do better?
8. Compare the bad joint with the good one. Which real welding defect does it model?
9. **Improve it.** Design the strongest joint you can using no more than 4 inches of total bead, test it, and explain why it worked.

Tips

- Let joints cool for 10 minutes before testing.
- Keep bead size consistent by counting the seconds you squeeze the trigger per inch.
- A luggage scale's hold function captures the peak force when the joint breaks.

Check your work

☐ I calculated strength per inch and per square inch of throat.

☐ I can name the failure mode of each joint and the welding defect it models.

☐ I can explain why longer and double-sided welds carry more.

SHOP NOTEBOOK

1. Labeled sketches of the five basic joints, and a cross-section of a fillet weld showing leg, throat, toe, root and face.
2. Your joint-test data table and bar chart, with failure modes.
3. A short case study of the Liberty ships: what failed, why, what Constance Tipper found, and what changed.

KEY FORMULAS

$t = 0.707\,a$ (throat of an equal-leg fillet)

$F_{\text{allow}} = \tau_{\text{allow}}\, t\, L, \quad \tau_{\text{allow}} = 0.30\, F_{EXX}$ (e.g. 21 ksi for E70)

$\sigma = \dfrac{F}{A}$ (stress in a butt weld or plate)

$\Delta L = \alpha L \Delta T, \quad \alpha_{\text{steel}} \approx 12 \times 10^{-6}/^{\circ}\text{C}$

From history. Constance Tipper's test helped make low-temperature toughness a standard requirement for ship and bridge steel. Engineers met cracks growing from sharp corners again in the de Havilland *Comet* airliner (metal fatigue at its window corners) and brittle fracture in later bridges and pressure vessels, and each time the lesson was the same: test materials under the conditions they will really meet.

WORKED EXAMPLES

Example 1. A 1/4-inch fillet weld 6 inches long is made with E70 electrodes. Using an allowable shear stress of 21 ksi, find the throat, the throat area and the allowable load.

Show solution

1. Throat: $t = 0.707 \times 0.25 = 0.177$ in.
2. Throat area: $A = 0.177 \times 6 = 1.06$ in^2.
3. Allowable load: $F = 21$ ksi $\times\ 1.06$ in$^2 \approx 22.3$ kips (about 22,300 lb).

Answer: Throat 0.177 in; about 22.3 kips.

Example 2. A steel bracket must carry 15,000 lb in shear through two equal fillet welds, one on each side, using 3/16-inch E70 fillets. How long must each weld be?

Show solution

1. Strength per inch of one weld: $21 \times 0.707 \times 0.1875 \approx 2.78$ kips/in.
2. Two welds share the load, so each carries 7.5 kips: $L = 7.5 \div 2.78 \approx 2.7$ in.
3. Round up and add a little for the weak start and stop of each bead: use 3 inches each.

Answer: About 2.7 in each; specify 3 in.

Example 3. A 600 mm strip of steel along a weld is heated an average of 500 °C above the surrounding plate. How much would it expand if it were free? What happens when it cools while held by the cold plate?

Show solution

1. $\Delta L = \alpha L \Delta T = (12 \times 10^{-6})(600)(500) = 3.6$ mm.
2. While hot, the strip is squeezed by the cold plate and is forced to yield (it is soft when hot). When it cools it tries to shrink by about the same amount, but now it is too short for the plate, so it pulls the plate into a bow or leaves a high residual tensile stress.

Answer: About 3.6 mm free expansion; on cooling the weld zone shrinks and distorts or stresses the plate.

Example 4. Reasoning. The hatch corners of a Liberty ship were nearly square. A square corner may concentrate stress about three times, while a well-rounded corner concentrates it about 1.5 times. If the deck's average stress in a storm was 12 ksi, estimate the peak stress at each corner.

Show solution

1. Square: $3 \times 12 = 36$ ksi, close to the yield strength of the ships' mild steel.
2. Rounded: $1.5 \times 12 = 18$ ksi, well below yield.
3. In cold, brittle steel a notch at 36 ksi can start a crack that runs; rounding the corners cut the peak in half.

Answer: About 36 ksi square versus 18 ksi rounded.

PRACTICE

1. Easy Name the five basic weld joints.

   Show answer

   Butt, lap, tee, corner and edge.

2. Easy Find the throat of a 5/16-inch equal-leg fillet weld.

   Show answer

   $0.707 \times 0.3125 \approx 0.221$ in.

3. **Easy** Name four weld defects and one cause of each.

Show answer

Porosity (dirty metal or lost shielding gas); undercut (too much current or poor angle); lack of fusion (too little heat or too fast); cracks (hydrogen, fast cooling, high-carbon steel). Others: trapped slag (not cleaning between passes).

4. **Medium** Find the allowable load of a 3/8-inch E70 fillet weld 4 inches long ($\tau = 21$ ksi).

Show answer

$21 \times 0.707 \times 0.375 \times 4 \approx 22.3$ kips.

5. **Medium** A 1/4-inch E70 fillet carries 3.71 kips per inch. How long must it be to hold 18 kips?

Show answer

$18 \div 3.71 \approx 4.9$ in; use 5 in.

6. **Medium** A 2-meter steel beam is heated evenly 80 °C by the sun and welding nearby. How much does it lengthen?

Show answer

$(12 \times 10^{-6})(2000)(80) = 1.92$ mm.

7. **Medium** Why do welders tack parts and weld in short alternating sequences?

Show answer

Tacks hold alignment, and alternating short welds balance the shrinkage on both sides so the part pulls less out of line.

8. **Hard** A butt weld joins two 1/2-inch by 4-inch steel bars end to end with full penetration. The weld metal's allowable tension stress is 30 ksi. What tension can the joint carry?

Show answer

Area $0.5 \times 4 = 2$ in^2; $F = 30 \times 2 = 60$ kips.

9. Hard A fillet weld's size is doubled from 1/4 in to 1/2 in. By what factor do its strength per inch and its volume of weld metal change? What does that suggest?

Show answer

Strength per inch doubles (throat doubles); cross-section area of metal goes up four times ($\propto a^2$). Oversized welds waste metal and cause much more distortion; size them to the load.

10. Hard **You are the inspector.** A weld on a steel trailer tongue looks smooth, but you suspect a crack at the toe. Which non-destructive tests could confirm it, and which would you choose in the field?

Show answer

Visual inspection with a light and magnifier first; then dye penetrant or magnetic particle testing, both simple and portable for surface cracks on steel. Ultrasonic testing finds deeper flaws but needs a trained technician.

11. Hard Conceptual. Constance Tipper showed that the Liberty ships' steel was not weak at room temperature. Why, then, did ships break?

Show answer

The steel became brittle below its transition temperature, near cold North Atlantic water temperatures. Sharp hatch corners and weld notches concentrated stress, and a crack that started could run through the continuous welded hull.

12. Challenge A lifting lug is welded to a steel beam with 1/4-inch E70 fillets all around a 3-inch by 1/2-inch plate (total length 7 in). The lug must lift a 4,000-lb machine with a factor of safety of 5 against the allowable load. Is the weld adequate?

Show answer

Required: $5 \times 4 = 20$ kips. Capacity: $3.71 \times 7 \approx 26$ kips. Adequate, provided the welds are sound and inspected; lifting lugs should be designed and checked by a qualified engineer.

COMMON MISTAKES

- Using the leg instead of the throat when finding the strength of a fillet weld.
- Forgetting that two welds on opposite sides share the load.
- Thinking bigger welds are always better; they add distortion and residual stress.

- Blaming the Liberty ship failures only on “bad welding”; the steel’s toughness in the cold and the design of the corners mattered just as much.

> **Make it a game · Weld Joint Draw.** Your parent calls one of the five basic weld joints: butt, tee, corner, lap or edge. Draw it in 15 seconds with a fillet or groove weld symbol. Then calculate the strength of a 6 mm fillet weld 100 mm long at a given allowable stress. Swap roles to check one another's work.

7.5 Welding Safety, Uses and Careers

OBJECTIVES

- Explain the main welding hazards (arc radiation and arc eye, fumes, fire, shock, hot metal, compressed gases) and the protection for each.
- Calculate gas left in a cylinder, ventilation air changes and the effect of distance on arc radiation.
- Describe where welding is used and the paths into the trade: school, certification, apprenticeship and inspection.
- Plan a hot-work job with a fire watch and interview a working welder.

> **Warm-up.** List every way you can think of that a welder could get hurt. Then, next to each, write the piece of equipment or habit that would prevent it. Compare your list with the six hazards in the video.

WATCH

Keep Yourself Safe: 6 Welding Safety Hazards & How To Avoid Them

Weld.com · 14:02

https://www.youtube.com/watch?v=-oq3mS7EBX8

> **WHEN TO WATCH**
> At the start of the lesson. Pause after each hazard and add it to your list from the warm-up.

Note: A Weld.com instructor in his shop; mentions sponsors' products briefly.

BACKUP VIDEO

Welding Safety: Personal Protective Equipment

Lincoln Electric Retail · 9:17

https://www.youtube.com/watch?v=fcIbUdPfoII

With the paragraph on protective gear: Lincoln Electric's own safety film on helmets, gloves, jackets, boots and respirators.

KEY TERMS

arc eye

A painful sunburn of the cornea (photokeratitis) from the arc's ultraviolet light; it usually appears hours after exposure and feels like sand in the eyes.

auto-darkening helmet

A helmet whose liquid-crystal lens darkens automatically in a fraction of a millisecond when the arc strikes.

hot work and fire watch

Hot work is any welding, cutting or grinding that can start a fire. A fire watch is a trained person with an extinguisher who watches during the work and for at least 30 minutes after (OSHA), longer where codes require.

filter shade

The darkness number of a welding lens. Most arc welding needs shade 10–13; gas welding and brazing need about shade 4–6.

fume

Tiny particles of metal oxide formed when metal boils in the arc; zinc from galvanized steel causes metal fume fever, and stainless and chrome plating give off hexavalent chromium.

certified welder

A welder who has passed a practical test to a written procedure and code (for example AWS D1.1 for structural steel); the certification covers the process, position and thickness tested.

CORE IDEAS

The story. Early welders often worked with little more than dark glasses and a leather apron, and many suffered burned eyes, lung trouble and shocks. The trade's great safety advances came from welders and engineers who would not accept that. The American Welding Society, founded in 1919, wrote safety standards that became ANSI Z49.1, *Safety in Welding, Cutting and Allied Processes*, still the basic rulebook. In the 1970s a Swedish engineer, Åke Hörnell, who saw welders lifting their helmets to see where to start the arc, developed a lens that turned dark by itself when the arc struck. His auto-darkening helmet reached the market in the early 1980s and is now standard, which means the welder's eyes are never exposed at the moment the arc starts.

The hazards and the science. Radiation: the arc gives off intense ultraviolet light that burns skin and eyes like a sunburn in minutes, plus visible glare and infrared

heat. Ultraviolet is stopped by the filter lens, by fire-resistant cotton or leather clothing buttoned to the neck, and by welding curtains that protect bystanders. Radiation spreads out with distance: intensity falls as $I \propto 1/d^2$, so stepping from 1 m to 3 m cuts it to one-ninth, but never to zero. **Fumes:** the arc boils metal into particles small enough to reach deep into the lungs. Zinc from galvanized steel causes "metal fume fever," manganese and chromium are worse over time, and coatings and solvents can make poisonous gases. The answer is ventilation and fume extraction that pull fumes away from the face, keeping the head out of the plume, removing coatings first, and a respirator where needed. **Shock:** welding machines run at low voltage (open-circuit roughly 50–80 V) but high current, and sweat, damp ground or standing in water make shock dangerous; keep gloves and clothing dry and never touch the electrode and the work together. **Fire:** sparks and spatter fly 35 feet or more and smolder in cracks; clear combustibles, cover what cannot be moved, and post a fire watch.

Compressed gases. An oxygen cylinder is filled to about 2,200 psi; if the valve were snapped off, it would become a rocket. Cylinders are always chained upright, capped when moved, and kept away from heat and the arc. Acetylene is unstable under pressure, so its cylinder is packed with a porous filler soaked in acetone, and it must never be used above 15 psi on the gauge. Oil or grease on oxygen fittings can ignite violently; oxygen is never used to blow off clothing or dust. Shielding gases such as argon are not toxic but can push the oxygen out of a closed tank or pit.

Where welding is used. Almost everything made of steel: pipelines and refineries, ships and offshore platforms, bridges and the moment connections of skyscraper frames, rail cars, trucks, tractors and farm equipment, power plants and water tanks, cars and motorcycles, aircraft and spacecraft, and handrails, gates and sculpture. Repair welding keeps old machines running: a farmer or a rural shop that can weld can fix a broken implement the same day.

On the job. Welding is a skilled, respected and needed trade, and good welders are in steady demand. People enter it through high school and community-college welding programs, trade schools, the military and apprenticeships with employers and trade associations (pipefitters, boilermakers, ironworkers and others). The American Welding Society's Certified Welder program, and tests to codes such as AWS D1.1 (structural steel) or ASME Section IX (boilers and pressure vessels), prove a welder's skill one process and position at a time. Experienced welders move on to become

certified welding inspectors (CWI), welding engineers and technicians, educators, shop owners, pipeline and offshore specialists, and even commercial divers who weld underwater. Pay rises with skill and certifications, and specialty welders who travel to pipelines, refineries and power plants can earn well above the average wage. The work is honest and visible: the welder’s bead is signed in steel.

PICTURE STUDY



Electric Welders at Work on a Liberty Ship, U.S. Office of War Information photographer, 1943 · Photograph · Library of Congress, Prints and Photographs Division

Image: Wikimedia Commons, public domain

Thousands of men and women learned to weld in a few weeks to build the Liberty ships. These two welders paused for the photographer while working on one of them, the *Frederick Douglass*, at the Bethlehem-Fairfield yard in Baltimore. Look at it as a safety inspector would.

Look closely

- Find each welder's helmet. How is it worn, and what does it protect?
- Look at their clothing, gloves and footing. What protects them from sparks and shock?
- Find the welding cables. Where do they run, and could anyone trip on them?
- Look for anything that would catch a spark.

Talk about it

1. What protective equipment would a modern inspector add to this scene?
2. Why do you think the yards could train new welders so quickly, and what problems did that cause (Lesson 7.4)?
3. Which of these welders' jobs would you most like to try, and why?

> **Safety first.** Do not weld or cut in this lesson. If you visit a welding shop for your interview or audit, wear safety glasses, long cotton clothing and closed leather shoes, stay outside the welding curtains, and never look at an arc without a proper filter.

SHOP PROJECT

A Hot-Work Plan and a Welder Interview

Professionals plan a weld before they strike an arc. You will write a hot-work permit and safety plan for a real repair, audit a welding area against a checklist, and interview a working welder about the trade.

You will need

- Shop notebook
- A copy of a sample hot-work permit (many insurers and fire departments publish free ones) or the outline in step 2
- A tape measure
- Access to a welding area: a school or community-college shop, a farm or fabrication shop, or your own garage as the site of an imagined job
- Phone for recording the interview (with permission)

Steps

1. Choose a real repair job someone near you needs: a broken trailer tongue, a gate, a mower deck, a railing. Describe the part, the metal and its coating.
2. Write a hot-work permit: location, date, process, person welding, fire watch, combustibles within 35 ft (moved or covered), extinguisher type and location, ventilation, coatings removed, cylinders secured, and the time the fire watch ends (at least 30 minutes after work stops).
3. Measure and sketch the site. Mark a 35-ft circle around the work and list everything combustible inside it.
4. Calculate the room's air changes per hour if it is indoors (measure the room; read the fan's CFM from its label).
5. Audit a real welding area with a checklist: helmets and shades, fire-resistant clothing, gloves, curtains, ventilation or fume arms, extinguisher, cylinder chains and caps, dry floors, cable condition, first aid and eyewash. Score each item yes/no and note fixes.
6. Arrange an interview with a welder, welding instructor or inspector. Prepare at least eight questions: how they learned, certifications, a typical day, the

hardest weld they have made, safety habits, mistakes they learned from, what employers look for, and advice for a beginner.

7. Interview them, take notes and write a one-page summary in their words and yours.
8. **Check your work.** Ask the welder or instructor to review your hot-work permit and mark anything you missed. Revise it.

Tips

- Community colleges often welcome visitors to their welding labs; call the program director.
- Farm equipment dealers, fabrication shops and pipeline contractors are good places to find welders.
- Thank your interviewee with a handwritten note.

Check your work

- ☐ My hot-work permit covers fire, fumes, shock, radiation and gases.
- ☐ I completed a checklist audit with at least 10 items.
- ☐ I can describe two paths into the welding trade from my interview.

SHOP NOTEBOOK

1. A hazard chart: radiation, fumes, shock, fire, hot metal, gases; for each, the cause, the effect on the body, and the protection.
2. Your hot-work permit and site sketch with the 35-ft circle.
3. A career map: the steps from beginner to certified welder, and three directions a career can go from there.

KEY FORMULAS

$V_{\text{left}} \approx V_{\text{full}} \times \dfrac{P_{\text{gauge}}}{P_{\text{full}}}$ (oxygen and argon cylinders, at constant temperature)

$\text{ACH} = \dfrac{60\,Q}{V_{\text{room}}}$ (air changes per hour; Q in ft³/min)

$\dfrac{I_2}{I_1} = \left(\dfrac{d_1}{d_2}\right)^2$ (inverse-square law)

From history. The welding trade grew enormously during the Second World War, when shipyards trained hundreds of thousands of new welders. Many of them went on to build the postwar pipelines, highways, bridges and power plants. Today the American Welding Society offers scholarships, the SENSE program that sets national standards for school welding courses, and its Certified Welder tests, and trade schools report steady demand as experienced welders retire.

WORKED EXAMPLES

Example 1. A full oxygen cylinder holds 244 ft³ of gas at 2,200 psi. The gauge now reads 900 psi. About how much oxygen is left, and how long will it last at 25 ft³/h?

Show solution

1. Gas left is proportional to pressure: $244 \times \dfrac{900}{2200} \approx 100$ ft³.
2. Time: $100 \div 25 = 4$ h.
3. (This works for oxygen and argon. It does not work for acetylene, which is dissolved in acetone; acetylene is measured by weighing the cylinder.)

Answer: About 100 ft³, about 4 hours.

Example 2. A school welding shop is 40 ft × 30 ft × 14 ft. Its exhaust fans move 4,000 ft³/min. How many air changes per hour is that? Why do welders still need local fume extraction at each booth?

Show solution

1. Room volume: $40 \times 30 \times 14 = 16{,}800$ ft³.
2. $\text{ACH} = \dfrac{60 \times 4000}{16{,}800} \approx 14.3$ air changes per hour.
3. General ventilation dilutes fumes for the whole room, but the plume rises straight past the welder's face first. A hood or fume arm at the arc captures it before it reaches the breathing zone.

Answer: About 14 air changes per hour; local extraction protects the welder's own breathing zone.

Example 3. A bystander stands 2 m from an arc. How much less ultraviolet reaches him if he moves to 6 m? What else should protect him?

Show solution

1. $\dfrac{I_2}{I_1} = \left(\dfrac{2}{6}\right)^2 = \dfrac{1}{9}$.
2. He receives about 11% as much, which can still burn eyes over time. A welding curtain or screen, and not looking toward the arc, protect bystanders.

Answer: One-ninth as much; use screens as well.

Example 4. Reasoning. A neighbor wants to weld a broken galvanized steel fence brace in his closed garage with his car parked inside, wearing sunglasses. List what is wrong and what he should do instead.

Show solution

1. Sunglasses give no protection from arc ultraviolet: he needs a welding helmet with the right shade (about 10–11) and safety glasses under it.
2. Galvanized steel gives off zinc fume: he should grind the zinc off the weld area (with a respirator) and weld outdoors or with strong fume extraction.
3. A closed garage with a car (fuel, tires, oil) is a fire hazard: move the work outside or move the car out, clear combustibles 35 ft, have an extinguisher and keep a fire watch for at least 30 minutes after.
4. He needs fire-resistant clothing, leather gloves and boots, and a dry place to stand.

Answer: Helmet with proper shade, remove the zinc and ventilate, clear combustibles and keep a fire watch, wear dry fire-resistant gear.

PRACTICE

1. Easy What is arc eye, and why can't sunglasses prevent it?

   Show answer

   A sunburn of the cornea from the arc's ultraviolet light. Sunglasses are far too light (and may pass UV) for an arc; a welding filter of the right shade is needed.

2. Easy How long must a fire watch continue after hot work stops, by the OSHA rule?

Show answer

At least 30 minutes (some codes and employers require longer).

3. Easy Why must oxygen fittings never be oiled or greased?

Show answer

Oil and grease can ignite violently in pure oxygen under pressure.

4. Medium An argon cylinder holds 330 ft^3 full at 2,640 psi. The gauge reads 660 psi. How much is left?

Show answer

$330 \times \dfrac{660}{2640} = 82.5$ ft^3.

5. Medium At 20 ft^3/h, how long will the argon in Problem 4 last?

Show answer

About 4.1 hours.

6. Medium A welding booth is 10 ft × 10 ft × 9 ft with a 600 ft^3/min exhaust. Find the air changes per hour.

Show answer

$\dfrac{60 \times 600}{900} = 40$ ACH.

7. Medium Why is welding on galvanized steel especially hazardous, and what should be done first?

Show answer

The zinc coating boils off as zinc oxide fume, which causes metal fume fever. Grind the coating off the weld area first (with a respirator), and weld with strong ventilation or fume extraction.

8. Hard A worker stands 1.5 m from an arc. How far away must he move to receive one-sixteenth of the radiation?

Show answer

Distance must increase 4 times: $1.5 \times 4 = 6$ m.

9. Hard **You are the tradesperson.** You are asked to weld a bracket on a 55-gallon steel drum that once held solvent. What do you do?

Show answer

Refuse to weld it as it is. Containers that held flammable liquids can ignite violently from vapor even when they look empty. Only a trained person may clean, ventilate and test such a container (or fill it with inert gas or water) under a written procedure; usually the right answer is to use a new drum.

10. Hard Conceptual. Why is a welding machine's low voltage still a shock hazard?

Show answer

Shock depends on current through the body, $I = V/R$. Dry skin has high resistance, but sweat, wet gloves or damp ground lower it greatly, letting dangerous current flow even at 50–80 V; the welder's body can also complete the circuit between electrode and work.

11. Challenge A student is choosing between two paths. Path A: a 1-year community-college welding certificate costing $6,000, then work at $22/h. Path B: an apprenticeship that pays $17/h while learning for 2 years, then $27/h. Using 2,000 hours per year, compare their total earnings (minus tuition) after 5 years. (These figures are made up for practice; real pay varies by region and specialty.)

Show answer

A: 4 years of work $4 \times 2000 \times 22 = 176{,}000$ minus 6,000 = $170,000. B: $2 \times 2000 \times 17 + 3 \times 2000 \times 27 = 68{,}000 + 162{,}000 = 230{,}000$ dollars. Path B earns more here, and it pays while you learn; the right choice also depends on what programs are available nearby.

COMMON MISTAKES

- Thinking a short glance at an arc is harmless; arc eye can come from seconds of exposure, and the pain arrives hours later.
- Leaving the fire watch the moment the arc stops; most welding fires smolder for a while before flaming.
- Reading acetylene left from the gauge; acetylene is dissolved in acetone and must be weighed.
- Assuming certification is one test for everything; it is specific to the process, position, metal and thickness.

Make it a game · Hazard Protection Match. From memory, list welding hazards and their protections in 60 seconds: arc eye and helmet shade, fumes and ventilation, fire and fire watch, shock and dry gloves, hot metal and leathers, gas cylinders secured. Your parent checks each pair. Then calculate how arc radiation drops when you double the distance. This is a spoken drill only.

Scripture. “And whatsoever ye do, do it heartily, as to the Lord, and not unto men;” (Colossians 3:23, KJV)

Much welding is hidden inside walls, hulls and machines where no customer will ever see it. A welder who works as for the Lord makes the hidden root pass as carefully as the visible cap.

UNIT 7

Welding: Science and Uses

Welding makes two pieces of metal into one. It holds together the ships, bridges, pipelines, skyscraper frames, trailers, tractors and car bodies of the modern world, and it is one of the most needed skilled trades. In this unit you will learn the science underneath it: how an electric arc makes a plasma hotter than the surface of the sun, how heat input and cooling rate change steel's grains, why the weld pool must be shielded from air, and how welds are sized, distorted, inspected and sometimes fail.

The stories run from Tubal-cain and the village forge through Davy's arc, Benardos, Thomson and Kjellberg, to the Liberty ships and Constance Tipper's discovery of brittle fracture. You will not weld in this course unless you are in a supervised school, community-college or professional shop with a qualified instructor. Instead you will survey real welds, heat-treat steel nails, solder a copper pipe joint, load-test model "weld beads," write a hot-work plan and interview a working welder.

PREREQUISITES

- Algebra I: formulas, unit conversions and solving for a variable
- Unit 1: stress $\sigma = F/A$, tension and shear, factor of safety
- Unit 2: joint loads (shear, tension, peel, cleavage)
- Unit 5: $P = VI$ and Ohm's law

MASTERY CHECKLIST

- ☐ I can tell the history of welding from the forge weld to the coated electrode and explain what each step solved.
- ☐ I can calculate arc power and heat input and explain how heat input and cooling rate affect the weld and heat-affected zone.
- ☐ I can describe stick, MIG, flux-core, TIG, oxy-fuel and spot welding, read an electrode code, and choose a process for a job.
- ☐ I can calculate the throat and strength of a fillet weld, estimate shrinkage, and name common defects and inspection methods.
- ☐ I can explain welding hazards and protection, write a hot-work plan, and describe the paths into the welding trade.

OPTIONAL KITS FOR THIS UNIT

- **Miller Electric (welding information and education)**: A major American welding-equipment maker. Its site has free articles and videos on processes, safety and choosing equipment; useful background for Lessons 7.3 and 7.5. No purchase is needed for this unit.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

7.1	**Joining Metal: Forge Welding to the Electric Arc**	3 sessions of 50 minutes
7.2	**The Science of the Arc and the Weld Pool**	3 sessions of 50 minutes

7.3	**Welding Processes: Stick, MIG, Flux-Core, TIG, Oxy-Fuel and Spot**	3 sessions of 50 minutes
7.4	**Joints, Strength, Distortion and Defects**	3 sessions of 50 minutes
7.5	**Welding Safety, Uses and Careers**	3 sessions of 50 minutes

Unit 7 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   Explain the difference between welding, brazing and soldering.

2. **6 pts**
   Tell what each of these people contributed: Humphry Davy, Nikolay Benardos, Elihu Thomson, Oscar Kjellberg.

3. **6 pts**
   An arc runs at 26 V and 160 A for 90 s. Find its power and the energy delivered.

4. **7 pts**
   Find the heat input of a weld at 23 V, 180 A and 9 in/min, and the net heat input for MIG ($\eta = 0.8$).

5. **6 pts**
   A procedure limits heat input to 25 kJ/in. At 25 V and 200 A, what is the slowest allowed travel speed?

6. **6 pts**
   Explain why a small, fast weld on thick, cold, medium-carbon steel can crack, and what a welder does to prevent it.

7. **5 pts**

   Find the carbon equivalent of a steel with 0.25% C and 1.20% Mn (no other alloys).

8. **5 pts**

   Decode E7018 and explain why it is stored in a heated rod oven.

9. **6 pts**

   A spot weld uses 12,000 A for 0.15 s through 120 μΩ. Find the heat.

10. **6 pts**

    Choose a process for each and give a reason: (a) aluminum boat repair, (b) bulldozer bucket repair in a muddy field, (c) car body panel on an assembly line.

11. **7 pts**

    A 5/16-inch E70 fillet weld is 5 inches long. Find its throat and its allowable load at 21 ksi.

12. **7 pts**

    A tab must carry 12 kips through two 1/4-inch E70 fillets (3.71 kips/in each). How long must each be?

13. **5 pts**

    A 1.2 m steel bar is heated 400 °C above its surroundings. How much would it expand freely?

14. **6 pts**

    Name four non-destructive tests for welds and what each finds.

15. **6 pts**

    You are the tradesperson. A friend wants you to weld a bracket onto a galvanized trailer in his garage, next to the lawn mower and gas can. List what you would do before striking an arc.

16. **5 pts**

    An oxygen cylinder holds 244 ft^3 at 2,200 psi. The gauge reads 1,650 psi. How much oxygen is left?

17. **6 pts**

Short essay (one paragraph). Explain what the Liberty ships and Constance Tipper taught engineers about welding, materials and design.

ANSWER KEY

1. Welding melts the base metal (fusion), usually with a filler of the same kind. Brazing and soldering melt only a lower-melting filler that bonds to the unmelted base metal; brazing fillers melt above 450 °C (840 °F), solder below.
2. Davy showed the continuous electric arc (early 1800s); Benardos showed and patented carbon-arc welding (1881–1887); Thomson invented resistance welding (1886); Kjellberg patented the coated electrode (1907), which shielded the weld from air.
3. $P = 4160$ W; $E = 4160 \times 90 \approx 374{,}000$ J $= 374$ kJ.
4. $HI = \dfrac{60(23)(180)}{9000} = 27.6$ kJ/in; net 22.1 kJ/in.
5. $S = \dfrac{60(25)(200)}{1000(25)} = 12$ in/min.
6. The thick cold plate cools the weld and heat-affected zone very fast, forming hard, brittle martensite; hydrogen in that hard zone causes cracking. Preheat the steel, use low-hydrogen rods kept dry, clean the joint, and cool slowly.
7. $CE = 0.25 + 0.20 = 0.45$; preheat is likely needed.
8. Electrode, 70 ksi tensile strength, all positions, low-hydrogen iron-powder coating. The coating absorbs moisture from the air, which would put hydrogen into the weld and cause cracking.
9. $Q = (12{,}000)^2(1.2 \times 10^{-4})(0.15) \approx 2590$ J.
10. (a) TIG or MIG with argon: aluminum needs inert shielding and good heat control. (b) Stick or self-shielded flux-core: portable, works on dirty steel outdoors. (c) Resistance spot welding: fast, automatic, no filler, ideal for thin sheet.
11. Throat $0.707 \times 0.3125 \approx 0.221$ in; load $21 \times 0.221 \times 5 \approx 23.2$ kips.
12. Each carries 6 kips: $6 \div 3.71 \approx 1.6$ in; specify 2 in each.
13. $(12 \times 10^{-6})(1200)(400) = 5.76$ mm.
14. Visual (surface shape and defects), dye penetrant (surface cracks), magnetic particle (surface and near-surface cracks in steel), ultrasonic (internal flaws by echoes), radiography (internal porosity and slag on film).
15. Move the job outdoors or move all fuel and combustibles at least 35 ft away; grind the zinc from the weld area with a respirator and weld with ventilation; have an extinguisher and a fire watch for at least 30 minutes after; wear a helmet

with the correct shade, safety glasses, fire-resistant clothing, gloves and boots; secure cylinders; stand dry.

16. $244 \times \dfrac{1650}{2200} = 183\ \text{ft}^3$.
17. Model answer: The welded Liberty ships cracked, some breaking in two, mostly in cold water. Tipper showed that the ships' steel became brittle below a transition temperature near North Atlantic winter temperatures, and that cracks started at sharp hatch corners and weld notches. Because the welded hull was continuous, a crack could run all the way around. Engineers learned to test steel toughness at service temperature (the Charpy test), round off corners, add crack arrestors, train and inspect welders, and design the whole system, not just the joint.

PORTFOLIO PIECE: A WELD-JOINT TEST REPORT AND A WELDER INTERVIEW

Write a 3–4 page report that combines your work in this unit: the hot-glue joint test (with your data table, chart, throat calculations and failure modes, and how each failure models a real welding defect), your heat-treating results and what they mean for the heat-affected zone, and your hot-work plan for a real repair.

Add a one-page summary of your interview with a working welder, welding instructor or inspector, and finish with a paragraph on whether you would consider the trade and what path you would take into it. If you have the chance to weld in a supervised school or community-college lab, include photos and a description of your test coupons.

LOOK FOR	WHAT IT MEANS
Joint test	Fair test with consistent beads; peak loads, throat areas and strength per inch calculated correctly with units; failure modes identified.
Science	Correct explanation of heat input, cooling and the heat-affected zone, tied to the nail heat-treating results.
Safety plan	Hot-work permit covers radiation, fumes, fire watch, shock, coatings and cylinders, and was reviewed by a welder or instructor.
Interview	At least eight thoughtful questions; a clear summary of how the welder learned, certifications and daily work.
Communication	Organized report with labeled sketches, tables and a clear conclusion.

UNIT 8

3D Printing

A 3D printer builds a part layer by layer from a digital model, and it has changed how engineers prototype, how shops make jigs and spare parts, and even how jet engines and rockets are built. In this unit you will learn where it came from, how a printer's motors, belts, extruder and heaters work, how a CAD model becomes G-code in a slicer, how to design parts that are strong and fit together, and which materials suit which jobs.

The stories are of Chuck Hull curing his first plastic cup with ultraviolet light in 1983, Scott Crump building a toy frog with a glue gun, Adrian Bowyer's self-copying RepRap, a wrench sent to the space station as a file, and GE's printed fuel nozzle. You will not need to own a printer: every project can be done with free CAD and slicer software, a library makerspace or school lab, or the hands-on models given. If you can print, you will finish the unit with a tested, useful part you designed yourself.

PREREQUISITES

- Algebra I: formulas, ratios and solving for a variable
- Unit 1: thread sizes, $T = KDF$, clamp force and stress $\sigma = F/A$
- Unit 5: $P = VI$ and $P = V^2/R$
- Unit 7: weld pools, heat and distortion (for metal printing)
- Basic computer skills; a free Tinkercad or Onshape account with a parent's permission

MASTERY CHECKLIST

- ☐ I can compare additive, subtractive and formative manufacturing and tell the story of Hull, Crump and Bowyer.
- ☐ I can explain how an FDM printer works and calculate steps per mm, flow rate, heater power and G-code extrusion.
- ☐ I can model a part in CAD, slice it, and estimate its plastic, cost and time.
- ☐ I can design for printing: orientation for strength, clearances, overhangs, snap fits and fasteners.
- ☐ I can choose a printing material for a job, calculate break-even against molding, and say when printing is the wrong answer.

OPTIONAL KITS FOR THIS UNIT

- **Tinkercad (Autodesk)**: Free browser-based CAD that builds parts from simple shapes; the easiest start for Lessons 8.3–8.5. Students under 13 need a parent or teacher account.
- **Onshape for education**: Free professional parametric CAD in the browser for students and teachers; a good next step after Tinkercad for Lessons 8.3–8.5.
- **Prusa Research**: Maker of the open-source Prusa printers (kits and assembled) and of the free PrusaSlicer. Optional: every lesson works with a library makerspace or school printer instead.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

8.1	**From Stereolithography to RepRap: How 3D Printing Began**	3 sessions of 50 minutes
8.2	**How an FDM Printer Works**	3 sessions of 50 minutes
8.3	**From CAD to Slicer**	3 sessions of 50 minutes
8.4	**Designing for Printing: Strength and Tolerances**	3 sessions of 50 minutes
8.5	**Materials and Real-World Uses**	3 sessions of 50 minutes

Unit 8 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   Explain the difference between additive, subtractive and formative manufacturing, with one example of each.

2. **6 pts**

   What did Chuck Hull, Scott Crump and Adrian Bowyer each contribute to 3D printing?

3. **5 pts**

   A part is 36 mm tall. How many layers at 0.12 mm and at 0.24 mm? Which prints faster and which looks smoother?

4. **6 pts**

   A part machined from a 640 g block weighs 80 g. Find the buy-to-fly ratio and the waste percentage.

5. **6 pts**

   A GT2 belt (2 mm pitch) runs on a 20-tooth pulley driven by a 200-step motor at 16 microsteps. Find the steps per mm.

6. **6 pts**

   Find the volumetric flow at 0.24 mm layers, 0.48 mm lines and 100 mm/s. Can a hot end rated 10 mm^3/s keep up?

7. **6 pts**

   How many millimeters of 1.75 mm filament (2.405 mm^2) are needed for a line 80 mm long, 0.45 mm wide and 0.2 mm high?

8. **5 pts**

   A 24 V heated bed has a resistance of 2.0 Ω. Find its power and current.

9. **6 pts**

   A slicer reports 54 g of PLA for a part. Filament costs $24/kg. Find the cost and the filament length ($\rho = 1.24\ \text{g/cm}^3$).

10. **5 pts**

    Explain why adding walls usually strengthens a part more than adding infill.

11. **6 pts**

    A hook is to be printed. Explain how you would orient it and why.

12. **6 pts**

A shaft is 10.0 mm. Holes print 0.15 mm small. Model a hole for a sliding fit with 0.25 mm clearance per side.

13. **6 pts**

A snap hook is 12 mm long and 1.2 mm thick and deflects 1.2 mm. Find the strain. Is it below 2%?

14. **5 pts**

An M4 screw is tightened to 0.5 N·m with $K = 0.2$. Find the clamp force and explain why a washer helps on a printed part.

15. **6 pts**

Choose a material for (a) a flexible phone-case bumper, (b) a mailbox flag left in the sun, (c) a shelf organizer. Give a reason for each.

16. **6 pts**

Printing costs $3.20 per part; molding needs a $9,000 mold and $0.20 per part. Find the break-even quantity.

17. **3 pts**

You are the tradesperson. A neighbor asks you to print a replacement brake-line bracket for his truck. What do you say?

18. **6 pts**

Short essay (one paragraph). When is 3D printing the right way to make a part, and when is it the wrong way? Use at least two examples from this unit.

ANSWER KEY

1. Additive builds layer by layer (3D printing a bracket); subtractive cuts material away (milling a part from a block); formative forces material into shape (injection molding a bottle cap).
2. Hull invented stereolithography (1983; patent 1986) and the STL format and founded 3D Systems; Crump invented fused deposition modeling (patent 1992) and founded Stratasys; Bowyer started RepRap (2005), the open self-copying printer that led to cheap desktop printers.
3. 300 and 150 layers; 0.24 mm prints about twice as fast; 0.12 mm is smoother.
4. $640/80 = 8$; waste $1 - 80/640 = 87.5\%$.
5. $3200 \div 40 = 80$ steps/mm.
6. $0.24 \times 0.48 \times 100 \approx 11.5\ \text{mm}^3/\text{s}$; no: slow to about 87 mm/s or lower the layer height.
7. $V = 7.2\ \text{mm}^3$; $7.2/2.405 \approx 2.99\ \text{mm}$.
8. $P = 576/2 = 288\ \text{W}$; $I = 12\ \text{A}$.
9. Cost $54 \times 0.024 \approx \$1.30$; volume $43.5\ \text{cm}^3$; length $43{,}500/2.405 \approx 18.1\ \text{m}$.
10. Bending and twisting stress is highest at the outer surface, where the walls are; infill lies near the middle, where stress is low.
11. Lying on its side, so the printed lines run around the curve of the hook and the load pulls along the lines; printed upright, the load would pull the layers apart at the bend, where the part is about half as strong.
12. $10.0 + 0.50 + 0.15 = 10.65\ \text{mm}$.
13. $\varepsilon = \dfrac{3(1.2)(1.2)}{2(144)} = 0.015 = 1.5\%$; yes.
14. $F = 0.5/(0.2 \times 0.004) = 625\ \text{N}$. A washer spreads the force over more area, lowering bearing stress and creep in the plastic.
15. (a) TPU: flexible. (b) ASA (or PETG): resists sunlight and heat. (c) PLA: easy to print, indoor, light load.
16. $9000 \div 3.00 = 3000$ parts.
17. No: brake parts are safety-critical and see heat, vibration and road chemicals. Buy the correct certified part from the maker or a parts store.
18. Model answer: Printing is right for one-off and low-volume parts, prototypes, custom parts, complex internal shapes and parts no longer sold: Hull's prototypes, the station's ratchet wrench, GE's one-piece fuel nozzle, shop jigs. It

is wrong for large quantities, where molding is cheaper past the break-even point; for simple metal parts better machined or bought; and for safety-critical parts such as brakes or car-seat latches, where a certified part must be used.

PORTFOLIO PIECE: A PRINTED FUNCTIONAL PART

Present the functional part from Lesson 8.5: the problem statement, your decision on whether to print or buy, the material decision matrix, dimensioned drawings, the CAD file and slicer settings, your cost and time estimates, test results (fit, dimensions, load), and what you changed in version 2.

If you could not print, submit a complete print package (STL or 3MF, slicer project, settings sheet and drawing) and have it reviewed by someone who prints: a makerspace staff member, a teacher or an engineer. Include your tolerance and orientation test results from Lesson 8.4.

LOOK FOR	WHAT IT MEANS
Need and judgment	A real need clearly stated; an honest comparison of printing with buying or other methods.
Design for printing	Orientation, clearances, overhangs, wall thickness and fasteners chosen by the rules of Lesson 8.4 and the student's own tolerance test.
Material and cost	Decision matrix with weighted criteria; mass, cost and time estimated and checked against the slicer.
Testing and iteration	Dimensions, fit and load tested and recorded; at least one improvement made and explained.
Documentation	Neat drawings, files and a clear write-up that someone else could use to print the part again.

8.1 From Stereolithography to RepRap: How 3D Printing Began

OBJECTIVES

- Explain the difference between additive, subtractive and formative manufacturing, and when each makes sense.
- Tell the story of Chuck Hull's stereolithography, Scott Crump's fused deposition modeling and Adrian Bowyer's RepRap.
- Calculate material waste (buy-to-fly ratio), number of layers and layer "stair-stepping."
- Build one shape both by carving and by stacking layers, and compare waste, time and accuracy.

> **Warm-up.** Pick up three plastic or metal objects near you: a bottle cap, a key, a toy, a hinge. For each, guess how it was made: carved or cut away from a block (subtractive), squeezed or poured into a mold (formative), or built up layer by layer (additive). Write the clue that made you guess.

WATCH

Printing What's Possible: The Chuck Hull Story

National Inventors Hall of Fame - NIHF · 13:25

https://www.youtube.com/watch?v=qk4fXVBktus

> **WHEN TO WATCH**
> After the story paragraph. Listen for the problem Chuck Hull was trying to solve at work, and for what he made first.

Note: A documentary from the National Inventors Hall of Fame with Chuck Hull and his wife Antoinette.

BACKUP VIDEO

RepRap

Adrian Bowyer · 7:52

https://www.youtube.com/watch?v=iMhG4fWQnlE

With the paragraph on RepRap: Adrian Bowyer and his team in 2009 explain a printer designed to print many of its own parts.

KEY TERMS

additive manufacturing

Making a part by adding material layer by layer from a digital model: 3D printing.

formative manufacturing

Making a part by forcing material into shape: casting, molding, forging, stamping.

fused deposition modeling (FDM)

Scott Crump's process: a plastic filament is melted and pushed through a nozzle that traces each layer; also called fused filament fabrication (FFF).

subtractive manufacturing

Making a part by cutting material away from a larger block: sawing, drilling, milling, turning.

stereolithography (SLA)

Chuck Hull's process: an ultraviolet light hardens a thin layer of liquid photopolymer resin, the part is lowered, and the next layer is drawn on top.

layer height

The thickness of each printed layer, typically 0.1–0.3 mm for FDM and 0.025–0.1 mm for resin.

CORE IDEAS

The story. In the early 1980s Chuck Hull was an engineer at Ultra Violet Products, a small California company that used ultraviolet lamps to harden thin plastic coatings on tables and furniture. Every time his company designed a new plastic part, it waited weeks or months for a toolmaker to make a prototype. Hull had an idea: if UV light could harden one thin coat of liquid plastic, why not harden thousands of coats, one on top of another, each in the shape of a slice of the part? His boss let him use a lab after hours. For months he worked nights and weekends. In March 1983 he called his wife Antoinette to come to the lab late at night to see the first part ever made this way: a small black cup. He filed for a patent in August 1984, received U.S. Patent 4,575,330 for "Apparatus for Production of Three-Dimensional Objects by Stereolithography" in March 1986, and founded 3D Systems to build the machines.

How they figured it out. Hull had to solve problems no one had solved: how to slice a computer model into layers, how to aim the light accurately, how to recoat the part with a perfectly level film of resin, and how to keep thin walls from sagging (he invented support structures). He also created the STL file format, which describes a

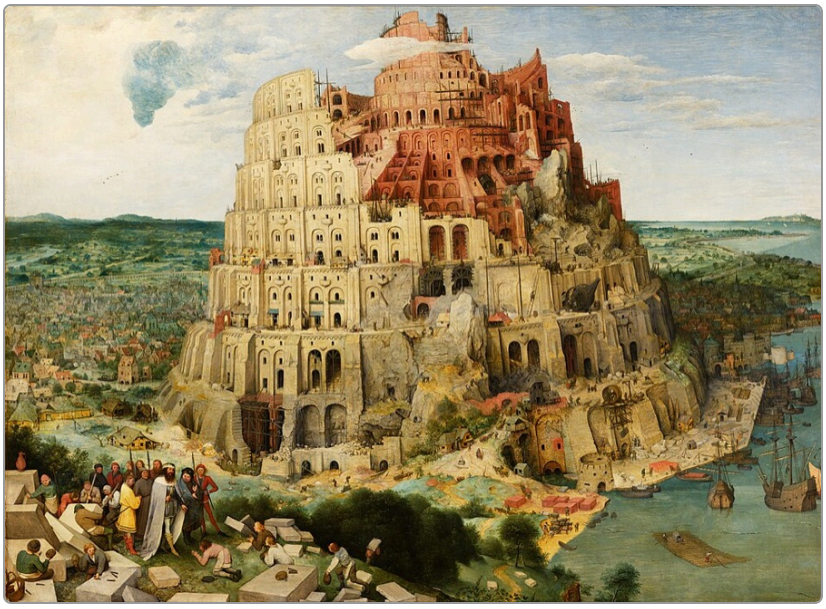
part's surface as a mesh of triangles and is still used today. Others had similar ideas at about the same time: Hideo Kodama in Japan published a layered photopolymer method in 1981, and three French engineers filed a patent a few weeks before Hull. In 1988 Scott Crump, a Minnesota engineer, wanted to make a toy frog for his young daughter and loaded a hot-glue gun with a mix of polyethylene and candle wax, building the frog up layer by layer. That became **fused deposition modeling**; he and his wife Lisa founded Stratasys in 1989 and received the patent in 1992. At the University of Texas, Carl Deckard developed selective laser sintering, which fuses powder with a laser.

RepRap. For twenty years 3D printers cost tens of thousands of dollars and were sold to companies. In 2005 Adrian Bowyer, a mechanical engineer at the University of Bath in England, started RepRap ("replicating rapid prototyper"): an open design for an FDM printer that could print many of its own plastic parts, shared freely so anyone could build and improve it. In 2008 a RepRap made a working set of parts for a "child" printer. When Crump's basic FDM patent expired in 2009, small companies built on RepRap designs, and desktop printers fell to a few hundred dollars. A Czech student and RepRap developer, Josef Průša, designed the Prusa Mendel and the widely copied Prusa i3, and founded Prusa Research in Prague.

The science. Every additive process does the same three things: it slices a 3D model into thin layers, it makes each layer from a raw material (liquid resin cured by light, melted plastic filament, or powder fused by a laser or bonded by glue), and it bonds each layer to the one below. Because the part is built in steps, a sloped or curved surface becomes a staircase. The height of each step is the layer height h; a part of height H needs $n = H/h$ layers. Thinner layers make smoother parts but take longer.

In the shop. Additive manufacturing does not replace machining and molding; it joins them. Machining is fast and precise for simple shapes in metal. Molding makes millions of identical parts for pennies each once the mold is paid for. Printing shines for one-off parts, prototypes, complex internal shapes that cannot be machined, custom parts like medical guides, and replacement parts that are no longer sold. Engineers measure material waste in machining with the **buy-to-fly ratio**, the mass of the raw block divided by the mass of the finished part; aircraft parts machined from solid titanium may have ratios of 10 or more, which is one reason aerospace companies adopted metal printing.

PICTURE STUDY



The Tower of Babel, Pieter Bruegel the Elder, 1563 · Oil on panel · Kunsthistorisches Museum, Vienna

Image: Wikimedia Commons, public domain

Long before 3D printers, builders made the largest objects on earth the additive way: one course of brick or stone laid on the one below. Bruegel painted the tower of Genesis 11 as a working construction site, full of real sixteenth-century machines. The story is also a warning against arrogance, which is worth remembering whenever people boast about what their new technology can do.

Look closely

- Find the layers. How does each tier sit on the one below? Is it exactly above it, or stepped in?
- Find the cranes and treadwheels lifting stone. Where is the material being added?
- Look at the lower tiers compared with the upper ones. Is the tower being built in perfect, level layers?
- Find the stonecutters in the foreground. Are they making something by adding or by cutting away?

Talk about it

1. Which parts of this site are additive manufacturing, and which are subtractive?

2. What would happen to the tower if one layer were badly bonded to the layer below? How is that like a weak 3D print?
3. Why does Bruegel's tower lean and look unfinished, and what does the Bible say happened to the builders (Genesis 11:1-9)?

Safety first. Carving soap uses a craft knife or paring knife: cut away from your body and fingers, on a cutting board, with an adult nearby. Cardboard cutting also uses a craft knife; use a metal ruler and a self-healing mat.

SHOP PROJECT

Carved or Stacked: Subtractive versus Additive

You will make the same simple shape twice: once by carving it from a bar of soap (subtractive) and once by stacking layers of cardboard cut to the shape of each slice (additive). You will weigh the waste, time each method and measure how accurate each is.

You will need

- Two bars of plain soap of the same size
- A paring or craft knife (adult supervision), a metal ruler, a cutting board
- Corrugated cardboard or foam board 3–5 mm thick, and thin card stock
- White glue or a glue stick
- A kitchen scale (0.1 g if possible)
- Calipers or a ruler; a stopwatch
- Graph paper

Steps

1. Choose a simple shape about 5 cm long with at least one sloped or curved side: a wedge, a dome, a small boat hull or a stepped pyramid. Draw it full size on graph paper in top and side views.
2. Weigh one soap bar. **Subtractive:** time yourself carving the shape from it. Weigh the finished part and the shavings. Find the buy-to-fly ratio and waste percentage.
3. **Slice the model.** Using the side view, draw the outline of the shape at each layer height for 4 mm cardboard. (A dome 20 mm high needs 5 slices.) This is exactly what a slicer program does.
4. **Additive:** time yourself cutting and gluing the slices into a stack. Weigh the stack and the cardboard scraps.
5. Repeat the additive build with thin card stock layers (about 0.5 mm, so many more layers) for just the top 10 mm of the shape. Compare the stair-stepping.
6. Measure the length, width and height of each part and compare with the drawing. Record the errors.

7. Make a table: method, time, part mass, waste mass, buy-to-fly, largest dimensional error, surface smoothness (1–5).
8. Write which method you would choose to make (a) one part, (b) one hundred identical parts, (c) a part with a hidden hollow inside, and why.
9. **Improve it.** Find one change to your slicing (thinner layers only where the slope is gentle, for example) that would make the stacked part smoother without many more layers. Real slicers call this adaptive layer height.

Tips

- Soften the soap for a few seconds in warm water if it crumbles.
- Number the cardboard slices as you cut them.
- Glue each layer squarely on the one below; misalignment between layers is a real 3D-printing defect called layer shift.

Check your work

☐ I calculated buy-to-fly and waste for both methods.

☐ I can explain stair-stepping and why layer height matters.

☐ I can tell how Hull, Crump and Bowyer each changed 3D printing.

SHOP NOTEBOOK

1. A timeline of 3D printing: Kodama (1981), Hull (1983–1986), Crump (1988–1992), Deckard (SLS), RepRap (2005–2008), the FDM patent expiring (2009), and today.
2. A comparison chart of subtractive, formative and additive manufacturing with two examples each and their strengths.
3. Your project data table and sketches of both parts, with the stair-stepping drawn to scale.

KEY FORMULAS

$n = \dfrac{H}{h}$ (number of layers)

$\text{buy-to-fly} = \dfrac{m_{\text{raw}}}{m_{\text{part}}}, \quad \text{waste} = 1 - \dfrac{m_{\text{part}}}{m_{\text{raw}}}$

$m = \rho V$

From history. Hull's machines were first used by automobile and aircraft companies to check the fit of new parts before ordering expensive molds. Dentists and surgeons were early adopters too: today clear dental aligners are formed over printed models of each patient's teeth, and surgeons practise difficult operations on printed copies of a patient's organs made from scans.

WORKED EXAMPLES

Example 1. A bracket of volume 45 cm^3 is machined from an aluminum block 8 cm × 6 cm × 5 cm. Aluminum's density is 2.70 g/cm^3. Find the buy-to-fly ratio and the percentage of the block that becomes chips.

Show solution

1. Block volume: $8 \times 6 \times 5 = 240$ cm^3.
2. Buy-to-fly: $\dfrac{240 \times 2.70}{45 \times 2.70} = \dfrac{240}{45} \approx 5.3$.
3. Waste: $1 - \dfrac{45}{240} \approx 0.81$, so about 81% becomes chips (which can be recycled, at a cost).

Answer: Buy-to-fly about 5.3; about 81% removed.

Example 2. A 42 mm tall figurine is printed on an FDM printer at 0.20 mm layers and on a resin printer at 0.05 mm layers. How many layers does each need? If the FDM printer averages 35 s per layer and the resin printer 9 s per layer, which finishes first?

Show solution

1. FDM: $n = 42 \div 0.20 = 210$ layers; time $210 \times 35 = 7350$ s ≈ 2.0 h.
2. Resin: $n = 42 \div 0.05 = 840$ layers; time $840 \times 9 = 7560$ s ≈ 2.1 h.
3. About the same time; the resin print has four times as many layers, so its surface is far smoother. (Resin printers cure a whole layer at once, which is why each layer is quick.)

Answer: 210 and 840 layers; both take about 2 hours.

Example 3. A ramp on a part rises 6 mm over a run of 30 mm. Printed at 0.30 mm layers, how many steps form its surface, and how long is each step? What happens at 0.10 mm?

Show solution

1. Steps: $6 \div 0.30 = 20$; each step is $30 \div 20 = 1.5$ mm long and 0.30 mm high.
2. At 0.10 mm: 60 steps, each 0.5 mm long and 0.10 mm high, a much smoother slope.
3. Shallow slopes show the stair-stepping most, which is why designers often orient parts so gentle curves are not nearly flat on the bed.

Answer: 20 steps of 1.5 mm; 60 steps of 0.5 mm at 0.10 mm layers.

PRACTICE

1. Easy Classify each as additive, subtractive or formative: (a) drilling a hole, (b) casting a bronze bell, (c) printing a phone stand, (d) stamping a car door, (e) turning a table leg on a lathe.

   Show answer

   (a) subtractive, (b) formative, (c) additive, (d) formative, (e) subtractive.

2. Easy How many layers does a 25 mm tall part need at 0.25 mm layer height?

   Show answer

   $25 \div 0.25 = 100$ layers.

3. Easy What problem was Chuck Hull trying to solve at work?

   Show answer

   Waiting weeks or months for prototype plastic parts to be made by hand before a design could be tested.

4. Medium A part has a mass of 120 g and is machined from a 900 g titanium bar. Find the buy-to-fly ratio and the waste percentage.

   Show answer

   $900 \div 120 = 7.5$; waste $1 - 120/900 \approx 87\%$.

5. Medium Why did desktop 3D printers become cheap after 2009?

Show answer

Scott Crump's basic FDM patent expired, and the open RepRap designs let many small companies build inexpensive printers.

6. Medium A 60 mm tall vase is printed at 0.16 mm layers, averaging 22 s per layer. How long will it take?

Show answer

$60 \div 0.16 = 375$ layers; $375 \times 22 = 8250$ s ≈ 2.3 h.

7. Medium What does the STL file format describe, and who created it?

Show answer

The surface of a part as a mesh of triangles; Chuck Hull and 3D Systems created it for their stereolithography machines.

8. Hard A designer must cut print time in half for the vase in Problem 6 without changing speed per layer. What layer height should she use, and what will she give up?

Show answer

Double the layer height to 0.32 mm (half as many layers). The surface will show more stair-stepping and less fine detail; she must also check that her nozzle can print 0.32 mm layers (usually up to about 75–80% of the nozzle diameter).

9. Hard **You are the tradesperson.** A farmer needs a plastic knob for a 40-year-old seed drill. The maker no longer sells it. Would you machine it, mold it or print it? Explain.

Show answer

Print it (or machine it from plastic stock if a lathe is handy). A mold would cost far too much for one part; printing needs only a measured CAD model and can be tested and adjusted quickly. Choose a tough, weather-resistant material such as PETG or ASA.

10. Hard Conceptual. Why can a 3D printer make a hollow ball with a smaller ball loose inside it, when a milling machine cannot?

Show answer

The printer builds the inner ball and the outer shell layer by layer at the same time, so it never has to reach a tool inside a closed space; a cutting tool cannot get inside a closed shell.

11. Challenge An aerospace bracket of 0.35 kg is machined from a 3.5 kg titanium block at $40/kg of titanium. A printed version uses 0.5 kg of titanium powder at $300/kg (including support material). Compare the material costs. Why might the printed part still be chosen?

Show answer

Machined: $3.5 \times 40 = \$140$; printed: $0.5 \times 300 = \$150$. Material cost is similar, but the printed part can have an optimized, lighter shape, needs no special fixtures, and can combine several parts into one; weight saved on an aircraft saves fuel for decades.

COMMON MISTAKES

- Thinking 3D printing will replace all other manufacturing; for large quantities molding and machining are usually cheaper.
- Confusing layer height with print resolution in the horizontal plane; they are set by different things.
- Assuming one person invented 3D printing all at once; several inventors in different countries worked on it in the same years.

Make it a game · Carve or Stack. Your parent names ten objects: a wooden spoon, a plastic cup, a chess piece, a pipe fitting, a dental crown. Call each as subtractive, additive or formative in five seconds, and say which process you would choose. Include the story of Chuck Hull, Scott Crump or Adrian Bowyer. Beat your accuracy.

Scripture. “And he hath filled him with the spirit of God, in wisdom, in understanding, and in knowledge, and in all manner of workmanship; And to devise curious works” (Exodus 35:31-32, KJV)

Bezalel was given skill both to devise (to design) and to make. A 3D printer is only a tool; the wisdom to design something useful and well made is the maker’s.

8.2 How an FDM Printer Works

OBJECTIVES

- Name and explain the parts of an FDM printer: frame, motion system, stepper motors, belts and lead screws, extruder, hot end, heated bed and controller.
- Calculate steps per millimeter, volumetric flow rate and heated-bed power.
- Read and write simple G-code, including how much filament an extrusion move uses.
- Explain how temperature, speed and layer height work together.

> **Warm-up.** Hold a pencil above a sheet of graph paper. Your partner calls out moves: "go to 2 right, 3 up; pen down; go to 8 right, 3 up; go to 8 right, 7 up; pen up." Draw what they say. What shape did you make? You just executed a program the way a printer does.

WATCH

How does a 3D Printer work? (A1 by Bambu Lab)

Jared Owen · 16:35

https://www.youtube.com/watch?v=f94CnlQ0eq4

> **WHEN TO WATCH**
> At the start of session 1. Pause at each part (motors, belts, extruder, hot end, bed) and label it on your sketch.

Note: Jared Owen's 3D animation uses one popular printer as its example; every FDM printer has the same parts. The links in the description are the creator's, not School Launch's.

BACKUP VIDEO

The Beginner 3D Printing Guide I Wish I Had

CNC Kitchen · 14:48

https://www.youtube.com/watch?v=B84CgaPdixc

Before you use a real printer: Stefan Hermann (CNC Kitchen) walks through setup, bed preparation, first layers and common beginner mistakes.

KEY TERMS

stepper motor

A motor that turns in exact small steps, usually 200 per turn (1.8° each), so the controller can position the print head without measuring it.

microstepping

Dividing each full motor step into smaller steps (often 16) by controlling the current in the coils, for smoother, finer motion.

extruder

The mechanism (gears driven by a motor) that grips the filament and pushes it into the hot end at a measured rate.

hot end

The heated block and nozzle that melt the filament; typically 190–260 °C, with a heat break and cooling fan above it so the filament melts only where it should.

heated bed

The flat build plate, warmed to 50–110 °C so the first layer sticks and the part does not warp as it cools.

G-code

The plain-text list of commands a printer follows: moves (G1 X Y Z E F), temperatures (M104, M140) and settings.

CORE IDEAS

The story. The language a 3D printer speaks is older than 3D printing. In the late 1940s John Parsons, who made helicopter rotor blades in Michigan, wanted a machine tool to cut precise curves by following numbers rather than a machinist's hands. With the U.S. Air Force, the MIT Servomechanisms Laboratory built the first numerically controlled milling machine, shown in 1952, reading its moves from punched paper tape. Those numerical-control commands grew into the standard called G-code. When RepRap builders needed a way to tell their printers where to go, they used the same G-code, so a desktop printer today is programmed much like a factory milling machine of the 1960s.

How it works: motion. An FDM printer is a robot that moves a nozzle in three directions. Stepper motors drive the X and Y axes through toothed belts and pulleys, and usually the Z axis through lead screws. A common belt (GT2) has teeth 2 mm apart; on a 20-tooth pulley, one turn of the motor moves the belt $20 \times 2 = 40$ mm. The motor has 200 full steps per turn and the driver divides each into 16 microsteps,

so the controller must send $\frac{200 \times 16}{40} = 80$ steps to move the head 1 mm. A lead screw with an 8 mm lead moves the bed only 8 mm per turn, giving 400 steps per millimeter in Z: slower but stronger and very precise. Different printers arrange the motion differently: a moving bed (“bed slinger”), a CoreXY frame where two motors share both axes, or a delta with three arms.

How it works: melting. The extruder’s gears grip 1.75 mm filament and push it through a tube into the **hot end**, where a heater cartridge and a thermistor (a temperature sensor) hold the block at a set temperature. Above it, a **heat break** and a fan keep the filament cold until the last moment, so it does not soften and jam too early. The melted plastic leaves a nozzle, usually 0.4 mm across, and is laid as a flattened line about 0.45 mm wide and one layer high. The **volumetric flow rate** the hot end must melt is $Q = h \times w \times v$, where h is layer height, w line width and v print speed. A typical hot end can melt about 10–15 mm^3/s; high-flow hot ends manage 25 or more. Print too fast and the plastic cannot melt in time: the extruder skips and the part comes out thin and weak.

The bed and the controller. The heated bed is a resistance heater: $P = V^2/R$. Warming it helps the first layer stick and keeps the bottom of the part from shrinking and curling up as it cools (warping). The controller board reads the G-code line by line, sends step pulses to each motor, and runs feedback loops (often PID control) that switch the heaters on and off to hold each temperature steady. Because it does not measure the head’s actual position, a skipped step from a collision or a loose belt shows up as a **layer shift**. Firmware also includes thermal runaway protection, which shuts the heaters off if a temperature reading stops making sense: an important safety feature.

Temperature, speed and layers. These settings are a three-way trade. Hotter plastic flows more easily and bonds layers better but strings and sags; faster printing needs more flow and more cooling; thicker layers print faster but look rougher and need more flow. Good settings start from the filament maker’s recommended range and are tuned with test prints.

Safety. The nozzle and heater block reach temperatures that burn skin instantly, and the bed can be over 100 °C. Moving belts and the head pinch fingers. Printers draw significant power from a wall outlet and should be bought from reputable makers with thermal runaway protection, set on a non-flammable surface, and never left

running unattended for long prints in a bedroom. A smoke alarm near the printer is wise.

PICTURE STUDY



The First 3D Printer in Space, NASA, November 2014 · Photograph · International Space Station; NASA

Image: Wikimedia Commons, public domain

In November 2014 the first 3D printer in orbit, built by the company Made In Space with NASA, printed its first parts aboard the International Space Station. Astronaut Barry "Butch" Wilmore holds out the printer's removable print tray after one of the first jobs. The first test pieces, called coupons, were sent back to Earth to compare with identical parts printed on the ground.

Look closely

- Find the print tray. Which part of an FDM printer is it, and what job does it do?
- Look closely at the tray's surface. What can you see of the parts printed on it?
- Find the label on the tray. Why would every removable part on the station be labeled?
- Look for anything that tells you he is weightless, and why the gloves might be worn.

Talk about it

1. On Earth, gravity helps hold melted plastic down on the layer below. What might be different in orbit?
2. Why would NASA want to print parts in space rather than launch every spare part?

3. Why print test coupons first instead of a useful part?

Safety first. If you use a real printer, keep fingers away from the nozzle, heater block and bed while they are hot (they stay hot for many minutes after a print), and away from belts and moving parts while it runs. Unplug it before any maintenance, never remove the printer's safety covers, and do not leave it running unattended for long prints.

SHOP PROJECT

The Human Printer: Executing and Writing G-code

You will be the printer. First you will execute a short G-code program by hand on graph paper; then you will write your own program for a shape, calculate its extrusion amounts, and have someone else execute it. If a printer is available, you will also check its calibration with a ruler.

You will need

- Graph paper (5 mm squares work well; each square = 5 mm)
- Pencil, colored pencils, ruler
- Calculator
- Optional: access to an FDM printer at home, a library makerspace or a school, with an adult or trained staff member

Steps

1. Mark an origin (0,0) at the lower-left of the graph paper. Execute this program, drawing a line only for G1 moves that have an E value. Line 1: G28 (go to 0,0). Line 2: G1 X10 Y10 F3000. Line 3: G1 X60 Y10 E1.87 F1500. Line 4: G1 X60 Y40 E1.12. Line 5: G1 X10 Y40 E1.87. Line 6: G1 X10 Y10 E1.12. Line 7: G1 X35 Y60 F3000.
2. What shape did you draw? Check that each E value matches its line length using $E = \frac{L \times 0.45 \times 0.20}{2.405}$.
3. Find the time for each move from its length and feed rate ($t = L \div (F/60)$). Add them for the total time of this "layer."
4. **Design.** Draw your initials or a simple house shape on graph paper using only straight lines. Write the G-code for it: travel moves without E, drawing moves with E calculated for 0.20 mm layers and 0.45 mm lines.
5. Trade programs with a partner. Execute each other's code without looking at the original drawing. Compare. Find and fix every bug.
6. Add a second layer: copy the moves with Z0.4 and explain in a comment why the second layer's E values are the same.

7. **If a printer is available:** with the staff member or adult, use the printer's control menu to move the X axis exactly 100 mm. Measure the actual move with a ruler or calipers against a fixed mark. Record the error.
8. If the move was not 100 mm, calculate the corrected steps per mm: $\text{new} = \text{old} \times \frac{100}{\text{measured}}$. (Do not change printer settings yourself; record the number for the owner.)
9. **Improve it.** Rewrite your program to draw the same shape with the fewest travel moves. How much time did you save?

Tips

- Use one color for travel moves (dashed) and another for extrusion moves.
- Remember F is in mm per minute.
- Comments in G-code start with a semicolon (;) and are ignored by the printer.

Check your work

- ☐ I executed the sample program correctly.
- ☐ My own G-code produced my shape when someone else ran it.
- ☐ I can calculate steps per mm and flow rate.

SHOP NOTEBOOK

1. A labeled diagram of an FDM printer: frame, X/Y/Z motors, belts and pulleys, lead screw, extruder, heat break, hot end and nozzle, part-cooling fan, heated bed, controller and power supply.
2. Your G-code program, the shape it draws, and a table of each move's length, E value and time.
3. A troubleshooting table: layer shift, under-extrusion, stringing, warping; the likely cause of each from this lesson.

KEY FORMULAS

$$\text{steps/mm} = \frac{\text{steps/rev} \times \text{microsteps}}{\text{mm/rev}}$$

$Q = h\,w\,v$ (mm³/s)

$L_f = \dfrac{V}{A_f}, \quad A_f = \pi(0.875)^2 \approx 2.405\ \text{mm}^2$ for 1.75 mm filament

$P = \dfrac{V^2}{R}$ (heater power)

$v_{\text{mm/s}} = \dfrac{F}{60}$ (G-code feed F is in mm/min)

From history. In December 2014, a month after the station's printer arrived, NASA needed a ratchet wrench in orbit. Engineers at Made In Space designed one on the ground and sent the file up by radio, and the station's printer made it in about four hours: the first tool ever designed on Earth and built in space. You will meet it in Lesson 8.4.

WORKED EXAMPLES

Example 1. A printer's X axis uses a GT2 belt (2 mm pitch) on a 16-tooth pulley and a 200-step motor with 16× microstepping. Find the steps per mm and the smallest move.

Show solution

1. Belt travel per turn: $16 \times 2 = 32$ mm.
2. Steps per turn: $200 \times 16 = 3200$.
3. Steps per mm: $3200 \div 32 = 100$. Smallest move: $1/100 = 0.01$ mm.

Answer: 100 steps/mm; 0.01 mm per microstep.

Example 2. A printer lays 0.20 mm layers with 0.45 mm lines at 120 mm/s. Find the volumetric flow. Its hot end can melt 12 mm³/s. Is that enough? What is the fastest speed it can print at these settings?

Show solution

1. $Q = 0.20 \times 0.45 \times 120 = 10.8$ mm³/s, under 12, so it is enough.
2. Fastest speed: $v = \dfrac{12}{0.20 \times 0.45} \approx 133$ mm/s.

Answer: 10.8 mm³/s, enough; about 133 mm/s maximum.

Example 3. Write the extrusion amount for a G-code line that draws a 50 mm line at 0.20 mm layer height and 0.45 mm width with 1.75 mm filament, at 25 mm/s.

Show solution

1. Volume of plastic in the line: $V = 50 \times 0.45 \times 0.20 = 4.5\ \text{mm}^3$.
2. Filament length: $L_f = 4.5 \div 2.405 \approx 1.87\ \text{mm}$.
3. Feed rate: $F = 25 \times 60 = 1500\ \text{mm/min}$.
4. If the head is at X10 Y10 with relative extrusion, the line is: G1 X60 Y10 E1.87 F1500.

Answer: E1.87 (about 1.87 mm of filament) at F1500.

Example 4. A 24 V heated bed has a resistance of 1.4 Ω. Find its power and the current it draws. Why is a 24 V bed better than a 12 V bed of the same power?

Show solution

1. $P = \dfrac{24^2}{1.4} \approx 411\ \text{W}$; $I = \dfrac{24}{1.4} \approx 17\ \text{A}$.
2. A 12 V bed of the same 411 W would draw $411 \div 12 \approx 34\ \text{A}$, twice the current, so its wires and connectors would carry four times the I^2R heating loss. Higher voltage means lower current and cooler, safer wiring.

Answer: About 411 W at 17 A; 24 V halves the current.

PRACTICE

1. Easy What does a stepper motor do that an ordinary motor does not?

   Show answer

   It turns in exact steps (often 200 per turn), so the controller knows how far it moved without measuring.

2. Easy Convert a G-code feed rate of F4800 to mm/s.

   Show answer

   $4800 \div 60 = 80\ \text{mm/s}$.

3. Easy What are the jobs of the heat break and the heated bed?

Show answer

The heat break keeps the filament cold until it reaches the melt zone, preventing jams; the heated bed helps the first layer stick and reduces warping.

4. Medium A Z axis uses a lead screw with a 2 mm lead and a 200-step motor at 16× microstepping. Find the steps per mm.

Show answer

$3200 \div 2 = 1600$ steps/mm.

5. Medium Find the volumetric flow at 0.28 mm layers, 0.5 mm lines and 80 mm/s.

Show answer

$0.28 \times 0.5 \times 80 = 11.2\ \text{mm}^3/\text{s}$.

6. Medium How many millimeters of 1.75 mm filament make a 120 mm line, 0.45 mm wide and 0.2 mm high?

Show answer

$V = 10.8\ \text{mm}^3$; $10.8 \div 2.405 \approx 4.49$ mm.

7. Medium A 12 V hot-end heater cartridge is rated 40 W. Find its current and resistance.

Show answer

$I = 40/12 \approx 3.33$ A; $R = V^2/P = 144/40 = 3.6\ \Omega$.

8. Hard A printer moved 97.5 mm when told to move 100 mm. Its setting is 80 steps/mm. What should the new setting be?

Show answer

$$80 \times \frac{100}{97.5} \approx 82.05 \text{ steps/mm}.$$

9. Hard **You are the technician.** Halfway up a print, every layer above a certain height is shifted 3 mm to the right. List the likely causes in order of what you would check.

Show answer

A skipped step: the head hit a curled-up part or blob, a belt is loose or its pulley set screw has slipped, the motor or driver overheated, or the speed and acceleration were set too high. Check for collisions and warping, then belt tension and pulley screws, then motor and driver temperature, then speed settings.

10. Hard Conceptual. Why does printing faster eventually make parts weaker even when the shape looks right?

Show answer

The hot end cannot fully melt and heat the plastic at high flow rates, so it is extruded cooler and thinner; layers bond less well and lines may be under-filled, leaving gaps.

11. Challenge A print has 180 layers. Each layer has 1,450 mm of extrusion moves at 60 mm/s and 600 mm of travel moves at 150 mm/s. Ignoring acceleration and layer changes, estimate the print time. Then estimate how much filament it uses (0.20 mm layers, 0.45 mm lines).

Show answer

Per layer: $1450/60 + 600/150 \approx 24.2 + 4.0 = 28.2$ s; total $180 \times 28.2 \approx 5070$ s ≈ 1.4 h. Plastic: $180 \times 1450 \times 0.45 \times 0.20 \approx 23{,}500$ mm^3, filament length $23{,}500 \div 2.405 \approx 9.8$ m. (Real prints take longer because of acceleration.)

COMMON MISTAKES

- Treating G-code feed rate F as mm/s; it is mm/min.
- Forgetting that the E value is a length of filament, not a length of line.
- Raising print speed without checking whether the hot end can melt that much plastic.
- Touching the nozzle to “check” it; it stays far above burning temperature after a print.

Make it a game · Human G-code Printer. Write a short G-code program on paper that draws a square with moves like G1 X10 Y0. Your parent acts as the printer and follows your commands with a pencil on a grid, lifting the pencil only when your code says so. Find and fix any mistakes. Then calculate steps per millimeter for a given belt pitch. Swap roles.

8.3 From CAD to Slicer

OBJECTIVES

- Model a simple functional part in free CAD (Tinkercad or Onshape) and export it as an STL or 3MF file.
- Explain what a slicer does: layers, walls (perimeters), top and bottom layers, infill, supports, and bed adhesion.
- Estimate a print's plastic volume, mass, filament length, cost and time, and check the estimate against the slicer.
- Choose slicer settings for strength, speed or appearance and explain the trade-offs.

> **Warm-up.** Slice a potato, an apple or a block of cheese into thin, even slices (with an adult and a sharp knife on a cutting board), then stack them back together. Look at the outline of each slice. Sketch three of them. A slicer does exactly this to a computer model before a printer can make it.

WATCH

Beginners guide to 3D printer slicers

Teaching Tech · 20:52

https://www.youtube.com/watch?v=yXNZ_2-rHNE

> **WHEN TO WATCH**
> Before you slice your own part. Keep your slicer open and follow along, pausing to find each setting he explains.

Note: Teaching Tech (Michael Laws) shows several slicers; the ideas are the same in all of them.

BACKUP VIDEO

Beginner's guide to slicing (using OrcaSlicer) - 3D Printing Mastery

Maker's Muse · 14:25

https://www.youtube.com/watch?v=AZNaGiMkKns

If you are using OrcaSlicer: a step-by-step setup and first slice from Maker's Muse.

KEY TERMS

CAD

Computer-aided design: software for drawing and modeling parts precisely. Tinkercad builds parts by adding and subtracting simple shapes; Onshape and other parametric programs build them from dimensioned sketches and features.

STL and 3MF

File formats for 3D printing. STL describes only the surface as triangles; 3MF also stores units, colors and settings.

slicer

Software that cuts a model into layers and writes the G-code: the path, speed, temperature and extrusion for every line.

walls (perimeters)

The outline loops printed around the edge of each layer; most of a part's strength comes from them.

infill

The internal pattern (grid, gyroid, honeycomb) that fills the inside of a part at a set percentage, usually 10–40%.

supports and adhesion

Supports are temporary structures under overhangs; a brim, skirt or raft helps the first layer stick to the bed.

CORE IDEAS

The story. In 1963 Ivan Sutherland, a graduate student at MIT, wrote Sketchpad, a program that let a person draw directly on a computer screen with a light pen and tell the computer that lines must stay parallel or equal. It was the beginning of computer-aided design. In the 1960s Pierre Bézier, an engineer at Renault, developed the smooth curves (Bézier curves) used to describe car bodies, and they are still in every CAD and drawing program. By the 1980s engineers drew on desktop computers with programs like AutoCAD, and in the 1990s parametric 3D modelers such as SolidWorks let them change one dimension and watch the whole part update. Free tools came next: Tinkercad (2011) runs in a web browser and is simple enough for children, and Onshape (2015), started by some of the founders of SolidWorks, puts professional parametric CAD in the browser free for students.

How the model becomes a print. A CAD model is mathematically exact: a hole is a perfect cylinder. To print it, the model is exported as a **mesh** of flat triangles that

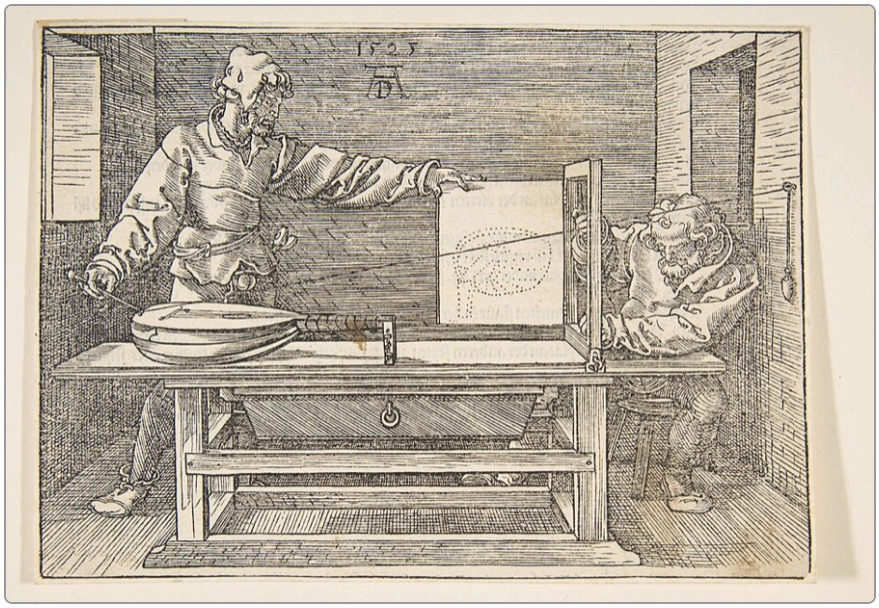
approximate every curve. Each triangle is stored as three corner points and a normal (an arrow pointing outward); a binary STL file uses 50 bytes per triangle plus an 84-byte header. Too few triangles make a round hole into a visible polygon; too many make huge files. The mesh must also be **watertight** (no gaps), or the slicer cannot tell inside from outside.

The slicer. The slicer cuts the mesh with a horizontal plane at every layer height and finds the outline of each slice, like the contour lines on a map. For each layer it plans the **walls** (perimeters) around the outline, solid **top and bottom layers**, and the **infill** inside. It adds **supports** under overhangs too steep to print in air (more than about 45° from vertical), a **skirt** or **brim** to prime the nozzle and hold the first layer down, and then writes every move as G-code with speeds, temperatures and fan settings. Finally it estimates the plastic used and the time.

The math of estimates. Printed plastic is roughly the shell plus a fraction of the interior: $V \approx A_s t_s + f\,(V_m - A_s t_s)$, where A_s is the surface area, t_s the shell thickness, f the infill fraction and V_m the model volume. Mass is $m = \rho V$ (PLA about 1.24 g/cm^3), filament length is volume divided by the filament's cross-section (2.405 mm^2 for 1.75 mm), cost is mass times price per gram, and time is roughly volume divided by the average flow rate, plus travel and acceleration. Slicers do this exactly, but an estimate tells you whether the slicer's answer makes sense.

In the shop. Strength comes mostly from walls, not infill: going from 2 to 4 walls usually strengthens a part more than going from 20% to 40% infill. A careful designer models parts in real units (millimeters), checks the model's dimensions in the slicer, orients the part so it needs few supports and is loaded the strong way (Lesson 8.4), and saves the project file with its settings so the part can be printed again identically, which is how a shop keeps quality consistent.

PICTURE STUDY



The Draughtsman of the Lute, Albrecht Dürer, 1525 · Woodcut, from *Underweysung der Messung* (Instruction in Measurement) · The Metropolitan Museum of Art, New York

Image: Wikimedia Commons, public domain

In his 1525 book on measurement, Albrecht Dürer showed a machine for drawing a three-dimensional object exactly. A string runs from a fixed point on the wall to a pointer touching the lute; where it passes through a frame, the draughtsman marks a dot. Point by point, the lute becomes accurate numbers on paper. A 3D scanner and a CAD mesh do the same thing with light and triangles.

Look closely

- Find where the string is fastened on the far wall, with its weight. What does that fixed point stand for?
- Find the pointer touching the lute. How many points would it take to describe the lute's curved body?
- Find the frame and the hinged panel. Why does the draughtsman close the panel to mark each dot?
- Look at the dots already marked on the panel. What shape are they starting to make?

Talk about it

1. How is a set of measured points like the corners of the triangles in an STL mesh?
2. Why would more points give a more accurate drawing, and what would it cost the two men in time?
3. What does a CAD program do that Dürer's machine could not?

Safety first. This lesson is done at a computer; if you slice food in the warm-up, use a sharp knife on a cutting board with an adult. If you print your part, follow the printer safety rules from Lesson 8.2.

SHOP PROJECT

Design and Slice a Useful Part

You will design a small, useful part in free CAD, export it, slice it with a free slicer (no printer needed), and run a set of slicer experiments to see how settings change time, plastic and cost. If a printer is available, you will print your best version.

You will need

- A computer with internet access
- A free Tinkercad or Onshape (education) account, with a parent's permission
- A free slicer: PrusaSlicer, OrcaSlicer or UltiMaker Cura
- Calipers or a ruler to measure the object your part must fit
- Optional: an FDM printer (home, library makerspace, school) and PLA filament

Steps

1. Choose a part someone in your home actually needs: a cable clip for a desk, a hook for a pegboard, a spacer, a drawer label holder, a broom-handle hanger, a small tool tray. Measure what it must fit and sketch it with dimensions.
2. Model it in Tinkercad or Onshape in millimeters. Use holes (negative shapes) for mounting screws, with a diameter about 0.3 mm larger than the screw. Give sharp inside corners a small fillet or chamfer.
3. Export it as STL or 3MF. Open it in the slicer and check its size with the slicer's measuring tool.
4. Choose the orientation: flat side down, fewest overhangs, and layers running along (not across) the direction it will be pulled or bent.
5. Slice it with default settings (0.20 mm layers, 2–3 walls, 15–20% infill). Record the estimated time, filament length and mass.
6. **Experiment.** Change one setting at a time and record the results: layer height 0.12, 0.20, 0.28 mm; infill 10%, 20%, 40%; walls 2, 3, 5; supports off and on (if needed).

7. Estimate the mass of the default version by hand with the shell-plus-infill formula and compare with the slicer's number.
8. Calculate the cost of each version at your filament's price per kilogram. Make a table and choose the settings you would use, with reasons.
9. Use the slicer's preview to look at layer 1, a middle layer and the top layer. Sketch what you see: walls, infill pattern, top surface.
10. **Print it (if possible)** and test it in use. **Improve it:** change the model or settings to fix whatever did not fit or work, and record version 2.

Tips

- Name each slicer experiment clearly (e.g. hook_L020_W3_I20) so you can compare.
- In Tinkercad, hold Shift to keep proportions and use the ruler tool to place holes exactly.
- If the part is larger than the bed or would need lots of support, split it into two parts that join.

Check your work

- ☐ My part is modeled to measured dimensions in millimeters.
- ☐ My table shows how layer height, infill and walls change time and mass.
- ☐ My hand estimate was within about 30% of the slicer's.

SHOP NOTEBOOK

1. A dimensioned sketch of your part in three views (top, front, side) before you modeled it.
2. Your slicer experiment table and a graph of print time against layer height.
3. Sketches of three sliced layers from the preview, labeled: walls, top/bottom, infill, supports.

KEY FORMULAS

STL size $= 84 + 50N$ bytes (N triangles)

$V \approx A_s t_s + f\,(V_m - A_s t_s)$

$m = \rho V, \quad L_f = V / 2.405\ \text{mm}^2, \quad \text{cost} = m \times \text{price per g}$

$t \approx \dfrac{V}{\overline{Q}}$ (time from average flow rate)

From history. Ivan Sutherland's Sketchpad ran on the TX-2, one of the largest computers of its day, and filled a room. Today the same ideas run in a web browser on a school laptop. Sutherland received the Turing Award, the highest prize in computer science, in 1988.

WORKED EXAMPLES

Example 1. A cube is stored in a binary STL file. How many triangles does it need, and how big is the file? A scanned statue has 400,000 triangles. How big is its file?

Show solution

1. A cube has 6 square faces, each split into 2 triangles: $N = 12$.
2. Size: $84 + 50(12) = 684$ bytes.
3. Statue: $84 + 50(400{,}000) \approx 20{,}000{,}000$ bytes ≈ 20 MB.

Answer: 12 triangles, 684 bytes; about 20 MB.

Example 2. A solid block 50 mm × 30 mm × 20 mm is printed with a shell about 1.0 mm thick and 20% infill in PLA (1.24 g/cm³). Estimate the plastic volume, mass, filament length and cost at $22 per kilogram.

Show solution

1. Model volume: $V_m = 50 \times 30 \times 20 = 30{,}000\ \text{mm}^3$.
2. Surface area: $A_s = 2(50 \cdot 30 + 50 \cdot 20 + 30 \cdot 20) = 6200\ \text{mm}^2$; shell $6200 \times 1.0 = 6200\ \text{mm}^3$.
3. Infill: $0.20 \times (30{,}000 - 6200) = 4760\ \text{mm}^3$; total $V \approx 10{,}960\ \text{mm}^3 \approx 11.0\ \text{cm}^3$.
4. Mass: $11.0 \times 1.24 \approx 13.6$ g; filament $10{,}960 \div 2.405 \approx 4560$ mm ≈ 4.6 m; cost $13.6 \times \$0.022 \approx \$0.30$.

Answer: About 11 cm³, 13.6 g, 4.6 m of filament, 30 cents.

Example 3. The same block prints at an average flow of 6 mm^3/s. Estimate the time. The slicer says 48 minutes. Why the difference?

Show solution

1. $t \approx 10{,}960 \div 6 \approx 1830$ s ≈ 30 min.
2. The slicer adds travel moves, slowing down for outer walls and small layers, acceleration and deceleration at every corner, and heating time. A 50% difference is common; the estimate shows the slicer's number is reasonable.

Answer: About 30 minutes of extrusion; the slicer's 48 minutes includes travel and acceleration.

Example 4. Reasoning. A student's wall hook broke at the bend. It was printed with 2 walls and 15% infill. She plans to raise the infill to 50%. Suggest a better change.

Show solution

1. Most of the bending stress is carried by the outer surfaces of the hook (like the flanges of an I-beam), which are the walls.
2. Raising walls from 2 to 4 or 5 strengthens the high-stress outer region and costs less plastic and time than 50% infill.
3. She should also check the orientation: if layers run across the bend, rotate the hook to print on its side (Lesson 8.4).

Answer: Add walls (4–5) and reorient the part; extra infill is the least efficient fix.

PRACTICE

1. Easy What does a slicer do?

   Show answer

   It cuts a 3D model into layers, plans walls, infill, top and bottom layers and supports for each, and writes the G-code the printer follows, with time and material estimates.

2. **Easy** How many triangles are in a binary STL file of 3,084 bytes?

   Show answer

   $(3084 - 84) \div 50 = 60$ triangles.

3. **Easy** Name the free CAD programs mentioned in this lesson and one difference between them.

   Show answer

   Tinkercad (adds and subtracts simple shapes; very easy) and Onshape (parametric sketches and features; professional).

4. **Medium** A slicer says a part uses 32 g of PLA. Filament costs $25 per kg. What is the material cost?

   Show answer

   $32 \times 0.025 = \$0.80$.

5. **Medium** How many meters of 1.75 mm PLA filament make 32 g? ($\rho = 1.24\ \text{g/cm}^3$)

   Show answer

   $V = 32/1.24 \approx 25.8\ \text{cm}^3 = 25{,}800\ \text{mm}^3$;
   $L = 25{,}800/2.405 \approx 10{,}700\ \text{mm} \approx 10.7\ \text{m}$.

6. **Medium** About how many 32 g parts can be printed from a 1 kg spool, allowing 5% waste for purging and failed starts?

   Show answer

   $950 \div 32 \approx 29$ parts.

7. **Medium** Why do slicers add supports, and at about what angle are they usually needed?

   Show answer

   Plastic cannot be printed on air; each layer needs something underneath. Overhangs steeper than about 45° from vertical (or horizontal bridges that are too long) need supports.

8. Hard Estimate the printed volume of a 40 × 40 × 40 mm cube with a 1.2 mm shell and 15% infill.

Show answer

Model $64{,}000\ \text{mm}^3$; area $6 \times 1600 = 9600\ \text{mm}^2$; shell $11{,}520\ \text{mm}^3$; infill $0.15(64{,}000 - 11{,}520) \approx 7870\ \text{mm}^3$; total about $19{,}400\ \text{mm}^3 \approx 19.4\ \text{cm}^3$ (about 24 g of PLA).

9. Hard **You are the tradesperson.** A customer's round 20 mm hole in a printed part came out as a visible 12-sided polygon and the pin will not fit. What went wrong, and how do you fix it?

Show answer

The model was exported with too coarse a mesh (too few triangles around the curve), so the hole's flat sides cut inside the circle. Export with a finer resolution or more segments, and add a small clearance (about 0.2–0.3 mm) to the hole, since printed holes also come out slightly small.

10. Hard Conceptual. Why does adding walls usually strengthen a part more than adding infill?

Show answer

In bending and twisting, stress is highest at the outer surfaces, which are the walls; infill sits near the middle where stress is low. Walls are also continuous loops, while infill lines are short and only touch the walls at their ends.

11. Challenge A small shop sells a printed bracket. Each uses 45 g of PETG ($28/kg) and prints in 2.5 hours on a printer that cost $800 and should last 4,000 printing hours; electricity is 0.12 kWh per hour at $0.15/kWh. Labor to remove supports and pack is 6 minutes at $20/h. Find the cost per bracket.

Show answer

Plastic $45 \times 0.028 = \$1.26$; printer wear $2.5 \times 800/4000 = \$0.50$; electricity $2.5 \times 0.12 \times 0.15 \approx \$0.05$; labor $0.1 \times 20 = \$2.00$; total about $3.81. Labor, not plastic, is the largest cost.

COMMON MISTAKES

- Modeling in inches or with no units, so the part imports 25.4 times too small or too large.
- Exporting curved surfaces with too few triangles.

- Raising infill to make a part stronger when more walls or a better orientation would do more.
- Trusting the slicer's time estimate exactly; real prints often run a little longer.

> **Make it a game · Slicer Settings Quiz.** Your parent names a slicer setting: perimeters, infill, supports, brim, layer height. You explain in one sentence what it does and what happens if it is set too low or too high. Then pick settings for a bracket that must be strong. Score a point per correct effect. Aim for seven of eight.

8.4 Designing for Printing: Strength and Tolerances

OBJECTIVES

- Explain why FDM parts are anisotropic (weaker across layer lines) and choose an orientation for the load.
- Design for overhangs and bridges, and choose clearances for sliding, turning and press-fit parts.
- Choose between printed threads, heat-set inserts and captured nuts, and calculate clamp force and bearing stress with $T = KDF$ from Unit 1.
- Calculate the strain in a snap-fit and test a tolerance gauge or orientation samples.

> **Warm-up.** Take a stack of ten sticky notes stuck together. Pull it apart along its length (sliding the notes past each other), then try to peel the top note straight up. Which way is it weak? A 3D print is a stack of layers glued together by heat; predict which direction it will be weakest.

WATCH

Stop Printing Flat: The 45° Secret for Stronger Parts

CNC Kitchen · 17:05

https://www.youtube.com/watch?v=7aJ4dDyyf20

> **WHEN TO WATCH**
> After the paragraph on anisotropy. Write down his strength results for each print angle.

Note: Stefan Hermann (CNC Kitchen) tests printed parts on a homemade tensile tester. A sponsor segment for a children's kit company runs in the middle.

BACKUP VIDEO

Test your 3D Printer's Clearance and Tolerance

Maker's Muse · 4:58

https://www.youtube.com/watch?v=XnJBpCWf9Mc

Before the shop project: Angus Deveson (Maker's Muse) explains tolerance and clearance and shows his printable tolerance-test gauge.

KEY TERMS

anisotropy

Having different strength in different directions. FDM parts are strongest along their printed lines and weakest when pulled apart between layers.

clearance

The designed gap between two parts that must move or fit together, measured per side or on the diameter.

heat-set insert

A knurled brass sleeve with internal threads, pressed into a printed hole with a hot soldering iron so the plastic melts around it; it gives strong, reusable metal threads.

overhang and bridge

An overhang leans outward over empty space; a bridge spans straight across a gap between two supports. Most printers manage overhangs to about 45° and short bridges without supports.

press fit

A fit with zero clearance or slight interference, so the parts hold together by friction.

snap fit

A flexible hook or tab that bends to pass a lip and springs back to lock; its strain must stay below what the plastic can take.

CORE IDEAS

The story. In December 2014 the commander of the International Space Station, Barry "Butch" Wilmore, mentioned that he needed a ratchet wrench. Engineers at Made In Space in California designed one in CAD, checked it, and sent the file to the station. The station's printer made it in about four hours, in plastic, in one piece, with the ratchet's moving pawl and gear already inside. Designing it took real skill: the moving parts needed exactly the right clearance so they would turn without fusing together, the handle had to be oriented so its layers would not split under a twisting load, and every overhang had to print without supports in weightlessness. That is design for additive manufacturing.

How they figured it out: anisotropy. Engineers and hobbyists began testing printed parts on tensile machines. Stefan Hermann of CNC Kitchen and many university labs found the same thing: a bar printed lying flat, pulled along its lines, is far stronger than the same bar printed standing up and pulled across its layers. The layers are bonded only where hot plastic was laid on cooler plastic, so the bond is weaker than

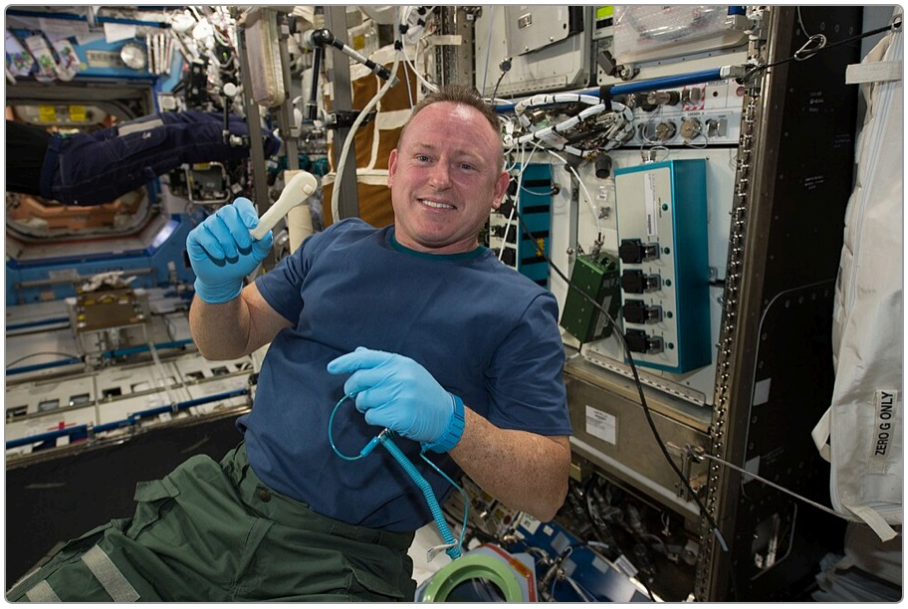
the plastic itself. Depending on the material and settings, the layer bond may be only about half as strong. So the first rule is: **orient the part so the main load runs along the layers, not across them.** A hook printed lying on its side is strong; the same hook printed standing up snaps at the bend.

The science of fit. Printers are not perfectly precise. Melted plastic squeezes out a little, so outside dimensions tend to come out slightly large and holes slightly small (a small hole often prints 0.1–0.2 mm under size), and the first layer may spread ("elephant's foot"). Designers therefore build in **clearance**: about 0.2–0.3 mm per side for parts that must slide or turn, and about 0–0.1 mm for a snug press fit, adjusted after printing a **tolerance gauge** on the actual printer. For a **snap fit** with a straight cantilever hook of length L, thickness t and deflection y, the strain at the root is $\varepsilon = \dfrac{3yt}{2L^2}$. Printed PLA tolerates only a couple of percent before cracking, so snap hooks must be long and thin, printed so they bend along their lines, with a rounded root.

Threads and fasteners (Unit 1 again). Large printed threads (M8 and up) can work for light loads, but small printed threads wear out and strip. Better options are a **tapped hole** for a few assemblies, a **captured hex nut** in a printed pocket, or a brass **heat-set insert** for parts that will be taken apart often. Remember the torque–tension relation from Unit 1, $T = KDF$: a small screw tightened by hand can clamp with hundreds of newtons. Plastic under a screw head creeps (slowly squashes) over time, so use washers to spread the load, do not overtighten, and expect some loss of clamp force.

Overhangs, bridges and holes. Each new layer can only stick out a little beyond the one below; the common rule is about 45° from vertical. Designers turn steep overhangs into 45° chamfers, print horizontal holes with a pointed "teardrop" top so they need no support, keep bridges short, and split complicated parts into pieces that each print flat. Thin walls should be a multiple of the line width (for example 0.9 or 1.2 mm with a 0.4 mm nozzle) so the slicer can fill them cleanly. Good design for printing makes parts stronger, faster and cheaper without any change to the printer.

PICTURE STUDY



A Wrench Designed on Earth and Printed in Space, NASA, December 2014 · Photograph · International Space Station; NASA

Image: Wikimedia Commons, public domain

This plastic ratchet wrench was the first tool designed on the ground and sent to space as a file. It printed as one piece, moving parts and all. Look at it as a designer for printing.

Look closely

- Find the ratchet head. Where are the moving parts, and how were they printed without being glued together?
- Look at the handle. Which way do you think its layers run? Why does that matter when the wrench is turned?
- Compare the wrench with the size of his hand. Why might a designer keep a printed tool small and simple?
- Look at the edges. Are they sharp or rounded?

Talk about it

1. If the wrench had been printed standing on end, where would it be most likely to break?
2. What clearance problems could make the ratchet either jam or rattle?
3. Why was it faster to send a file than to send a wrench?

> **Safety first.** If you print, follow the printer safety rules from Lesson 8.2. Heat-set inserts are installed with a soldering iron at about 200–250 °C: an adult supervises, the iron sits in its stand, and you wear safety glasses. During pull tests, wear safety glasses; printed parts and glue bars can snap and fly.

SHOP PROJECT

A Tolerance Gauge and an Orientation Strength Test

You will find your printer's real clearances with a tolerance gauge, and measure how much print orientation changes strength by pulling hooks printed flat and standing up. If no printer is available, Part B has a hot-glue model of layer bonding that shows the same effect.

You will need

- Access to an FDM printer (home, library makerspace, school, community-college lab) and PLA or PETG
- Free CAD and slicer from Lesson 8.3
- Calipers (a digital caliper is inexpensive and worth owning)
- A luggage scale and a bucket of sand, or a spring scale
- Safety glasses
- If no printer: a hot-glue gun and sticks, a sheet of parchment paper, and a ruler

Steps

1. **Part A – Tolerance gauge.** In CAD, design a plate with five round pegs 10.0 mm in diameter and a separate plate with five holes of 10.1, 10.2, 10.3, 10.4 and 10.5 mm. (Or print a published tolerance-test model.)
2. Print both plates flat at 0.20 mm layers. Measure every peg and hole with calipers and record the actual sizes and the error from the CAD size.
3. Try each peg in each hole. Record which fits are press (must be pushed), snug, sliding and loose. Find the clearance per side for each kind of fit on your printer.
4. **Part B – Orientation.** Design a simple test hook or bar (for example 80 mm long, 10 × 4 mm section with a hole at each end). Slice two copies with the same settings: one lying flat, one standing upright.
5. **Predict** the ratio of their breaking loads.
6. Hang each from a sturdy hook and load it with the bucket and luggage scale (or pull steadily on a spring scale) until it breaks. Record peak force and

where and how it broke.

7. Compute the stress at failure $\sigma = F/A$ for each and the ratio upright ÷ flat.
8. **No printer?** Model the layers with hot glue on parchment: make Bar 1 by laying five long beads side by side along its 10 cm length (like printing flat), and Bar 2 by stacking many short 1 cm beads across its length one after another, letting each cool a moment (like layers). Bend-test both over a table edge with the luggage scale.
9. **Improve it.** Redesign the upright hook (thicker at the stress point, a fillet at the bend, or printed at 45°) and test again.

Tips

- Measure holes with the caliper's inside jaws at two angles; printed holes are often slightly oval.
- Print all test parts with the same filament, temperature and settings so only one variable changes.
- Record the slicer settings in your notebook with every result.

Check your work

- ☐ I know my printer's clearance for a press, sliding and loose fit.
- ☐ I measured how much weaker parts are across layers.
- ☐ I can explain how to orient a part for its load.

SHOP NOTEBOOK

1. Your tolerance-gauge table: CAD size, measured size, error, and fit for each peg and hole.
2. Sketches of a hook printed flat and upright, with layer lines drawn and the break location marked.
3. A design-for-printing checklist of at least eight rules from this lesson (orientation, 45° overhangs, teardrop holes, clearances, wall thickness, fillets, inserts, splitting parts).

KEY FORMULAS

$\sigma = \dfrac{F}{A}$ (compare with the layer-bond or along-layer strength)
$\varepsilon = \dfrac{3yt}{2L^2}$ (straight cantilever snap fit)
$T = KDF$ (Unit 1; $K \approx 0.2$ for dry steel threads)
$\sigma_b = \dfrac{F}{A_{\text{bearing}}}, \quad A_{\text{bearing}} = \frac{\pi}{4}(d_o^2 - d_i^2)$

From history. Printing moving assemblies in one piece, called print-in-place, is now common for hinges, chains and toys. Its secret is the clearance gap the designer leaves between the parts, often about 0.3–0.5 mm, so the slicer never lets the two surfaces touch.

WORKED EXAMPLES

Example 1. A printed PLA hook has a 10 mm × 5 mm cross-section where it is pulled with 400 N. Assume PLA is about 50 MPa strong along its lines and about 25 MPa across layers. Find the stress and the factor of safety in each orientation.

Show solution

1. Area: $10 \times 5 = 50$ mm^2; stress $\sigma = 400 \div 50 = 8$ MPa (N/mm^2 = MPa).
2. Along the lines (printed flat, on its side): $FS = 50 \div 8 \approx 6.3$.
3. Across layers (printed standing up): $FS = 25 \div 8 \approx 3.1$.
4. The orientation alone halves or doubles the safety margin. (Bending at a hook's curve raises stress further, so real hooks need even more margin.)

Answer: 8 MPa; FS about 6.3 printed flat, about 3.1 standing up.

Example 2. A snap-fit hook is 15 mm long and 1.5 mm thick and must deflect 1.0 mm to pass its catch. Find the strain. Is it acceptable if PLA should stay below 2%? What if it were 10 mm long?

Show solution

1. $\varepsilon = \dfrac{3(1.0)(1.5)}{2(15)^2} = \dfrac{4.5}{450} = 0.010 = 1.0\%$, acceptable.
2. At 10 mm: $\varepsilon = \dfrac{4.5}{2(100)} = 0.0225 = 2.25\%$, too high; it would likely crack.
3. Strain depends on $1/L^2$, so a slightly longer hook is much safer.

Answer: 1.0% at 15 mm (good); 2.25% at 10 mm (too high).

Example 3. A printed wheel must turn freely on an 8.0 mm steel axle. The printer makes holes about 0.15 mm under size. With a target running clearance of 0.25 mm per side, what hole diameter should be drawn in CAD?

Show solution

1. Desired actual hole: $8.0 + 2(0.25) = 8.5$ mm.
2. Add the printer's undersize: $8.5 + 0.15 = 8.65$ mm.
3. Draw 8.65 mm (or 8.6–8.7 mm), print a test ring first, and adjust.

Answer: Model the hole at about 8.65 mm.

Example 4. An M4 screw ($D = 4$ mm) clamps a printed bracket. It is tightened to 0.6 N·m with $K = 0.2$. Find the clamp force and the bearing stress on the plastic under (a) the screw head alone (contact ring 7.0 mm outside, 4.3 mm inside) and (b) a 9.0 mm washer.

Show solution

1. Clamp force: $F = \dfrac{T}{KD} = \dfrac{0.6}{0.2 \times 0.004} = 750$ N.
2. (a) $A = \frac{\pi}{4}(7.0^2 - 4.3^2) \approx 24$ mm^2; $\sigma_b = 750/24 \approx 31$ MPa. That is a large fraction of PLA's strength, and the plastic will creep.
3. (b) $A = \frac{\pi}{4}(9.0^2 - 4.3^2) \approx 49$ mm^2; $\sigma_b \approx 15$ MPa. The washer halves the stress. Also use less torque on plastic.

Answer: 750 N; about 31 MPa without a washer, about 15 MPa with one.

PRACTICE

1. Easy Why is an FDM part usually weakest when pulled across its layers?

Show answer

The layers bond only where hot plastic meets cooler plastic below, and that bond is weaker than the continuous plastic within each printed line.

2. Easy What overhang angle can most FDM printers manage without supports?

Show answer

About 45° from vertical.

3. Easy Give two better ways than printed threads to put a small machine screw into a printed part.

Show answer

A brass heat-set insert, a captured hex nut in a printed pocket, or a tapped hole for occasional assembly.

4. Medium A pin is 6.0 mm. You want a sliding fit with 0.2 mm clearance per side, and holes print 0.1 mm small. What hole size do you model?

Show answer

$6.0 + 0.4 + 0.1 = 6.5$ mm.

5. Medium A printed bar 12 mm × 6 mm breaks at 1,800 N when printed flat. Find the stress at failure.

Show answer

$1800 \div 72 = 25$ MPa.

6. Medium A snap hook is 20 mm long and 2 mm thick and deflects 1.5 mm. Find the strain.

Show answer

$$\frac{3(1.5)(2)}{2(400)} = 0.01125 \approx 1.1\%.$$

7. Medium Why do designers give horizontal holes a teardrop or pointed top?

Show answer

The pointed top turns the flat overhang at the top of the hole into two 45° slopes, so it prints cleanly without support.

8. Hard The snap hook in Problem 6 must stay below 1.0% strain with the same 1.5 mm deflection and thickness. What is the shortest length allowed?

Show answer

$L^2 = \dfrac{3(1.5)(2)}{2(0.010)} = 450$; $L \approx 21.2$ mm.

9. Hard An M3 screw is tightened to 0.4 N·m ($K = 0.2$). Find the clamp force.

Show answer

$F = \dfrac{0.4}{0.2 \times 0.003} \approx 667$ N.

10. Hard **You are the designer.** A customer's printed shelf bracket (an L shape) keeps snapping at the inside corner. It was printed standing up with the corner's layers horizontal. Give three changes.

Show answer

Print it lying flat on its side so the layers run around the L; add a generous fillet or a gusset at the inside corner to reduce stress concentration; add walls or thicken the corner; consider a tougher material such as PETG.

11. Hard Conceptual. Why might a printed part pass its test the first day but loosen or crack weeks later around a tightened screw?

Show answer

Plastic creeps under constant stress, especially when warm, so the clamp force slowly drops and the screw loosens; high bearing stress or overtightening can also start cracks that grow.

12. Challenge A hook printed flat failed at 600 N; one printed upright failed at 270 N. (a) Find the ratio. (b) A design must hold 150 N with a factor of safety of 3. Which orientations pass? (c) By what factor would you need to enlarge the upright hook's cross-section area to pass?

Show answer

(a) $270/600 = 0.45$. (b) Required 450 N: only the flat hook passes. (c) $450/270 \approx 1.67$, so about 67% more area, assuming strength scales with area.

COMMON MISTAKES

- Modeling holes at exactly the pin size; they will be too tight.
- Orienting a part for the best-looking surface instead of for its load.

- Printing small threads and expecting them to survive repeated assembly.
- Tightening screws into plastic as hard as into steel.

> **Make it a game · Orientation Decision.** Sketch an L-shaped bracket on paper. Decide how to orient it on the print bed so the layer lines do not split under load, and where overhangs need support. Your parent picks a loading direction and you re-decide. Then choose a clearance in millimeters for a sliding fit versus a press fit. Defend each choice.

> **Scripture.** "From whom the whole body fitly joined together and compacted by that which every joint supplieth" (Ephesians 4:16, KJV)
>
> Paul pictures the church as a body whose parts are "fitly joined together," each joint doing its part. A good assembly is the same: every fit and fastener sized for its job, so the whole works as one.

8.5 Materials and Real-World Uses

OBJECTIVES

- Compare PLA, PETG, ABS/ASA, TPU, nylon and resin for strength, toughness, heat resistance, ease of printing and safety.
- Describe metal printing and real uses: GE's LEAP fuel nozzle, rocket parts, printed concrete, medical and dental parts, shop jigs and replacement parts.
- Calculate part cost and the break-even quantity between printing and injection molding.
- Decide when a printed part is the right answer and when it is not, and design a functional part for a real need.

> **Warm-up.** Leave a plastic bottle cap, a crayon and a gummy candy on the dashboard of a car in the sun (or near a warm oven vent) for 30 minutes. Which one softens? Write a guess about which 3D-printing plastic would survive there and which would droop.

WATCH

The BEST 3D printing material? Comparing PLA, PETG & ASA (ABS) - feat. PRUSAMENT by Josef Prusa

CNC Kitchen · 17:13

https://www.youtube.com/watch?v=ycGDR752fT0

> **WHEN TO WATCH**
> After the materials paragraph. Make a table of his results for price, printability, strength, toughness and heat resistance.

Note: CNC Kitchen tests three filaments from one maker; the comparison applies to other brands.

BACKUP VIDEO

The CFM LEAP Fuel Nozzle

GE Aerospace · 4:40

https://www.youtube.com/watch?v=rMzVSbNebCg

With the paragraph on metal printing: GE engineers explain the LEAP fuel nozzle made by laser powder-bed fusion.

KEY TERMS

glass transition temperature

The temperature at which a rigid plastic softens and begins to sag under load: about 55–60 °C for PLA, 80 °C for PETG, 100–105 °C for ABS and ASA.

PLA

Polylactic acid, made from plant starch: easy to print, stiff and accurate, but brittle and soft in heat.

PETG, ABS and ASA

Tougher engineering plastics. PETG is tough and easy; ABS and ASA resist heat, and ASA resists sunlight, but they need an enclosure and ventilation.

TPU

Thermoplastic polyurethane: a flexible, rubbery filament for gaskets, bumpers, grips and tires.

powder-bed fusion

Metal (or nylon) printing in which a laser or electron beam melts a thin layer of powder in the shape of each slice.

break-even quantity

The number of parts at which two processes cost the same; above it the one with the higher fixed cost but lower cost per part wins.

CORE IDEAS

The story. A jet engine's fuel nozzle sprays fuel into the combustor, where it burns near 1,500 °C. In the CFM LEAP engine, which entered airline service in 2016, GE Aviation's engineers wanted a nozzle with complex internal passages and cooling channels that could not be machined or brazed together. The old design was assembled from about twenty separate parts. By printing it in cobalt-chrome alloy with a laser that melts thin layers of metal powder, they made it as a single piece, about 25% lighter and, by GE's figures, about five times as durable. GE built a factory in Auburn, Alabama, to print them, and has made well over a hundred thousand. NASA used the same technology to print rocket-engine injectors and tested them in hot fire. 3D printing had grown up from prototypes into flight hardware.

How they figured it out: plastics. Each filament was adopted for its properties. **PLA** prints at about 190–220 °C on a 50–60 °C bed, barely warps and smells mild, but softens at about 55–60 °C (a hot car will droop it) and is brittle. **PETG** (230–250 °C) is tougher, bends before it breaks and handles about 80 °C. **ABS** (the plastic of LEGO bricks) and **ASA** take more heat and ASA resists sunlight, but they shrink as they

cool, so they warp unless printed in a warm enclosure, and they give off styrene fumes. **TPU** is rubbery. **Nylon** is very tough and wears well but soaks up water from the air and must be dried. Fiber-filled filaments (carbon fiber or glass) are stiffer but wear brass nozzles quickly. **Resin** printers make fine, smooth parts from liquid photopolymer, but the uncured resin irritates skin and can cause allergies, so it needs gloves, ventilation and careful washing and curing.

The science. Thermoplastics are long chain molecules. Above the glass transition temperature the chains can slide past one another, so the plastic softens; that is why it can be extruded, and why a part loses stiffness when it gets hot. Every thermoplastic shrinks as it cools, and the hot top of a print shrinks against the cooler bottom, which curls the corners up: that is warping, worst in ABS. Metals are printed by fully melting powder in tiny pools that freeze in milliseconds, much like a weld bead (Unit 7). The parts have the same welding-type problems: residual stress, distortion and porosity, so they are often heat-treated and hot isostatically pressed (squeezed in hot gas) and inspected with X-rays or CT scans.

Where printing is used. In factories and shops, the most common printed parts are not products but **jigs and fixtures**: holders, guides and gauges that position work for drilling, gluing or inspection, made overnight for a few dollars. Repair shops print replacement knobs, clips and covers that are no longer sold. Dentists print models and surgical guides; hospitals print models of patients' hearts and bones for surgeons to plan on; prosthetic hands are printed for children who will outgrow them. Construction firms have printed the concrete walls of houses with giant gantry printers. Rocket companies print engine parts. Hobbyists print tools, organizers, model parts and toys.

When not to print. For thousands of identical plastic parts, injection molding is far cheaper per part once the mold is paid for. For simple metal parts, machining or buying a standard part is faster, stronger and cheaper. Printed plastic should not be used for parts that hold up people or heavy loads overhead, that carry hot fluids, pressure or food contact without the right certified material, or for car brakes, steering, child car seats or safety equipment. Many replacement parts are better bought from the maker. Printing is a powerful tool, but a wise maker counts the cost and the risk.

Safety. FDM printing releases tiny particles and some vapors, more from ABS and ASA than PLA, so print in a ventilated room, use an enclosure with a filter for ABS and ASA, and keep printers out of bedrooms. Resin printing requires nitrile gloves, eye protection and ventilation; isopropyl alcohol for washing is flammable, and uncured resin and dirty alcohol must never be poured down a drain.

PICTURE STUDY



A 3-D Printed Rocket Injector in Hot Fire, NASA Marshall Space Flight Center, 2013 · Photograph · NASA Marshall Space Flight Center, Huntsville, Alabama

Image: Wikimedia Commons, public domain

In 2013 NASA engineers at Marshall Space Flight Center tested a rocket-engine injector made by melting metal powder layer by layer with a laser. The injector, which mixes fuel and oxidizer, normally takes many machined and welded parts; the printed one was made in far fewer pieces. Look at the test as an engineer checking a new process.

Look closely

- Find the engine and the test stand. How is the engine held, and why so firmly?
- Look at the color and shape of the flame. What does it tell you about the temperatures the printed part must survive?
- Find any pipes or lines feeding the engine. What do you think they carry?
- Look for anything that protects people or equipment from the flame.

Talk about it

1. Why do engineers hot-fire a printed part many times before trusting it in flight?
2. What welding-type problems (Unit 7) might a printed metal part have?

3. Why is printing a good choice for a part with many complicated internal passages?

Safety first. Print only in a ventilated room, never in a bedroom, and never leave a long print running unattended. ABS and ASA need an enclosure and good ventilation. Resin requires nitrile gloves, safety glasses and ventilation; keep resin and isopropyl alcohol away from flames and drains. A printed part must never be used for anything that protects or holds up a person.

SHOP PROJECT

A Functional Printed Part for a Real Need

You will find a real need in your home, shop or church (a replacement part, a jig, an organizer, a tool holder), choose a material with a decision matrix, design the part for printing, estimate its cost, and print it, or slice it completely if no printer is available. This becomes your unit portfolio.

You will need

- Calipers or ruler; the object your part must fit
- Free CAD and slicer
- Access to an FDM printer if possible (home, library makerspace, school, community college) and suitable filament
- A luggage scale or kitchen scale for testing
- Shop notebook

Steps

1. Find a need and write a one-paragraph problem statement: what the part must do, what it fits, its loads, its temperature and its environment (indoors, outdoors, wet, sunny).
2. Check whether the part can be bought from the original maker or a hardware store, and at what price. Decide honestly whether printing is the right answer, and say why.
3. Make a decision matrix for at least four materials (PLA, PETG, ASA or ABS, TPU) with weighted criteria: strength, toughness, heat, UV, ease of printing, cost, safety. Choose one.
4. Design the part in CAD using the rules from Lesson 8.4: orientation for the load, clearances from your tolerance test, 45° overhangs, fillets, walls in multiples of the line width, inserts or nuts for screws.
5. Slice it. Record time, mass and cost. Estimate the mass by hand and compare.
6. Print it (or arrange printing at a makerspace). If you cannot print, prepare a full print package: the STL or 3MF, the slicer project, a settings sheet and a

drawing with critical dimensions.

7. Test it: check every critical dimension with calipers, check the fit, and load-test it to at least twice its expected load if that is safe to do.
8. Use it for a week. Record what worked and what did not.
9. **Improve it.** Make version 2 to fix at least one problem, and record the changes.

Tips

- Start with a simple part; a well-made bracket beats an unfinished robot.
- Keep every version's file; engineers call this version control.
- Ask the person who will use the part what they need before you design it.

Check your work

- ☐ My material choice is justified by a decision matrix.
- ☐ My part was tested for fit and load (or fully prepared to print).
- ☐ I can explain whether printing was the right choice for this part.

SHOP NOTEBOOK

1. A materials chart: PLA, PETG, ABS/ASA, TPU, nylon, resin, with print temperature, bed temperature, glass transition, strengths, weaknesses and safety notes.
2. Your decision matrix and a dimensioned drawing of your functional part.
3. A cost and break-even calculation comparing printing your part with buying or molding it.

KEY FORMULAS

$C_{\text{total}} = C_{\text{fixed}} + c\,N$ (fixed cost plus cost per part times quantity)

$N_{\text{break-even}} = \dfrac{C_{\text{fixed},2} - C_{\text{fixed},1}}{c_1 - c_2}$

$m = \rho V$ (PLA 1.24, PETG 1.27, ABS 1.04, TPU 1.21, nylon about 1.14 g/cm^3)

From history. The plastic in most PLA filament comes from fermented plant sugars, usually corn starch. It was first made in a laboratory in the 1930s by Wallace Carothers at DuPont, the chemist who also invented nylon, but it was too expensive to use widely until large factories began making it in the early 2000s.

WORKED EXAMPLES

Example 1. A shop needs plastic clips. Printing costs \$2.40 per clip with no setup cost. Injection molding needs a \$6,000 aluminum mold and then costs \$0.35 per clip. Find the break-even quantity. Which process should be used for 500 clips and for 10,000 clips?

Show solution

1. $N = \dfrac{6000 - 0}{2.40 - 0.35} = \dfrac{6000}{2.05} \approx 2930$ clips.
2. 500 clips: print $500 \times 2.40 = \$1200$; mold $6000 + 500 \times 0.35 = \$6175$. Print.
3. 10,000 clips: print \$24,000; mold $6000 + 3500 = \$9500$. Mold.

Answer: About 2,930 clips; print 500, mold 10,000.

Example 2. The same 30 cm³ part is printed in PLA (\$22/kg), PETG (\$26/kg) and ABS (\$24/kg). Find the mass and material cost of each.

Show solution

1. PLA: $30 \times 1.24 = 37.2$ g; $37.2 \times 0.022 \approx \$0.82$.
2. PETG: $30 \times 1.27 = 38.1$ g; $38.1 \times 0.026 \approx \$0.99$.
3. ABS: $30 \times 1.04 = 31.2$ g; $31.2 \times 0.024 \approx \$0.75$.
4. ABS is cheapest per part because it is less dense, even though its price per kilogram is higher than PLA's.

Answer: PLA 37.2 g, \$0.82; PETG 38.1 g, \$0.99; ABS 31.2 g, \$0.75.

Example 3. Reasoning. Choose a material for each: (a) a phone holder for a car dashboard, (b) a garden hose guide left outdoors, (c) a soft bumper for a cabinet door, (d) a desk organizer, (e) a bracket inside a car engine bay.

Show solution

1. (a) Dashboards can exceed 70 °C in summer: PETG at least, better ASA. PLA would droop.
2. (b) Sunlight and weather: ASA (UV-resistant) or PETG.
3. (c) Flexible: TPU.
4. (d) Indoors, light load: PLA, the easiest to print.
5. (e) Do not print it: heat, oil and vibration in an engine bay call for the maker's metal or high-temperature part.

Answer: (a) ASA/PETG, (b) ASA/PETG, (c) TPU, (d) PLA, (e) buy the proper part.

PRACTICE

1. Easy Which common filament would sag first on a hot car dashboard, and why?

   Show answer

   PLA: its glass transition temperature (about 55–60 °C) is below the temperature a dashboard can reach.

2. Easy Name a printed part used in a jet engine and one reason it was printed.

   Show answer

   The LEAP fuel nozzle: printing made about twenty parts into one, with complex internal passages, lighter and more durable.

3. Easy Why must resin printing be done with gloves?

   Show answer

   Uncured resin irritates skin and can cause allergic sensitization with repeated contact.

4. Medium Find the mass of a 45 cm^3 part in PETG and in ABS.

   Show answer

   PETG $45 \times 1.27 \approx 57.2$ g; ABS $45 \times 1.04 = 46.8$ g.

5. Medium A printed part costs $4.00 each; molding costs $12,000 for the mold plus $0.50 each. Find the break-even quantity.

Show answer

$12{,}000 \div 3.50 \approx 3430$ parts.

6. Medium Why does ABS warp more than PLA, and what helps?

Show answer

ABS shrinks more as it cools from its higher printing temperature, so the cooling upper layers pull the corners up. A heated bed near 100 °C, an enclosure to keep the air warm, a brim and no drafts help.

7. Medium A jig costs $3 in plastic and saves a cabinet shop 2 minutes on each of 600 drawers. Labor costs $30 per hour. What is it worth?

Show answer

Time saved $1200 \text{ min} = 20 \text{ h}$; worth $600 for a $3 jig.

8. Hard **You are the tradesperson.** A customer wants you to print a replacement plastic latch for a child's car seat because the original broke. What do you tell him?

Show answer

Do not print it. A car seat is safety equipment tested as a whole; a printed latch could fail in a crash. Contact the manufacturer for a certified replacement part, or replace the seat.

9. Hard Conceptual. Why do printed metal parts often need heat treatment and X-ray inspection, like welds?

Show answer

Each layer is a tiny weld pool that melts and freezes quickly, leaving residual stress, distortion, unmelted powder or gas porosity. Heat treatment relieves stress and evens out the structure; X-ray or CT inspection finds hidden pores.

10. Hard A part printed in PLA weighs 40 g. What would it weigh in ABS (same volume)?

Show answer

Volume $40/1.24 \approx 32.3 \text{ cm}^3$; ABS $32.3 \times 1.04 \approx 33.5$ g.

11. **Challenge** A dental lab can print aligner models for $1.10 each on printers costing $25,000 total, or send them out at $6.00 each. How many models must it make to pay for the printers? If it makes 40 models a day, 250 days a year, how long does that take?

    Show answer

    $25{,}000 \div (6.00 - 1.10) \approx 5100$ models; at $40 \times 250 = 10{,}000$ a year, about half a year.

COMMON MISTAKES

- Choosing PLA for everything, including parts that get hot or sit in the sun.
- Printing a part that can be bought cheaply and certified from its maker.
- Forgetting to dry nylon and other moisture-absorbing filaments.
- Treating printed plastic as a substitute for metal in safety-critical parts.

> **Make it a game · Filament Face-Off.** Your parent names a job: a phone case, a garden hook, a flexible gasket, a high-heat bracket. Pick PLA, PETG, ABS, TPU or nylon in five seconds with a reason. Include one safety note about fumes or ventilation. Parent plants a wrong claim each round, and you win a bonus for catching it.

UNIT 8

3D Printing

A 3D printer builds a part layer by layer from a digital model, and it has changed how engineers prototype, how shops make jigs and spare parts, and even how jet engines and rockets are built. In this unit you will learn where it came from, how a printer's motors, belts, extruder and heaters work, how a CAD model becomes G-code in a slicer, how to design parts that are strong and fit together, and which materials suit which jobs.

The stories are of Chuck Hull curing his first plastic cup with ultraviolet light in 1983, Scott Crump building a toy frog with a glue gun, Adrian Bowyer's self-copying RepRap, a wrench sent to the space station as a file, and GE's printed fuel nozzle. You will not need to own a printer: every project can be done with free CAD and slicer software, a library makerspace or school lab, or the hands-on models given. If you can print, you will finish the unit with a tested, useful part you designed yourself.

PREREQUISITES

- Algebra I: formulas, ratios and solving for a variable
- Unit 1: thread sizes, $T = KDF$, clamp force and stress $\sigma = F/A$
- Unit 5: $P = VI$ and $P = V^2/R$
- Unit 7: weld pools, heat and distortion (for metal printing)
- Basic computer skills; a free Tinkercad or Onshape account with a parent's permission

MASTERY CHECKLIST

- ☐ I can compare additive, subtractive and formative manufacturing and tell the story of Hull, Crump and Bowyer.
- ☐ I can explain how an FDM printer works and calculate steps per mm, flow rate, heater power and G-code extrusion.
- ☐ I can model a part in CAD, slice it, and estimate its plastic, cost and time.
- ☐ I can design for printing: orientation for strength, clearances, overhangs, snap fits and fasteners.
- ☐ I can choose a printing material for a job, calculate break-even against molding, and say when printing is the wrong answer.

OPTIONAL KITS FOR THIS UNIT

- **Tinkercad (Autodesk)**: Free browser-based CAD that builds parts from simple shapes; the easiest start for Lessons 8.3–8.5. Students under 13 need a parent or teacher account.
- **Onshape for education**: Free professional parametric CAD in the browser for students and teachers; a good next step after Tinkercad for Lessons 8.3–8.5.
- **Prusa Research**: Maker of the open-source Prusa printers (kits and assembled) and of the free PrusaSlicer. Optional: every lesson works with a library makerspace or school printer instead.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

8.1	**From Stereolithography to RepRap: How 3D Printing Began**	3 sessions of 50 minutes
8.2	**How an FDM Printer Works**	3 sessions of 50 minutes
8.3	**From CAD to Slicer**	3 sessions of 50 minutes
8.4	**Designing for Printing: Strength and Tolerances**	3 sessions of 50 minutes
8.5	**Materials and Real-World Uses**	3 sessions of 50 minutes

Unit 8 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   Explain the difference between additive, subtractive and formative manufacturing, with one example of each.

2. **6 pts**

   What did Chuck Hull, Scott Crump and Adrian Bowyer each contribute to 3D printing?

3. **5 pts**

   A part is 36 mm tall. How many layers at 0.12 mm and at 0.24 mm? Which prints faster and which looks smoother?

4. **6 pts**

   A part machined from a 640 g block weighs 80 g. Find the buy-to-fly ratio and the waste percentage.

5. **6 pts**

   A GT2 belt (2 mm pitch) runs on a 20-tooth pulley driven by a 200-step motor at 16 microsteps. Find the steps per mm.

6. **6 pts**

   Find the volumetric flow at 0.24 mm layers, 0.48 mm lines and 100 mm/s. Can a hot end rated 10 mm^3/s keep up?

7. **6 pts**

   How many millimeters of 1.75 mm filament (2.405 mm^2) are needed for a line 80 mm long, 0.45 mm wide and 0.2 mm high?

8. **5 pts**

   A 24 V heated bed has a resistance of 2.0 Ω. Find its power and current.

9. **6 pts**

   A slicer reports 54 g of PLA for a part. Filament costs $24/kg. Find the cost and the filament length ($\rho = 1.24\ \text{g/cm}^3$).

10. **5 pts**

    Explain why adding walls usually strengthens a part more than adding infill.

11. **6 pts**

    A hook is to be printed. Explain how you would orient it and why.

12. **6 pts**

A shaft is 10.0 mm. Holes print 0.15 mm small. Model a hole for a sliding fit with 0.25 mm clearance per side.

13. **6 pts**

A snap hook is 12 mm long and 1.2 mm thick and deflects 1.2 mm. Find the strain. Is it below 2%?

14. **5 pts**

An M4 screw is tightened to 0.5 N·m with $K = 0.2$. Find the clamp force and explain why a washer helps on a printed part.

15. **6 pts**

Choose a material for (a) a flexible phone-case bumper, (b) a mailbox flag left in the sun, (c) a shelf organizer. Give a reason for each.

16. **6 pts**

Printing costs $3.20 per part; molding needs a $9,000 mold and $0.20 per part. Find the break-even quantity.

17. **3 pts**

You are the tradesperson. A neighbor asks you to print a replacement brake-line bracket for his truck. What do you say?

18. **6 pts**

Short essay (one paragraph). When is 3D printing the right way to make a part, and when is it the wrong way? Use at least two examples from this unit.

ANSWER KEY

1. Additive builds layer by layer (3D printing a bracket); subtractive cuts material away (milling a part from a block); formative forces material into shape (injection molding a bottle cap).
2. Hull invented stereolithography (1983; patent 1986) and the STL format and founded 3D Systems; Crump invented fused deposition modeling (patent 1992) and founded Stratasys; Bowyer started RepRap (2005), the open self-copying printer that led to cheap desktop printers.
3. 300 and 150 layers; 0.24 mm prints about twice as fast; 0.12 mm is smoother.
4. $640/80 = 8$; waste $1 - 80/640 = 87.5\%$.
5. $3200 \div 40 = 80$ steps/mm.
6. $0.24 \times 0.48 \times 100 \approx 11.5\ \text{mm}^3/\text{s}$; no: slow to about 87 mm/s or lower the layer height.
7. $V = 7.2\ \text{mm}^3$; $7.2/2.405 \approx 2.99\ \text{mm}$.
8. $P = 576/2 = 288\ \text{W}$; $I = 12\ \text{A}$.
9. Cost $54 \times 0.024 \approx \$1.30$; volume $43.5\ \text{cm}^3$; length $43{,}500/2.405 \approx 18.1\ \text{m}$.
10. Bending and twisting stress is highest at the outer surface, where the walls are; infill lies near the middle, where stress is low.
11. Lying on its side, so the printed lines run around the curve of the hook and the load pulls along the lines; printed upright, the load would pull the layers apart at the bend, where the part is about half as strong.
12. $10.0 + 0.50 + 0.15 = 10.65\ \text{mm}$.
13. $\varepsilon = \dfrac{3(1.2)(1.2)}{2(144)} = 0.015 = 1.5\%$; yes.
14. $F = 0.5/(0.2 \times 0.004) = 625\ \text{N}$. A washer spreads the force over more area, lowering bearing stress and creep in the plastic.
15. (a) TPU: flexible. (b) ASA (or PETG): resists sunlight and heat. (c) PLA: easy to print, indoor, light load.
16. $9000 \div 3.00 = 3000$ parts.
17. No: brake parts are safety-critical and see heat, vibration and road chemicals. Buy the correct certified part from the maker or a parts store.
18. Model answer: Printing is right for one-off and low-volume parts, prototypes, custom parts, complex internal shapes and parts no longer sold: Hull's prototypes, the station's ratchet wrench, GE's one-piece fuel nozzle, shop jigs. It

is wrong for large quantities, where molding is cheaper past the break-even point; for simple metal parts better machined or bought; and for safety-critical parts such as brakes or car-seat latches, where a certified part must be used.

PORTFOLIO PIECE: A PRINTED FUNCTIONAL PART

Present the functional part from Lesson 8.5: the problem statement, your decision on whether to print or buy, the material decision matrix, dimensioned drawings, the CAD file and slicer settings, your cost and time estimates, test results (fit, dimensions, load), and what you changed in version 2.

If you could not print, submit a complete print package (STL or 3MF, slicer project, settings sheet and drawing) and have it reviewed by someone who prints: a makerspace staff member, a teacher or an engineer. Include your tolerance and orientation test results from Lesson 8.4.

LOOK FOR	WHAT IT MEANS
Need and judgment	A real need clearly stated; an honest comparison of printing with buying or other methods.
Design for printing	Orientation, clearances, overhangs, wall thickness and fasteners chosen by the rules of Lesson 8.4 and the student's own tolerance test.
Material and cost	Decision matrix with weighted criteria; mass, cost and time estimated and checked against the slicer.
Testing and iteration	Dimensions, fit and load tested and recorded; at least one improvement made and explained.
Documentation	Neat drawings, files and a clear write-up that someone else could use to print the part again.

UNIT 9

Small Engines

A gasoline engine turns a pint of fuel into hours of mowing, cutting, pumping or generating. In this unit you will learn how a small engine works from the inside: the four-stroke cycle Nikolaus Otto built in 1876, the two-stroke engines in chainsaws and trimmers, the carburetor that mixes fuel and air by Bernoulli's principle, the magneto that makes a spark with no battery, and the governor that holds a mower's speed.

This is a hands-on unit. You will measure a real engine's stroke, mix and check two-stroke fuel, build a venturi and measure its suction, test a spark and a running engine's speed, and finish with a complete lawn-mower tune-up and a maintenance log. Along the way you will meet the people who made small engines common, from Otto and Dugald Clerk to Briggs and Stratton, and the honest trade of the small-engine technician.

PREREQUISITES

- Algebra I: formulas, ratios, unit conversions and square roots
- Area of a circle and volume of a cylinder
- Units 1 and 5: torque and fasteners; voltage and coils, simply
- Access to a gasoline mower or other small engine for the shop projects (a neighbor's or a shop's is fine)

MASTERY CHECKLIST

- ☐ I can explain the four-stroke and two-stroke cycles and calculate displacement and compression ratio.
- ☐ I can mix two-stroke fuel at any ratio and explain the trade-offs between two- and four-stroke engines.
- ☐ I can explain how a carburetor meters fuel, using continuity and Bernoulli's principle, and calculate air–fuel ratios and fuel use.
- ☐ I can explain how a magneto makes a spark, read and gap a plug, and calculate blade-tip speed and spark timing.
- ☐ I can tune up a mower safely, diagnose a no-start with the fuel–spark–compression–air tree, and keep a maintenance log.

OPTIONAL KITS FOR THIS UNIT

- **Briggs & Stratton manuals and parts lookup**: Free owner's and repair manuals by engine model number, with specifications for oil capacity, plug gap and torques; fits every lesson in this unit.
- **Honda Engines**: The maker of many mower and generator engines; its site has owner's manuals, specifications and maintenance schedules for the GCV and GX series engines used in this unit's examples.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

9.1 The Four-Stroke Cycle — 3 sessions of 50 minutes

9.2	**Two-Stroke Engines**	3 sessions of 50 minutes
9.3	**Fuel, Air and the Carburetor**	3 sessions of 50 minutes
9.4	**Ignition, Compression and the Governor**	3 sessions of 50 minutes
9.5	**Maintenance and Troubleshooting**	3 sessions of 50 minutes

Unit 9 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   List the four strokes of an Otto-cycle engine and state the position of the intake and exhaust valves in each.

2. **7 pts**
   An engine has a bore of 70 mm and a stroke of 54 mm. Find its displacement in cc.

3. **7 pts**
   A 180 cc cylinder has a compression ratio of 8.0:1. Find its clearance volume and its ideal Otto efficiency.

4. **6 pts**
   An engine makes 7.0 lb·ft of torque at 3,200 rpm. Find its horsepower and its power strokes per second.

5. **6 pts**
   How much two-stroke oil, in fl oz and in mL, goes into 2.5 gal at 50:1? (1 gal = 128 fl oz; 1 fl oz ≈ 29.6 mL)

6. **6 pts**
   Explain how a crankcase-scavenged two-stroke gets fresh mixture into the cylinder without intake valves.

7. **5 pts**

   Give two advantages and two disadvantages of two-stroke engines compared with four-strokes.

8. **7 pts**

   Air enters a venturi at 8 m/s, and the throat has one-quarter the inlet area. Find the throat speed and the pressure drop (air 1.2 kg/m^3).

9. **7 pts**

   A 140 cc four-stroke runs at 3,000 rpm with 85% volumetric efficiency and an air–fuel ratio of 14.7. Find its fuel use in kg/h.

10. **6 pts**

    Explain why E10 gasoline left in a mower over winter often causes a no-start in spring, and give two ways to prevent it.

11. **6 pts**

    An armature has a 90:1 turns ratio and a 220 V primary spike. Find the secondary voltage. Why is the spark timed before TDC?

12. **6 pts**

    Find the tip speed of a 20-in blade at 3,400 rpm and state whether it meets the 19,000 ft/min limit.

13. **6 pts**

    A blade has a 6 g imbalance at 0.24 m. Find the rotating force at 3,300 rpm.

14. **7 pts**

    You are the tradesperson. A mower will not start. It has fresh fuel, the plug is wet with fuel after pulling, and a spark tester shows no spark. List your checks in order.

15. **5 pts**

    Describe the correct way to tip a walk-behind mower and explain what goes wrong if it is tipped the other way.

16. **3 pts**

    Where should used oil and old gasoline go?

17. **5 pts**

Short essay. A neighbor says, “Mowers are junk now; they only last a couple of years.” Using what you learned in this unit, write a paragraph explaining why most small engines fail and how a careful owner can make one last a decade.

ANSWER KEY

1. Intake: intake open, exhaust closed. Compression: both closed. Power: both closed (exhaust opens near the bottom). Exhaust: exhaust open, intake closed.
2. $0.7854 \times 7.0^2 \times 5.4 = 0.7854 \times 49 \times 5.4 \approx 208$ cc.
3. $V_c = 180/7 \approx 25.7$ cc; $8^{0.4} \approx 2.297$, $\eta = 1 - 1/2.297 \approx 56\%$.
4. $7.0 \times 3200/5252 \approx 4.3$ hp; $1600/60 \approx 26.7$ per second.
5. $320/50 = 6.4$ fl oz ≈ 189 mL.
6. The rising piston lowers crankcase pressure and draws mixture in through a reed or port; the falling piston compresses it in the crankcase; when the piston uncovers the transfer ports the mixture flows up into the cylinder and pushes out the exhaust through the exhaust port.
7. Advantages: light and powerful for their size; run at any angle; simple, few moving parts. Disadvantages: burn oil and need mixed fuel; waste some fresh charge out the exhaust (more fuel use and emissions); noisier; shorter life.
8. $v_2 = 32$ m/s; $\Delta p = 0.6(1024 - 64) = 576$ Pa.
9. Air $140 \times 1500 \times 0.85 = 178{,}500$ cm^3/min; $0.1785 \times 1.2 = 0.214$ kg/min; fuel $0.214/14.7 \approx 0.0146$ kg/min ≈ 0.87 kg/h.
10. Gasoline oxidizes into gum and varnish that clog tiny jets, and ethanol absorbs water that can separate and collect in the bowl. Prevent it with fuel stabilizer (and run it into the carburetor), by running the engine dry or draining the bowl, or by using ethanol-free fuel.
11. $220 \times 90 = 19{,}800$ V. The flame needs time to build pressure; firing early puts peak pressure just after TDC.
12. $\pi(20/12)(3400) \approx 17{,}800$ ft/min; it meets the limit.
13. $\omega \approx 345.6$ rad/s; $F = 0.006 \times 0.24 \times 345.6^2 \approx 172$ N.
14. Check the stop circuit (bail cable and stop wire not grounded), try a new plug, check the armature air gap and clean magnets, then check the flywheel key and test or replace the armature.
15. Disconnect the plug wire and tip it with the air filter and carburetor side up. Tipped the other way, oil runs into the air filter and cylinder and fuel can leak, causing smoke, a soaked filter and a hard start or hydraulic lock.
16. In sealed containers to an auto-parts store, recycling center or household hazardous-waste collection, never on the ground, down a drain or in the trash.

17. Model answer: most small engines are not worn out but neglected. Stale fuel left over winter varnishes the carburetor jets; dirt past a clogged or missing air filter wears the cylinder and rings; old or low oil lets bearings wear; and dull, unbalanced blades shake the engine. An owner who changes oil each season, keeps a clean filter, sharpens and balances the blade, uses fresh stabilized fuel, stores the engine properly for winter and keeps a log can expect many years of service, as the manuals' service schedules are designed to give.

PORTFOLIO PIECE: A TUNED-UP MOWER WITH ITS LOG

Tune up a gasoline mower (or another small engine) completely and safely: oil, air filter, spark plug with correct gap, a sharpened and balanced blade, and fresh stabilized fuel. Document it with before-and-after tests, measurements, photos and a maintenance log that stays with the machine.

Add your engine specification card from Lesson 9.1, your ignition and speed check from Lesson 9.4, and a one-page seasonal and winter-storage checklist written for the owner.

LOOK FOR	WHAT IT MEANS
Safety	Plug wire disconnected before blade or crankshaft work; mower tipped air-filter side up; fuel handled outdoors; engine run only outdoors; used oil recycled.
Workmanship	Correct oil and level, plug gapped to specification, blade sharpened at the original angle, balanced and torqued, filter replaced or cleaned.
Measurement and data	Before-and-after observations, plug gap, oil quantity, top speed and blade-tip speed recorded with units.
Maintenance log and checklist	Clear, dated log with parts and fluids; a practical seasonal checklist the owner can follow.
Explanation	Explains how the engine works and why each maintenance step matters, using the unit's science.

9.1 The Four-Stroke Cycle

OBJECTIVES

- Explain the intake, compression, power and exhaust strokes and what the valves and piston do in each.
- Calculate engine displacement from bore and stroke, and compression ratio from swept and clearance volumes.
- Tell the story of Nikolaus Otto's 1876 engine and why compressing the charge made it so much better than earlier gas engines.
- Measure the stroke of a real small engine and check your displacement calculation against the maker's figure.

> **Warm-up.** Pull the starter rope of a mower very slowly (spark-plug wire off) and count how often you feel it get hard to pull. Or, if you have no engine, squeeze the air out of a capped syringe and let go. Write down what you notice and one question you want answered today.

WATCH

4 Stroke Engine Theory | Briggs & Stratton

Briggs & Stratton · 10:05

https://www.youtube.com/watch?v=kMCfZL9HgSk

> **WHEN TO WATCH**
> After the story and before the science paragraph. Pause at each stroke and say aloud where the piston is and which valve is open.

Note: Made by the Briggs & Stratton customer education department for technicians in training; clear cutaway animations of a real mower engine.

BACKUP VIDEO

How Engines Work - (See Through Engine in Slow Motion) - Smarter Every Day 166

SmarterEveryDay · 8:31

https://www.youtube.com/watch?v=xflY5uS-nnw

After the worked examples: watch the burn spread across the cylinder through a clear head.

KEY TERMS

four-stroke cycle

The Otto cycle: intake, compression, power and exhaust, taking two turns of the crankshaft for each power stroke.

bore and stroke

The bore is the cylinder's diameter; the stroke is how far the piston travels from top dead center (TDC) to bottom dead center (BDC).

displacement

The volume the piston sweeps in one stroke, times the number of cylinders, usually given in cubic centimeters (cc) or cubic inches.

clearance volume

The space left above the piston at top dead center: the combustion chamber.

compression ratio

The total cylinder volume at BDC divided by the clearance volume at TDC; most mower engines are about 8:1 to 9:1.

overhead valve (OHV)

An engine with its valves in the cylinder head above the piston, worked by pushrods and rocker arms; older "flathead" engines had the valves beside the cylinder.

CORE IDEAS

The story. Nikolaus August Otto was a traveling grocery salesman in Germany when, around 1860, he read about Étienne Lenoir's new gas engine in Paris. Lenoir's engine drew a mixture of coal gas and air into a cylinder and lit it without squeezing it first; it ran, but it turned only about 4 percent of its fuel's energy into work. Otto taught himself engineering, and in 1864 he and the sugar manufacturer Eugen Langen founded a company near Cologne. Their noisy "atmospheric" engine won a gold medal at the Paris Exposition of 1867 for using far less gas than Lenoir's. In 1876, at the company that became Gasmotoren-Fabrik Deutz (where Gottlieb Daimler and Wilhelm Maybach also worked), Otto built a new engine that drew in its charge, compressed it, burned it and pushed out the exhaust in four strokes. It was so much quieter than what came before that people called it the "Otto Silent," and it sold by the thousands.

How they figured it out. Otto had tried compressing the charge as early as 1861 and given up when his test engine ran roughly. He came back to it after years of

experience with the atmospheric engine, and his notebooks show him testing what happened when the mixture was squeezed before it was lit. A French engineer, Alphonse Beau de Rochas, had described the same four-stroke idea in a pamphlet in 1862 but never built an engine, and in 1886 a German court cancelled part of Otto's patent because of that earlier pamphlet. The lesson for engineers is double: a good idea on paper is not yet a machine, and the person who builds and tests it carefully is the one who changes the world. Otto received United States patent 194,047 in 1877. Every gasoline lawn mower, chainsaw-sized four-stroke, motorcycle and car engine is a descendant of his machine.

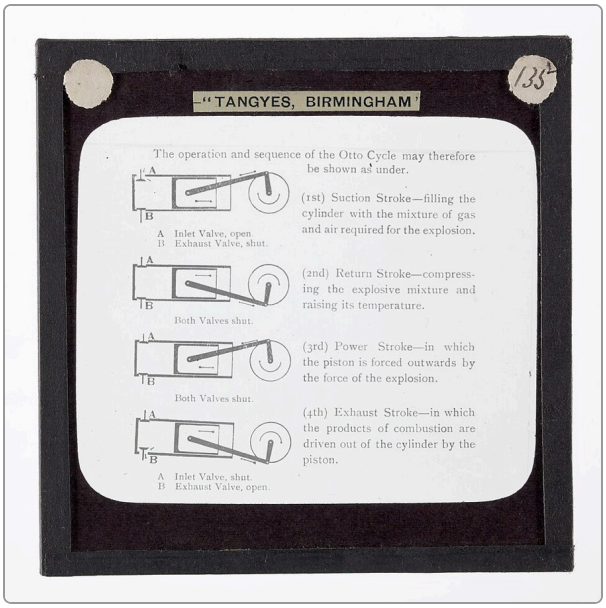
The science. On the **intake** stroke the piston moves down with the intake valve open, and the falling pressure draws in air and fuel. On the **compression** stroke both valves close and the piston squeezes the mixture into the small combustion chamber, raising its pressure and temperature. Near the top, the spark plug fires; the burning gas reaches pressures of hundreds of pounds per square inch and drives the piston down on the **power** stroke. On the **exhaust** stroke the exhaust valve opens and the rising piston pushes out the burned gas. The connecting rod and crankshaft turn the piston's up-and-down motion into rotation, and a heavy flywheel carries the engine through the three strokes that do not make power. Displacement is the swept volume, $V_d = \frac{\pi}{4} b^2 s$ per cylinder, and the compression ratio is $r = (V_d + V_c)/V_c$. Thermodynamics shows why Otto was right to compress: the ideal efficiency of this cycle is $\eta = 1 - 1/r^{\gamma - 1}$, with $\gamma \approx 1.4$ for air, so a higher compression ratio turns more of the fuel's heat into work.

In the shop. A small-engine technician reads the engine's model and type numbers stamped on the shroud or valve cover and looks up its bore, stroke, displacement, oil capacity and spark-plug gap in the maker's manual. Most new mower engines are single-cylinder, air-cooled, overhead-valve four-strokes of about 125 to 200 cc with a vertical crankshaft that turns the blade directly. Riding mowers use larger single or V-twin engines. Real engines do not reach the ideal efficiency: friction, heat lost through the cooling fins and incomplete burning mean a small air-cooled engine turns roughly a quarter of its fuel energy into work. Power is torque times speed; in U.S. units, $P_{\text{hp}} = T\,n / 5252$, with torque in pound-feet and speed in rpm.

Safety. An engine's exhaust contains carbon monoxide, a gas you cannot see or smell that can be deadly in a closed space within minutes. Never run any engine in a

garage or shed, even with the door open. Work on a cool engine, and pull the spark-plug wire off before you turn the crankshaft by hand.

PICTURE STUDY



The Otto Cycle: A Teaching Slide, Tangye Ltd, Birmingham, About 1910 · Glass lantern slide · Museums Victoria, Melbourne

Image: Wikimedia Commons, public domain

Tangye was an English engine builder that made gas engines on Otto's principle. Its engineers projected glass slides like this one onto a screen to teach customers and apprentices how the four strokes work, the same job today's animations do.

Look closely

- Find valves A and B in each diagram. Which are open and which are shut in each stroke?
- Follow the crank in the four drawings. How far does it turn from the first stroke to the fourth?
- Read the slide's name for the first stroke. What do we call it today?
- Notice that the cylinder lies on its side. Where would the flywheel be on a real engine?

Talk about it

1. The slide says the power stroke is driven by "the force of the explosion." Is it a sudden blast, or a fast but controlled burn? Why does that matter to an engine designer?

2. Does the four-stroke cycle care whether the cylinder lies flat, as here, or stands upright as in a mower?
3. Why would an engine company want its customers to understand how the engine works?

Safety first. Work only on a cool engine with the spark-plug wire pulled off and kept well away from the plug. Never run any engine indoors or in a garage, because its exhaust contains carbon monoxide. Keep your hands away from the blade even with the plug removed, and wear safety glasses.

SHOP PROJECT

Measure a Real Engine

You will find a real small engine's specifications, measure its stroke yourself through the spark-plug hole, feel the four-stroke rhythm, and check your displacement and compression-ratio calculations against the maker's numbers. If no engine is available, borrow one from a neighbor, ask a small-engine shop for an old engine to study, or use a large syringe as a model cylinder (see the tips).

You will need

- A walk-behind mower or other small four-stroke engine (cool, not run for at least an hour)
- Spark-plug socket and ratchet, a rag, safety glasses and work gloves
- A thin wooden skewer or plastic straw at least 20 cm long and a fine marker
- A ruler or caliper reading millimeters
- The engine's model/type numbers and the maker's manual or specification page
- Shop notebook and calculator

Steps

1. Put on safety glasses. Make sure the engine is cool. Pull the spark-plug wire off and tuck it where it cannot touch the plug. Set the fuel shut-off to off if there is one.
2. Copy the engine model and type numbers from the engine. Look up the bore, stroke, displacement, compression ratio (if given), oil capacity and plug gap. Record them in your notebook.
3. Remove the spark plug with the plug socket and set it on a clean rag. Look at its tip and note its color for Lesson 9.4.
4. Put your thumb lightly over the plug hole and pull the starter rope slowly through several turns. Count how many turns pass between the puffs of air you feel. Explain the count using the four strokes.

5. Slide the skewer gently into the plug hole until it rests on the piston. (On engines where the plug points across the chamber, the skewer may not reach the piston; then skip to step 7 and use the maker's stroke.) Pull the rope slowly and watch the skewer rise and fall. Mark it at its highest point (TDC) and its lowest point (BDC).
6. Measure the distance between the two marks: that is your measured stroke. Repeat twice and average.
7. Calculate the displacement from the maker's bore and your measured stroke. Find the percent difference from the maker's displacement.
8. From the compression ratio (or a typical 8.5:1 if none is listed), calculate the clearance volume and the ideal efficiency.
9. Thread the plug back in by hand first so it cannot cross-thread, then tighten it with the socket to the manual's torque or turn. Reconnect the wire only when all work is done.
10. **Check your work.** List two reasons your measured stroke might differ from the specification and how you would measure more accurately.

Tips

- No engine? Fill a 60 mL syringe with air, cap the tip with your finger, and push the plunger to 10 mL: you have made a 6:1 compression ratio. Feel how hard it pushes back and repeat at 8 mL (7.5:1).
- Pull the rope slowly; a sudden pull can yank the skewer out of your hand.
- If the manual gives the stroke in inches, convert at 25.4 mm per inch.

Check your work

- ☐ I can explain all four strokes and why there are two turns per power stroke.
- ☐ My displacement calculation agrees with the maker's figure within a few percent, or I can explain why not.
- ☐ I can find a clearance volume from a compression ratio.

SHOP NOTEBOOK

1. A four-panel labeled sketch of the four strokes: piston position, valve positions and the direction gas flows in each.
2. A specification card for your engine: model and type, bore, stroke, displacement, compression ratio, oil type and capacity, plug type and gap.

3. Your stroke measurements, the average, and the percent difference from the maker's figure.

KEY FORMULAS

$V_d = \dfrac{\pi}{4}\, b^2\, s \times (\text{number of cylinders})$

$r = \dfrac{V_d + V_c}{V_c} \quad \Rightarrow \quad V_c = \dfrac{V_d}{r - 1}$ (per cylinder)

$\eta_{\text{Otto}} = 1 - \dfrac{1}{r^{\gamma - 1}}, \quad \gamma \approx 1.4$

$P_{\text{hp}} = \dfrac{T\,(\text{lb·ft}) \times n\,(\text{rpm})}{5252}$, power strokes per minute (four-stroke) $= n/2$ per cylinder

From history. Two of Otto's colleagues at Deutz, Gottlieb Daimler and Wilhelm Maybach, left in 1882 to build a small, fast four-stroke that could run on gasoline instead of town gas. Their 1885 "grandfather clock" engine powered a motorcycle, and the same year Karl Benz, working separately, drove his first motor car. Within forty years Otto's cycle was moving most of the world's cars, boats and farm machines.

WORKED EXAMPLES

Example 1. A popular push-mower engine has a bore of 64 mm and a stroke of 50 mm. Find its displacement in cubic centimeters.

Show solution

1. Convert to centimeters: $b = 6.4$ cm, $s = 5.0$ cm.
2. Piston area: $\frac{\pi}{4}(6.4)^2 = 0.7854 \times 40.96 = 32.17$ cm^2.
3. Swept volume: $32.17 \times 5.0 = 160.8$ cm^3.
4. One cylinder, so the displacement is about 161 cc; the maker rounds it to 160 cc.

Answer: ≈ 161 cc

Example 2. The same engine has a compression ratio of 8.5:1. What is its clearance volume?

Show solution

1. Use $V_c = V_d/(r-1)$.
2. $V_c = 160\ \text{cm}^3 \div (8.5-1) = 160 \div 7.5 = 21.3\ \text{cm}^3$.
3. Check: $(160 + 21.3)/21.3 = 8.5$.

Answer: $\approx 21\ \text{cm}^3$

Example 3. Find the ideal (Otto-cycle) efficiency for a compression ratio of 8.5, and compare it with a real small engine that turns about 25% of its fuel energy into work.

Show solution

1. Exponent: $\gamma - 1 = 0.4$.
2. $8.5^{0.4} = e^{0.4 \ln 8.5} = e^{0.4 \times 2.140} = e^{0.856} \approx 2.354$.
3. $\eta = 1 - 1/2.354 = 1 - 0.425 = 0.575$,
4. The ideal engine would convert about 57%; the real one converts about 25%, less than half the ideal, because of heat loss through the fins, friction, pumping and incomplete burning.

Answer: About 57% ideal versus about 25% real.

Example 4. A mower engine makes 6.0 lb·ft of torque at 3,600 rpm. Find its power in horsepower and the number of power strokes each second.

Show solution

1. $P = 6.0 \times 3600/5252 = 21{,}600/5252 \approx 4.1$ hp.
2. A four-stroke fires once every two turns:
   $3600/2 = 1800$ power strokes per minute,
3. $1800/60 = 30$ per second.

Answer: About 4.1 hp; 30 power strokes per second.

PRACTICE

1. Easy Name the four strokes in order and say which valve (if any) is open during each.

   Show answer

   Intake (intake valve open), compression (both closed), power (both closed until near the bottom), exhaust (exhaust valve open).

2. Easy How many crankshaft turns make one complete four-stroke cycle? How many power strokes per minute does a single-cylinder engine make at 3,000 rpm?

   Show answer

   Two turns; $3000/2 = 1500$.

3. Easy Convert 190 cc to cubic inches (1 in^3 = 16.39 cc).

   Show answer

   $190/16.39 \approx 11.6\ \text{in}^3$.

4. Medium An engine has a bore of 68 mm and a stroke of 45 mm. Find its displacement.

   Show answer

   $0.7854 \times 6.8^2 \times 4.5 \approx 163$ cc.

5. Medium A V-twin riding-mower engine has a bore of 3.12 in and a stroke of 2.75 in. Find its displacement in cubic inches and in cc.

   Show answer

   Per cylinder $0.7854 \times 3.12^2 \times 2.75 \approx 21.0\ \text{in}^3$; two cylinders $\approx 42.0\ \text{in}^3 \approx 689$ cc.

6. Medium A cylinder sweeps 200 cc and has a clearance volume of 25 cc. Find the compression ratio.

   Show answer

   $(200 + 25)/25 = 9.0$, or 9:1.

7. Medium An engine makes 8.5 lb·ft at 2,800 rpm. Find its horsepower.

   Show answer

   $8.5 \times 2800/5252 \approx 4.5$ hp.

8. Hard What clearance volume gives a 150 cc cylinder a compression ratio of 10:1?

Show answer

$V_c = 150/9 \approx 16.7$ cc.

9. Hard Compare the ideal efficiencies at compression ratios of 6 and 10. Why don't mower engines simply use 10:1?

Show answer

$6^{0.4} \approx 2.048$, $\eta \approx 51\%$; $10^{0.4} \approx 2.512$, $\eta \approx 60\%$. Higher compression on regular gasoline risks knock (the mixture igniting on its own), runs hotter in an air-cooled engine, and is harder to pull-start by hand.

10. Hard Conceptual. Lenoir's 1860 engine burned its mixture without compressing it and converted only about 4% of its fuel energy. Explain in your own words why compressing first helps.

Show answer

Model answer: compressing raises the pressure and temperature before burning, so the burned gas starts its expansion at a much higher pressure and expands through a larger ratio, doing more work on the piston for the same fuel; the ideal efficiency rises with compression ratio.

11. Challenge You are the tradesperson. A customer's mower blew a cloud of white-blue smoke and now will not start; she says her son turned it on its side to clean the deck. The oil level is above the full mark. What happened, and what do you do?

Show answer

Model answer: it was likely tipped with the carburetor or air filter side down, so oil ran into the air filter and the cylinder. Disconnect the plug wire, remove the plug, set the mower upright, drain oil to the correct level, replace the oil-soaked air filter, pull the rope with the plug out (standing clear) to blow out oil, clean or replace the plug, reinstall and start outdoors; some smoke is normal for a minute. Teach the customer to tip the mower with the air filter and carburetor up.

COMMON MISTAKES

- Thinking a four-stroke fires every turn. It fires every other turn, so the flywheel must carry it through three non-power strokes.
- Using the radius instead of the diameter in $\frac{\pi}{4} b^2 s$, or mixing millimeters and centimeters.
- Computing the compression ratio as V_d / V_c instead of $(V_d + V_c) / V_c$.
- Running an engine in a garage "just for a minute." Carbon monoxide builds up quickly even with the door open.

> **Make it a game · Four Stroke Acting.** Act out the four strokes with your arm as the piston and your fingers as the valves: intake, compression, power, exhaust. Your parent calls a stroke and you demonstrate and name the valve positions in five seconds. Then compute compression ratio from swept volume 400 cc and clearance 50 cc. The engine stays off throughout.

9.2 Two-Stroke Engines

OBJECTIVES

- Explain how a crankcase-scavenged two-stroke engine uses ports instead of valves to fire once every turn.
- Mix two-stroke fuel at a given ratio in ounces or milliliters, and correct a wrong mix.
- Weigh the trade-offs between two-stroke and four-stroke engines for chainsaws, trimmers, outboards and mowers.
- Inspect a two-stroke engine's piston through the exhaust port as a technician does.

> **Warm-up.** Hold a leaf blower or string trimmer (not running) in one hand and a push mower's engine in your imagination in the other. A chainsaw must run upside down and sideways. List what would go wrong for an engine with an oil sump if you turned it upside down.

WATCH

The Two-Stroke Engine | Shell Historical Film Archive

Shell · 26:10

https://www.youtube.com/watch?v=fVV7IeKe0iU

> **WHEN TO WATCH**
> After the story paragraph. Watch at least the first 15 minutes, which animate the crankcase, transfer and exhaust ports; the rest shows how designers improved scavenging.

Note: A classic 1959 teaching film made by the Shell Film Unit, with excellent colored animations. Older narration, but the engineering is sound and clearly explained.

BACKUP VIDEO

Two-Stroke Engine - Explained

Engineering Explained · 4:37

https://www.youtube.com/watch?v=z-7AkC3gh4w

Before the worked examples, as a quick whiteboard summary.

KEY TERMS

two-stroke engine

An engine that completes intake, compression, power and exhaust in two strokes of the piston, one turn of the crankshaft, firing every turn.

port

An opening in the cylinder wall that the piston itself uncovers and covers, taking the place of valves.

crankcase compression

Using the sealed crankcase under the piston as a pump: the rising piston draws mixture into it, and the falling piston pushes it up through the transfer ports.

scavenging

Sweeping the burned gas out of the cylinder with the incoming fresh charge.

mix ratio

The ratio of gasoline to two-stroke oil by volume, such as 50:1; the oil in the fuel lubricates the bearings and cylinder.

reed valve

A thin flexible flap that lets mixture flow into the crankcase but not back out.

CORE IDEAS

The story. Otto's engine made one power stroke in every two turns, and other inventors soon asked whether an engine could fire every turn. The Scottish engineer Dugald Clerk built a gas engine in 1878–1881 that did just that, using a second pumping cylinder to push fresh charge into the working cylinder while the exhaust escaped through ports; he received a U.S. patent for it in 1881. In 1889 Joseph Day, an English engineer in Bath, simplified the idea: he used the sealed crankcase beneath the piston as the pump and let the piston open and close ports in the cylinder wall. Day's design had only three moving parts (piston, connecting rod and crankshaft), and it is still the heart of most chainsaws, string trimmers, leaf blowers and small outboard motors. Ole Evinrude's first practical outboard motor, sold around 1909 in Milwaukee, was a two-stroke.

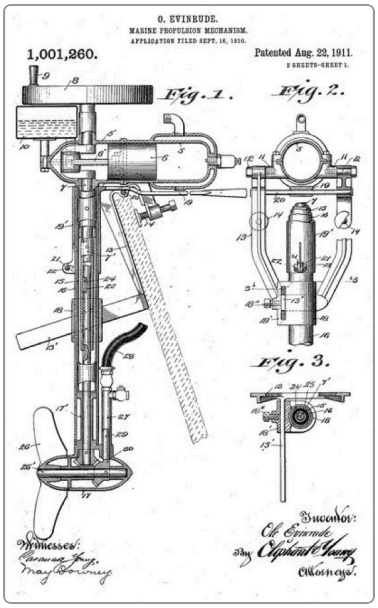
How they figured it out. The great difficulty was cleaning out the burned gas without wasting fresh fuel. Clerk and later designers tried many port shapes, and testing showed that some of the fresh mixture always slips straight out of the exhaust port.

Engineers improved scavenging by shaping the transfer ports to aim the fresh charge up and away from the exhaust (loop scavenging, developed by Adolf Schnürle in the 1920s), by tuning the exhaust pipe so a pressure wave pushes escaping charge back into the cylinder, and in recent decades by “stratified” designs that send a layer of clean air ahead of the fuel mixture. These changes were driven by better testing and by emission rules for small engines.

The science. As the piston rises, it compresses the charge above it and, at the same time, lowers the pressure in the sealed crankcase, drawing fresh mixture in through a reed valve or intake port. Near the top the spark fires. The piston is driven down; partway down it uncovers the exhaust port and the hot gas rushes out, and a moment later it uncovers the transfer ports, through which the mixture squeezed in the crankcase flows up into the cylinder and pushes out the remaining exhaust. Every downstroke is a power stroke, so a two-stroke fires twice as often as a four-stroke at the same speed. Because the crankcase is full of fuel mixture, it cannot hold an oil sump; the oil travels with the fuel, mixed at a ratio such as 50:1 (50 parts gasoline to 1 part oil). With no sump, the engine runs at any angle.

In the shop. The trade-offs are plain. Two-strokes are light, simple and powerful for their size, run in any position, and start easily: perfect for a chainsaw or trimmer held in the hands. But they burn oil, waste some fuel out the exhaust, are noisy, and need fuel mixed accurately. Four-strokes are heavier and more complex but more fuel-efficient, cleaner and longer-lived, which is why lawn mowers, generators and most outboards today are four-strokes. A technician’s first rule: use the mix ratio printed on the tool or in its manual, use two-stroke oil (never automotive engine oil), and mix in an approved fuel container, shaking before each fill. Straight gasoline in a two-stroke can score the piston and seize the engine in minutes. To check for damage, a technician removes the muffler and shines a light through the exhaust port: a smooth, gray piston is healthy; vertical scratches and smeared aluminum mean the engine ran lean or without oil.

PICTURE STUDY



Ole Evinrude's Outboard Motor, U.S. Patent 1,001,260, Ole Evinrude (patent drawing), Filed 1910, patented August 22, 1911 · Patent drawing · United States Patent and Trademark Office

Image: Wikimedia Commons, public domain

Ole Evinrude, a Norwegian-born machinist in Milwaukee, built a small motor that could be clamped onto the back of a rowboat. His two-stroke outboard became the first commercially successful one, and the American Society of Mechanical Engineers later named it a historic engineering landmark.

Look closely

- Find the cylinder (6) and the flywheel (8) at the top. Which way does the cylinder point?
- Follow the vertical shaft down to the propeller. How must the power turn a corner to drive it?
- Find the clamp that holds the motor to the boat and the handle used to steer.
- Find the fuel tank. Where is the oil for this two-stroke engine?

Talk about it

1. Why was a light, simple two-stroke a good choice for a motor a man might carry down to the dock?
2. The whole motor swings to steer the boat. What does that mean for an engine with no oil sump?

3. Most outboards sold today are four-strokes. What trade-offs might have changed the choice?

Safety first. Mix and pour fuel only outdoors, with the engine cool and off, using an approved fuel container, and with no flames, pilot lights or sparks nearby. Wear safety glasses and gloves; wash gasoline off skin. When inspecting a two-stroke tool, take the spark-plug boot off first, and never run one indoors.

SHOP PROJECT

Mix Right, Look Inside

Part A is a measuring lab: you will practice making accurate mix ratios using water and a little cooking oil, then check your accuracy with a kitchen scale. Part B is a technician's inspection of a real two-stroke tool's piston through its exhaust port. Part C compares two-stroke and four-stroke tools on paper.

You will need

- Measuring cup marked in mL or ounces, a 10 mL oral syringe or medicine cup, a clean 1 L bottle
- Water and cooking oil with a drop of food coloring (a stand-in for gasoline and two-stroke oil; never use real fuel indoors)
- Kitchen scale reading to 1 g
- Optional for Part B: an old two-stroke trimmer, blower or chainsaw; screwdriver or Torx driver; flashlight; safety glasses
- Manufacturer specification pages for two trimmers or blowers (one two-stroke, one four-stroke or battery)

Steps

1. **Part A.** Calculate the oil needed for 1 L at 50:1, 40:1 and 32:1. Record the three answers.
2. Make a 1 L "mix" at 50:1 using water and colored oil and your syringe. Weigh the oil you added (cooking oil is about 0.92 g/mL) and compute the ratio you actually made.
3. Repeat with a different measuring tool (a marked medicine cup, or the scale alone). Which method was most accurate? Record percent error for each.
4. Shake the bottle and watch how quickly the oil separates. Write why a technician shakes a two-stroke fuel can before every fill.
5. **Part B (with an adult).** On a cool, dry tool, pull off the spark-plug boot. Remove the muffler screws and the muffler (most trimmers and saws use two screws).

6. Pull the starter rope slowly until the piston is visible in the exhaust port. Shine the flashlight in. Sketch what you see and rate it: smooth and gray; light scratches; or deep vertical scoring.
7. Reinstall the muffler and its gasket, tighten the screws firmly, and reconnect the plug boot.
8. **Part C.** From the maker's pages, record weight, displacement or power, fuel or battery type, and price for two tools. Compute power-to-weight where both figures are given.
9. **Improve it.** Write a one-paragraph recommendation for a family choosing a trimmer for a quarter-acre lot, using your data.

Tips

- Measure oil with a syringe or a ratio cup made for two-stroke mixing; small errors matter at 50:1.
- Many two-stroke oils come in bottles sized to mix with exactly 1 or 2.5 gallons; check the label.
- If you have no two-stroke tool, ask a small-engine shop if you may watch a technician do the exhaust-port inspection.

Check your work

- ☐ I can calculate the oil for any mix ratio in ounces or milliliters.
- ☐ I can explain how ports and the crankcase replace valves.
- ☐ I can name two advantages and two disadvantages of two-stroke engines.

SHOP NOTEBOOK

1. A two-panel diagram of a crankcase-scavenged two-stroke: piston rising (compression above, intake below) and piston falling (power, then exhaust and transfer). Label every port.
2. Your Part A data table: target ratio, oil volume, oil mass, actual ratio, percent error.
3. A trade-off table: two-stroke versus four-stroke for weight, fuel use, oil, noise, emissions, maintenance and best uses.

KEY FORMULAS

$V_{\text{oil}} = \dfrac{V_{\text{fuel}}}{R}$ (mix ratio R:1), 1 US gal $= 128$ fl oz

power strokes per minute $= n$ (two-stroke) versus $n/2$ (four-stroke)

From history. In 1929 Andreas Stihl in Germany introduced one of the first gasoline-powered chainsaws, a two-man machine weighing over 100 pounds. Light one-man saws came after the Second World War, and the lightweight two-stroke is what made them possible. Today's professional saws weigh around 10 to 15 pounds.

WORKED EXAMPLES

Example 1. A trimmer calls for a 50:1 mix. How much oil goes into 1 gallon of gasoline? Into 5 liters?

Show solution

1. One gallon is 128 fl oz: $128 \div 50 = 2.56$ fl oz.
2. Five liters is 5,000 mL: $5000 \div 50 = 100$ mL.

Answer: About 2.6 fl oz per gallon; 100 mL per 5 L.

Example 2. A student poured 2.6 fl oz of oil into 1 gallon of gasoline for a saw that calls for 40:1. What ratio did he make, and how much oil must he add?

Show solution

1. Ratio made: $128 \div 2.6 \approx 49$:1,
2. close to 50:1, which is too lean on oil for this saw.
3. Oil needed for 40:1: $128 \div 40 = 3.2$ fl oz.
4. Add $3.2 - 2.6 = 0.6$ fl oz and shake the can well.

Answer: He made about 49:1; add 0.6 fl oz.

Example 3. A two-stroke and a four-stroke engine each displace 25 cc and run at 8,000 rpm. Compare their power strokes per second and the volume swept in power strokes each minute.

Show solution

1. Two-stroke: $8000/60 \approx 133$ power strokes/s; four-stroke: $4000/60 \approx 67$.
2. Volume per minute in power strokes: two-stroke $25 \times 8000 = 200{,}000$ cc; four-stroke $25 \times 4000 = 100{,}000$ cc.
3. The two-stroke fires twice as often. Because some charge escapes and scavenging is imperfect, real two-strokes make roughly 1.3 to 1.6 times the power of a similar four-stroke, not twice.

Answer: Twice as many power strokes; in practice about one and a half times the power.

PRACTICE

1. Easy How much oil goes into 2 gallons of gasoline at 50:1?

   Show answer

   $256/50 \approx 5.1$ fl oz.

2. Easy A two-stroke runs at 6,000 rpm. How many power strokes does it make each second?

   Show answer

   $6000/60 = 100$.

3. Easy Name the ports in a simple crankcase-scavenged two-stroke and the job of each.

   Show answer

   Intake (or reed valve) port: lets mixture into the crankcase. Transfer ports: carry it from the crankcase up into the cylinder. Exhaust port: lets burned gas out.

4. Medium How much oil is needed for 4 L at 32:1?

   Show answer

   $4000/32 = 125$ mL.

5. **Medium** How much oil for 2.5 L at 40:1?

Show answer

$2500/40 = 62.5$ mL.

6. **Medium** Someone mixed 100 mL of oil into 4 L of gasoline. What ratio is that?

Show answer

$4000/100 = 40{:}1$.

7. **Medium** Conceptual. Why must you never run a two-stroke chainsaw on straight gasoline?

Show answer

Its only lubrication is the oil carried in the fuel. Without it the piston, rings and bearings run dry, overheat and score, and the engine can seize within minutes.

8. **Hard** In a simple two-stroke, suppose 25% of the fresh fuel escapes out the exhaust unburned. If the engine uses 0.40 kg of fuel an hour, how much leaves unburned, and what does that mean for the user?

Show answer

$0.25 \times 0.40 = 0.10$ kg/h. A quarter of the fuel is wasted and pollutes the air the operator breathes; this is why emission rules pushed makers toward stratified two-strokes and four-strokes.

9. **Hard** Dugald Clerk's engine fired every turn. At 150 rpm, how many power strokes per minute did it make, compared with an Otto four-stroke at the same speed?

Show answer

150 versus 75: twice as many.

10. Hard You are the tradesperson. A string trimmer starts, smokes heavily, then dies; the plug is wet, black and oily. List the likely causes and what you would check.

Show answer

Model answer: too much oil in the mix (wrong ratio), flooding from over-choking or over-priming, or a clogged air filter making it rich. Check the fuel ratio (make fresh fuel at the correct mix), clean or replace the air filter, dry or replace the plug, and start with the correct choke procedure.

11. Challenge You have exactly 1 gallon of 50:1 mix, but your old saw needs 40:1. How much more oil should you add? (Treat the gasoline as 128 fl oz.)

Show answer

Present oil $128/50 = 2.56$; needed $128/40 = 3.2$; add about 0.64 fl oz.

COMMON MISTAKES

- Using automotive engine oil in two-stroke fuel. Two-stroke oil is made to mix with gasoline and burn cleanly.
- Guessing at the oil amount, or mixing in the tool's tank instead of a separate can.
- Thinking a two-stroke makes twice the power of a four-stroke of the same size; scavenging losses take much of that advantage away.
- Storing mixed fuel for months. Mixed fuel goes stale like plain gasoline; mix only what you will use in a month or two, or use stabilizer.

> **Make it a game · Fuel Mix Math Sprint.** Your parent names a gallon amount and a ratio, such as 50 to 1 or 40 to 1, and you calculate the ounces of oil in 20 seconds. Then correct a wrong mix: what to add if you mixed too lean? Parent plants a mistake each round. Five rounds; beat your fastest total time.

9.3 Fuel, Air and the Carburetor

OBJECTIVES

- Explain how a venturi, a float bowl, jets, a choke and a throttle meter fuel into the air using continuity and Bernoulli's principle.
- Calculate venturi speeds and pressure drops, air–fuel ratios and an engine's fuel use.
- Explain why stale fuel and ethanol blends cause most small-engine starting problems, and how to prevent them.
- Build a model venturi and measure its pressure drop with a water manometer.

> **Warm-up.** Stand a drinking straw upright in a glass of water and blow hard across its top with a second straw. What happens? Write a one-sentence guess about why.

WATCH

How Does A Carburetor Work? | Transparent Carburetor at 28,546 fps Slow Mo - Smarter Every Day 259

SmarterEveryDay · 24:38

https://www.youtube.com/watch?v=toVfvRhWbj8

> **WHEN TO WATCH**
> After the science paragraph. Watch for the moment the choke closes and fuel sprays from the jet.

Note: Destin Sandlin and a retired engineer build a clear carburetor for a small engine and film the fuel in slow motion. Begins with a sponsor message; skip the first minute.

BACKUP VIDEO

How a Trimmer Carburetor Works

Sanya Tsvay · 8:22

https://www.youtube.com/watch?v=59RPnNe7syQ

After Lesson 9.2 and this lesson: a diaphragm carburetor, used on trimmers and saws because it works at any angle.

KEY TERMS

venturi

A smooth narrowing in a pipe where the flow speeds up and its pressure drops.

Bernoulli's principle

Along a streamline, where a fluid moves faster its pressure is lower: $p + \frac{1}{2}\rho v^2 = \text{constant}$.

float bowl

A small fuel reservoir under the carburetor whose float and needle valve keep the fuel at a constant level.

jet

A precisely sized hole that meters fuel into the airstream; main jets feed at speed, idle jets at low throttle.

choke

A plate ahead of the venturi that closes to restrict air, making a rich mixture for a cold start.

air–fuel ratio (AFR)

The mass of air per mass of fuel; 14.7:1 is the chemically correct (stoichiometric) ratio for gasoline.

CORE IDEAS

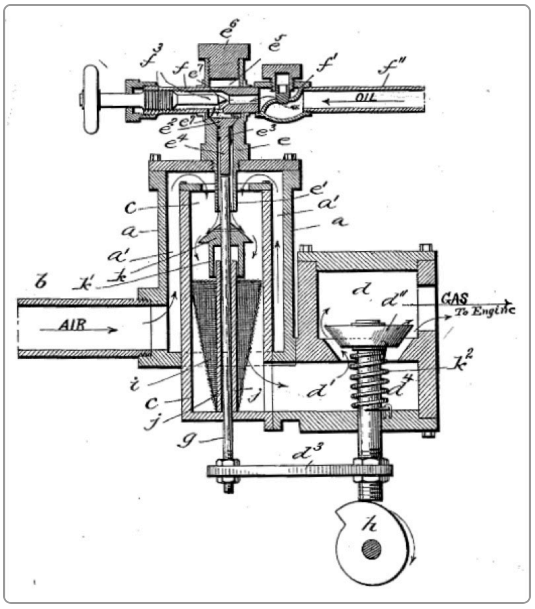
The story. An engine cannot burn liquid gasoline poured in a puddle; it needs a fine mist mixed with the right amount of air. The first engines that ran on gasoline used "surface carburetors" that simply passed air over a pan of fuel, and they were fussy and dangerous. In 1893 Wilhelm Maybach, working with Gottlieb Daimler, designed a spray-nozzle carburetor with a float to hold the fuel level steady, and in the same year the Hungarian engineers Donát Bánki and János Csonka patented a spray carburetor of their own. Their principle, a jet of fuel drawn into a fast-moving stream of air, fed nearly every gasoline engine for the next century. Cars switched to electronic fuel injection in the 1980s, but most lawn mowers, trimmers and chainsaws still use carburetors because they are cheap, light and need no battery.

How they figured it out. Early designers learned by trial what the physics later explained: if the air passage narrows, the air speeds up and its pressure falls, and that small suction can lift fuel from a bowl kept at atmospheric pressure. The float and needle valve, like a toilet tank's fill valve, keep the fuel level just below the jet so the flow depends only on the air. Designers then added an idle circuit for low speeds, a choke for cold starts and a throttle plate to control power. Each was the answer to a problem found in testing.

The science. Air entering the carburetor obeys continuity: the same mass passes every cross-section each second, so $A_1 v_1 = A_2 v_2$ and a throat one-third the area makes the air move three times as fast. Bernoulli's principle then gives the pressure drop, $\Delta p = \tfrac{1}{2}\rho(v_2^2 - v_1^2)$, with air density $\rho \approx 1.2\ \text{kg/m}^3$. Only a few hundred pascals of suction are needed to draw fuel through the jet. The fuel must match the air: burning gasoline completely takes about 14.7 kg of air for each kilogram of fuel. Mixtures richer than this (more fuel, such as 12.5:1) give the most power and run cooler, which is why small air-cooled engines are set slightly rich; leaner mixtures save fuel but run hot. Closing the choke increases the suction at the jet and enriches the mixture so a cold engine, where fuel condenses on cold metal, will start.

In the shop. Most small-engine repairs are fuel problems. Gasoline begins to oxidize within about a month, forming gums and varnish that clog jets smaller than a pinhead. Most pump gasoline in the United States is E10 (10% ethanol), which absorbs water from the air; with enough water the ethanol and water separate and sink to the bottom of the tank, where the engine draws them in. The cures are simple: buy fuel in small amounts, add fuel stabilizer when you fill the can, use ethanol-free fuel for engines that sit, and run the carburetor dry or drain the float bowl before storage. A technician cleans a gummed carburetor by removing the bowl, the main jet and the emulsion tube, spraying them with carburetor cleaner, and clearing the jet with compressed air or a cleaning wire smaller than the hole, never a drill bit that would enlarge it. Diaphragm carburetors on trimmers and saws use a flexible pump and metering diaphragm instead of a float, so they work at any angle.

PICTURE STUDY



John W. Lambert's Carburetor Patent, John William Lambert (patent drawing), 1894 · Patent drawing · United States Patent and Trademark Office

Image: Wikimedia Commons, public domain

John W. Lambert of Ohio City, Ohio, built one of the first American gasoline automobiles in 1891 and patented this carburetor in 1894. Early makers had to invent every part of the car themselves, including the device that turns liquid fuel into a burnable mixture. In the 1890s light petroleum fuels were often simply called "oil."

Look closely

- Find the arrows marked AIR and OIL. Where does each enter?
- Find the needle valve and hand wheel at the top. What does turning it change?
- Look at the cone in the middle chamber. How might it spread the fuel out so the air can pick it up?
- Find the valve at the right that lets mixture go "to engine," and the cam (h) at the bottom that works it.

Talk about it

1. What problems do you think early carburetors had in cold weather?
2. Why does a carburetor need a constant fuel level to give a steady mixture?

3. What would happen to the mixture if the air passage became partly blocked by a dirty filter?

Safety first. Use only water in the model venturi. If you inspect a real carburetor, do it outdoors on a cool engine with the fuel shut off and drained into an approved container, with no flames or sparks nearby; wear safety glasses and gloves, since carburetor cleaner and gasoline are flammable and harm eyes and skin. Never use your mouth to siphon fuel.

SHOP PROJECT

A Model Venturi and a Water Manometer

You will build a venturi from two plastic bottles, blow air through it, and measure the pressure drop at the throat with a homemade water manometer. From the pressure drop you will calculate the air speed with Bernoulli's equation, then show that the suction can lift water just as a carburetor lifts fuel.

You will need

- Two empty 500 mL or 1 L plastic bottles with smooth necks, cut and taped neck-to-neck (or one bottle and a cardboard tube)
- 1 m of clear vinyl tubing (about 6 mm inside diameter), a ruler, tape and a board to mount the tubing in a U shape
- Water with a drop of food coloring
- A hair dryer on the cool, no-heat setting, or a shop-vacuum blower port
- Drinking straws, a hot-glue gun (adult), a small drill or awl (adult)
- Safety glasses

Steps

1. Cut the bottoms off two bottles and tape them neck-to-neck so air can flow in one wide end, through the narrow necks (the throat) and out the other wide end. Measure the inside diameters of the wide part and the throat and compute the area ratio.
2. With an adult, make a small hole in the throat and another in the wide inlet section. Glue a short piece of straw into each as a pressure tap.
3. Bend the clear tubing into a U on the board and fill it partly with colored water. Mark the level. Connect one end to the throat tap and leave the other end open to the air.
4. **Predict.** When air blows through, will the water in the throat side rise or fall? By how much compared with the inlet tap?
5. Blow air through the venturi with the hair dryer on its cool setting. Measure the height difference h in the manometer. Repeat three times and average.
6. Move the tubing to the inlet tap and measure again.

7. Compute each pressure difference with $\Delta p = \rho g h$, using $\rho = 1000\ \text{kg/m}^3$ for water and h in meters.
8. Compute the throat air speed from $v \approx \sqrt{2\,\Delta p / \rho_{\text{air}}}$, and check whether the throat-to-inlet speed ratio matches your area ratio.
9. Put a straw through the throat wall down into a cup of colored water below the venturi. Blow again: does water rise or spray into the airstream? You have built a carburetor's main jet.
10. **Improve it.** Make the throat narrower (tape a cardboard collar inside it) and test again. Record how h changes.

Tips

- Seal every joint with tape; leaks spoil the reading.
- A 1 cm water column is about 98 Pa, a typical reading for this model.
- Keep the hair dryer on its cool setting so the bottles do not soften.

Check your work

- ☐ I can explain why the throat pressure is lower, using continuity and Bernoulli.
- ☐ I can convert a manometer reading to pascals and an air speed.
- ☐ I can explain how a float, jet, choke and throttle work together.

SHOP NOTEBOOK

1. A labeled cross-section of a float carburetor: air inlet, choke plate, venturi, main jet, float bowl, float and needle, idle circuit, throttle plate.
2. Your manometer data table, calculated pressures and speeds, and a comparison of the speed ratio with the area ratio.
3. A fuel-care card for your family's equipment: fuel type, stabilizer, storage limit and what to do before winter.

KEY FORMULAS

$A_1 v_1 = A_2 v_2$
$\Delta p = \tfrac{1}{2}\rho\,(v_2^2 - v_1^2), \quad \rho_{\text{air}} \approx 1.2\ \text{kg/m}^3$
$\text{AFR} = \dfrac{m_{\text{air}}}{m_{\text{fuel}}}, \quad \text{AFR}_{\text{stoich}} \approx 14.7$
$\dot m_{\text{air}} = \rho\, V_d \dfrac{n}{2}\,\eta_v$ (four-stroke), $\Delta p = \rho g h$ (manometer)

From history. Carburetors reached their most complex form in the 1960s and 1970s, with multiple barrels, accelerator pumps and power valves. By the late 1980s nearly all new American cars used electronic fuel injection, which measures the air with sensors and sprays exactly the right fuel with solenoid injectors. Some newer small engines now use electronic fuel injection too.

WORKED EXAMPLES

Example 1. Air enters a carburetor at 10 m/s, and the venturi throat has one-third the inlet area. Find the throat speed and the pressure drop.

Show solution

1. Continuity: $v_2 = v_1 (A_1/A_2) = 10 \times 3 = 30$ m/s.
2. Bernoulli: $\Delta p = \tfrac{1}{2}(1.2)(30^2 - 10^2) = 0.6 \times 800 = 480$ Pa.
3. That is about 0.07 psi, small but enough to lift fuel a few centimeters through the jet.

Answer: $30\ \text{m/s},\ 480\ \text{Pa}$

Example 2. A 160 cc four-stroke runs at 3,600 rpm at full throttle with a volumetric efficiency of 85%. At an air–fuel ratio of 14.7, how much fuel does it use per hour, in kilograms and liters (gasoline 0.74 kg/L)?

Show solution

1. Intake strokes per minute: $3600/2 = 1800$.
2. Air volume per minute: $160\ \text{cm}^3 \times 1800 \times 0.85 = 244{,}800\ \text{cm}^3 = 0.245\ \text{m}^3$.
3. Air mass: $0.245 \times 1.2 = 0.294$ kg/min.
4. Fuel: $0.294 / 14.7 = 0.0200$ kg/min $= 1.20$ kg/h.
5. Volume: $1.20 / 0.74 \approx 1.6$ L/h. Real mowing at part load uses less.

Answer: About 1.2 kg (1.6 L) per hour at full load.

Example 3. You are the tradesperson. A mower sat all winter with E10 fuel in the tank. It now has a good spark, but the plug comes out dry after a dozen pulls. Reason through the problem.

Show solution

1. A dry plug means no fuel is reaching the cylinder; spark and compression are not the issue yet.
2. Likely causes: stale fuel gummed in the main jet or float needle, water at the bottom of the bowl from phase separation, or a stuck float.
3. Drain the old fuel into an approved container outdoors and take it to a hazardous-waste drop-off. Remove the float bowl and look for varnish, white crust or water.
4. Clean the jet and passages with carburetor cleaner and compressed air, check the float moves freely, reassemble, and refill with fresh, stabilized fuel.
5. Prevention: stabilizer at every fill, or run the engine dry before storage.

Answer: Fuel delivery is blocked by stale fuel; clean the carburetor and use fresh, stabilized fuel.

PRACTICE

1. Easy How many kilograms of air are needed to burn 0.50 kg of gasoline completely?

   Show answer

   $0.50 \times 14.7 = 7.35$ kg.

2. Easy What does the choke do, and why does a cold engine need it?

   Show answer

   It restricts the air entering the carburetor, increasing the suction at the jet and enriching the mixture; in a cold engine much of the fuel condenses on cold metal instead of vaporizing.

3. Easy What is the job of the float and needle valve?

   Show answer

   They keep the fuel in the bowl at a constant level, shutting off incoming fuel when the bowl is full, so the jet always sees the same fuel height.

4. **Medium** Air enters a 4.0 cm² inlet at 12 m/s. The throat is 1.5 cm². Find the throat speed.

Show answer

$12 \times 4.0/1.5 = 32$ m/s.

5. **Medium** For the venturi in problem 4, find the pressure drop from inlet to throat.

Show answer

$0.6 \times (32^2 - 12^2) = 0.6 \times 880 = 528$ Pa.

6. **Medium** How many cubic meters of air are needed to burn 1 L of gasoline (0.74 kg) at 14.7:1?

Show answer

$0.74 \times 14.7 = 10.9$ kg; $10.9/1.2 \approx 9.1$ m³.

7. **Medium** An exhaust analyzer reads an air–fuel ratio of 12.5:1. Is the engine rich or lean? Is that necessarily bad for an air-cooled mower engine?

Show answer

Rich (less air than 14.7). Slightly rich is normal for small air-cooled engines at full load; it gives power and keeps the engine cooler.

8. **Hard** A 190 cc four-stroke runs at 3,000 rpm with a volumetric efficiency of 80%. Find its fuel use in L/h at 14.7:1 (gasoline 0.74 kg/L).

Show answer

Air: $190 \times 1500 \times 0.80 = 228{,}000$ cm³; $0.228 \times 1.2 = 0.274$ kg/min; fuel 0.0186 kg/min ≈ 1.12 kg/h ≈ 1.5 L/h.

9. **Hard** Conceptual. A mower tuned at sea level runs rich and sooty in the mountains. Explain using the venturi equations.

Show answer

Thinner air has lower density. The engine still draws about the same volume, so the air mass falls in proportion to density, but the fuel flow depends on the square root of the pressure drop, which falls more slowly. The mixture gets richer; a smaller high-altitude main jet corrects it.

10. Hard You are the tradesperson. A mower surges up and down at steady throttle (hunting). The air filter is clean. What is the likely cause and repair?

Show answer

A lean condition, usually a partly clogged main jet or emulsion tube from stale fuel, or an air leak at the carburetor gasket. Clean the jet and passages, replace the gasket if needed, and refill with fresh fuel.

11. Challenge Ethanol contains about two-thirds as much energy per liter as gasoline. Estimate the percent less energy in a liter of E10 than in pure gasoline.

Show answer

$0.90 + 0.10 \times 0.67 = 0.967$; about 3% less energy per liter.

COMMON MISTAKES

- Saying the venturi “sucks” fuel. The higher atmospheric pressure on the fuel in the vented bowl pushes it toward the lower pressure in the throat.
- Clearing a jet with a drill bit or a pin that enlarges it; the engine will then run rich forever.
- Leaving fuel in a carburetor over the winter, then blaming the engine.
- Mixing up mass and volume in air–fuel ratios. 14.7:1 is by mass.

> **Make it a game · Carburetor Part Chain.** Name, from memory and in order, the path of air and fuel through a carburetor: air filter, choke, venturi, jet, float bowl, throttle. Explain the Bernoulli effect at the venturi. Your parent plays a customer whose engine runs rich or lean and asks what happened. Calculate an air-fuel ratio for 14.7 to 1 and 1 gram of fuel.

9.4 Ignition, Compression and the Governor

OBJECTIVES

- Explain how a flywheel magneto uses Faraday's law and a step-up coil to make a spark of many thousands of volts.
- Gap and read a spark plug, check for spark safely, and explain what a compression test tells you.
- Explain how a mechanical governor holds engine speed, and calculate blade tip speed and spark timing.
- Tell the story of Briggs & Stratton and the engine that made the power mower common.

> **Warm-up.** Rub a magnet quickly past a coil of wire connected to an LED or a cheap galvanometer (or watch the video's first minute). Faster or slower: which makes more voltage? Write your guess.

WATCH

Lawnmower Coil Pack Sparking System - Induction Coil, Transistor! (by Craig Kirkman)

TheRepairSpecialist · 16:14

https://www.youtube.com/watch?v=NNlYbvDY6pI

> **WHEN TO WATCH**
> After the science paragraph. Follow the magnet past the armature and note when the primary current is switched off.

Note: A British engineer and teacher explains the Briggs & Stratton style ignition armature with clear drawings, from electrons in copper up to the spark. The atom section in the middle is review; keep going.

BACKUP VIDEO

How the Small Engine Governor Works

Rehlko Engines University · 5:09

https://www.youtube.com/watch?v=3jUpb71D3is

With the governor paragraph.

KEY TERMS

magneto

A generator that makes the ignition spark from magnets passing a coil, needing no battery.

armature (ignition coil)

The coil mounted beside the flywheel, with a primary winding of a few hundred turns and a secondary of many thousands.

air gap

The small gap between the armature and the flywheel magnets, often about 0.010 in (0.25 mm); too wide weakens the spark.

spark-plug gap

The distance between the plug's center and side electrodes, set with a feeler or wire gauge, often about 0.030 in (0.76 mm).

compression test

Measuring the cylinder's cranking pressure with a gauge in the plug hole to check rings, valves and head gasket.

governor

A speed-control system, usually spinning flyweights balanced against a spring, that opens or closes the throttle to hold a set engine speed.

CORE IDEAS

The story. In 1908 Stephen Foster Briggs, a young engineering graduate, and Harold M. Stratton, a businessman, started a company in Milwaukee. They made electrical switches and ignition parts for the young auto industry, and in 1919 they bought the rights to the Smith Motor Wheel, a small engine on its own wheel that clamped onto a bicycle. They used it to make the Briggs & Stratton Flyer, a tiny buckboard car that was among the cheapest ever sold. The company's real future was small engines for washing machines, farm equipment and, after 1950, lawn mowers. In 1953 it introduced a lightweight aluminum engine that made the rotary push mower cheap and easy to handle, and Briggs & Stratton became for many decades the world's largest maker of small gasoline engines. Its customer-education department still trains small-engine technicians.

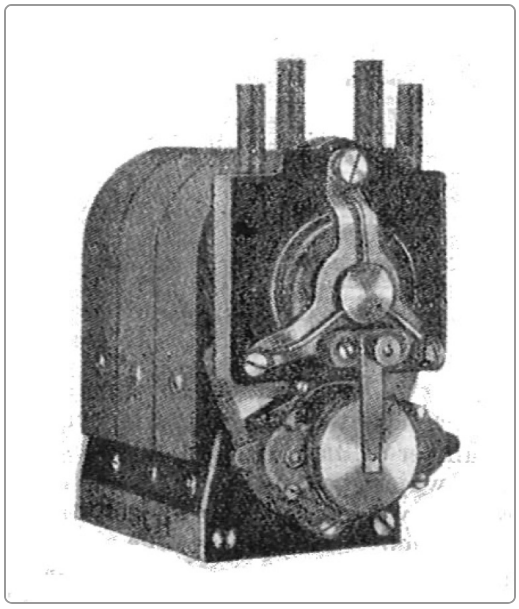
How they figured it out. An engine needs a spark of several thousand volts at exactly the right moment, many times a second. Robert Bosch's company built a low-voltage magneto in 1897, and in 1902 Bosch's engineer Gottlob Honold built the high-voltage magneto with a spark plug, which became the standard for engines with no battery.

Early small engines used breaker points, mechanical contacts that opened to stop the primary current; they wore and needed adjusting. From the 1980s, makers replaced the points with a small transistor circuit sealed in the armature, which is why most modern mowers need no ignition adjustment except the air gap.

The science. Magnets are cast into the flywheel. Each time they sweep past the iron armature, the magnetic flux through its coils changes rapidly, and Faraday's law, $\mathcal{E} = -N\,\Delta\Phi/\Delta t$, drives a current in the primary winding. At the right instant the transistor (or points) suddenly stops that current. The magnetic field collapses in microseconds, and the secondary winding, with roughly a hundred times as many turns, has a voltage induced in it that is roughly the turns ratio times the primary voltage: 10,000 to 20,000 volts or more. That is enough to jump the plug gap through compressed gas. The spark is fixed to fire a set number of degrees before top dead center, so the flame has time to build pressure as the piston starts down; the flywheel's soft-metal key locates the magnets on the crankshaft, and a sheared key throws the timing off. A healthy engine also needs **compression**: worn rings or a leaking valve let the charge escape, and the engine pulls easily but will not start or runs weakly. Finally, a mower engine must hold its speed whether the grass is thin or thick. The **governor** does this: flyweights spun by the camshaft gear move outward as speed rises and pull the throttle closed against a spring, and when tall grass slows the engine the spring wins and opens the throttle.

In the shop. A technician reads a spark plug like a doctor reads a thermometer. A light tan or gray tip means a healthy engine; dry black soot means too rich (choke stuck, dirty air filter); wet and oily means oil reaching the chamber (worn rings, overfilled crankcase or a mower tipped the wrong way); white and blistered means running lean and hot. To check for spark, use an inexpensive inline spark tester between the plug wire and the plug, never your fingers. Set the plug gap with a gauge to the manual's figure, and set the armature air gap with the maker's gauge or a business card about 0.010 in thick. The governor is also a safety device: the industry safety standard for walk-behind mowers (ANSI/OPEI B71.1) limits blade-tip speed to 19,000 feet per minute, so never bend governor springs or linkages to make an engine run faster.

PICTURE STUDY



A Bosch High-Tension Magneto, Unknown illustrator, from a British Army training manual, 1911 · Halftone illustration · Army Service Corps Training, Mechanical Transport (1911)
Image: Wikimedia Commons, public domain

This is the kind of magneto that fired the engines of early cars, trucks, motorcycles and airplanes. It was printed in a 1911 manual that taught army drivers to keep their vehicles running, much as you are learning to keep a small engine running.

Look closely

- Find the curved horseshoe magnets that make up most of the body. What spins between their ends?
- Find the contact-breaker arm on the end cover. What job does it do in the ignition circuit?
- Look for the screws that let a mechanic adjust or remove the breaker. Why would that matter?
- Compare the size of this magneto with a mower's flywheel magnets and armature.

Talk about it

1. This magneto has its own spinning part driven by the engine. Where are the magnets on a mower engine instead?

2. Why was a magneto, which needs no battery, a good choice for early vehicles and for lawn mowers today?
3. What part of this old design was later replaced by a transistor?

Safety first. Check spark only with an inline spark tester, never by holding the plug wire, and keep hands clear of the blade while pulling the rope. Run engines only outdoors. Stop the engine and pull the plug wire before touching the governor linkage, and never adjust the governor above the maker’s top speed.

SHOP PROJECT

Spark, Gap and Speed: An Ignition and Governor Check

You will read and gap a spark plug, check the spark with a tester, measure the armature air gap, and measure a running engine's top speed with a tachometer to calculate its blade-tip speed. The engine is run only outdoors, with an adult present.

You will need

- A walk-behind mower (or other small engine) and its manual
- Spark-plug socket, wire-type or feeler gap gauge, an inline spark tester (inexpensive at auto-parts stores)
- Feeler gauge or a plain business card (about 0.010 in) for the armature air gap
- A small-engine tachometer, an inexpensive vibration tachometer, or a phone tachometer app
- Safety glasses, gloves and hearing protection

Steps

1. Disconnect the plug wire. Remove the plug and compare its tip with a plug-reading chart. Record what it tells you.
2. Measure the plug gap with the gauge and compare it with the manual. Adjust by bending only the side electrode, gently.
3. Reinstall the plug. Connect the spark tester between the plug wire and the plug. Hold the bail lever as for starting, stand clear, and pull the rope. Record whether you see a strong blue spark in the tester's window. Release the bail: the spark should stop.
4. With the plug wire disconnected again, remove the engine shroud if the manual allows, and check the armature air gap with a feeler gauge or business card at the magnets. Record it.
5. Reassemble everything. Outdoors, with an adult, start the engine and let it warm up for two minutes.

6. Measure the top no-load speed with the tachometer three times and average. Compare with the manual's rated speed.
7. Calculate the blade-tip speed with $v = \pi D n$ and compare it with the 19,000 ft/min limit.
8. Stop the engine with the bail lever. Calculate how long before top dead center the spark fires if it is set at 20° before TDC at your measured speed.
9. **Check your work.** Write what you would suspect if the speed were 500 rpm too high or too low, and why you would never fix it by bending the governor spring.

Tips

- Phone tachometer apps that listen to the engine can count the firing frequency; remember that a single-cylinder four-stroke fires once every two turns.
- Use a feeler gauge rather than pliers to judge the plug gap.
- If there is no spark, look first at the stop-switch wire and bail cable; this is the most common cause.

Check your work

☐ I can read a spark plug and set its gap.

☐ I can explain how the magneto makes a high voltage.

☐ I can calculate blade-tip speed and explain the governor's safety role.

SHOP NOTEBOOK

1. A labeled diagram of the flywheel magneto: magnets, armature, primary and secondary windings, transistor or points, plug lead and stop wire.
2. Your ignition data: plug reading, plug gap (measured and specified), spark test result, armature gap, top speed and blade-tip speed.
3. A diagnostic flowchart titled "No Spark," in the order a technician would check.

KEY FORMULAS

$$\mathcal{E} = -N\,\frac{\Delta \Phi}{\Delta t}, V_s \approx V_p\,\frac{N_s}{N_p}$$

$v_{\text{tip}} = \pi D n$ (ft/min with D in ft and n in rpm)

$t = \dfrac{\theta}{360^\circ} \times \dfrac{60}{n}$ (time to turn θ degrees at n rpm, in seconds)

From history. Briggs & Stratton's 1953 aluminum engine was made by die casting, forcing molten aluminum into steel molds under pressure, the same method used for many toy cars and engine parts today. The lighter engine let a homeowner push a rotary mower and lift it into a car trunk, and power mowers became common on suburban lawns in the following decade.

WORKED EXAMPLES

Example 1. An ignition armature has 150 turns in its primary and 15,000 in its secondary. When the primary current is cut off, the primary voltage spikes to 200 V. Estimate the secondary voltage.

Show solution

1. Turns ratio: $15{,}000/150 = 100$.
2. $V_s \approx 200 \times 100 = 20{,}000\ \text{V}$.

Answer: About 20,000 V

Example 2. A 21-in mower blade turns at 3,300 rpm. Find the blade-tip speed and compare it with the 19,000 ft/min limit. What if the governor were bent to give 3,600 rpm?

Show solution

1. Diameter in feet: $21/12 = 1.75$ ft.
2. $v = \pi(1.75)(3300) \approx 18{,}140$ ft/min, just under the limit.
3. At 3,600 rpm: $\pi(1.75)(3600) \approx 19{,}790$ ft/min, over the limit. That is why technicians never adjust the governor above the maker's top speed.

Answer: About 18,100 ft/min (within the limit); about 19,800 ft/min at 3,600 rpm (over it).

Example 3. The spark fires 25° before top dead center. At 3,000 rpm, how long before TDC is that in milliseconds?

Show solution

1. One turn takes $60/3000 = 0.020$ s.
2. $t = (25/360) \times 0.020 = 0.00139$ s ≈ 1.4 ms.

Answer: About 1.4 ms

Example 4. You are the tradesperson. A mower has no spark. List your checks in order, and explain each.

Show solution

1. Stop-switch circuit: on most push mowers the blade-control bail grounds the armature when released. Check that the bail cable works and that the stop wire is not rubbing on metal; a grounded wire stops all spark.
2. Test with a spark tester, plug wire off the plug, while pulling the rope. Still no spark? Try a new plug, because a fouled plug can look like no spark.
3. Check the armature air gap and that the flywheel magnets are clean.
4. Pull the flywheel (with a puller, following the manual) and check the key; then replace the armature if the rest is good.

Answer: Stop circuit, then spark tester and plug, then air gap, then flywheel key and armature.

PRACTICE

1. Easy Convert a spark-plug gap of 0.030 in to millimeters.

   Show answer

   $0.030 \times 25.4 \approx 0.76$ mm.

2. Easy An armature has 120 primary turns and 12,000 secondary turns. What is its turns ratio?

   Show answer

   100:1

3. Easy Match each plug condition to a cause: (a) dry black soot, (b) wet oil, (c) light tan, (d) white blistered.

Show answer

(a) rich mixture or clogged air filter; (b) oil getting into the cylinder; (c) healthy; (d) lean and overheating.

4. Medium Find the tip speed of a 22-in blade at 3,000 rpm.

Show answer

$\pi(22/12)(3000) \approx 17{,}300$ ft/min.

5. Medium What is the highest speed a 21-in blade may turn and stay at or under 19,000 ft/min?

Show answer

$19{,}000/(\pi \times 1.75) \approx 3{,}450$ rpm.

6. Medium Many mower magnetos fire every turn, including on the exhaust stroke (a “wasted spark”). At 3,600 rpm, how many sparks per second are made, and how many are useful?

Show answer

60 sparks per second; 30 are useful (one per power stroke).

7. Medium Conceptual. Why does the spark fire before top dead center rather than exactly at it?

Show answer

The flame takes time to spread and raise pressure. Firing early lets peak pressure arrive just after TDC, when the piston can use it to push down.

8. Hard A primary spike of 250 V feeds an 80:1 coil. The plug needs 12 kV to fire under compression. What is the secondary voltage, and what reserve is left?

Show answer

$250 \times 80 = 20{,}000$ V; reserve 8,000 V, or 40% of the available voltage.

9. Hard The spark is set at 20° BTDC. At 3,200 rpm, how many milliseconds before TDC does it fire?

Show answer

$(20/360)(60/3200) \approx 1.04$ ms.

10. Hard Conceptual. The mower slows as you push into tall, wet grass. Describe what the governor does, step by step.

Show answer

The engine slows, so the flyweights move inward with less force; the governor spring now pulls harder than the flyweights push, so the linkage opens the throttle; more mixture enters and the engine returns toward its set speed.

11. Challenge You are the tradesperson. A mower hit a tree root. Now it is very hard to pull, kicks back and backfires, though the spark is strong. What is the likely cause, and what else should you check?

Show answer

Model answer: the soft flywheel key probably sheared, letting the flywheel shift on the crankshaft so the spark fires at the wrong time. Replace the key after removing the flywheel. Also check for a bent crankshaft (blade wobble when turned slowly) and a bent blade, and inspect the blade adapter.

COMMON MISTAKES

- Holding a plug wire to "feel for spark." Use a spark tester.
- Prying the center electrode to set the gap; only the side electrode is bent.
- Blaming the coil when the stop wire or bail cable is the real cause.
- Bending the governor spring to make a mower "stronger," which overspeeds the blade and can break the engine.

Make it a game · Spark Sequence Teach-Back. Teach your parent how a flywheel magneto makes a spark in 60 seconds, using Faraday's law and a step-up coil. Your parent plays curious student and asks three questions. Then name how to gap a plug safely and what a compression test reads. This is a talking game, with no engine running or testing.

Scripture. "Seest thou a man diligent in his business? he shall stand before kings; he shall not stand before mean men." (Proverbs 22:29, KJV)

Two men who were diligent in a small business making small engines built a company whose work reached almost every home. Skilled, careful work in a humble trade is honorable.

9.5 Maintenance and Troubleshooting

OBJECTIVES

- Perform a complete lawn-mower tune-up: oil, air filter, spark plug, blade and fuel, following the maker's manual.
- Use the fuel–spark–compression–air diagnostic tree to find why an engine will not start or runs poorly.
- Calculate the force from an unbalanced blade and compare the cost of maintenance with the cost of neglect.
- Prepare an engine properly for winter storage.

> **Warm-up.** Think of a machine in your house that quit working. Was the cause sudden, or did it build up over time from neglect? Write three things you think an owner could do every season to keep a mower running for ten years.

WATCH

How To Tune Up Your Lawn Mower - Ace Hardware

Ace Hardware · 10:19

https://www.youtube.com/watch?v=y3F60ImVZh0

> **WHEN TO WATCH**
> Before the shop project; keep it open on a phone or tablet as you work, pausing after each step.

Note: Ace's home expert Lou Manfredini does the plug, air filter, oil, blade and fuel on a walk-behind mower. He removes the plug first, which disconnects the ignition before he touches the blade. Mentions products sold by the store.

BACKUP VIDEO

How to Tune Up a Lawn Mower in 3 Easy Steps

Family Handyman · 6:16

https://www.youtube.com/watch?v=9x2aFUGK7BA

As a review before the tune-up.

KEY TERMS

tune-up

Routine service that restores an engine to good running: fresh oil, clean air filter, new or cleaned spark plug, sharp balanced blade and fresh fuel.

service interval

How often a task should be done, in hours of running or seasons, as given in the owner's manual.

diagnostic tree

An ordered set of checks that rules out causes one at a time, beginning with the simplest and most likely.

blade balance

Equal mass on both sides of the blade's center hole; an unbalanced blade shakes the engine and mower.

fuel stabilizer

An additive that slows the oxidation of gasoline during storage.

maintenance log

A written record of the date, engine hours and work done, with parts used.

CORE IDEAS

The story. In 1830 Edwin Budding, an engineer in Gloucestershire, England, who had seen a machine that trimmed the nap of woollen cloth with a spinning cylinder of blades, patented the first lawn mower on the same idea. For seventy years mowers were pushed by people or pulled by horses (with leather boots on their hooves to protect the turf). Around 1902 Ransomes of Ipswich sold one of the first gasoline-powered mowers, and after the Second World War the rotary power mower, with a single blade spinning under a deck, became the tool on millions of lawns. A mower engine is simple, but it lives in the worst conditions: dust and grass clippings, months of sitting with old fuel, hard knocks against roots and stones. Most mowers that end up at the curb are not worn out. They were neglected.

How they figured it out. Small-engine makers learned from warranty returns what ruins engines: dirt that gets past a clogged or missing air filter and wears out the cylinder; old, thin or low oil; and stale fuel left over winter. Their manuals reflect what they found, with service intervals for each task. Technicians learned the fastest way to find a fault: an engine needs only four things to run, so check them in order. Fuel: is fresh fuel getting to the cylinder? Spark: is there a strong spark at the right time? Compression: does the cylinder hold pressure? Air: can clean air get in freely? Check the simple, likely and cheap things first.

The science. Oil does three jobs: it separates moving metal parts with a thin film, carries away heat, and holds dirt in suspension. Heat breaks oil down and dirt thickens it, so it must be changed; most mower manuals call for every 50 hours or each season (more often for the first few hours of a new engine), using SAE 30 or 10W-30 as the manual says. A clogged air filter starves the engine of air and makes it run rich and smoky. A dull blade tears grass instead of cutting it, leaving brown, ragged tips. An unbalanced blade is worse: a small extra mass m at radius r spinning at angular speed ω needs a force $F = mr\omega^2$ to keep it in its circle, and at 3,000 rpm a 10 g imbalance near the blade tip produces a rotating force of about 250 N (55 lb), which shakes bolts loose and wears out the crankshaft bearings.

In the shop. A tune-up goes in a safe order. Disconnect the spark-plug wire first. Change the oil: run the engine briefly outdoors to warm it, stop it, disconnect the plug wire, then drain the oil through the drain plug or by tipping the mower with the air filter and carburetor side up, and refill to the full mark on the dipstick (never overfill). Replace a paper air filter, or wash and lightly oil a foam one. Replace the spark plug and set its gap. Remove the blade (wedge a block of wood to keep it from turning, wear gloves), sharpen it with a file or grinder at its original angle, check its balance on a nail or cone balancer, and reinstall it with the correct side down and the bolt tightened to the manual's torque. Finish with fresh fuel. Write it all in a maintenance log. For winter, either add stabilizer and run the engine five minutes so treated fuel fills the carburetor, or run it dry; change the oil; and store the mower dry. Used oil goes in a sealed container to an auto-parts store or recycling center, never on the ground or in the trash.

On the job. Small-engine technicians repair mowers, saws, generators, outboards and power equipment at dealers, rental yards and their own shops. Many learn through community-college programs, manufacturer training and certification, or by working alongside an experienced mechanic. It is a good trade for someone who likes figuring out why something will not run, and it leads naturally to work on motorcycles, marine engines and cars.

PICTURE STUDY



Cleaning an Air Cleaner, Fort Knox, Alfred T. Palmer, Office of War Information, 1942 · Photograph · Library of Congress

Image: Wikimedia Commons, public domain

During the Second World War, the army trained thousands of mechanics to keep trucks running in dust and mud, and the photographer Alfred Palmer recorded their work. The job shown, keeping dirt out of the engine's air, is the same one you will do on a mower.

Look closely

- Find the air cleaner. Where does the air enter, and where does it go next?
- Look at the mechanic's hands and tools. What is he doing to the filter?
- Find signs of dust or oil. Why would an army truck's air cleaner get dirty quickly?
- Look at how the mechanic is dressed for the work.

Talk about it

1. What would happen inside an engine if the air cleaner were left off in dusty country?
2. Why do you think the army made maintenance a daily routine, not a repair after failure?

Safety first. Disconnect the spark-plug wire before touching the blade or turning the engine by hand, and wear gloves when handling the blade. Tip a mower only with the air filter and carburetor side up. Handle gasoline outdoors only, with the engine cool and no flames or sparks nearby, and take used oil and old fuel to a recycling or hazardous-waste center.

SHOP PROJECT

A Full Lawn-Mower Tune-Up with a Maintenance Log

You will tune up a real mower from start to finish, measure what you replace, test it before and after, and start a maintenance log that will travel with the mower. If your family has no gasoline mower, ask a neighbor, grandparent or church member if you may tune up theirs, or offer to service one at a small-engine shop under a technician's eye.

You will need

- Walk-behind mower and its manual (look it up by model number if lost)
- New spark plug, air filter and the oil type in the manual; fuel stabilizer
- Plug socket and ratchet, gap gauge, wrench for the blade bolt, a block of wood, a torque wrench if available
- A mill file or bench grinder (adult), a blade balancer or a large nail in the wall
- Drain pan, funnel, rags, a sealed container for used oil, safety glasses and gloves
- Shop notebook for the log

Steps

1. **Before.** Outdoors, start the mower and record: pulls to start, how it sounds and smokes, and whether it holds speed. Stop it and let it cool for at least 30 minutes.
2. Disconnect the plug wire and tuck it away. Remove and read the old plug; record its condition and gap. Install and gap the new plug; leave the wire disconnected until the end.
3. Remove the air filter. Hold it to a light and record how dirty it is. Install the new filter and clean the housing.
4. Drain the oil into the pan (warm oil drains faster, so drain it while the engine is still warm but not hot). Record its color and smell and whether you see metal flakes. Refill to the full mark with the correct oil, checking the dipstick as the manual says.

5. With the air filter side up, tip the mower and wedge the wood block to keep the blade from turning. Remove the blade bolt and blade, wearing gloves. Note which side faces down.
6. Sharpen both cutting edges evenly at the original angle. Balance the blade on a nail or balancer and file the heavy end until it hangs level. Record how much you filed.
7. Reinstall the blade the right way up and tighten the bolt to the manual's torque. Scrape caked grass from under the deck.
8. Add fresh fuel with stabilizer. Reconnect the plug wire.
9. **After.** Start the mower outdoors and repeat your "before" checks. Mow a test strip and look at the cut grass tips.
10. Start the maintenance log with the date, the engine hours or season, every part and fluid used, the torques and gaps, and the results.
11. **Improve it.** Write a one-page seasonal checklist for this mower, including winter storage.

Tips

- Take a photo of the blade and the order of its washers before removing it.
- Most push-mower engines hold about 15 to 20 fl oz of oil; pour slowly and check often.
- If the mower has a fuel shut-off valve, close it before tipping.

Check your work

- ☐ I did every step with the plug wire disconnected until the end.
- ☐ My log records what I found and what I replaced.
- ☐ I can use the fuel–spark–compression–air tree to diagnose a no-start.

SHOP NOTEBOOK

1. Your maintenance log page: date, hours or season, work done, parts and fluids, gaps and torques, before-and-after notes.
2. A diagnostic tree for "Engine will not start," with the four branches (fuel, spark, compression, air) and the check for each.
3. A labeled sketch of the blade showing the cutting edges, the lift (sail) and the side that faces the ground.

KEY FORMULAS

$$F = mr\omega^2, \quad \omega = \frac{2\pi n}{60}\ \text{rad/s}$$

$$1\ \text{fl oz} \approx 29.6\ \text{mL}$$

$$\text{annual cost} = \frac{\text{purchase price} + \text{total upkeep}}{\text{years of service}}$$

From history. Edwin Budding's 1830 mower was advertised as a healthy exercise for country gentlemen. His cylinder (reel) mower is still the choice for golf greens, because a reel cuts like scissors and gives the cleanest, lowest cut.

WORKED EXAMPLES

Example 1. A sharpened blade has 10 g more mass on one end, effectively at a radius of 0.25 m. Find the rotating force at 3,000 rpm.

Show solution

1. Angular speed: $\omega = 2\pi(3000)/60 = 314.2$ rad/s.
2. $F = (0.010)(0.25)(314.2)^2 = 0.0025 \times 98{,}700 \approx 247$ N.
3. That is about 55 lb, swinging around 50 times a second. Balance the blade by filing metal from the heavy end.

Answer: About 250 N (55 lb)

Example 2. A mower engine holds 18 fl oz of oil. How many milliliters is that, and how many 1-quart (32 fl oz) bottles must you buy for two oil changes?

Show solution

1. $18 \times 29.6 \approx 533$ mL.
2. Two changes: 36 fl oz, more than one quart, so buy two bottles (or one 48-oz bottle).

Answer: About 530 mL; two quarts for two changes.

Example 3. Compare: a \$350 mower given \$25 a year of maintenance lasts 8 years; a neglected one lasts 4 years. Find the yearly cost of each.

Show solution

1. Maintained: $(350 + 8 \times 25)/8 = 550/8 \approx \$68.75$ per year.
2. Neglected: $350/4 = \$87.50$ per year.
3. Maintenance saves about \$18.75 a year, and the maintained mower also starts reliably and cuts better.

Answer: \$68.75 versus \$87.50 per year

Example 4. You are the tradesperson. A mower starts, runs for five seconds, and dies. It restarts and dies again. Use the diagnostic tree.

Show solution

1. It starts, so spark and compression are basically present; suspect fuel or air.
2. Runs briefly then stops: it uses up fuel in the bowl but no more comes in. Check that the fuel valve is open and the tank has fresh fuel.
3. Check the gas cap vent: loosen the cap. If it now keeps running, the vent is clogged and the tank is in a vacuum.
4. Otherwise, look for a clogged fuel line or a stuck float needle, or a main jet blocked by varnish. Clean the carburetor.

Answer: A fuel-supply fault: fuel valve, cap vent, fuel line or carburetor.

PRACTICE

1. Easy Why must the spark-plug wire be disconnected before you touch the blade?

   Show answer

   Turning the blade turns the crankshaft and flywheel; with the wire connected, the magneto can fire and start the engine.

2. Easy Convert 20 fl oz of oil to milliliters.

   Show answer

   $20 \times 29.6 \approx 590$ mL.

3. Easy Name the four things an engine needs to run, in the order a technician checks them.

Show answer

Fuel, spark, compression and air (many technicians check air with fuel, since both form the mixture).

4. Medium A blade has a 5 g imbalance at 0.25 m. Find the force at 3,200 rpm.

Show answer

$\omega \approx 335$ rad/s; $F = 0.005 \times 0.25 \times 335^2 \approx 140$ N.

5. Medium A stabilizer label says 1 fl oz treats 2.5 gal. How much do you add to a 1-gal can?

Show answer

$1/2.5 = 0.4$ fl oz.

6. Medium The manual says to change oil every 50 hours or each season. You mow 75 minutes a week for 26 weeks. How many hours is that, and how many changes per year?

Show answer

$1.25 \times 26 = 32.5$ h; one change per season.

7. Medium Conceptual. Why does an engine run better after a clogged air filter is replaced?

Show answer

A clogged filter restricts air, so the carburetor delivers too much fuel for the air, making the mixture rich: black smoke, poor power and sooty plugs. A clean filter restores the correct mixture.

8. Hard A balanced blade hangs level; after sharpening, the left end dips. What do you do and why?

Show answer

File metal from the cutting edge of the left (heavy) end, not the tip, until it hangs level. An unbalanced blade creates a large rotating force ($F = mr\omega^2$) that shakes the mower and wears the bearings.

9. Hard A small-engine shop charges $95 for a tune-up. Your parts cost $6 for oil, $11 for a filter, $5 for a plug and $2 for stabilizer. What do you save, and what is your hourly “wage” if the job takes you 1.5 hours?

   Show answer

   Parts $24; savings $95 - 24 = \$71$; $71/1.5 \approx \$47$ per hour.

10. Hard You are the tradesperson. A mower runs but smokes black, has little power and leaves sooty plugs. List the causes in the order you would check them.

    Show answer

    Rich mixture: (1) clogged air filter, (2) choke stuck partly closed, (3) carburetor float stuck or needle leaking (fuel too high), (4) wrong or loose main jet.

11. Challenge Write the steps to store a mower for winter, and explain the physics or chemistry behind each.

    Show answer

    Model answer: add stabilizer and run 5 minutes so treated fuel fills the carburetor (slows oxidation and gum), or run it dry (no fuel left to varnish); change the oil (old oil holds acids and moisture that corrode); clean the deck (wet clippings rust steel); store dry and covered; remove the plug, add a teaspoon of oil and pull the rope slowly to coat the cylinder (prevents rust on the cylinder wall), then reinstall the plug.

COMMON MISTAKES

- Tipping a mower with the carburetor side down, flooding the air filter and cylinder with oil.
- Overfilling the oil, which causes smoking and oil leaks; fill to the mark, not above it.
- Reinstalling the blade upside down, so it pushes air down and cuts poorly.
- Skipping the log, so no one knows when the oil was last changed.

> **Make it a game · Diagnostic Tree Quiz.** Your parent describes an engine that will not start: no spark, flooded, stale fuel, clogged air filter. You walk the fuel, spark, compression, air tree aloud and name the first check to make in 20 seconds. Then list the tune-up steps in order. All work is discussed, not done. Beat your streak.

> **Scripture.** “I went by the field of the slothful, and by the vineyard of the man void of understanding; And, lo, it was all grown over with thorns, and nettles had covered the face thereof, and the stone wall thereof was broken down. Then I saw, and considered it well: I looked upon it, and received instruction.” (Proverbs 24:30-32, KJV)
>
> Neglect is quiet, and its results come slowly, then all at once. Good maintenance is a form of wisdom and of faithfulness with what we have been given.

UNIT 9

Small Engines

A gasoline engine turns a pint of fuel into hours of mowing, cutting, pumping or generating. In this unit you will learn how a small engine works from the inside: the four-stroke cycle Nikolaus Otto built in 1876, the two-stroke engines in chainsaws and trimmers, the carburetor that mixes fuel and air by Bernoulli's principle, the magneto that makes a spark with no battery, and the governor that holds a mower's speed.

This is a hands-on unit. You will measure a real engine's stroke, mix and check two-stroke fuel, build a venturi and measure its suction, test a spark and a running engine's speed, and finish with a complete lawn-mower tune-up and a maintenance log. Along the way you will meet the people who made small engines common, from Otto and Dugald Clerk to Briggs and Stratton, and the honest trade of the small-engine technician.

PREREQUISITES

- Algebra I: formulas, ratios, unit conversions and square roots
- Area of a circle and volume of a cylinder
- Units 1 and 5: torque and fasteners; voltage and coils, simply
- Access to a gasoline mower or other small engine for the shop projects (a neighbor's or a shop's is fine)

MASTERY CHECKLIST

- ☐ I can explain the four-stroke and two-stroke cycles and calculate displacement and compression ratio.
- ☐ I can mix two-stroke fuel at any ratio and explain the trade-offs between two- and four-stroke engines.
- ☐ I can explain how a carburetor meters fuel, using continuity and Bernoulli's principle, and calculate air–fuel ratios and fuel use.
- ☐ I can explain how a magneto makes a spark, read and gap a plug, and calculate blade-tip speed and spark timing.
- ☐ I can tune up a mower safely, diagnose a no-start with the fuel–spark–compression–air tree, and keep a maintenance log.

OPTIONAL KITS FOR THIS UNIT

- **Briggs & Stratton manuals and parts lookup**: Free owner's and repair manuals by engine model number, with specifications for oil capacity, plug gap and torques; fits every lesson in this unit.
- **Honda Engines**: The maker of many mower and generator engines; its site has owner's manuals, specifications and maintenance schedules for the GCV and GX series engines used in this unit's examples.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

9.1 The Four-Stroke Cycle — 3 sessions of 50 minutes

9.2	**Two-Stroke Engines**	3 sessions of 50 minutes
9.3	**Fuel, Air and the Carburetor**	3 sessions of 50 minutes
9.4	**Ignition, Compression and the Governor**	3 sessions of 50 minutes
9.5	**Maintenance and Troubleshooting**	3 sessions of 50 minutes

Unit 9 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **5 pts**
   List the four strokes of an Otto-cycle engine and state the position of the intake and exhaust valves in each.

2. **7 pts**
   An engine has a bore of 70 mm and a stroke of 54 mm. Find its displacement in cc.

3. **7 pts**
   A 180 cc cylinder has a compression ratio of 8.0:1. Find its clearance volume and its ideal Otto efficiency.

4. **6 pts**
   An engine makes 7.0 lb·ft of torque at 3,200 rpm. Find its horsepower and its power strokes per second.

5. **6 pts**
   How much two-stroke oil, in fl oz and in mL, goes into 2.5 gal at 50:1? (1 gal = 128 fl oz; 1 fl oz ≈ 29.6 mL)

6. **6 pts**
   Explain how a crankcase-scavenged two-stroke gets fresh mixture into the cylinder without intake valves.

7. **5 pts**

   Give two advantages and two disadvantages of two-stroke engines compared with four-strokes.

8. **7 pts**

   Air enters a venturi at 8 m/s, and the throat has one-quarter the inlet area. Find the throat speed and the pressure drop (air 1.2 kg/m^3).

9. **7 pts**

   A 140 cc four-stroke runs at 3,000 rpm with 85% volumetric efficiency and an air–fuel ratio of 14.7. Find its fuel use in kg/h.

10. **6 pts**

    Explain why E10 gasoline left in a mower over winter often causes a no-start in spring, and give two ways to prevent it.

11. **6 pts**

    An armature has a 90:1 turns ratio and a 220 V primary spike. Find the secondary voltage. Why is the spark timed before TDC?

12. **6 pts**

    Find the tip speed of a 20-in blade at 3,400 rpm and state whether it meets the 19,000 ft/min limit.

13. **6 pts**

    A blade has a 6 g imbalance at 0.24 m. Find the rotating force at 3,300 rpm.

14. **7 pts**

    You are the tradesperson. A mower will not start. It has fresh fuel, the plug is wet with fuel after pulling, and a spark tester shows no spark. List your checks in order.

15. **5 pts**

    Describe the correct way to tip a walk-behind mower and explain what goes wrong if it is tipped the other way.

16. **3 pts**

    Where should used oil and old gasoline go?

17. **5 pts**

Short essay. A neighbor says, “Mowers are junk now; they only last a couple of years.” Using what you learned in this unit, write a paragraph explaining why most small engines fail and how a careful owner can make one last a decade.

ANSWER KEY

1. Intake: intake open, exhaust closed. Compression: both closed. Power: both closed (exhaust opens near the bottom). Exhaust: exhaust open, intake closed.
2. $0.7854 \times 7.0^2 \times 5.4 = 0.7854 \times 49 \times 5.4 \approx 208$ cc.
3. $V_c = 180/7 \approx 25.7$ cc; $8^{0.4} \approx 2.297$, $\eta = 1 - 1/2.297 \approx 56\%$.
4. $7.0 \times 3200/5252 \approx 4.3$ hp; $1600/60 \approx 26.7$ per second.
5. $320/50 = 6.4$ fl oz ≈ 189 mL.
6. The rising piston lowers crankcase pressure and draws mixture in through a reed or port; the falling piston compresses it in the crankcase; when the piston uncovers the transfer ports the mixture flows up into the cylinder and pushes out the exhaust through the exhaust port.
7. Advantages: light and powerful for their size; run at any angle; simple, few moving parts. Disadvantages: burn oil and need mixed fuel; waste some fresh charge out the exhaust (more fuel use and emissions); noisier; shorter life.
8. $v_2 = 32$ m/s; $\Delta p = 0.6(1024 - 64) = 576$ Pa.
9. Air $140 \times 1500 \times 0.85 = 178{,}500$ cm^3/min; $0.1785 \times 1.2 = 0.214$ kg/min; fuel $0.214/14.7 \approx 0.0146$ kg/min ≈ 0.87 kg/h.
10. Gasoline oxidizes into gum and varnish that clog tiny jets, and ethanol absorbs water that can separate and collect in the bowl. Prevent it with fuel stabilizer (and run it into the carburetor), by running the engine dry or draining the bowl, or by using ethanol-free fuel.
11. $220 \times 90 = 19{,}800$ V. The flame needs time to build pressure; firing early puts peak pressure just after TDC.
12. $\pi(20/12)(3400) \approx 17{,}800$ ft/min; it meets the limit.
13. $\omega \approx 345.6$ rad/s; $F = 0.006 \times 0.24 \times 345.6^2 \approx 172$ N.
14. Check the stop circuit (bail cable and stop wire not grounded), try a new plug, check the armature air gap and clean magnets, then check the flywheel key and test or replace the armature.
15. Disconnect the plug wire and tip it with the air filter and carburetor side up. Tipped the other way, oil runs into the air filter and cylinder and fuel can leak, causing smoke, a soaked filter and a hard start or hydraulic lock.
16. In sealed containers to an auto-parts store, recycling center or household hazardous-waste collection, never on the ground, down a drain or in the trash.

17. Model answer: most small engines are not worn out but neglected. Stale fuel left over winter varnishes the carburetor jets; dirt past a clogged or missing air filter wears the cylinder and rings; old or low oil lets bearings wear; and dull, unbalanced blades shake the engine. An owner who changes oil each season, keeps a clean filter, sharpens and balances the blade, uses fresh stabilized fuel, stores the engine properly for winter and keeps a log can expect many years of service, as the manuals' service schedules are designed to give.

PORTFOLIO PIECE: A TUNED-UP MOWER WITH ITS LOG

Tune up a gasoline mower (or another small engine) completely and safely: oil, air filter, spark plug with correct gap, a sharpened and balanced blade, and fresh stabilized fuel. Document it with before-and-after tests, measurements, photos and a maintenance log that stays with the machine.

Add your engine specification card from Lesson 9.1, your ignition and speed check from Lesson 9.4, and a one-page seasonal and winter-storage checklist written for the owner.

LOOK FOR	WHAT IT MEANS
Safety	Plug wire disconnected before blade or crankshaft work; mower tipped air-filter side up; fuel handled outdoors; engine run only outdoors; used oil recycled.
Workmanship	Correct oil and level, plug gapped to specification, blade sharpened at the original angle, balanced and torqued, filter replaced or cleaned.
Measurement and data	Before-and-after observations, plug gap, oil quantity, top speed and blade-tip speed recorded with units.
Maintenance log and checklist	Clear, dated log with parts and fluids; a practical seasonal checklist the owner can follow.
Explanation	Explains how the engine works and why each maintenance step matters, using the unit's science.

UNIT 10

Auto Mechanics

A car is a collection of the systems you have studied all year: fasteners and torque, adhesives, electrical circuits, heat and fluids, and the engine of Unit 9. In this unit you will see how they work together, beginning with Henry Ford's Model T and the moving assembly line and ending with the routine jobs every car owner should be able to do safely.

You will learn how oil, coolant and brake fluid protect the engine and the driver; how Pascal's principle stops a two-ton vehicle with a push of the foot; how to read a tire; how Charles Kettering's electric self-starter made the modern car possible; and how to test a battery, read diagnostic codes, change a wheel and count the real cost of owning a car. You will also meet the ASE-certified technician, whose skilled trade keeps families safe on the road.

PREREQUISITES

- Unit 1: torque, preload and bolted joints
- Unit 5: Ohm's law, power and the multimeter
- Unit 9: the four-stroke cycle, ignition and the diagnostic habit
- Access to a family car and its owner's manual, with an adult for every hands-on project

MASTERY CHECKLIST

- ☐ I can name a car's systems and find their main parts, and explain how the moving assembly line changed manufacturing.
- ☐ I can check a car's fluids correctly, read an oil grade, and explain how the cooling system and pressure cap work.
- ☐ I can calculate hydraulic brake force, kinetic energy and stopping distance, and inspect tires for pressure, tread, wear and age.
- ☐ I can test a battery and charging system, read OBD-II codes, map fuses, and explain the safe jump-start order.
- ☐ I can change a wheel safely with chocks, the jacking point, jack stands and a torqued star pattern, and calculate the cost of owning a car.

OPTIONAL KITS FOR THIS UNIT

- **Innova OBD-II code readers**: A maker of consumer code readers and scan tools; a basic reader is enough for Lesson 10.4. Many auto-parts stores also lend readers free or read codes for you.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

10.1	**How a Car Works: From the Model T to Today**	3 sessions of 50 minutes
10.2	**The Engine and Its Fluids**	3 sessions of 50 minutes
10.3	**Brakes, Tires and Steering**	3 sessions of 50 minutes
10.4	**The Electrical System and Diagnostics**	3 sessions of 50 minutes
10.5	**Routine Maintenance and Roadside Skills**	3 sessions of 50 minutes

Unit 10 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **4 pts**
   Name five major systems of a car and give the job of each in a few words.

2. **6 pts**
   Chassis assembly fell from 12.5 hours to 1.5 hours. Find the productivity ratio and the percent decrease in time.

3. **4 pts**
   Explain what the numbers in 0W-20 mean.

4. **7 pts**
   Coolant flows at 0.90 kg/s and warms by 9 °C (c = 3.5 kJ/kg·K). Find the heat removed. Why must the radiator cap never be opened when hot?

5. **6 pts**

   A cooling system holds 9 qt with a 40% mix. You drain 3 qt and add 3 qt of pure concentrate. What is the new mix?

6. **8 pts**

   A master cylinder piston is 0.875 in in diameter and a caliper piston 2.25 in. The master cylinder receives 300 lb. Find the line pressure and the force on the caliper piston.

7. **7 pts**

   A 1,400 kg car travels at 25 m/s. Find its kinetic energy and its braking distance with $\mu = 0.70$.

8. **6 pts**

   Find the diameter of a 235/65R17 tire in inches.

9. **6 pts**

   A tire's tread is 2/32 in on both edges and 5/32 in in the center. Diagnose the wear and state what must be done.

10. **6 pts**

    A starter draws 160 A at 10.2 V. Find its power. A terminal with 0.008 Ω resistance is in the circuit: what voltage does it waste?

11. **6 pts**

    A car's parasitic draw is 35 mA. How many days can a 70 Ah battery sit before falling to half charge?

12. **6 pts**

    List the four jumper-cable connections in order and explain why the last one is made where it is.

13. **4 pts**

    A reader shows code P0302. What does it mean, and why is it not yet a diagnosis?

14. **6 pts**

    Lug nuts must be torqued to 90 lb·ft. What force is needed on a torque wrench held 1.5 ft from the nut? Why is a star pattern used?

15. **7 pts**

A car costs $14,000 and resells for $6,000 after 4 years. It gets 30 mpg over 11,000 miles a year with gas at $3.30. Insurance is $1,500, maintenance $700 and registration $120 a year. Find the yearly cost and cost per mile.

16. **5 pts**

You are the tradesperson. A customer says the brake pedal goes nearly to the floor and the brake warning light is on. What do you tell them, and what do you check?

17. **6 pts**

Short essay. Charles Kettering's self-starter, Ford's assembly line and the hydraulic brake each solved a real problem for ordinary drivers. Choose one, explain the problem and the engineering solution, and say what it teaches a young tradesperson about how to approach their own work.

ANSWER KEY

1. Engine: makes power. Drivetrain: carries power to the wheels. Brakes: turn motion into heat to stop. Steering and suspension: direct the car and keep tires on the road. Electrical: starts the engine and powers ignition, lights and computers. (Body and safety: protects occupants.)
2. $12.5/1.5 \approx 8.3$; $11/12.5 = 88\%$decrease.
3. 0W: the oil's cold-temperature (winter) flow rating, very easy-flowing when cold. 20: its viscosity grade at the 100 °C operating temperature.
4. $0.90 \times 3.5 \times 9 \approx 28.4$ kW. The system is pressurized and above the normal boiling point; opening the cap lets coolant flash to steam and spray out.
5. Remaining glycol $0.40 \times 6 = 2.4$ qt; plus 3 is 5.4 qt in 9 qt, or 60%.
6. $A_1 = 0.601$ in^2; $p \approx 499$ psi; $A_2 = 3.98$ in^2; $F_2 \approx 1{,}990$ lb.
7. $KE = 437{,}500$ J; $d = 625/13.7 \approx 45.5$ m.
8. $2(235 \times 0.65) + 17(25.4) = 305.5 + 431.8 = 737$ mm ≈ 29.0 in.
9. Edge wear means the tire was run underinflated. At 2/32 in it is at the legal limit and must be replaced; check the pressures on the other tires and keep them at the placard value.
10. $P \approx 1{,}630$ W; $V = 160 \times 0.008 = 1.28$ V.
11. $35/0.035 = 1000$ h ≈ 42 days.
12. Red to dead +, red to good +, black to good −, black to bare metal on the dead car's engine away from the battery. The last connection may spark, and batteries can give off hydrogen, so the spark is kept away from the battery.
13. A misfire detected in cylinder 2. The cause could be a plug, coil, injector, vacuum leak or low compression; the technician must test to find which.
14. $90/1.5 = 60$ lb. A star pattern draws the wheel down evenly and centers it on the hub.
15. Depreciation \$2,000; fuel $(11{,}000/30)(3.30) = \$1{,}210$; total \$5,530; per mile $\approx \$0.50$.
16. Do not drive the car; have it towed or inspected where it sits. Check the brake-fluid level and look for leaks at lines, hoses, calipers and wheel cylinders, then check the master cylinder.
17. Model answer (on the starter): hand cranking was hard and dangerous, and many said an electric starter would be too big. Kettering saw that a motor run for only a few seconds could be heavily overloaded, built a small motor-

generator, tested it until it worked, and made the car something anyone could start. A tradesperson learns to state the problem clearly, question assumptions, test carefully, and keep the customer's safety and needs at the center of the work.

PORTFOLIO PIECE: A VEHICLE INSPECTION AND MAINTENANCE PLAN

Prepare a complete inspection report and one-year plan for a real car: the vehicle fact sheet, fluid log, tire report, battery and charging test with any trouble codes, and a record of a supervised wheel change torqued to specification.

Finish with a one-year maintenance plan from the owner's manual (what, when, cost, who does it), a cost-of-ownership table with cost per mile, and a glove-box roadside checklist.

LOOK FOR	WHAT IT MEANS
Safety	Every hands-on step done with an adult, wheels chocked, jack stands or ramps for any under-car work, engine run only outdoors, hot caps never opened, fluids recycled.
Inspection data	Fluid levels and conditions, tire pressures, tread depths, date codes, battery voltages and codes recorded with units and dates.
Diagnosis	Findings are explained with the unit's science, with clear recommendations and a sensible line between owner jobs and technician jobs.
Plan and budget	Maintenance plan follows the manual; cost-of-ownership table is complete and realistic.
Presentation	Neat, organized report that the car's owner could actually use.

10.1 How a Car Works: From the Model T to Today

OBJECTIVES

- Name the major systems of a car (engine, drivetrain, brakes, steering and suspension, electrical, body and safety) and say what each does.
- Tell the story of the Model T and the moving assembly line, and calculate the productivity gain it brought.
- Use the owner's manual and the vehicle identification number to find a car's key facts.
- Map the systems on a real car in a guided walkaround.

> **Warm-up.** Without looking anything up, sketch a car from the side and label every part you can think of. Circle the parts you think would cost the most to repair. Keep the sketch; you will add to it at the end of the unit.

WATCH

Car anatomy: The Basics / How cars work? (3D animation)

CARinfo3d (En) · 9:04

https://www.youtube.com/watch?v=fPjOWekzeGI

> **WHEN TO WATCH**
> After the story. Pause each time a new system appears and add it to your notebook's systems list.

Note: A calm, clear 3D tour of a modern car's body, frame, engine, transmission, suspension, steering and electrical systems. Ends with a short promotion for the channel's longer course.

BACKUP VIDEO

History of the Model T | The Henry Ford's Innovation Nation

The Henry Ford · 3:16

https://www.youtube.com/watch?v=gglrbduPbQ0

With the story paragraph.

KEY TERMS

drivetrain

The parts that carry the engine's power to the wheels: transmission, driveshaft or axles, differential.

transmission

A set of gears (or a belt system) that lets the engine stay in its useful speed range while the car moves slowly or fast.

differential

A gear set that lets the left and right drive wheels turn at different speeds in a turn.

suspension

Springs, shock absorbers and linkages that keep the tires on the road and the ride smooth.

moving assembly line

A production method in which the work moves past stationed workers, each doing one task, instead of workers moving to the work.

VIN

The 17-character vehicle identification number; its 10th character gives the model year, and the whole number identifies the exact car.

CORE IDEAS

The story. On October 1, 1908, Henry Ford's company introduced the Model T. It was simple, tough and high off the ground for rough country roads, with a 177-cubic-inch (2.9 L) four-cylinder engine of about 20 horsepower, a two-speed planetary transmission worked by foot pedals, and parts made of strong, light vanadium steel. Ford wanted a car that an ordinary farmer or tradesman could buy and fix. The first touring cars cost $850, a large sum then. To bring the price down, Ford and his production men, including Charles Sorensen, Clarence Avery and Peter Martin, studied every motion in the Highland Park plant in Michigan.

How they figured it out. In April 1913 they tried an experiment on one small part: the flywheel magneto, the Model T's ignition generator. Instead of one man building a whole magneto at a bench, the parts slid along a waist-high line past a row of workers, each doing a few steps. The time per magneto fell from about twenty minutes to about thirteen, and with further changes to about five. They borrowed ideas from flour mills, canneries and the overhead conveyors of Chicago meat-packing plants, then moved the whole chassis onto a rope-pulled line. By early 1914 a chassis that had taken about 12½ hours to assemble took about an hour and a half.

Prices fell year after year, to $260 for the simplest model by the mid-1920s, and more than 15 million Model Ts were built by 1927. Measuring each step, changing one thing, and measuring again is the engineering design process applied to a factory.

The science. A modern car is still a set of systems that each obey simple physics. The **engine** turns chemical energy into motion (Unit 9). The **drivetrain** uses gear ratios to trade speed for torque: low gears multiply torque to start moving, high gears let the engine turn slowly at highway speed. The **brakes** turn motion into heat by friction. **Steering and suspension** keep the tires in contact with the road, since every force that moves, stops or turns the car passes through four contact patches each about the size of a hand. The **electrical system** starts the engine, fires the spark, runs the computers and lights. The **body and safety** systems (crumple zones, seat belts, airbags) manage the energy of a crash. Hybrids and electric vehicles change the source of power, using an electric motor and a large battery for some or all of the driving, but they still have brakes, tires, steering, suspension, a 12-volt electrical system and fluids to check.

In the shop. The most useful tool a car owner has is the owner's manual. It gives fluid types and capacities, tire pressures, maintenance intervals, fuse locations, jacking points and what every warning light means. A technician begins every job by identifying the vehicle exactly: year, make, model, engine and VIN, because parts differ even within one model. Then the technician listens to the customer, verifies the problem, and checks the simplest causes first, just as with small engines. In this unit you will learn the routine inspections and simple jobs every car owner should be able to do, and you will learn to recognize what belongs to a trained technician.

PICTURE STUDY



The First Moving Assembly Line: Flywheel Magnetos at Highland Park, Unknown photographer, Ford Motor Company, 1913 · Photograph · Highland Park, Michigan

Image: Wikimedia Commons, public domain

This photograph shows the line where Ford's men first tried moving the work past the workers. The round parts are Model T flywheel magnetos, the same kind of spark generator you studied in Lesson 9.4.

Look closely

- Find the magnetos on the line. Which ones are nearly finished and which are just begun?
- Look at the bins under the line. Why are the parts kept within arm's reach?
- Look at the belts and pulleys overhead. What powered the machines in this factory?
- Find a worker's hands. What single task might he do to every magneto that passes?

Talk about it

1. Why would doing one small task many times be faster than building a whole magneto?
2. What would a careful engineer measure to know whether the line was really better?

3. What could go wrong on a line if one station worked more slowly than the rest?

Safety first. During the walkaround, keep the engine off and the key out unless an adult is starting the car outdoors for a check. Open the hood only when the engine is cool, keep hands, hair and loose sleeves away from the fan (electric fans can start even with the engine off), and never get under a car that is supported only by a jack.

SHOP PROJECT

A Systems Walkaround of a Real Car

With the owner's manual and an adult, you will find and map every major system on a family car, decode its VIN, and build a one-page "vehicle fact sheet" that you will use through the rest of this unit.

You will need

- A car (family car, a relative's or a neighbor's) and its owner's manual (most makers post manuals online)
- Flashlight, rag, safety glasses
- Shop notebook, camera or phone
- Optional: a free online VIN decoder from the National Highway Traffic Safety Administration (NHTSA)

Steps

1. Find the VIN on the dashboard (through the windshield) and on the driver's door jamb sticker. Record it, and decode the model year (10th character), maker and engine using the NHTSA decoder or the manual.
2. Read the door-jamb tire placard and record the tire size and recommended cold pressures.
3. With the engine cool, open the hood. Find and photograph the engine, the oil dipstick and filler cap, the coolant reservoir, the brake fluid reservoir, the washer fluid tank, the battery and the air filter box. Label each photo.
4. Find the fuse boxes using the manual (often one under the hood and one inside the cabin). Record their locations.
5. Walk around the car. Find the suspension springs or struts and the brake rotors behind the wheels (look through the spokes with the flashlight).
6. Decide whether the car is front-, rear- or all-wheel drive, and find where the power reaches the wheels (axle shafts, driveshaft).
7. In the manual, find the maintenance schedule. Copy the intervals for oil, tire rotation, air filter, brake fluid and coolant.

8. Make a one-page vehicle fact sheet: VIN and year, engine, drive type, tire size and pressures, fluid types and capacities, fuse box locations, and the maintenance schedule.
9. **Check your work.** Compare your opening sketch with what you found. List three things you did not know were there.

Tips

- Many fluid caps are color-coded or marked with symbols; the manual shows them.
- If the car is a hybrid, look for orange high-voltage cables and do not touch them; they are for trained technicians only.
- Photograph labels and stickers so you can read them later.

Check your work

☐ I can name each system and point to its main parts on a real car.

☐ I can decode a VIN's model year and read a tire placard.

☐ I can explain how the moving assembly line raised productivity.

SHOP NOTEBOOK

1. A labeled top-view diagram of your car showing the engine, transmission, drive wheels, brakes, steering, battery and fuel tank.
2. Your vehicle fact sheet.
3. A short paragraph comparing the Model T with your car: power, systems, safety features and what an owner could fix at home.

KEY FORMULAS

$$\text{productivity ratio} = \frac{\text{old time per unit}}{\text{new time per unit}}$$

$$\text{percent change} = \frac{\text{new} - \text{old}}{\text{old}} \times 100\%$$

$$V_d = \frac{\pi}{4} b^2 s \times (\text{cylinders}), \quad 1 \text{ in}^3 = 16.39 \text{ cm}^3$$

$$\text{gear ratio} = \frac{\text{output torque}}{\text{input torque}} = \frac{\text{input speed}}{\text{output speed}} \quad \text{(ignoring losses)}$$

From history. The Model T's planetary transmission was worked by three pedals: one for low and high gear, one for reverse and one for the transmission brake, with a hand lever for neutral and the parking brake. Drivers who learned on a Model T often had to relearn when the sliding-gear transmission with a clutch pedal and a gearshift became standard in the late 1920s.

WORKED EXAMPLES

Example 1. Chassis assembly at Highland Park fell from about 12½ hours to about 93 minutes. By what factor did productivity rise?

Show solution

1. Convert: $12.5\ \text{h} = 750\ \text{min}$.
2. Ratio: $750/93 \approx 8.1$.
3. The same workers could assemble about eight times as many chassis in a day.

Answer: About 8 times

Example 2. The Model T engine had four cylinders with a bore of 3.75 in and a stroke of 4.0 in. Find its displacement in cubic inches and liters.

Show solution

1. One cylinder: $0.7854 \times 3.75^2 \times 4.0 = 0.7854 \times 14.06 \times 4.0 \approx 44.2\ \text{in}^3$.
2. Four cylinders: $4 \times 44.2 \approx 177\ \text{in}^3$.
3. Liters: $177 \times 16.39 \approx 2{,}900\ \text{cm}^3 = 2.9\ \text{L}$.

Answer: $177\ \text{in}^3 \approx 2.9\ \text{L}$

Example 3. A Model T touring car cost \$850 in 1908, and the cheapest Model T cost \$260 in the mid-1920s. Find the percent change.

Show solution

1. $(260 - 850)/850 \times 100\% = -590/850 \times 100\% \approx -69\%$.
2. The price fell by about 69%, even before allowing for inflation.

Answer: About a 69% decrease

Example 4. A car's first gear has a ratio of 3.5:1 and its final drive 3.9:1. The engine makes 150 lb·ft. Ignoring losses, what torque reaches the axles in first gear?

Show solution

1. Overall ratio: $3.5 \times 3.9 = 13.65$.
2. $150 \times 13.65 \approx 2{,}050$ lb·ft, shared between the two drive wheels.
3. That is why first gear can start a heavy car moving from rest, while the axles turn 13.65 times slower than the engine.

Answer: About 2,050 lb·ft

PRACTICE

1. Easy Match each system to its job: drivetrain, brakes, suspension, electrical. (a) turns motion into heat, (b) carries power to the wheels, (c) keeps tires on the road, (d) starts the engine and runs the lights.

   Show answer

   (a) brakes, (b) drivetrain, (c) suspension, (d) electrical.

2. Easy Convert a 2.0 L engine to cubic inches.

   Show answer

   $2000/16.39 \approx 122$ in^3.

3. Easy Which character of a VIN gives the model year?

   Show answer

   The 10th character.

4. Medium Magneto assembly fell from about 20 minutes to about 5 minutes per unit. Find the productivity ratio and the percent decrease in time.

   Show answer

   Ratio $20/5 = 4$; decrease $15/20 = 75\%$.

5. Medium More than 15 million Model Ts were built from 1908 to 1927. Estimate the average per year.

   Show answer

   $15{,}000{,}000/19 \approx 790{,}000$ per year.

6. Medium An engine has six cylinders with a 3.5 in bore and 3.4 in stroke. Find the displacement in liters.

Show answer

Per cylinder $0.7854 \times 12.25 \times 3.4 \approx 32.7$ in^3; total 196 in^3 ≈ 3.2 L.

7. Medium A top gear has a ratio of 0.7:1 and the final drive is 3.5:1. Find the overall ratio and the engine speed when the axles turn at 800 rpm.

Show answer

Overall $0.7 \times 3.5 = 2.45$; engine $800 \times 2.45 = 1{,}960$ rpm.

8. Hard Conceptual. Why does a car need a transmission at all? Why not connect the engine straight to the wheels?

Show answer

An engine makes useful power only in a band of speeds (and none at zero). Gears let it run fast enough to make power while the car starts from rest, and slow enough to be efficient at highway speed; low gears also multiply torque for starting and climbing.

9. Hard A line has five stations with times of 50, 62, 48, 55 and 51 seconds. How often does a finished part come off the line, and how would you improve it?

Show answer

The slowest station (62 s) sets the pace: one part every 62 s. Rebalance the work so no station is much slower, for example by splitting the 62 s task or moving part of it to the 48 s station.

10. Hard You are the tradesperson. A customer says, “My car makes a noise.” List the first four questions you ask before touching a tool.

Show answer

Model answer: When does it happen (cold, warm, turning, braking, accelerating, speed)? Where does it seem to come from? What does it sound like (squeal, grind, click, knock, hum)? When did it start, and has any work been done recently? Then verify the noise on a test drive.

11. **Challenge** Ford's 1908 touring car cost $850. If a typical worker earned about $2.50 a day then and about $5 a day in 1914, how many working days of pay did an $850 car cost at $2.50 a day, and a $440 car at $5 a day?

    Show answer

    $850 / 2.50 = 340$ days; $440 / 5 = 88$ days. The car became about four times easier to afford.

COMMON MISTAKES

- Saying Ford invented the automobile or the assembly line. Karl Benz built the first practical motor car in 1885–86; Ford's contribution was the moving assembly line and the low-cost car.
- Thinking a hybrid or electric car has no maintenance. It still has tires, brakes, suspension, a 12-volt battery, coolant and fluids.
- Ignoring the owner's manual. It is written for your exact car.

> **Make it a game · Car Systems Walkaround.** Stand by the family car, parked and off, with your parent. Point to and name seven systems in 60 seconds, such as engine bay, brakes, suspension, steering, electrical, body and safety equipment, saying what each does. Then find the VIN and decode what you can. Calculate Model T output gains for a bonus.

10.2 The Engine and Its Fluids

OBJECTIVES

- Explain what engine oil, coolant, brake fluid and transmission fluid each do, and how to check each one correctly.
- Read an SAE oil grade such as 5W-30 and explain viscosity and why oil must be changed.
- Calculate heat removed by a cooling system and explain how a pressure cap raises the boiling point.
- Inspect and record every fluid on a real car and measure how temperature changes oil viscosity.

> **Warm-up.** Put a spoonful of honey and a spoonful of cooking oil in the refrigerator for ten minutes, then tip each spoon and time how long the liquid takes to run off. Compare with room-temperature spoons. Write what you notice about cold liquids.

WATCH

How To: Check and Fill Your Vehicle's Fluids

O'Reilly Auto Parts · 8:25

https://www.youtube.com/watch?v=3NiEikrHV7c

> **WHEN TO WATCH**
> Before the shop project. Watch it once straight through, then again with your car’s manual open, pausing at each fluid.

Note: A clear, step-by-step guide from an auto-parts company: oil, coolant, power steering, brake, clutch, transmission and washer fluid. Mentions products sold by the store.

BACKUP VIDEO

Engine Oil Codes Explained, SAE (Society of Automotive Engineers) numbers

TheRepairSpecialist · 5:15

https://www.youtube.com/watch?v=Hb6CX_rWoIA

With the science paragraph on viscosity grades.

KEY TERMS

viscosity

A fluid's resistance to flow; honey has high viscosity, water low. Oil thins as it heats.

multigrade oil (5W-30)

Oil that flows like a thin grade when cold (the "W," for winter, number) and protects like a thicker grade at operating temperature (the second number).

coolant (antifreeze)

A mixture of glycol and water, usually 50/50, that carries heat from the engine to the radiator, resists freezing and boiling, and contains corrosion inhibitors.

thermostat

A heat-operated valve that keeps coolant in the engine until it warms up, then opens (often around 180–195 °F) to send it to the radiator.

hygroscopic

Absorbing water from the air. Brake fluid is hygroscopic, so it must be replaced on a schedule.

dipstick

A metal or plastic blade used to measure the level and condition of engine oil or transmission fluid.

CORE IDEAS

The story. Early motorists carried oil cans and topped up their engines constantly; oil changes every few hundred miles were normal, because the oils of the day broke down quickly and filtered nothing. In its early years the Society of Automobile Engineers (founded in 1905, now SAE International) began writing standards so that parts and fluids from different makers would fit and work together, and its oil viscosity grades, first issued in 1911 and revised many times since, are why a bottle marked 5W-30 means the same thing at every store. Multigrade oils, made possible by polymer additives in the 1950s, let one oil serve both cold mornings and hot summer driving. Today's synthetic and blended oils can last many thousands of miles, and many cars have an oil-life monitor that estimates when to change it.

How they figured it out. Engineers learned what fluids must do by watching engines fail: bearings wiped out by thin or dirty oil, blocks cracked by frozen water, brakes that faded when their fluid boiled. Each failure became a test. SAE grades are set by measuring viscosity at 100 °C and how easily oil can be pumped and cranked at low

temperatures. Coolant makers measure freezing and boiling points of glycol mixtures. Brake-fluid standards set by the U.S. Department of Transportation (DOT 3, DOT 4, DOT 5.1) set minimum boiling points for fresh fluid and for fluid that has absorbed water.

The science. Oil keeps a thin film between moving parts so they never touch; the film's strength depends on viscosity, which drops as temperature rises. A 5W-30 flows almost like a thin 5-weight oil when cold, so it reaches the bearings quickly at startup, and holds the viscosity of a 30-weight at 100 °C. Oil also cools, cleans and seals, and its additives wear out, which is why it must be changed. About a third of a gasoline engine's fuel energy leaves as heat in the coolant. The heat carried away is $Q = \dot{m}\, c\, \Delta T$, and a 50/50 coolant mix has a specific heat of about $3.5\ \mathrm{kJ/(kg{\cdot}K)}$. Water boils at 212 °F at sea level, but raising the pressure raises the boiling point, by roughly 3 °F for each psi; a 15-psi radiator cap with a 50/50 mix keeps coolant from boiling until about 265 °F, and the same mix protects against freezing to about −34 °F. That pressure is why a hot radiator or reservoir cap must never be opened: the coolant can flash to steam and spray out.

In the shop. Check engine oil with the car on level ground and the engine off (most makers say to wait a few minutes after stopping): pull the dipstick, wipe it, reinsert it fully, pull it again and read the level between the marks. Note the color and feel: amber is fresh, dark is used, milky or foamy can mean coolant is getting in, and a gritty or burnt smell means trouble. Check coolant only in the see-through reservoir and only when the engine is cold. Check brake fluid in its reservoir; a dropping level usually means worn pads (the caliper pistons have moved out) or a leak, both of which need attention. Transmission fluid is checked by dipstick on some cars, often with the engine running and warm, and on many newer cars only by a technician; follow the manual. Use exactly the fluid types the manual names: the wrong coolant or transmission fluid can damage seals and parts. Used fluids are recycled at auto-parts stores and collection centers.

PICTURE STUDY



A Student Mechanic Torques a Cylinder Head, Marjory Collins, Office of War Information, April 1943 · Photograph · Library of Congress; Burgard Vocational High School, Buffalo, New York
Image: Wikimedia Commons, public domain

During the Second World War many people trained in vocational schools to keep cars and trucks running. This student is tightening (“drawing down”) the cylinder head bolts with a torque wrench, the tool you met in Unit 1.

Look closely

- Find the torque wrench and its scale. Why does she watch the dial as she pulls?
- Find the cylinder head bolts. What does the head gasket under them keep apart?
- Find the round canister in the middle. It is an oil filter of the period. What does it remove from the oil?
- Find a radiator hose. Where does the coolant go after it leaves the engine?

Talk about it

1. Why must head bolts be tightened to an exact torque and in a set order?
2. If the head gasket failed, which two fluids might mix, and how would an owner notice?
3. What does this photo tell you about how mechanics were trained?

Safety first. Check fluids only with the engine off and cool, except where the manual says to check transmission fluid with the engine running (then an adult starts it outdoors and you keep hands, hair and sleeves away from belts and the fan). Never open a radiator or coolant reservoir cap on a hot engine. Wear safety glasses and gloves; coolant is poisonous and sweet-tasting, so wipe up spills at once and keep it away from pets and small children.

SHOP PROJECT

A Fluid Inspection and an Oil Viscosity Test

Part A is a complete fluid inspection of a real car, recorded in a log. Part B is a lab: you will time how fast engine oil flows at different temperatures and see why the “W” number matters on a cold morning.

You will need

- A car with its owner’s manual; rags, flashlight, safety glasses and nitrile gloves
- Optional: a coolant hydrometer or antifreeze test strips (inexpensive at auto-parts stores)
- For Part B: a small amount of new motor oil (and, if available, two different grades), a clean funnel or a narrow-necked bottle with a small hole, a stopwatch, a measuring cup, a kitchen thermometer, a refrigerator and freezer

Steps

1. **Part A.** Park on level ground with the engine off and cool. Open the hood.
2. Check the engine oil level and condition on the dipstick (wipe, reinsert, read). Record the level as a fraction between the marks, the color and any smell.
3. Check the coolant level in the reservoir against its marks (cold engine only). If you have a tester, measure its freeze protection and record it.
4. Check the brake fluid level and color through the reservoir. Fresh fluid is clear to light amber; dark fluid is old.
5. Check washer fluid and, if your car has them, the power-steering fluid and transmission dipstick as the manual directs.
6. Record everything in a fluid log with the date and odometer reading. Note anything low and, with an adult, top it up with the exact fluid type in the manual.
7. **Part B.** Pour 50 mL of oil at room temperature through the funnel and time how long it takes to drain. Record the temperature.

8. Repeat with oil cooled in the refrigerator (about 4 °C) and in the freezer for 30 minutes. If you have two grades (for example 0W-20 and 10W-40), test both.
9. Graph drain time against temperature. Explain what your results mean for an engine starting on a cold morning.
10. **Improve it.** Repeat each trial three times and report the average and spread. Which source of error is largest?

Tips

- Read the oil level twice; the first pull often gives a false reading.
- Wipe each reservoir cap before opening it so dirt cannot fall in.
- Put used test oil in a sealed container for recycling with other used oil.

Check your work

- ☐ I can check oil, coolant and brake fluid correctly and know what is normal.
- ☐ I can explain what 5W-30 means.
- ☐ My viscosity graph shows how temperature changes flow.

SHOP NOTEBOOK

1. A labeled sketch of your engine bay showing each fluid's location, cap symbol and correct type.
2. Your fluid log page.
3. Your viscosity data table and graph, with a sentence on why multigrade oil exists.

KEY FORMULAS

$Q = \dot{m}\, c\, \Delta T$

$T_{\text{boil}} \approx 212^\circ\text{F} + 3^\circ\text{F}$ per psi of cap pressure (water, approximate)

$V_{\text{concentrate}} = f \times V_{\text{system}}$ (for a mix fraction f)

From history. Early cars were often water-cooled with plain water, and owners drained their radiators every winter night or covered them with blankets. Alcohol was used as an antifreeze until ethylene glycol, which does not boil off, became common in the late 1920s and 1930s.

WORKED EXAMPLES

Example 1. Coolant flows through an engine at 1.0 kg/s and warms by 8 °C. With $c = 3.5\ \text{kJ/(kg·K)}$, how much heat does it carry away?

Show solution

1. $Q = 1.0 \times 3.5 \times 8 = 28\ \text{kJ/s} = 28\ \text{kW}$.
2. That is about 37 horsepower of heat, which the radiator must pass to the air.

Answer: 28 kW

Example 2. Estimate the boiling point of plain water under a 15-psi radiator cap. Why do cars use a 50/50 glycol mix as well?

Show solution

1. $212 + 3 \times 15 = 257^\circ\text{F}$.
2. Glycol raises the boiling point further (to about 265 °F with the cap), lowers the freezing point to about −34 °F, and carries corrosion inhibitors. Plain water would freeze and crack the engine in winter.

Answer: About 257 °F

Example 3. A cooling system holds 8.0 quarts. How much coolant concentrate is needed for a 50/50 mix? If the system now holds a 30% mix and you drain 3 quarts and replace them with pure concentrate, what is the new mix?

Show solution

1. 50/50: $0.50 \times 8.0 = 4.0\ \text{qt}$.
2. After draining 3 qt of 30% mix, 5 qt remain with $0.30 \times 5 = 1.5\ \text{qt}$glycol.
3. Add 3 qt concentrate: $1.5 + 3 = 4.5\ \text{qt}$in 8 qt, or $4.5/8 \approx 56\%$.

Answer: 4.0 qt; about 56% after the change

Example 4. You are the tradesperson. A customer keeps adding coolant every week. There is a sweet smell after driving and some white exhaust on cold mornings. What do you check, and what must you never do?

Show solution

1. Never open the cap on a hot engine; wait until it is cold.
2. Look for external leaks: wet hoses and clamps, the radiator, the water pump's weep hole, the heater core (damp carpet or fogged windows).
3. Pressure-test the cooling system with a hand pump on the cold system and watch for a falling gauge.
4. Check the oil for a milky color and test the coolant for combustion gases. Both point to an internal leak such as a failed head gasket, which is a job for a technician.

Answer: Find whether the leak is external or internal; never open a hot cap.

PRACTICE

1. Easy In 10W-40, what does the 10W tell you, and what does the 40 tell you?

   Show answer

   10W: its cold-temperature (winter) flow rating, like a 10-weight oil when cold. 40: its viscosity grade at the operating temperature of 100 °C.

2. Easy Why should you never open a radiator cap on a hot engine?

   Show answer

   The coolant is under pressure and above its normal boiling point; releasing the pressure lets it flash to steam and spray out, causing severe burns.

3. Easy Name three things engine oil does besides lubricating.

   Show answer

   Cools, cleans (holds dirt and carries it to the filter), seals the piston rings and protects against corrosion.

4. Medium Coolant flows at 1.2 kg/s and warms by 6 °C (c = 3.5 kJ/kg·K). Find the heat removed.

   Show answer

   $1.2 \times 3.5 \times 6 = 25.2$ kW.

5. Medium Estimate the boiling point of water under a 13-psi cap.

Show answer

$212 + 39 = 251^\circ\text{F}$.

6. Medium A cooling system holds 10 qt. How much concentrate makes a 60% mix?

Show answer

6 qt.

7. Medium The car's manual calls for an oil change every 7,500 miles. You drive 13,000 miles a year. How many oil changes per year? At $45 each, what is the yearly cost?

Show answer

$13{,}000/7{,}500 \approx 1.7$; about 2 changes a year, or $1.7 \times 45 \approx \$78$.

8. Hard DOT 3 brake fluid boils at about 401 °F when fresh and about 284 °F when it has absorbed about 3.7% water. Explain why old brake fluid is dangerous on a long mountain descent.

Show answer

Long braking heats the calipers and fluid. Wet fluid can boil at a much lower temperature, forming vapor bubbles; vapor compresses, so the pedal goes soft or to the floor and braking force is lost.

9. Hard A 30% coolant mix in an 8-qt system protects only to about 0 °F. You drain 4 qt and add 4 qt of concentrate. What is the new mix?

Show answer

Remaining glycol $0.30 \times 4 = 1.2$ qt; plus 4 qt is 5.2 qt in 8 qt, or 65%.

10. Hard You are the tradesperson. The oil on the dipstick is light brown and milky. What could this mean, and what would you do?

Show answer

Water or coolant in the oil. From short trips in cold weather it may be condensation (often only on the filler cap). If heavy, with coolant loss, suspect a head gasket or cracked head: pressure-test the cooling system, test for combustion gases, and do not keep driving it.

11. **Challenge** An engine burns fuel at a rate of 60 kW of chemical energy at highway speed and about one-third goes into the coolant. If the coolant warms by 7 °C through the engine, what mass flow is needed (c = 3.5 kJ/kg·K)?

    Show answer

    Heat $Q = 20\ \text{kW}$; $\dot{m} = 20/(3.5 \times 7) \approx 0.82\ \text{kg/s}$.

COMMON MISTAKES

- Checking oil right after shutdown on a slope, which gives a false low reading and leads to overfilling.
- Topping up with whatever coolant is on the shelf. Coolant types differ; follow the manual and do not mix types without flushing.
- Adding brake fluid every month without asking why the level is dropping.
- Pouring used oil or coolant on the ground or down a drain.

> **Make it a game · Fluid Check Cards.** Make cards for oil, coolant, brake fluid and transmission fluid. Your parent describes a symptom, such as low pedal or overheating, and you choose the fluid and say how to check it in five seconds. Include decoding 5W-30. Parent adds one wrong fact; spot it. First to five points wins.

> **Scripture.** “Be thou diligent to know the state of thy flocks, and look well to thy herds.” (Proverbs 27:23, KJV)
>
> A farmer who looked well to his herds knew trouble before it grew. A car owner who checks the fluids regularly does the same with the machine that carries the family.

10.3 Brakes, Tires and Steering

OBJECTIVES

- Use Pascal's principle to calculate the force multiplication of a hydraulic brake system.
- Calculate a car's kinetic energy, brake temperature rise and stopping distance.
- Read a tire's size code, check pressure and tread depth, and diagnose uneven wear.
- Build a two-syringe hydraulic system and measure its force multiplication.

> **Warm-up.** Push down on a bathroom scale with one finger as hard as you can. Now stand on it. A car's brake pedal turns a push like the first into a force many times larger at each wheel. Write a guess about how.

WATCH

BRAKES: How They Work | Science Garage

Donut · 8:21

https://www.youtube.com/watch?v=6H7nwlT_qNY

> **WHEN TO WATCH**
> After the story paragraph. Note the friction equation and how the hydraulic system multiplies the pedal force.

Note: A lively but clear explanation of drum and disc brakes, hydraulics, friction and weight transfer. Begins and ends with sponsor messages; skip them.

BACKUP VIDEO

The Ultimate Guide To Tire Sidewalls - How Good Are Your Tires?

Engineering Explained · 11:33

https://www.youtube.com/watch?v=ucHS2LCiUVw

With the tire paragraph; have a tire nearby to read along.

KEY TERMS

Pascal's principle

Pressure applied to an enclosed fluid is transmitted undiminished to every part of the fluid.

master cylinder

The cylinder pushed by the brake pedal that pressurizes the brake fluid.

caliper

The clamp on a disc brake whose hydraulic piston presses the pads against the spinning rotor.

brake fade

Loss of braking from overheated pads, rotors or boiling brake fluid.

aspect ratio

A tire's sidewall height as a percentage of its width; the 60 in 225/60R16.

alignment

The angles of the wheels (toe, camber, caster) relative to the car and road; poor alignment wears tires and pulls the car.

CORE IDEAS

The story. Early cars stopped with mechanical brakes: rods and cables pulled shoes against drums, usually on the rear wheels only, and keeping them equal side to side was a constant chore. Malcolm Loughead (whose brothers later spelled the name Lockheed for their aircraft company) filed a patent for hydraulic brakes in 1917, using fluid in tubes instead of rods. The Duesenberg Model A of 1921 was the first production car with hydraulic brakes on all four wheels, and Chrysler made them common from 1924. Disc brakes, patented by the English engineer Frederick Lanchester in 1902, came into their own after Jaguar's disc-braked cars proved them in the 24-hour endurance contest at Le Mans in 1953. Tires have a story too: John Boyd Dunlop made a practical air-filled tire for his son's tricycle in 1888, and Michelin's radial tire of 1946 made tires last far longer.

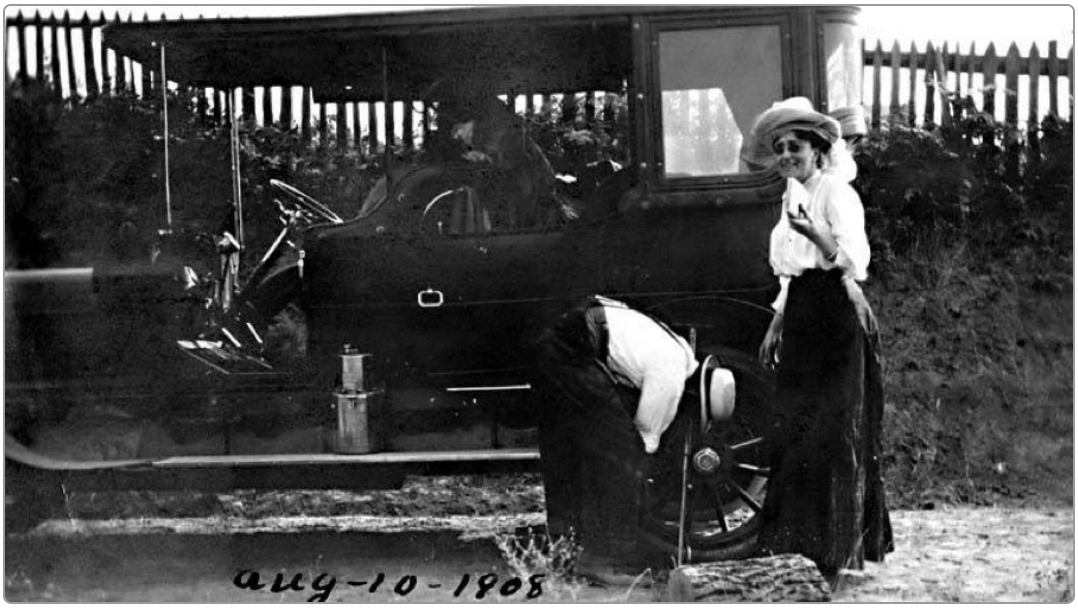
How they figured it out. Engineers learned that a fluid cannot be compressed and pushes equally in every direction, so a single tube network can deliver equal pressure to every wheel without the fussy adjustment of rods and cables. They learned from fade on long hills that brakes are heat machines: every bit of a car's motion they stop becomes heat that must be shed into the air, which is why rotors are vented and why brake fluid needs a high boiling point. Tire makers learned by

testing thousands of tires how pressure, load and heat affect wear and safety, and their findings are printed on every sidewall and door-jamb placard.

The science. The pedal is a lever, multiplying the driver's foot force perhaps four times; a vacuum or electric booster multiplies it again. The master cylinder turns that force into pressure, $p = F_1 / A_1$, and by Pascal's principle the same pressure acts on each caliper piston, giving $F_2 = p A_2 = F_1 (A_2 / A_1)$. Because the caliper pistons are much larger than the master-cylinder piston, the force is multiplied again, though the pistons move only a fraction of a millimeter. Friction between pads and rotor, $f = \mu N$, slows the wheel. A 1,500 kg car at 60 mph (26.8 m/s) has kinetic energy $\tfrac{1}{2} m v^2 \approx 540$ kJ, and a hard stop turns all of it into heat in a few seconds. The shortest stop is limited by the tires' grip: $d = v^2 / (2 \mu g)$, so doubling speed quadruples braking distance.

In the shop. Check tire pressure monthly with a gauge, when the tires are cold, and set it to the door-jamb placard (the number on the sidewall is the maximum, not the recommended pressure). Pressure drops about 1 psi for every 10 °F of cooling, so check it as the weather turns. Measure tread depth in the main grooves: new car tires have about 10/32 to 11/32 inch; most states set 2/32 inch as the legal minimum, and many tire makers advise replacing at 4/32 inch for wet-road safety. In the classic penny test, if you can see all of Lincoln's head when the penny is put head-down in a groove, the tread is at or below 2/32 inch. Wear on both edges means underinflation; wear in the center, overinflation; wear on one edge, an alignment problem. Brake warning signs are a high-pitched squeal from the wear indicators, grinding (metal on metal: stop and repair now), a soft or sinking pedal, pulling to one side, and a dropping brake-fluid level. Brake repair is safety-critical work for a trained technician or an experienced adult with the right tools and service information.

PICTURE STUDY



Changing a Tire, 1908, Unknown photographer, August 10, 1908 · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

In 1908 a flat tire was an ordinary part of any trip. Roads were rough, tires were thin, and there were no service stations on most roads, so motorists carried tools, patches and pumps and fixed their own tires by the roadside.

Look closely

- Find the wheel being worked on. What is it made of, and how is it different from a modern wheel?
- Find the log under the car. What job is it doing?
- Look at the road surface. Why would tires fail often on roads like this?
- Find the can on the running board. What might the driver carry for a roadside repair?

Talk about it

1. Would you trust a log to hold up a car while you worked on it? What do we use today, and why?
2. Why do you think tire technology improved so much between 1908 and today?
3. What should a driver today carry in the trunk for a flat tire?

Safety first. Use water, never brake fluid, in the syringe lab, and wear safety glasses. Check tires with the car parked, in gear or Park, with the parking brake set, and away from traffic. Brake fluid is toxic and removes paint; brake repairs are safety-critical and are done by a technician or an experienced adult with service information, never as a first project.

SHOP PROJECT

Pascal in a Syringe, and a Tire Inspection

Part A: you will connect a small and a large syringe with water-filled tubing, measure the input and output forces on kitchen scales, and compare the force multiplication with the area ratio. Part B: you will inspect the tires of a real car: pressure, tread depth across each tire, wear pattern, size and age.

You will need

- Two syringes of different sizes (e.g. 10 mL and 60 mL), 30–50 cm of tubing that fits both, water with a drop of food coloring
- Two kitchen or postal scales, a ruler, a caliper if available
- A tire pressure gauge and a tread-depth gauge (or a penny)
- Chalk, notebook, flashlight, safety glasses

Steps

1. **Part A.** Measure each syringe's inside barrel diameter (or compute it from its volume per centimeter of plunger travel). Compute the area ratio $(d_2/d_1)^2$.
2. Fill both syringes and the tubing with water with no air bubbles (push water back and forth until bubbles are gone).
3. Stand the large syringe's plunger on one scale (tape the barrel to a support). Press the small syringe's plunger down on the other scale with your hand on top so you can read your push.
4. Record the input force and output force for five different pushes. Graph output against input and find the slope.
5. Compare the slope with the area ratio. Measure how far each plunger moves for one push, and show that what you gain in force you lose in distance.
6. Add one small air bubble on purpose and repeat. Describe how the system feels. Connect this to a "spongy" brake pedal.
7. **Part B.** On a cold car, read and record each tire's size and four-digit DOT date code (week and year of manufacture).
8. Measure each tire's pressure and compare with the door-jamb placard. With an adult, adjust to the placard.

9. Measure tread depth at the inner, center and outer grooves of each tire. Record in a table and diagnose the wear pattern.
10. **Check your work.** Write a short tire report: which tires are healthy, which need attention soon, and why.

Tips

- Weigh in grams and convert: 1 kg on a scale is a force of about 9.8 N.
- Friction in the syringes makes the output a little less than ideal; that difference is your efficiency.
- The DOT date code 2321 means the 23rd week of 2021. Many makers advise replacing tires about six to ten years after manufacture regardless of tread.

Check your work

- ☐ My measured force ratio is close to the area ratio, and I can explain the difference.
- ☐ I can read a tire size and date code and judge tread depth and wear.
- ☐ I can explain why air in brake lines is dangerous.

SHOP NOTEBOOK

1. A labeled diagram of a hydraulic disc-brake system: pedal, booster, master cylinder, lines, caliper, piston, pads and rotor.
2. Your syringe data table and force graph with the slope and area ratio.
3. Your tire report table: position, size, date code, pressure (found and set), tread at three points, wear diagnosis.

KEY FORMULAS

$$p = \frac{F_1}{A_1} = \frac{F_2}{A_2} \quad \Rightarrow \quad F_2 = F_1 \, \frac{A_2}{A_1} = F_1 \left(\frac{d_2}{d_1} \right)^2$$

$$KE = \tfrac{1}{2} m v^2, \quad Q = m c \Delta T$$

$$d_{\text{brake}} = \frac{v^2}{2 \mu g}, \quad d_{\text{total}} = v \, t_r + \frac{v^2}{2 \mu g}$$

$$D_{\text{tire}} = 2 \left(W \times \tfrac{AR}{100} \right) + D_{\text{rim}}$$

From history. Anti-lock brakes (ABS), which rapidly release and reapply each wheel's brake to keep it from skidding, appeared on production cars in the late 1970s, and electronic stability control, which brakes individual wheels to keep a skidding car on course, has been required on new cars in the United States since the 2012 model year.

WORKED EXAMPLES

Example 1. A master cylinder has a 22 mm piston and each front caliper has a 54 mm piston. The pedal and booster push on the master cylinder with 1,200 N. Find the line pressure and the force on one caliper piston.

Show solution

1. Master area: $A_1 = \frac{\pi}{4}(0.022)^2 = 3.80 \times 10^{-4}\ \text{m}^2$.
2. Pressure: $p = 1200 / 3.80 \times 10^{-4} \approx 3.16 \times 10^{6}\ \text{Pa} = 3.16\ \text{MPa}$(about 460 psi).
3. Area ratio: $(54/22)^2 \approx 6.02$; $F_2 \approx 1200 \times 6.02 \approx 7{,}200\ \text{N}$.

Answer: About 3.2 MPa; about 7,200 N on each caliper piston

Example 2. A 1,500 kg car brakes hard from 60 mph (26.8 m/s) to a stop. Find its kinetic energy. If all the heat went into four 8.0 kg iron rotors (c = 460 J/kg·K), how much would they warm?

Show solution

1. $KE = \frac{1}{2}(1500)(26.8)^2 = 750 \times 718 \approx 539{,}000\ \text{J}$.
2. $\Delta T = 539{,}000 / (32 \times 460) \approx 37^\circ\text{C}$.
3. In practice the front rotors take most of the load and get hotter, and repeated stops on a hill can push them past 300 °C.

Answer: About 540 kJ; about 37 °C average rise

Example 3. At 26.8 m/s, with a reaction time of 1.5 s and tire grip $\mu = 0.70$, find the total stopping distance. What if the road is wet (μ = 0.40)?

Show solution

1. Reaction distance: $26.8 \times 1.5 = 40.2$ m.
2. Dry braking: $26.8^2/(2 \times 0.70 \times 9.81) = 718/13.7 \approx 52.3$ m; total about 93 m.
3. Wet braking: $718/(2 \times 0.40 \times 9.81) \approx 91.5$ m; total about 132 m.

Answer: About 93 m dry, 132 m wet

Example 4. Find the overall diameter of a P225/60R16 tire and how many times it turns per mile.

Show solution

1. Sidewall height: $225 \times 0.60 = 135$ mm.
2. Diameter: $2(135) + 16(25.4) = 270 + 406 = 676$ mm ≈ 26.6 in.
3. Circumference: $\pi \times 26.6 \approx 83.6$ in; turns per mile $63{,}360/83.6 \approx 758$.

Answer: About 26.6 in; about 758 turns per mile

PRACTICE

1. Easy A tire is 205/55R16. What are its width, aspect ratio and rim diameter?

   Show answer

   205 mm wide; sidewall 55% of the width; fits a 16-inch rim.

2. Easy Where do you find the correct tire pressure for a car?

   Show answer

   On the placard on the driver's door jamb (or in the owner's manual), not the maximum printed on the sidewall.

3. Easy A tread gauge reads 3/32 in. Is the tire legal in most states? Is it advisable to keep it for wet roads?

   Show answer

   It is above the usual 2/32 in legal minimum, but below the 4/32 in many makers advise for wet roads; plan to replace it soon.

4. **Medium** A master cylinder piston is 20 mm across and a caliper piston 50 mm. What is the force multiplication?

   Show answer

   $(50/20)^2 = 6.25$.

5. **Medium** A 1,200 kg car moves at 20 m/s. Find its kinetic energy.

   Show answer

   $\tfrac{1}{2}(1200)(400) = 240{,}000$ J.

6. **Medium** With μ = 0.75, find the braking distance from 20 m/s (ignore reaction time).

   Show answer

   $400/(2 \times 0.75 \times 9.81) \approx 27$ m.

7. **Medium** Find the diameter of a 265/70R17 tire in inches.

   Show answer

   $2(265 \times 0.70) + 17(25.4) = 371 + 432 = 803$ mm ≈ 31.6 in.

8. **Hard** Conceptual. Why does doubling speed quadruple braking distance? What does that mean for following distance on a highway?

   Show answer

   Kinetic energy and braking distance go as v^2, so twice the speed needs four times the distance to stop with the same grip. At highway speed you must leave much more room, and more still on wet roads.

9. **Hard** Tires were set to 35 psi at 70 °F. Estimate the pressure on a 20 °F morning.

   Show answer

   A drop of 50 °F lowers pressure by about 5 psi, to about 30 psi; add air to the placard pressure when cold.

10. Hard You are the tradesperson. A customer says the brake pedal feels soft and sinks slowly toward the floor at a stoplight. What are the likely causes, and should the car be driven?

    Show answer

    Air in the lines, a leak (check the fluid level and look for wet lines or calipers), or a master cylinder leaking internally. The car should not be driven until it is inspected and repaired.

11. Challenge A 1,800 kg SUV descends a mountain road, dropping 600 m in elevation at steady speed using only the brakes. How much energy do the brakes absorb? Why do truck drivers use a lower gear on such hills?

    Show answer

    $mgh = 1800 \times 9.81 \times 600 \approx 10.6$ MJ. That much heat can overheat pads and boil the fluid. A lower gear lets engine braking absorb much of the energy and keeps the brakes cool for when they are needed.

COMMON MISTAKES

- Inflating tires to the maximum pressure on the sidewall instead of the door-jamb placard.
- Checking tire pressure after driving, when the tires are warm and read high.
- Ignoring the squeal of a brake wear indicator until it becomes a grind.
- Thinking larger brakes stop a car in a shorter distance on their own; the tires' grip sets the limit.

> **Make it a game · Brake Force Multiplier.** Your parent names a master cylinder piston area of 1 square centimeter, a caliper piston area of 10, and a pedal force of 50 newtons. Compute the output force in 30 seconds with Pascal's principle. Then estimate stopping distance at 60 versus 30 miles per hour. Compare and say why speed matters so much.

10.4 The Electrical System and Diagnostics

OBJECTIVES

- Explain how the 12-volt battery, starter and alternator work together, and what cold-cranking amps and reserve capacity mean.
- Use Ohm's law and P = VI to calculate starter power, voltage drop at a bad connection and battery run-down time.
- Test a battery and charging system with a multimeter, read OBD-II trouble codes, and map a fuse box.
- Jump-start a car safely in the correct order, and tell the story of Charles Kettering's electric self-starter.

> **Warm-up.** Look at the dashboard of a car with the key on but the engine off. Write down every warning light you see and guess what each one means. Check your guesses in the owner's manual later in the lesson.

WATCH

How A Car Battery Works - basic working principle

The Engineering Mindset · 16:01

https://www.youtube.com/watch?v=VnPRX5zQWLw

> **WHEN TO WATCH**
> After the science paragraph. The second half is a review of current and voltage; it is good practice for the worked examples.

Note: Clear animations of the starting and charging circuit and the inside of a lead–acid battery. Includes a short sponsor message near the start.

BACKUP VIDEO

How to Properly Jump Start a Car

ChrisFix · 7:35

https://www.youtube.com/watch?v=iI1o2hNy2hE

Before the jump-start discussion in the shop project; compare his order of connections with the lesson's.

KEY TERMS

lead–acid battery

The standard car battery: six cells of lead and lead dioxide plates in sulfuric acid, each about 2.1 V, for about 12.6 V when fully charged.

cold-cranking amps (CCA)

The current a battery can deliver for 30 seconds at 0 °F (−18 °C) while staying above 7.2 V; a measure of starting power.

reserve capacity

How many minutes a battery can supply 25 A before falling to 10.5 V, a measure of how long it can run the car if the alternator fails.

alternator

The belt-driven generator that recharges the battery and powers the car while the engine runs, usually at about 13.8–14.7 V.

OBD-II

On-Board Diagnostics, second generation: the standard computer-diagnostic system and 16-pin connector required on cars sold in the United States since the 1996 model year.

parasitic draw

The small current the car's computers and clock draw when the car is off.

CORE IDEAS

The story. Before 1912, a car was started by turning a hand crank at the front. If the spark was set wrong, the engine could kick back and spin the crank backward, and broken arms were common. According to the usual account, Henry Leland of Cadillac resolved to end hand cranking after a friend, Byron Carter, died of injuries from a crank that kicked back. Leland turned to Charles F. Kettering, an Ohio farm boy who had become an inventor at the National Cash Register Company and had built an electric motor to run a cash register. With Edward Deeds, Kettering had founded the Dayton Engineering Laboratories Company (Delco). The 1912 Cadillac, with Kettering's electric self-starter, electric lights and battery ignition, was the first car you could start by pressing a switch, and Cadillac won Britain's Dewar Trophy for it.

How they figured it out. Other engineers had said an electric starter was impossible because a motor strong enough to turn over a cold engine would be far too large and

heavy to carry. Kettering's insight came from the cash register: a motor that only has to run for a few seconds can be overloaded far beyond its continuous rating without overheating. His small motor-generator cranked the engine briefly at very high current, then ran as a generator to recharge the battery. He tested it in a barn in Dayton, made it work, and within a few years nearly every new car had one. Kettering went on to lead research at General Motors for decades and said that a problem well stated is a problem half solved.

The science. The battery stores energy chemically: when it discharges, both plates turn to lead sulfate and the acid weakens; charging reverses the reaction. A fully charged battery rests at about 12.6 V; about 12.4 V means 75%, 12.2 V about 50%, and 12.0 V or less is nearly flat. The starter draws a very large current, often 100 to 200 A or more, so even a tiny resistance at a corroded terminal causes a big voltage drop, $V = IR$, and wastes power as heat, $P = I^2R$. That is why a car with dirty terminals may click but not crank. Once the engine runs, the alternator, spun by a belt, generates alternating current that diodes turn into direct current at about 14 V, enough to push charge back into the battery. Fuses protect each circuit: if a short circuit draws too much current, the fuse's metal strip melts before the wiring overheats. Charging also produces a little hydrogen gas at the battery, which can ignite from a spark; that is why the last jumper-cable connection is made away from the battery.

In the shop. A technician tests the battery's resting voltage, its voltage while cranking (it should stay above roughly 9.6 V), and the charging voltage with the engine running (about 13.8–14.7 V), often with a load tester or an electronic battery analyzer. Since 1996, every car sold in the United States has an OBD-II port under the dashboard. When the engine computer finds a fault, it stores a trouble code and may light the check-engine lamp. A code reader, inexpensive or lent free by many auto-parts stores, shows codes such as P0301 (cylinder 1 misfire) or P0420 (catalytic converter efficiency below threshold). A code is the start of a diagnosis, not the answer: P0301 might be a plug, a coil, an injector or low compression, and the technician tests to find which. A flashing check-engine light means a severe misfire; the car should be driven gently and repaired soon to avoid damaging the catalytic converter.

PICTURE STUDY



Charles F. Kettering with His Electric Starter, Unknown photographer, About 1930s · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Years after his invention, Kettering posed beside an early Delco starting motor. It is cut away so you can see inside it, the way museum engineers often display machines.

Look closely

- Find the starter on the counter. Where is the electric motor, and where are the gears?
- Look for the opening where the starter's gear would meet the engine's flywheel.
- Compare its size with Kettering's hand. Why was a small, light motor so important?
- Look at how Kettering is dressed and posed. What does the photographer want you to think about him?

Talk about it

1. Why do the starter's gears need such a large reduction between the motor and the engine?
2. Kettering's starter also worked as a generator. Why was that clever?

3. Who do you think benefited most from the self-starter, and why?

Safety first. Wear safety glasses and remove rings and metal watch bands before working near a battery; a wrench across the terminals can weld itself and burn you. Never lay tools on the battery, and keep sparks and flames away, because a charging battery gives off hydrogen. Battery acid burns skin and eyes: rinse with plenty of water. Run the engine only outdoors, and keep hands, hair and sleeves clear of belts and the fan. Never touch the orange high-voltage cables on a hybrid or electric car.

SHOP PROJECT

Battery, Charging and Code Check

With an adult, you will test a car's battery and charging system with a multimeter, read any trouble codes through the OBD-II port, map the fuse box, and walk through the correct jump-start order without connecting cables.

You will need

- A car and its owner's manual
- A digital multimeter set to DC volts (the same one used in Unit 5)
- An OBD-II code reader (many auto-parts stores lend one free or will read codes for you)
- Safety glasses, gloves, a rag, and jumper cables (for the walk-through only)

Steps

1. With the car off for at least an hour, put on safety glasses and remove rings. Measure the resting battery voltage across the terminals (red to +, black to −). Record and estimate the state of charge.
2. Have the adult crank the engine (outdoors) while you watch the meter. Record the lowest cranking voltage.
3. With the engine idling, measure the charging voltage. Then turn on the headlights, blower and rear defroster and measure again. Record both.
4. Turn the engine off. Find the OBD-II port under the dashboard. Plug in the code reader with the key on, engine off, and record any codes and readiness monitors.
5. Look up each code's meaning. Write what a technician would test next for each, and why a code is not by itself a diagnosis.
6. Open each fuse box and compare it with the manual's diagram. Make a map of the ten fuses you think matter most (lights, horn, wipers, power outlets, fuel pump) with their ratings.
7. Read the battery label: CCA, reserve capacity or Ah, and date. Compare the CCA with what the manual calls for.

8. **Jump-start walk-through (no connections).** With the cables in hand and both cars off, point to each connection in order and say why: red to the dead battery +, red to the good battery +, black to the good battery −, black to bare unpainted metal on the dead car's engine, away from the battery. Then say the removal order (reverse).
9. **Check your work.** Write a one-paragraph report on the health of this car's battery and charging system, with your numbers.

Tips

- If the resting voltage seems high right after driving, turn the headlights on for one minute to remove surface charge, then off, and measure again.
- A cranking voltage that drops below about 9.6 V points to a weak battery or poor connections.
- If a reader shows a code, the free fix is never to clear it and hope; write it down first.

Check your work

- ☐ I can measure and interpret resting, cranking and charging voltages.
- ☐ I can read OBD-II codes and explain that they guide, not replace, diagnosis.
- ☐ I can explain the jump-start order and why the last clamp goes to bare metal away from the battery.

SHOP NOTEBOOK

1. A simple schematic of the starting and charging circuit: battery, starter solenoid and motor, ignition switch, alternator, fuse, ground.
2. Your battery and charging data table with the state of charge and your conclusion.
3. A fuse map and a list of any trouble codes with their meanings and next tests.

KEY FORMULAS

$$V = IR, \quad P = VI = I^2R$$

$$\text{capacity (Ah)} = I \times t, \quad t = \frac{\text{usable Ah}}{I}$$

$$E\,(\text{Wh}) = V \times \text{Ah}$$

From history. Kettering also helped develop leaded gasoline to stop engine knock in the 1920s, and later research showed that the lead harmed people's health; it was phased out of U.S. automotive gasoline by 1996. It is a reminder that engineers must keep testing the effects of their solutions long after the first problem is solved.

WORKED EXAMPLES

Example 1. A starter draws 150 A while the battery voltage falls to 10.5 V during cranking. Find the electrical power in watts and horsepower (1 hp = 746 W).

Show solution

1. $P = VI = 10.5 \times 150 = 1{,}575$ W.
2. $1575/746 \approx 2.1$ hp,
3. delivered for only a few seconds, as Kettering intended.

Answer: About 1,600 W, or 2.1 hp

Example 2. A corroded battery terminal has a resistance of 0.010 Ω. What voltage is lost across it at 150 A, and how much power turns to heat there?

Show solution

1. $V = IR = 150 \times 0.010 = 1.5$ V.
2. $P = I^2R = 150^2 \times 0.010 = 225$ W.
3. The starter loses 1.5 V of its roughly 10.5 V, enough to make it crank slowly or just click. Cleaning the terminal fixes it.

Answer: 1.5 V lost; 225 W of heat

Example 3. Headlights (two at 55 W) and taillights (four at 5 W) are left on with the engine off. The battery is rated 60 Ah, and starting needs at least half its charge. About how long until the car will not start?

Show solution

1. Power: $110 + 20 = 130$ W.
2. Current: $130/12.6 \approx 10.3$ A.
3. Usable: $60/2 = 30$ Ah; $t = 30/10.3 \approx 2.9$ h.

Answer: About 3 hours

Example 4. A car's parasitic draw is 50 mA. Starting from a full 60 Ah battery, how long can it sit before losing half its charge?

Show solution

1. $t = 30\ \text{Ah} / 0.050\ \text{A} = 600\ \text{h}$,
2. $600 / 24 = 25$ days. A car stored longer needs a battery maintainer or a disconnected battery.

Answer: About 25 days

PRACTICE

1. Easy A battery rests at 12.2 V. About what is its state of charge?

   Show answer

   About 50%.

2. Easy Blade fuses are color coded: red 10 A, blue 15 A, yellow 20 A, green 30 A. A blue fuse is blown. What rating must the replacement have?

   Show answer

   15 A, the same rating. Never use a larger fuse.

3. Easy In what model year did OBD-II become required on new cars sold in the United States?

   Show answer

   1996.

4. Medium A starter draws 180 A at 9.8 V. Find its power.

   Show answer

   $9.8 \times 180 \approx 1{,}760\ \text{W}$.

5. Medium A ground strap has 0.006 Ω of resistance. What voltage drop does it cause at 180 A?

   Show answer

   $180 \times 0.006 = 1.08\ \text{V}$.

6. Medium A dome light draws 0.8 A. How long can it run before a full 50 Ah battery is half discharged?

Show answer

$25/0.8 \approx 31$ h.

7. Medium With the engine idling, the voltage at the battery is 12.3 V. Is the alternator charging? Explain.

Show answer

No. A charging system should hold about 13.8–14.7 V; 12.3 V means the battery is supplying the car. Check the belt, connections and alternator.

8. Hard A battery is rated 650 CCA. The manual calls for 600 CCA. A family moving from Texas to Minnesota asks whether they should replace it with a higher-CCA battery when it wears out. Explain.

Show answer

A cold engine is harder to turn (thick oil) while a cold battery delivers less current, so in Minnesota a battery at or above the recommended CCA, possibly higher, is a wise choice; 650 meets the 600 requirement.

9. Hard Conceptual. Why must the last jumper clamp go on bare metal away from the battery?

Show answer

The last connection usually makes a small spark. A battery, especially one being charged, can give off hydrogen, which can ignite. Making the final connection away from the battery keeps the spark away from the gas.

10. Hard You are the tradesperson. A car cranks slowly every morning and starts fine after a jump. Resting voltage is 12.5 V; cranking drops to 8.9 V; charging is 14.3 V. What is the likely problem and next test?

Show answer

The charging system works. The battery may be weak (failing under load) or the connections may be poor. Clean and tighten the terminals and grounds, then load-test the battery; replace it if it fails.

11. **Challenge** A battery holds 60 Ah at 12 V. How much energy is that in watt-hours and kilowatt-hours? A small electric car stores about 60 kWh. How many car batteries is that equal to?

    Show answer

    $60 \times 12 = 720\ \text{Wh} = 0.72\ \text{kWh}$; $60 / 0.72 \approx 83$ batteries.

COMMON MISTAKES

- Replacing a fuse with a higher-rated one. The fuse protects the wire; a bigger fuse can let the wire overheat.
- Connecting the last jumper clamp to the dead battery's negative post.
- Clearing a check-engine code without writing it down or fixing the cause.
- Assuming a dead battery is always the battery. Check the charging voltage and the connections.

> **Make it a game · Voltage Drop Detective.** Your parent gives a starter drawing 200 amps through a corroded connection of 0.02 ohm. Calculate the voltage lost in 20 seconds, and the power wasted as heat. Then explain what cold-cranking amps mean. Play five scenarios with new numbers and see if you can solve each faster than before.

10.5 Routine Maintenance and Roadside Skills

OBJECTIVES

- Change a wheel safely, using wheel chocks, the correct jacking point, jack stands for any under-car work, and a star tightening pattern with a torque wrench.
- Explain the steps of an oil change and when to leave a job to a technician.
- Calculate fuel cost, depreciation and the total cost of owning a car per year and per mile.
- Describe the work, training and certification of an ASE-certified automotive technician.

> **Warm-up.** List everything you think it costs to own a car for a year besides the purchase price. Estimate each item, then add them up. Keep the list to compare with the worked example.

WATCH

How to Change a Tire (plus jacking it up)

ChrisFix · 14:21

https://www.youtube.com/watch?v=314HE4aMG-g

> **WHEN TO WATCH**
> Before the shop project. Watch for each safety step: chocks, breaking the lug nuts loose on the ground, the jacking point, the jack stand, and the star pattern.

Note: A careful, beginner-level demonstration that uses jack stands and wheel chocks.

BACKUP VIDEO

How to Change Your Oil (COMPLETE Guide)

ChrisFix · 20:29

https://www.youtube.com/watch?v=O1hF25Cowv8

With the oil-change paragraph.

KEY TERMS

lug nuts

The nuts that hold a wheel to the hub studs; tightened to a set torque in a star pattern.

jacking point

The reinforced spot on the car's body or frame, shown in the manual, where a jack may lift it safely.

jack stand

A fixed, locking stand that holds a raised car safely; a jack is only for lifting.

wheel chock

A wedge placed against a tire to keep the car from rolling.

depreciation

The loss in a car's value over time, usually its largest cost of ownership.

ASE certification

Certification from the National Institute for Automotive Service Excellence, earned by passing tests in specific areas and having hands-on work experience.

CORE IDEAS

The story. As cars filled the roads in the twentieth century, repair shops filled with mechanics of every level of skill, and customers had no way to tell a careful technician from a careless one. In 1972 the National Institute for Automotive Service Excellence (ASE) was founded as an independent nonprofit to test and certify technicians. To be certified, a technician must pass a written exam in an area such as brakes, electrical systems or engine performance and have hands-on work experience (school training can count toward part of it). A technician certified in all eight core automobile areas earns the title Master Automobile Technician, and certifications must be renewed every five years. The blue-and-white ASE sign in a shop window tells a customer that someone there has proved their knowledge.

How they figured it out. Owners and makers learned which maintenance matters from experience written into every owner's manual: oil changed on time, tires kept at the right pressure and rotated, filters replaced, fluids checked, brakes inspected. They also learned, often painfully, which jobs are dangerous. A car on a jack alone can drop without warning, so no part of a person goes under a car held only by a jack. Lug nuts tightened unevenly can warp a brake rotor or let a wheel come loose,

so they are tightened in a star pattern to a set torque. Each rule in this lesson exists because someone once got hurt or a wheel once came off.

The science. A wrench is a lever: the torque on a nut is $T = F \times L$, so an 18-inch lug wrench turns a 50-pound push into 75 lb·ft. Tightening in a star pattern draws the wheel down evenly onto the hub, like the head bolts in Lesson 10.2 and the bolted joints of Unit 1. Owning a car follows the counting-the-cost principle: the total yearly cost is depreciation plus fuel, insurance, maintenance and repairs, registration and taxes. Fuel cost is $(\text{miles}/\text{mpg}) \times \text{price per gallon}$, and dividing the total by the miles driven gives the true cost per mile, which is usually much more than the cost of gas alone.

In the shop. Changing a wheel: pull well off the road onto level, firm ground, turn on the hazard lights, set the parking brake and put the car in Park (or in gear). Chock the wheel diagonally opposite the flat. Loosen the lug nuts a half turn while the tire is still on the ground. Place the jack at the jacking point shown in the manual and raise the car until the tire clears the ground. Remove the nuts and wheel, mount the spare, and snug the nuts by hand in a star pattern. Lower the car, then tighten the nuts in a star pattern to the torque in the manual, and check them again after 50 miles. Temporary spares are usually limited to about 50 mph and short distances; read the spare's sidewall. **An oil change** needs the car raised on drive-up ramps or jack stands on level concrete with the wheels chocked: drain the warm oil, replace the drain-plug washer and torque the plug, change the filter (oil a new gasket, tighten by hand as directed), refill with the correct oil, run, check for leaks and recheck the level, and recycle the old oil and filter. **Leave to a technician:** brake hydraulics, airbags, high-voltage hybrid and EV systems, steering and suspension parts that hold the wheels on, air-conditioning refrigerant, and anything you are unsure about.

On the job. Automotive technicians diagnose and repair cars at dealerships, independent shops, fleets and their own businesses; many specialize in diesel, collision repair, transmissions or electric and hybrid vehicles. Most train at a high-school career program, a community college or a manufacturer program, then earn ASE certifications as they gain experience. Skilled technicians are in steady demand, the work pays well as skill and certifications grow, and many go on to become shop foremen, service managers and owners. It is honorable work that keeps families safe on the road.

PICTURE STUDY



Garage Mechanic near Newark, New Jersey, Marjory Collins, Office of War Information, December 1943 · Color transparency (photograph) · Library of Congress

Image: Wikimedia Commons, public domain

During the Second World War, new cars were not being built for civilians, so the cars already on the road had to be kept running for years. Mechanics like this man were essential workers; the button on his shirt shows he belonged to the government's transportation program.

Look closely

- Look at his clothes and cap. What do they tell you about his work?
- Find the coin changer on his belt. What else might this man do at a garage besides repairs?
- Find the sign behind him. What room is he standing in front of?
- Look at his face. What does it say about how he feels about his work?

Talk about it

1. Why would keeping old cars running matter so much when no new ones could be bought?
2. What qualities would make a customer trust a mechanic?
3. What would you want to ask this man about his trade?

> **Safety first.** Never put any part of your body under a car supported only by a jack; use jack stands rated for the car on level, hard ground, or drive-up ramps, and always chock the wheels. Do roadside work only where you are safely off the road; if traffic is close or fast, call for help. Let a hot engine cool before draining oil, wear safety glasses and gloves, and take used oil and filters to a recycling center. An adult supervises every step of this project.

SHOP PROJECT

Wheel Change, Oil Check and a Cost-of-Ownership Plan

With an adult, you will practice a wheel change in the driveway until you can do it safely and confidently, inspect the oil-change points on the car, and write a one-year maintenance plan and budget for the car using the owner's manual.

You will need

- A car with its owner's manual, jack, lug wrench and spare tire
- Two wheel chocks (or bricks), one jack stand rated for the car, a torque wrench and the correct socket
- Gloves, safety glasses, a flashlight, a timer
- Your vehicle fact sheet (Lesson 10.1), fluid log (10.2), tire report (10.3) and battery report (10.4)

Steps

1. On level concrete or asphalt, with the parking brake set and the car in Park, find the spare, jack and lug wrench and read the manual's wheel-change page. Locate the jacking point for the wheel you will remove.
2. Chock the wheel diagonally opposite. Loosen each lug nut about a half turn with the tire on the ground.
3. Position the jack at the jacking point and raise the car until the tire just clears the ground. Slide the jack stand under the nearest support point the manual shows as a safety backup.
4. Remove the nuts in a star pattern and the wheel. Look at the brake rotor and pads through the opening and note their condition.
5. Mount the spare (or reinstall the same wheel), and run the nuts on by hand. Snug them in a star pattern.
6. Remove the jack stand, lower the car, and tighten the nuts in a star pattern to the manual's torque with the torque wrench. Record the torque and your total time.
7. Do it a second time and try to be smoother, not faster. Record the second time.

8. Under the car (only on ramps or jack stands with an adult), use the flashlight to find the oil drain plug and the oil filter. Record the oil type, capacity and filter number from the manual. If the adult agrees and the oil is due, do the oil change together, following the manual.
9. Using the manual's schedule and your earlier reports, write a one-year maintenance plan: what is due, when (date or miles), estimated cost, and whether you or a technician will do it.
10. **Count the cost.** Build a yearly cost-of-ownership table for this car: depreciation, fuel, insurance, maintenance, registration. Find the cost per mile.

Tips

- If a lug nut will not budge, use the wrench as a lever and press with your body weight, keeping the handle level; never jump on it.
- Write down the order of the lug nuts you tightened; a star pattern on five nuts goes 1-3-5-2-4.
- Your family's insurance agent or your parents can give you a real insurance figure.

Check your work

- ☐ I changed a wheel with chocks, the correct jacking point, a jack stand backup and a star pattern torqued to specification.
- ☐ My maintenance plan follows the manual and says who will do each job.
- ☐ My cost table gives a realistic yearly cost and cost per mile.

SHOP NOTEBOOK

1. A step-by-step roadside checklist for a flat tire, written small enough to keep in the glove box.
2. Your wheel-change record: date, torque, times, rotor and pad observations.
3. Your one-year maintenance plan and cost-of-ownership table.

KEY FORMULAS

$$T = F \times L$$

$$\text{fuel cost} = \frac{\text{miles}}{\text{mpg}} \times \text{price per gallon}$$

$$\text{yearly depreciation} = \frac{\text{purchase price} - \text{resale value}}{\text{years}}$$

$$\text{cost per mile} = \frac{\text{total yearly cost}}{\text{miles per year}}$$

From history. The National Institute for Automotive Service Excellence (ASE) now certifies technicians in automobiles, medium and heavy trucks, school buses, collision repair, parts and more, and offers a certification in light-duty hybrid and electric vehicles. Hundreds of thousands of technicians hold ASE certifications.

WORKED EXAMPLES

Example 1. The manual calls for lug nuts at 80 lb·ft. With a torque wrench whose handle is held 1.5 ft from the nut, what force must you apply? With a 2-ft breaker bar, what force breaks loose a nut that needs 120 lb·ft?

Show solution

1. $F = T/L = 80/1.5 \approx 53$ lb.
2. $F = 120/2.0 = 60$ lb.
3. Pushing down with body weight on a level wrench handle, not jumping on it, gives steady, controlled force.

Answer: About 53 lb; 60 lb

Example 2. A car gets 28 mpg and is driven 12,000 miles a year. Gasoline costs $3.40 a gallon. Find the yearly fuel cost.

Show solution

1. Gallons: $12{,}000/28 \approx 429$.
2. Cost: $429 \times 3.40 \approx \$1{,}457$.

Answer: About $1,460

Example 3. A used car costs $9,000 and is expected to sell for $4,000 after 4 years. Yearly insurance is $1,600, fuel $1,457, maintenance and repairs $900, and registration $150. It is driven 12,000 miles a year. Find the yearly cost and cost per mile.

Show solution

1. Depreciation: $(9000 - 4000)/4 = \$1{,}250$ per year.
2. Total: $1250 + 1600 + 1457 + 900 + 150 = \$5{,}357$.
3. Per mile: $5357/12{,}000 \approx \$0.45$.
4. Fuel is only about a quarter of the true cost of driving.

Answer: About $5,360 a year, or about 45 cents a mile

Example 4. You are the tradesperson. A teenager calls: a front tire went flat on a busy two-lane road. What should she do, in order?

Show solution

1. Signal, slow down and pull as far off the road as possible onto level, firm ground; never stop on a curve or hill if she can roll on to a safer spot. Turn on the hazard lights.
2. Set the parking brake, put the car in Park, and get passengers out on the side away from traffic.
3. If the shoulder is narrow, traffic is fast, or she is unsure, stay safely off the road and call for roadside help.
4. If it is safe: chock the diagonal wheel, loosen the lugs on the ground, jack at the jacking point, swap the wheel, tighten in a star pattern, lower, torque, and drive slowly to a tire shop on the temporary spare.

Answer: Safety first: off the road, hazards on, parking brake, passengers clear, then the wheel change only if it is safe.

PRACTICE

1. Easy Why must you loosen the lug nuts before you jack up the car?

Show answer

With the tire on the ground, friction with the road keeps the wheel from turning while you apply force. In the air, the wheel would just spin.

2. Easy Which wheel should you chock when changing the right front tire?

Show answer

The left rear wheel, diagonally opposite.

3. Easy What is the torque on a nut if you push 60 lb at the end of a 1.25-ft wrench?

Show answer

$60 \times 1.25 = 75$ lb·ft.

4. Medium A car gets 32 mpg and is driven 10,000 miles a year with gas at \$3.20. Find the yearly fuel cost.

Show answer

$10{,}000/32 = 312.5$ gal; $312.5 \times 3.20 = \$1{,}000$.

5. Medium A car bought for \$24,000 is worth \$13,200 after 3 years. Find the yearly depreciation and the percent of value lost.

Show answer

$10{,}800/3 = \$3{,}600$ per year; $10{,}800/24{,}000 = 45\%$.

6. Medium A temporary spare is limited to 50 mph. How long does a 90-mile drive to a tire shop take at that limit?

Show answer

$90/50 = 1.8$ h, about 1 hour 48 minutes.

7. Medium Conceptual. Why are lug nuts tightened in a star pattern rather than around the circle?

Show answer

A star pattern pulls the wheel down evenly and centers it on the hub; going around the circle can cock the wheel to one side, leaving some nuts loose and possibly warping the rotor.

8. Hard Compare yearly costs: Car A costs $8,000, resells for $3,000 after 5 years, gets 25 mpg, and needs $1,100 a year in repairs. Car B costs $16,000, resells for $8,000 after 5 years, gets 35 mpg, and needs $400 a year. Both drive 12,000 miles at $3.40 a gallon; insurance is $1,400 for A and $1,700 for B. Which is cheaper per year?

Show answer

A: $1000 + 1632 + 1100 + 1400 = \$5{,}132$. B: $1600 + 1166 + 400 + 1700 = \$4{,}866$. Car B is about $270 a year cheaper.

9. Hard You are the tradesperson. A customer had new tires installed yesterday and now hears a clicking that gets faster with speed, and the steering wheel shakes. What do you check first?

Show answer

Stop driving and check the lug nuts at once; loose nuts can let a wheel come off. Retorque in a star pattern to specification. Then check for a stone in a tread or a lost balance weight.

10. Hard Luke 14:28 speaks of counting the cost before building a tower. A student earns $600 a month. Using the cost-per-mile figure from Worked Example 3 (about $0.45) and 9,000 miles a year, what share of his income would a car take?

Show answer

Yearly cost $0.45 \times 9000 \approx \$4{,}050$; income $7,200; about 56% of his income, which is a strong reason to count the cost carefully.

11. Challenge An oil change costs $40 in parts if you do it and $85 at a shop. A drive-up ramp set, drain pan and filter wrench cost $95 together. You do three oil changes a year. After how many changes have the tools paid for themselves?

Show answer

Savings $45per change; $95/45 \approx 2.1$, so after the third change (the first year).

COMMON MISTAKES

- Getting under a car held only by a jack, even “for a second.”
- Jacking at the wrong point, which can bend the floor, crack a plastic panel or let the car slip.
- Tightening lug nuts with an impact gun or by guesswork instead of a torque wrench.

- Counting only the gas when figuring what a car costs.

> **Make it a game · Wheel Change Planner.** On paper only, put the steps of changing a wheel in the right order: park on level ground, set the brake, chock the wheel, loosen lug nuts, jack at the proper point, remove and mount, star-pattern tighten, torque. Your parent shuffles the cards; you sort them in 60 seconds. Beat your time.

> **Scripture.** “For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he have sufficient to finish it?” (Luke 14:28, KJV)
>
> A car is a great help and a real cost. Counting it honestly before buying, and maintaining what you own, is the wisdom Jesus describes.

UNIT 10

Auto Mechanics

A car is a collection of the systems you have studied all year: fasteners and torque, adhesives, electrical circuits, heat and fluids, and the engine of Unit 9. In this unit you will see how they work together, beginning with Henry Ford's Model T and the moving assembly line and ending with the routine jobs every car owner should be able to do safely.

You will learn how oil, coolant and brake fluid protect the engine and the driver; how Pascal's principle stops a two-ton vehicle with a push of the foot; how to read a tire; how Charles Kettering's electric self-starter made the modern car possible; and how to test a battery, read diagnostic codes, change a wheel and count the real cost of owning a car. You will also meet the ASE-certified technician, whose skilled trade keeps families safe on the road.

PREREQUISITES

- Unit 1: torque, preload and bolted joints
- Unit 5: Ohm's law, power and the multimeter
- Unit 9: the four-stroke cycle, ignition and the diagnostic habit
- Access to a family car and its owner's manual, with an adult for every hands-on project

MASTERY CHECKLIST

- ☐ I can name a car's systems and find their main parts, and explain how the moving assembly line changed manufacturing.
- ☐ I can check a car's fluids correctly, read an oil grade, and explain how the cooling system and pressure cap work.
- ☐ I can calculate hydraulic brake force, kinetic energy and stopping distance, and inspect tires for pressure, tread, wear and age.
- ☐ I can test a battery and charging system, read OBD-II codes, map fuses, and explain the safe jump-start order.
- ☐ I can change a wheel safely with chocks, the jacking point, jack stands and a torqued star pattern, and calculate the cost of owning a car.

OPTIONAL KITS FOR THIS UNIT

- **Innova OBD-II code readers**: A maker of consumer code readers and scan tools; a basic reader is enough for Lesson 10.4. Many auto-parts stores also lend readers free or read codes for you.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

10.1	**How a Car Works: From the Model T to Today**	3 sessions of 50 minutes
10.2	**The Engine and Its Fluids**	3 sessions of 50 minutes
10.3	**Brakes, Tires and Steering**	3 sessions of 50 minutes
10.4	**The Electrical System and Diagnostics**	3 sessions of 50 minutes
10.5	**Routine Maintenance and Roadside Skills**	3 sessions of 50 minutes

Unit 10 test

Time allowed: 50 minutes. Calculators are allowed. Show your work and units for every calculation. The test is worth 100 points.

1. **4 pts**
   Name five major systems of a car and give the job of each in a few words.

2. **6 pts**
   Chassis assembly fell from 12.5 hours to 1.5 hours. Find the productivity ratio and the percent decrease in time.

3. **4 pts**
   Explain what the numbers in 0W-20 mean.

4. **7 pts**
   Coolant flows at 0.90 kg/s and warms by 9 °C (c = 3.5 kJ/kg·K). Find the heat removed. Why must the radiator cap never be opened when hot?

5. **6 pts**

   A cooling system holds 9 qt with a 40% mix. You drain 3 qt and add 3 qt of pure concentrate. What is the new mix?

6. **8 pts**

   A master cylinder piston is 0.875 in in diameter and a caliper piston 2.25 in. The master cylinder receives 300 lb. Find the line pressure and the force on the caliper piston.

7. **7 pts**

   A 1,400 kg car travels at 25 m/s. Find its kinetic energy and its braking distance with $\mu = 0.70$.

8. **6 pts**

   Find the diameter of a 235/65R17 tire in inches.

9. **6 pts**

   A tire's tread is 2/32 in on both edges and 5/32 in in the center. Diagnose the wear and state what must be done.

10. **6 pts**

    A starter draws 160 A at 10.2 V. Find its power. A terminal with 0.008 Ω resistance is in the circuit: what voltage does it waste?

11. **6 pts**

    A car's parasitic draw is 35 mA. How many days can a 70 Ah battery sit before falling to half charge?

12. **6 pts**

    List the four jumper-cable connections in order and explain why the last one is made where it is.

13. **4 pts**

    A reader shows code P0302. What does it mean, and why is it not yet a diagnosis?

14. **6 pts**

    Lug nuts must be torqued to 90 lb·ft. What force is needed on a torque wrench held 1.5 ft from the nut? Why is a star pattern used?

15. **7 pts**

A car costs $14,000 and resells for $6,000 after 4 years. It gets 30 mpg over 11,000 miles a year with gas at $3.30. Insurance is $1,500, maintenance $700 and registration $120 a year. Find the yearly cost and cost per mile.

16. **5 pts**

You are the tradesperson. A customer says the brake pedal goes nearly to the floor and the brake warning light is on. What do you tell them, and what do you check?

17. **6 pts**

Short essay. Charles Kettering's self-starter, Ford's assembly line and the hydraulic brake each solved a real problem for ordinary drivers. Choose one, explain the problem and the engineering solution, and say what it teaches a young tradesperson about how to approach their own work.

ANSWER KEY

1. Engine: makes power. Drivetrain: carries power to the wheels. Brakes: turn motion into heat to stop. Steering and suspension: direct the car and keep tires on the road. Electrical: starts the engine and powers ignition, lights and computers. (Body and safety: protects occupants.)
2. $12.5/1.5 \approx 8.3$; $11/12.5 = 88\%$decrease.
3. 0W: the oil's cold-temperature (winter) flow rating, very easy-flowing when cold. 20: its viscosity grade at the 100 °C operating temperature.
4. $0.90 \times 3.5 \times 9 \approx 28.4$ kW. The system is pressurized and above the normal boiling point; opening the cap lets coolant flash to steam and spray out.
5. Remaining glycol $0.40 \times 6 = 2.4$ qt; plus 3 is 5.4 qt in 9 qt, or 60%.
6. $A_1 = 0.601$ in^2; $p \approx 499$ psi; $A_2 = 3.98$ in^2; $F_2 \approx 1{,}990$ lb.
7. $KE = 437{,}500$ J; $d = 625/13.7 \approx 45.5$ m.
8. $2(235 \times 0.65) + 17(25.4) = 305.5 + 431.8 = 737$ mm ≈ 29.0 in.
9. Edge wear means the tire was run underinflated. At 2/32 in it is at the legal limit and must be replaced; check the pressures on the other tires and keep them at the placard value.
10. $P \approx 1{,}630$ W; $V = 160 \times 0.008 = 1.28$ V.
11. $35/0.035 = 1000$ h ≈ 42 days.
12. Red to dead +, red to good +, black to good −, black to bare metal on the dead car's engine away from the battery. The last connection may spark, and batteries can give off hydrogen, so the spark is kept away from the battery.
13. A misfire detected in cylinder 2. The cause could be a plug, coil, injector, vacuum leak or low compression; the technician must test to find which.
14. $90/1.5 = 60$ lb. A star pattern draws the wheel down evenly and centers it on the hub.
15. Depreciation \$2,000; fuel $(11{,}000/30)(3.30) = \$1{,}210$; total \$5,530; per mile $\approx \$0.50$.
16. Do not drive the car; have it towed or inspected where it sits. Check the brake-fluid level and look for leaks at lines, hoses, calipers and wheel cylinders, then check the master cylinder.
17. Model answer (on the starter): hand cranking was hard and dangerous, and many said an electric starter would be too big. Kettering saw that a motor run for only a few seconds could be heavily overloaded, built a small motor-

generator, tested it until it worked, and made the car something anyone could start. A tradesperson learns to state the problem clearly, question assumptions, test carefully, and keep the customer's safety and needs at the center of the work.

PORTFOLIO PIECE: A VEHICLE INSPECTION AND MAINTENANCE PLAN

Prepare a complete inspection report and one-year plan for a real car: the vehicle fact sheet, fluid log, tire report, battery and charging test with any trouble codes, and a record of a supervised wheel change torqued to specification.

Finish with a one-year maintenance plan from the owner's manual (what, when, cost, who does it), a cost-of-ownership table with cost per mile, and a glove-box roadside checklist.

LOOK FOR	WHAT IT MEANS
Safety	Every hands-on step done with an adult, wheels chocked, jack stands or ramps for any under-car work, engine run only outdoors, hot caps never opened, fluids recycled.
Inspection data	Fluid levels and conditions, tire pressures, tread depths, date codes, battery voltages and codes recorded with units and dates.
Diagnosis	Findings are explained with the unit's science, with clear recommendations and a sensible line between owner jobs and technician jobs.
Plan and budget	Maintenance plan follows the manual; cost-of-ownership table is complete and realistic.
Presentation	Neat, organized report that the car's owner could actually use.

COURSE EXAM

Midterm Exam

Covers Units 1–5. Time: 100 minutes.

You have 100 minutes. A scientific calculator is allowed. Show your work for every calculation: the formula, the numbers with units and the answer with its unit; correct setup earns partial credit even if the arithmetic slips. Use $K = 0.20$ for dry steel threads unless told otherwise. For “you are the tradesperson” questions, give your reasoning and the safe course of action. Answer the essay in complete sentences. The exam has 26 problems worth a total of 100 points.

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1. **3 pts** **Lesson 1.1**

   A metric bolt is marked M10 × 1.5. (a) About how many threads per inch is that? (b) How many full turns does a nut need to travel 30 mm along it? (c) A 3/8-16 nut (3/8 in ≈ 9.5 mm) seems close in size. Why will it not thread on?

2. **5 pts** **Lesson 1.3**

   A 7/16-14 Grade 5 bolt (proof strength 85,000 psi) is to be preloaded to 75% of its proof load. (a) Find its tensile stress area with $A_t = 0.7854\,(D - 0.9743/n)^2$, its proof load and the target preload. (b) Find the dry torque with $T = KDF$ and $K = 0.20$. (c) A mechanic oils the threads ($K = 0.15$) but still applies the dry torque. What preload results, and what torque should he have used?

3. **4 pts** **Lesson 1.3**

   You are the tradesperson. The bolt holding a trailer’s ball mount, fitted with a split lock washer, keeps working loose on rough roads, although the owner tightens it “good and tight” by feel every week. Using what Junker’s test showed, explain why, and say what you would do.

4. **4 pts** **Lesson 1.4**

   A 3/8 in Grade 8 bolt (tensile strength 150,000 psi) is the pin of a clevis in double shear, with the smooth shank across both shear planes. Estimate its ultimate shear capacity, using $\tau_u \approx 0.6\,S_u$, and the allowable load with a factor of safety of 4. What happens to the capacity if the threads cross a shear plane?

5. **3 pts** **Lesson 1.4**

   (a) A bolt head has three radial lines. What grade is it, and what are its proof and tensile strengths? (b) What does “10.9” on a metric bolt mean? (c) A farmer replaces a broken Grade 8 hitch bolt with an unmarked hardware-store bolt of the same size. What is wrong with that?

6. **3 pts** **Lesson 2.1**

   An aluminum lap-shear coupon 25 mm wide with a 20 mm overlap breaks at 6.0 kN. Find the average shear strength in MPa and psi. Both broken faces are covered with a layer of hardened glue. Name the failure mode and what it tells you.

7. **3 pts** **Lesson 2.3**

   A marine epoxy mixes 5:1 resin to hardener by volume. (a) How much of each part makes 90 mL of mix? (b) Its pot life is 24 minutes at 21 °C. Estimate the pot life at 31 °C and at 11 °C. (c) Why should you pour the mixed batch into a shallow tray?

8. **4 pts** **Lesson 2.4**

   You are the tradesperson. A customer glued plastic laminate onto a plywood countertop with solvent contact cement. A week later the laminate has soft bubbles in the middle and is lifting at one edge. Diagnose the likely causes and describe the right method, including one safety rule.

9. **4 pts** **Lesson 2.5**

   An adhesive has an average lap-shear strength of 15 MPa and a peel strength of 2.5 N per mm of width. A joint is 40 mm wide with a 20 mm overlap. Compare its capacity in shear and in peel, and give two ways a designer keeps peel out of a bonded joint.

10. **3 pts** **Lesson 2.1**

    Water beads up into tall drops on a polyethylene bin you need to glue. Explain what that tells you about wetting and surface energy, and give two practical ways to get a joint that holds.

11. **4 pts** **Lesson 3.1**

(a) A red-oak sample weighs 94.5 g as cut and 81.0 g oven-dry. Find its moisture content. Is it ready for indoor furniture? (b) A 32-in-wide flat-sawn red-oak tabletop ($C_T = 0.00369$) goes from 7% to 10% moisture content. How much does it widen? How much if it were quartersawn ($C_R = 0.00158$)? How must it be fastened?

12. **3 pts** **Lesson 3.2**

Using $p = F/A$, explain why a dull chisel is more dangerous than a sharp one, and connect your answer to Ecclesiastes 10:10, where a blunt iron makes one “put to more strength.”

13. **4 pts** **Lesson 3.3**

A 10-in (0.254 m) table-saw blade turns at 4,800 rpm. (a) Find the rim speed in m/s and mph (1 m/s = 2.237 mph). (b) A sound meter reads 94 dBA at the saw. Using the NIOSH rule $t = 8\ \text{h} \div 2^{(L-85)/3}$, how long can you work there without hearing protection?

14. **4 pts** **Lesson 3.3**

You are the shop supervisor. A student has removed the riving knife and is about to crosscut a 5-in piece off a board on the table saw, using the rip fence as a length stop while pushing the board with the miter gauge. Say what you do and why, in order.

15. **3 pts** **Lesson 3.4**

A chair’s leg-to-apron joint must last for generations. Explain why a glued end-grain butt joint would fail there and why a mortise and tenon works, naming both the glue surfaces and the mechanical lock.

16. **4 pts** **Lesson 4.1**

A house wall puts 2,600 lb on each linear foot of footing, and the soil is rated 2,000 psf. (a) Find the minimum footing width and choose a standard width. (b) The perimeter footing is 140 ft long, 16 in wide and 10 in deep. How much concrete should be ordered, with 10% extra?

17. **4 pts** **Lesson 4.2**

Floor joists of 2×10 lumber (1.5 × 9.25 in) at 16 in on center span 13 ft and carry 50 psf. Find the load per foot on one joist, the maximum moment $M = wL^2/8$, the section modulus $S = bd^2/6$ and the bending stress. Is it reasonable against about 1,000 psi allowable?

18. **4 pts** **Lesson 4.3**

A house measures 44 × 30 ft in plan, including the overhangs, and has an 8:12 gable roof. Find the roof angle, the slope factor, the roof area, and the number of squares and bundles of shingles to buy with 10% for waste.

19. **4 pts** **Lesson 4.4**

A bedroom has 140 ft² of net outside wall at an effective R-12 and a 20 ft² window with $U = 0.30$. It is 70 °F inside and 10 °F outside. Using $Q = A\,\Delta T/R$ (or $UA\,\Delta T$), find the total heat loss. How much would it be if the window were old single glass at R-1?

20. **3 pts** **Lesson 4.5**

You are the plumber. In one house: (a) the basement floor drain, which is almost never used, smells of sewer gas; (b) the kitchen sink gurgles and its trap sucks dry whenever the washing machine drains. Diagnose each and give the fix.

21. **4 pts** **Lesson 5.2**

A 1,500 W space heater will run all evening along with 200 W of lamps and a computer. (a) Find the current at 120 V. (b) Check it against the 80 percent continuous-load rule on a 15 A circuit and on a lightly loaded 20 A circuit. (c) What if the heater is set to its 750 W low setting on the 15 A circuit?

22. **4 pts** **Lesson 5.2**

A 12 AWG circuit (1.59 Ω per 1,000 ft) runs 100 ft from the panel to a shop receptacle feeding a 15 A load at 120 V. Find the voltage drop and percent drop. Repeat for 10 AWG (1.00 Ω per 1,000 ft). Which meets the 3 percent guideline?

23. **4 pts** **Lesson 5.3**

(a) A GFCI measures 9.250 A on the hot and 9.243 A returning on the neutral. Does it trip? Why? (b) A person with wet hands (2,400 Ω) touches a 120 V hot while grounded. Find the current, and say whether a 15 A breaker or a GFCI would trip.

24. **4 pts** **Lesson 5.4**

You are the young tradesperson. A homeowner's 15 A garage circuit, wired with 14 AWG cable, keeps tripping. He wants to swap in a 20 A breaker and asks you to take off the panel cover so the two of you can "just look at the wiring." What do you tell him?

25. **3 pts** **Lesson 5.4**

A box is marked 20.3 in^3. It will hold two 12-2 NM cables with ground and one 12-3 cable with ground, one duplex receptacle and internal cable clamps. Using 2.25 in^3 per count for 12 AWG, does it pass box fill?

26. **8 pts** **Lesson 1.4**

Short essay (one or two paragraphs). The Hyatt Regency walkways fell after a "small" change to a connection was approved without a calculation, and Deuteronomy 22:8 required a parapet before anyone could fall. Using examples from at least three of Units 1–5 (for example a bolt grade, a lubricated torque, a glue chosen for a peel load, a notched joist, a larger breaker on small wire), explain why a tradesperson must never make an unchecked substitution, and describe what a responsible worker does instead.

ANSWER KEY

1. (a) $n = \dfrac{25.4\ \text{mm/in}}{1.5\ \text{mm}} \approx 16.9$ threads per inch. (b) $30\ \text{mm} \div 1.5\ \text{mm/turn} = 20$ turns. (c) The pitch of 3/8-16 is $25.4/16 = 1.59$ mm, not 1.5 mm. After 10 threads the two helixes are $10 \times (1.59 - 1.50) \approx 0.9$ mm out of step, more than half a thread, so the nut binds after a turn or two.

2. (a) $A_t = 0.7854\,(0.4375 - 0.0696)^2 = 0.7854\,(0.3679)^2 \approx 0.1063\ \text{in}^2$. Proof load: $85{,}000\ \text{psi} \times 0.1063\ \text{in}^2 \approx 9{,}040$ lb. Preload: $0.75 \times 9{,}040 \approx 6{,}780$ lb. (b) $T = 0.20 \times 0.4375\ \text{in} \times 6{,}780\ \text{lb} \approx 593$ in·lb; $593 \div 12 \approx 49$ ft·lb. (c) $F = \dfrac{593\ \text{in·lb}}{0.15 \times 0.4375\ \text{in}} \approx 9{,}040$ lb, right at the proof load, so the bolt may stretch permanently. Correct oiled torque: $T = 0.15 \times 0.4375 \times 6{,}780 \approx 445$ in·lb ≈ 37 ft·lb.

3. Junker showed that sideways slip of a joint lets thread and head friction let go for an instant, so the nut backs off a little on each cycle; split lock washers do almost nothing to stop it. Tightening by feel gives an unknown, probably low, preload, so the plates slip. Fix: replace any stretched or worn bolt with the specified grade, tighten to the maker's torque with a torque wrench so the preload clamps the plates hard enough that they do not slip, and replace the split washer with a nylon-insert locknut, threadlocker or a wedge-locking washer pair (or a castle nut and cotter pin where the design allows).

4. Shank area: $A = \frac{\pi}{4}(0.375\ \text{in})^2 \approx 0.110\ \text{in}^2$. Shear strength: $\tau_u \approx 0.6 \times 150{,}000\ \text{psi} = 90{,}000$ psi. Two planes: $F = 90{,}000\ \text{psi} \times 0.110\ \text{in}^2 \times 2 \approx 19{,}900$ lb. Allowable: $19{,}900\ \text{lb} \div 4 \approx 4{,}970$ lb. If threads cross a shear plane, only the smaller root area resists there, so the capacity drops sharply; choose the bolt length so threads stay out of the shear planes.

5. (a) Grade 5: proof 85,000 psi, tensile 120,000 psi. (b) Tensile strength about 1,000 MPa and yield about 90% of that, 900 MPa. (c) An unmarked bolt is Grade 2, with a proof strength of 55,000 psi, less than half of Grade 8's 120,000 psi. A replacement must be the same grade or better, with a nut of matching grade.

6. Area: $A = 25\ \text{mm} \times 20\ \text{mm} = 500\ \text{mm}^2$. Stress: $\tau = \dfrac{6{,}000\ \text{N}}{500\ \text{mm}^2} = 12.0\ \text{MPa}$; $12.0 \times 145 \approx 1{,}740$ psi. Glue on both faces is cohesive failure: the bond to the metal held, and the glue itself was the weakest link.

7. (a) Resin: $90\ \text{mL} \times \frac{5}{6} = 75$ mL; hardener: $90\ \text{mL} \times \frac{1}{6} = 15$ mL. (b) The rate roughly doubles every 10 °C: about $24 \div 2 = 12$ min at 31 °C and $24 \times 2 = 48$ min at 11 °C. (c) The cure is exothermic; a thin layer has far more surface per

milliliter to lose heat, so it stays cool and workable, while a deep cup heats itself and can run away.

8. Likely the parts were pressed together before the solvent had evaporated (trapped solvent leaves a soft bond and blisters), or one surface was coated thinly or not at all, or the laminate was not rolled down firmly. Right method: coat both surfaces evenly, let both films dry until they are dry to the touch, align the laminate carefully (it grabs at once and cannot be moved), then press it down with a J-roller from the center outward. Safety: solvent vapors are flammable, so ventilate well and put out every flame and pilot light (or use a water-based cement).

9. Shear: $15\ \text{N/mm}^2 \times (40 \times 20)\ \text{mm}^2 = 15 \times 800 = 12{,}000\ \text{N}$ (an upper estimate). Peel: $2.5\ \text{N/mm} \times 40\ \text{mm} = 100\ \text{N}$. Ratio: $12{,}000 \div 100 = 120$. Keep peel out by designing the joint to carry shear or compression (overlap, not butt; a stiff, wide part), and by adding a screw or rivet at the ends of the overlap as a peel stopper.

10. Beading means a contact angle near or above 90°: polyethylene has a low surface energy (about 31 mN/m), lower than the surface tension of most liquid adhesives (about 35–45 mN/m), so they cannot spread and make molecular contact. Options: abrade it and use a primer or adhesive system made for polyolefins (or a quick flame treatment by an experienced adult), or skip glue and use a mechanical fastener such as bolts or rivets through a backing plate.

11. (a) Water: $94.5 - 81.0 = 13.5\ \text{g}$; $MC = \dfrac{13.5\ \text{g}}{81.0\ \text{g}} \times 100\% \approx 16.7\%$. Too wet: indoor furniture should be about 6–8%. (b) Flat-sawn: $\Delta W = 32\ \text{in} \times 0.00369 \times 3 \approx 0.35\ \text{in}$. Quartersawn: $32\ \text{in} \times 0.00158 \times 3 \approx 0.15\ \text{in}$. Fasten it with slotted cleats, metal clips or screws in slotted holes so it can move across its width.

12. A dull edge is wider, so the same push is spread over a larger area and gives far less pressure at the edge. To reach the pressure needed to sever wood fibers, you must push much harder; the tool then crushes and tears, resists, and slips suddenly, and the extra force carries your hand into the edge's path. Ecclesiastes says the same thing: with a blunt iron, more force is needed for the same cut.

13. (a) $n = 4{,}800 \div 60 = 80\ \text{rev/s}$; $v = \pi D n = \pi(0.254\ \text{m})(80\ \text{s}^{-1}) \approx 63.8\ \text{m/s}$; $63.8 \times 2.237 \approx 143\ \text{mph}$. (b) $t = \dfrac{8\ \text{h}}{2^{(94-85)/3}} = \dfrac{8\ \text{h}}{2^3} = 1\ \text{h}$. Wear hearing protection for any longer exposure.

14. Calmly have him stop and switch off the saw (without startling him), wait for the blade to stop and unplug it. Explain the danger: with the fence and miter gauge used together, the short offcut is trapped between the blade and the fence, and

the rising back teeth can catch it and throw it back at him (kickback), and with no riving knife nothing keeps the kerf from closing on the blade. Reinstall the riving knife and guard. Set up a safe cut: a stop block clamped to the fence ahead of the blade (so the offcut is free once cut) or a crosscut sled. Have him make the cut standing to the side of the blade line, with you beside him.

15. End grain is a bundle of open cell ends that wick the glue away and give almost no surface to grip, so a butt joint fails at a small fraction of long-grain strength. A mortise and tenon gives long-grain to long-grain glue surfaces on the tenon's cheeks, where good glue is stronger than the wood beside it, and its shoulders bear against the leg to resist racking even if the glue ages. A draw-bored peg can add a lasting mechanical lock.

16. (a) $b = \dfrac{2{,}600\ \text{lb/ft}}{2{,}000\ \text{lb/ft}^2} = 1.30\ \text{ft} = 15.6\ \text{in}$; use a 16-in footing. (b) $V = 140\ \text{ft} \times 1.333\ \text{ft} \times 0.833\ \text{ft} \approx 155.6\ \text{ft}^3$; $155.6 \div 27 \approx 5.76\ \text{yd}^3$; with 10% extra $\approx 6.34\ \text{yd}^3$, so order about 6½ yd³.

17. Load: $w = 50\ \text{psf} \times 1.333\ \text{ft} \approx 66.7\ \text{lb/ft}$. Moment: $M = \dfrac{66.7 \times 13^2}{8} \approx 1{,}409\ \text{ft·lb} \approx 16{,}900\ \text{in·lb}$. Section modulus: $S = \dfrac{1.5 \times 9.25^2}{6} \approx 21.4\ \text{in}^3$. Stress: $f_b = 16{,}900 \div 21.4 \approx 790\ \text{psi}$, under 1,000 psi, so it is reasonable for strength; the span table also checks deflection.

18. Angle: $\theta = \arctan(8/12) \approx 33.7°$. Slope factor: $\sqrt{1 + (8/12)^2} \approx 1.202$. Plan area: $44 \times 30 = 1{,}320\ \text{ft}^2$; roof area: $1{,}320 \times 1.202 \approx 1{,}587\ \text{ft}^2 = 15.9$ squares. With 10%: $15.9 \times 1.10 \approx 17.5$, so buy 18 squares $= 18 \times 3 = 54$ bundles.

19. $\Delta T = 60\ °\text{F}$. Wall: $Q = \dfrac{140 \times 60}{12} = 700\ \text{BTU/h}$. Window: $Q = 0.30 \times 20 \times 60 = 360\ \text{BTU/h}$. Total: 1,060 BTU/h. With single glass the window alone loses $20 \times 60 \div 1 = 1{,}200\ \text{BTU/h}$, so the total is 1,900 BTU/h.

20. (a) The floor drain's trap seal (only 2–4 in of water) has evaporated, letting sewer gas through. Pour water in to refill it, and add a trap primer or seal for a drain that is seldom used. (b) The rush of water from the washer is siphoning the sink's trap because the vent is blocked or missing; the vent must keep the drain at outdoor air pressure. Clear the vent (for example at the roof) or add a proper vent; new venting is a plumber's job, often with a permit.

21. (a) $I = \dfrac{1{,}700\ \text{W}}{120\ \text{V}} \approx 14.2\ \text{A}$. (b) 15 A circuit: limit $0.80 \times 15\ \text{A} = 12\ \text{A}$ (1,440 W), so 14.2 A is too much. 20 A circuit: limit $0.80 \times 20\ \text{A} = 16\ \text{A}$ (1,920 W), so 14.2 A is acceptable. (c) $950\ \text{W} \div 120\ \text{V} \approx 7.9\ \text{A}$, under 12 A, so the low setting is acceptable.

22. Round trip: $2 \times 100 = 200$ ft. 12 AWG: $R = 1.59 \times 200/1{,}000 \approx 0.318\ \Omega$; $V = 15\ \text{A} \times 0.318\ \Omega \approx 4.8\ \text{V}$; $4.8 \div 120 \approx 4.0\%$. 10 AWG: $R = 1.00 \times 200/1{,}000 = 0.200\ \Omega$; $V = 15 \times 0.200 = 3.0\ \text{V}$; $3.0 \div 120 = 2.5\%$. Only 10 AWG meets 3 percent; larger wire on the 20 A breaker is always permitted.

23. (a) Leakage: $9.250 - 9.243 = 0.007\ \text{A} = 7\ \text{mA}$, above the 4–6 mA trip level, so it trips: that current is leaving by some other path, perhaps a person. (b) $I = \dfrac{120\ \text{V}}{2{,}400\ \Omega} = 0.050\ \text{A} = 50\ \text{mA}$: above the let-go level and dangerous to the heart. The 15 A breaker will not trip (50 mA is far below 15 A); the GFCI will, because 50 mA leaves through the person instead of returning on the neutral.

24. No to both. The breaker protects the wire: 14 AWG belongs on 15 A, and a 20 A breaker would let it carry up to 20 A, about 78% more I^2R heat inside the walls, without tripping. Tripping means the circuit is overloaded or faulty: move loads to other circuits, or have a new 20 A circuit with 12 AWG wire installed. The panel cover is never removed by a student or untrained homeowner; even with the main off, the service conductors are live. Panel work and new circuits are for a licensed electrician with a permit, and no one works on anything energized.

25. Insulated conductors: $2 + 2 + 3 = 7$; all grounds together: 1; device (double count): 2; internal clamps: 1. Total $= 11$. Required: $11 \times 2.25\ \text{in}^3 = 24.75\ \text{in}^3 > 20.3\ \text{in}^3$. It fails; use a larger box.

26. A strong answer: explains that the Hyatt change from continuous rods to two rods doubled the load on the fourth-floor connections, which were already below code, and 114 people died; that any substitution changes the load path or the margin of safety even when it looks minor; gives three specific examples with the reason each is dangerous (an unmarked Grade 2 bolt has less than half a Grade 8's proof strength; oiling threads at a dry torque can stretch a bolt to proof load; glue loaded in peel holds about a hundredth of its shear strength; a notch in a joist's bottom edge at mid-span cuts its tension side; a 20 A breaker lets 14 AWG wire overheat without tripping); and describes the responsible habit: trace the load path, calculate or look up the new capacity, compare with the code and a factor of safety, ask the designer, a licensed professional or the building department when unsure, document the approval, and refuse to proceed until the change is shown to be safe, which is the preventive spirit of Deuteronomy's parapet.

COURSE EXAM

Final Exam

Covers Units 1–10. Time: 120 minutes.

You have 120 minutes. A scientific calculator is allowed. Show your work for every calculation, with units in every line; correct setup earns partial credit. Use 1 W = 3.412 BTU/h, 1 ton = 12,000 BTU/h and $g = 9.81\ \text{m/s}^2$. For "you are the tradesperson" questions, explain your reasoning and choose the safe course of action. Answer the essay in complete sentences. The exam has 29 problems worth a total of 100 points.

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1. **4 pts** **Lesson 1.3**

   A car's 7/16-20 wheel studs are torqued to 65 ft·lb. With $K = 0.20$, find the clamp force on each stud and the total on a five-lug wheel. Give the star tightening order, and say how the car must be supported while you torque the nuts.

2. **3 pts** **Lesson 1.5**

   You are the tradesperson. A homeowner attached a new deck's joist hangers to pressure-treated lumber with ordinary electroplated nails, and the ledger board to the house with nails only. Name the two problems and the fixes.

3. **4 pts** **Lesson 2.3**

   An epoxy mixes 3:1 resin to hardener by volume. The resin's density is 1.17 g/mL and the hardener's 0.97 g/mL. Find the mix ratio by weight and the grams of each part for 120 g of mix. Why does adding extra hardener not make it cure harder?

4. **3 pts** **Lesson 2.5**

   Tests on 25 mm-wide lap joints show that doubling the overlap from 12.5 mm to 25 mm raises the strength only about 40 percent. Explain why, and name two design changes that strengthen a bonded joint more effectively.

5. **4 pts** **Lesson 3.5**

   A 10-lb step stool has its weight acting 6.0 in inside the line of its feet. A 180-lb person steps with full weight 0.4 in outside the foot line, on the overhanging top. Take moments about the foot edge: does the stool tip? How far outside the foot line could the person stand before it tips, and what is the right fix?

6. **3 pts** **Lesson 3.3**

   Explain what a riving knife does on a table saw, why the back of the blade causes kickback while the front does not, and where you should stand while ripping.

7. **4 pts** **Lesson 4.4**

   A 2×6 wall has 23% framing with a through-stud value of R-8.0 and 77% cavity at R-23.0. Combine the parallel paths by their U-factors to find the whole-wall R-value. Then find the heat loss through 200 ft² of it when $\Delta T = 55\ ^\circ\text{F}$, using $Q = A\,\Delta T / R$.

8. **4 pts** **Lesson 4.5**

   Water reaches the basement meter at 50 psi. (a) Find the static pressure at a shower head 22 ft higher. (b) What is the greatest height water at 50 psi could rise? (c) A drain runs 16 ft to the stack at ¼ in per foot. How far does it fall?

9. **4 pts** **Lesson 5.1**

   An electric dryer is rated 5,400 W. (a) Find its current at 240 V and what it would be at 120 V. (b) Its cable has a resistance of 0.060 Ω. Compare the heat lost in the cable at each voltage, and explain why large appliances use 240 V.

10. **3 pts** **Lesson 5.4**

    A qualified adult is replacing a receptacle with you watching. List the steps of live–dead–live testing and what each guards against, and explain why a non-contact tester alone is not enough.

11. **4 pts** **Lesson 6.3**

    A 2.5-ton air conditioner draws 2,500 W. Find its capacity in BTU/h (12,000 BTU/h per ton), its EER, its COP and the heat rejected at the outdoor condenser. Explain what “moves heat, not makes cold” means for this unit.

12. **3 pts** **Lesson 6.5**

    A furnace has an input of 90,000 BTU/h at 95% AFUE. A technician measures 1,400 CFM with return air at 68 °F and supply air at 123 °F. Find the rated output and the heat the air is carrying, using $\dot{Q} = 1.08 \times \text{CFM} \times \Delta T$. Is the airflow about right?

13. **3 pts** **Lesson 6.3**

You are the technician. In July a homeowner finds the indoor coil caked with ice, the house warm and the filter black with dust. He has bought a can of refrigerant online and asks you to help him “top it off.” What do you tell him and what do you do?

14. **3 pts** **Lesson 6.4**

Find the cost of 1 million BTU of delivered heat from (a) electric resistance heat at \$0.14/kWh, (b) a heat pump with a seasonal COP of 3.0 at the same price, and (c) a 96% gas furnace at \$1.30 per therm (1 kWh = 3,412 BTU).

15. **4 pts** **Lesson 7.2**

A welder runs a MIG bead at 25 V and 190 A with a travel speed of 11 in/min. (a) Find the heat input with $HI = \dfrac{60VI}{1000S}$ and the net heat input ($\eta = 0.8$). (b) The procedure limits heat input to 24 kJ/in. Is he within it? What is the slowest travel speed allowed?

16. **3 pts** **Lesson 7.4**

A steel tab must carry 20 kips through two equal 5/16-in E70 fillet welds, one on each side. Using a throat of $0.707a$ and an allowable shear stress of 21 ksi, how long must each weld be?

17. **3 pts** **Lesson 7.5**

A classmate has bought a cheap flux-core welder and wants your help welding a broken galvanized gate in his family’s closed garage, next to the lawn mower and a gas can, wearing sunglasses. Give your answer, naming each hazard.

18. **3 pts** **Lesson 7.3**

Choose a joining process for each job and give one reason: (a) a stainless-steel railing in a food-processing plant; (b) a farm trailer repair outdoors in a stiff wind; (c) car-body sheet metal on an assembly line; (d) a copper water line in a house.

19. **3 pts** **Lesson 8.2**

A printer's X axis uses a GT2 belt (2 mm pitch) on a 20-tooth pulley and a 200-step motor at 16 microsteps. (a) Find the steps per mm. (b) Told to move 100 mm, it moves 98.4 mm. What should the new setting be? (c) Its Z lead screw has an 8 mm lead. Find the Z steps per mm.

20. **3 pts** **Lesson 8.2**

A print uses 0.28 mm layers, 0.50 mm lines and 90 mm/s. (a) Find the volumetric flow $Q = hwv$. Can a hot end rated 11 mm^3/s keep up? If not, what is the fastest speed at these settings? (b) How many millimeters of 1.75 mm filament (2.405 mm^2) make a 200 mm line?

21. **3 pts** **Lesson 8.5**

A shop can print a clip for $2.80 each, or injection-mold it with a $7,500 mold plus $0.30 per clip. Find the break-even quantity, and say which process to use for 1,200 clips and for 10,000 clips.

22. **3 pts** **Lesson 8.4**

You are the tradesperson. A customer brings three printed-part problems: (a) a PLA phone holder that drooped on his car dashboard in July; (b) a PLA hook printed standing up that snapped at its bend; (c) a request to print a replacement latch for his child's car seat. Answer each.

23. **3 pts** **Lesson 9.1**

A mower engine has a bore of 66 mm, a stroke of 52 mm and a compression ratio of 8.0:1. Find its displacement, its clearance volume and its ideal Otto efficiency ($\gamma = 1.4$). Why does a real small engine convert only about 25 percent of its fuel energy?

24. **3 pts** **Lesson 9.4**

A 22-in mower blade turns at 3,200 rpm. (a) Find the blade-tip speed with $v = \pi D n$ and compare it with the 19,000 ft/min limit. (b) After sharpening, the blade has an 8 g imbalance at 0.26 m. Find the rotating force $F = m r \omega^2$.

25. **3 pts** **Lesson 9.5**

You are the tradesperson. A mower sat all winter with E10 fuel in its tank. It has a strong spark, but the plug is dry after ten pulls. The owner also wants the blade sharpened. Give your first safety step, then the diagnosis and repair.

26. **3 pts** **Lesson 10.3**

A master cylinder piston is 0.75 in in diameter and a caliper piston 2.0 in. The pedal and booster push on the master cylinder with 280 lb. Find the line pressure and the force on the caliper piston.

27. **3 pts** **Lesson 10.4**

A car clicks but will not crank. The battery rests at 12.6 V. The starter tries to draw 160 A through a corroded terminal of 0.012 Ω. (a) Find the voltage lost at the terminal and the power wasted there. (b) After cleaning, it starts, and the voltage at idle is 14.2 V. Is the charging system working?

28. **3 pts** **Lesson 10.5**

You are the tradesperson. A friend wants to slide under his car to look at an oil leak. The car is held up by the scissor jack from the trunk, on a gravel driveway that slopes a little. What do you tell him, and how should it be done?

29. **8 pts** **Lesson 10.5**

Short essay (one or two paragraphs). This course has drawn firm lines: students never open the electrical panel or work on anything live; never handle refrigerant; weld only in a supervised shop; never go under a car held only by a jack; and disconnect the spark-plug wire before touching a mower blade. Choose two of these rules, explain the physics behind each and the kind of accident it prevents, and then explain how a good tradesperson decides which jobs a homeowner may do and which belong to a licensed or certified professional.

ANSWER KEY

1. $T = 65 \times 12 = 780$ in·lb. Per stud: $F = \dfrac{T}{KD} = \dfrac{780 \text{ in·lb}}{0.20 \times 0.4375 \text{ in}} \approx 8{,}910$ lb. Five studs: $5 \times 8{,}910 \approx 44{,}600$ lb. Star order: 1-3-5-2-4. Torque with the tire on the ground (or the car on rated jack stands on level, hard ground with the wheels chocked), never with anyone under a car held by a jack.
2. The copper preservative in treated wood corrodes thin plating and then the steel, so the hanger nails will weaken within years; use the hanger maker's hot-dip galvanized (G185) or stainless nails or listed structural screws. Nails in a ledger are loaded in withdrawal and pull loose (codes do not allow nailed ledgers); support the deck and fasten the ledger to the rim joist with through-bolts or code-listed ledger screws in the required pattern, with flashing, under a permit and inspection.
3. Masses for 3 mL and 1 mL: $3 \times 1.17 = 3.51$ g and 0.97 g; ratio $3.51 : 0.97 \approx 3.62 : 1$ by weight. Resin: $120 \text{ g} \times \dfrac{3.62}{4.62} \approx 94$ g; hardener: $120 - 94 = 26$ g. The ratio matches reactive groups one for one; extra hardener has nothing to react with and stays as soft, unreacted material, so the cured epoxy is weaker and may stay tacky.
4. The parts stretch differently along the overlap, so the shear stress peaks at the two ends of the overlap and is low in the middle; extra length adds mostly lightly loaded area, and the ends also see peel. Better: make the joint wider (adds area at the highly stressed ends along the whole joint), taper the ends of the overlap, use a tougher adhesive, or add a screw or rivet at each end as a peel stopper.
5. Overturning: $180 \text{ lb} \times 0.4 \text{ in} = 72$ lb·in. Resisting: $10 \text{ lb} \times 6.0 \text{ in} = 60$ lb·in. Since $72 > 60$, it tips. Limit: $x = \dfrac{60 \text{ lb·in}}{180 \text{ lb}} \approx 0.33$ in, so practically no overhang is safe. The fix is geometric: make the base at least as wide as the top (or splay the legs) so a person standing anywhere on it is inside the feet.
6. At the front the teeth move down and toward you, pressing the board onto the table. At the back they rise toward you; if the kerf closes or the board drifts from the fence, they catch the wood, lift it and fling it back at nearly blade speed. The riving knife, a curved plate just behind the blade, keeps the kerf open and the board from swinging into those back teeth. Stand slightly to the side of the blade line, out of the path of anything thrown, and use push sticks for narrow rips.

7. $U = \dfrac{0.23}{8.0} + \dfrac{0.77}{23.0} = 0.0288 + 0.0335 = 0.0622$; $R = 1/0.0622 \approx 16.1$. $Q = \dfrac{200\ \text{ft}^2 \times 55\ ^\circ\text{F}}{16.1} \approx 685\ \text{BTU/h}$. The studs (thermal bridging) pull the R-23 cavity down to about R-16 for the whole wall.

8. (a) $0.433\ \text{psi/ft} \times 22\ \text{ft} \approx 9.5\ \text{psi}$ lost; $50 - 9.5 = 40.5\ \text{psi}$ (less while flowing). (b) $h = 50\ \text{psi} \div 0.433\ \text{psi/ft} \approx 115\ \text{ft}$. (c) $0.25\ \text{in/ft} \times 16\ \text{ft} = 4.0\ \text{in}$.

9. (a) $I = 5{,}400\ \text{W} \div 240\ \text{V} = 22.5\ \text{A}$; at 120 V, $5{,}400 \div 120 = 45\ \text{A}$. (b) At 240 V: $P = I^2R = (22.5)^2 \times 0.060 \approx 30\ \text{W}$. At 120 V: $(45)^2 \times 0.060 \approx 122\ \text{W}$, four times as much. Doubling the voltage halves the current and cuts the I^2R heating to a quarter, so thinner, cheaper copper can be used safely.

10. With the breaker off and locked or taped and labeled: (1) test the tester on a known live receptacle, to prove it works; (2) test the receptacle being worked on, both slots, to prove it is dead; (3) test the tester again on the known live source, to prove it did not fail during the test. Then check every wire in the box, since a box can hold a second circuit. A non-contact tester can miss shielded or buried conductors or read falsely with a weak battery, and cannot prove the absence of voltage. Students never work on anything energized and never open the panel cover.

11. Capacity: $2.5 \times 12{,}000 = 30{,}000\ \text{BTU/h}$. EER: $30{,}000 \div 2{,}500 = 12.0$. COP: $12.0 \div 3.412 \approx 3.5$. Condenser: $30{,}000 + 2{,}500 \times 3.412 \approx 30{,}000 + 8{,}530 = 38{,}530\ \text{BTU/h}$. The refrigerant boils in the indoor coil, absorbing house heat, and the compressor pushes that heat, plus the heat of its own work, out through the outdoor coil.

12. Output: $90{,}000 \times 0.95 = 85{,}500\ \text{BTU/h}$. Air: $\Delta T = 123 - 68 = 55\ ^\circ\text{F}$; $\dot{Q} = 1.08 \times 1{,}400 \times 55 \approx 83{,}200\ \text{BTU/h}$, about 97% of the rated output, so the airflow is about right.

13. No refrigerant: handling it legally requires EPA Section 608 certification, it is under pressure and can cause frostbite, and a low charge means a leak that a certified technician must find and repair. First steps he can do: turn cooling off and run the fan to thaw the coil, replace the clogged filter (arrow toward the blower) and make sure registers and returns are open. The dirty filter starved the coil of warm air, so it froze. If it ices again with a clean filter and full airflow, call a certified technician.

14. (a) $10^6 \div 3{,}412 \approx 293\ \text{kWh}$; $293 \times \$0.14 \approx \$41.02$. (b) $293 \div 3.0 \approx 97.7\ \text{kWh}$; $97.7 \times \$0.14 \approx \$13.68$. (c) $10\ \text{therms} \div 0.96 \approx 10.42\ \text{therms}$; $10.42 \times \$1.30 \approx \$13.54$. The heat pump and the gas furnace are close; resistance heat costs about three times as much.

15. (a) $HI = \dfrac{60(25)(190)}{1000(11)} = \dfrac{285{,}000}{11{,}000} \approx 25.9$ kJ/in; net $0.8 \times 25.9 \approx 20.7$ kJ/in. (b) No: 25.9 kJ/in is over 24 kJ/in. Slowest speed: $S = \dfrac{285{,}000}{1000 \times 24} \approx 11.9$ in/min; he must travel at least that fast, using more passes to fill a wide joint.

16. Strength per inch of one weld: $21 \text{ ksi} \times 0.707 \times 0.3125 \text{ in} \approx 4.64$ kips/in. Each weld carries $20 \div 2 = 10$ kips: $L = 10 \div 4.64 \approx 2.2$ in. Allow for the weak start and stop of each bead: specify 2½ in each.

17. Do not do it: students weld only in a supervised shop with an instructor, so take the gate to the school shop or a certified welder. The hazards are real: sunglasses give no protection from arc ultraviolet (a helmet of about shade 10–11 with safety glasses beneath is needed); the zinc coating boils off as fume that causes metal fume fever, so it must be ground off with a respirator and the work ventilated; sparks fly 35 ft or more, so fuel and combustibles must be removed and a fire watch kept at least 30 minutes; and damp clothing or ground makes shock dangerous even at 50–80 V.

18. (a) TIG with argon: clean, precise, sanitary welds on stainless. (b) Stick with E7018 rods (or self-shielded flux-core): the flux makes its own shielding, which wind cannot blow away as it would MIG gas. (c) Resistance spot welding: fast, automatic, no filler, ideal for thin sheet. (d) Soldering (or brazing): capillary action draws the filler into the tight joint without melting the copper.

19. (a) Belt per turn: $20 \times 2 = 40$ mm; steps per turn: $200 \times 16 = 3{,}200$; $3{,}200 \div 40 = 80$ steps/mm. (b) $80 \times \dfrac{100}{98.4} \approx 81.3$ steps/mm. (c) $3{,}200 \div 8 = 400$ steps/mm.

20. (a) $Q = 0.28 \times 0.50 \times 90 = 12.6$ mm^3/s, more than 11, so no: the plastic will not melt in time and the part will be under-filled and weak. Fastest: $v = \dfrac{11}{0.28 \times 0.50} \approx 79$ mm/s. (b) $V = 200 \times 0.50 \times 0.28 = 28$ mm^3; $L_f = 28 \div 2.405 \approx 11.6$ mm.

21. $N = \dfrac{7{,}500}{2.80 - 0.30} = \dfrac{7{,}500}{2.50} = 3{,}000$ clips. For 1,200: print $1{,}200 \times \$2.80 = \$3{,}360$; mold $\$7{,}500 + 1{,}200 \times \$0.30 = \$7{,}860$: print. For 10,000: print \$28,000; mold $\$7{,}500 + \$3{,}000 = \$10{,}500$: mold.

22. (a) PLA softens at about 55–60 °C, below dashboard temperatures; reprint in ASA (or at least PETG). (b) Printed upright, the load pulled the layers apart, where the bond is only about half as strong; reprint it lying on its side so the lines run around the bend, and add walls. (c) Do not print it: a car seat is safety equipment

tested as a whole and a printed latch could fail in a crash; get the maker's certified part or replace the seat.

23. $V_d = \frac{\pi}{4}(6.6\text{ cm})^2(5.2\text{ cm}) = 0.7854 \times 43.56 \times 5.2 \approx 178\text{ cm}^3$.
$V_c = \dfrac{178}{8.0 - 1} \approx 25.4\text{ cm}^3$. $8^{0.4} \approx 2.297$; $\eta = 1 - 1/2.297 \approx 0.565 = 56.5\%$. Real engines lose heat through the cooling fins and to friction, pumping and incomplete burning.

24. (a) $D = 22/12 \approx 1.833$ ft; $v = \pi(1.833\text{ ft})(3{,}200\text{ rpm}) \approx 18{,}400$ ft/min, under the limit. (b) $\omega = 2\pi(3{,}200)/60 \approx 335$ rad/s;
$F = (0.008\text{ kg})(0.26\text{ m})(335\text{ rad/s})^2 \approx 234$ N, about 53 lb swinging around 53 times a second; file the heavy end until it balances.

25. First pull the spark-plug wire off and keep it away from the plug before touching the blade or turning the engine; tip the mower only with the air filter and carburetor side up. A dry plug means no fuel reaches the cylinder: stale fuel has varnished the main jet or float needle, or water from phase-separated ethanol sits in the bowl. Outdoors, with the engine cool, drain the old fuel into an approved container for hazardous-waste disposal, remove the bowl, clean the jet and passages with carburetor cleaner and compressed air, check the float, and refill with fresh, stabilized fuel. Run it only outdoors.

26. $A_1 = \frac{\pi}{4}(0.75)^2 \approx 0.442\text{ in}^2$; $p = 280\text{ lb} \div 0.442\text{ in}^2 \approx 634$ psi.
$A_2 = \frac{\pi}{4}(2.0)^2 \approx 3.14\text{ in}^2$; $F_2 = 634\text{ psi} \times 3.14\text{ in}^2 \approx 1{,}990$ lb (a multiplication of $(2.0/0.75)^2 \approx 7.1$).

27. (a) $V = IR = 160\text{ A} \times 0.012\ \Omega \approx 1.9$ V; $P = I^2R = (160)^2 \times 0.012 \approx 307$ W of heat at the terminal, enough to leave the starter only clicking. (b) Yes: 14.2 V is within the normal 13.8–14.7 V charging range.

28. Stop: never put any part of your body under a car supported only by a jack; it can drop without warning, especially on a slope or soft gravel. Move to level, hard ground (concrete), set the parking brake, put it in Park and chock the wheels; raise it at the manual's jacking points and set it on jack stands rated for the car (or drive it up on ramps); let a hot engine cool; wear safety glasses; and have an adult supervise. Then look at the leak.

29. A strong answer: explains two rules with real physics, for example that service conductors stay live with the main off and can deliver enormous fault currents, and that a 50 mA current through the chest can disturb the heart while a 15 A breaker never trips; that refrigerant is under high pressure, causes frostbite and by law (EPA Section 608) is handled only by certified technicians; that an arc's ultraviolet burns eyes, zinc fume and sparks are hazards, so welding needs a

supervised shop; that a car on a jack alone can drop thousands of pounds without warning, so rated jack stands on level, hard ground are required; that turning a mower blade turns the flywheel and can fire the magneto and start the engine. It then describes the decision: read the manual and local rules, check with the building department, keep homeowner work to routine maintenance and like-for-like jobs with proper verification, and call a licensed or certified professional for panels, new circuits, gas, refrigerant, brake hydraulics, airbags and structural changes, counting the cost and the risk to others before acting.