

GRADE 7 ENGINEERING & PHYSICS

First edition

8 units

32 lessons + Toy Lab

A video for every lesson

FIRST EDITION

COURSE GUIDE

This course follows the same eight strands of engineering as every year of School Launch, now with the vocabulary and arithmetic of real engineers: energy and engines, bridges, architecture and structures, electronics, public utilities, ships, flight, and robotics. The stories are some of the most important in engineering history: James Watt walking on Glasgow Green when the idea of the separate condenser came to him, the Quebec Bridge falling twice before it stood, the engineers who quietly saved the Leaning Tower of Pisa, William LeMessurier discovering a hidden weakness in his own skyscraper, the Panama Canal lifting ships over a mountain range, and Chuck Yeager flying faster than sound.

Every lesson follows the same path. First comes **the story**. Then **how they figured it out**: what stood in the way, what they tried, what failed, what they measured and what they changed. Then **the physics**, now with simple equations worked out with real numbers and units ($\text{work} = \text{force} \times \text{distance}$, efficiency , $\text{pressure} = \text{force} \div \text{area}$, stress and strain , $V = IR$, $\tau = RC$, $P = \rho g Q h$, $c = f\lambda$), and **the engineering**: how the idea becomes a safe, affordable, lasting thing. Last, the student repeats the discovery in miniature, with a prediction, a fair test, a data table, a calculation and an improvement round in the engineer's notebook.

God made an orderly world that can be measured and understood, and He made people in His image to be makers. Engineering, rightly done, is a way of loving our neighbors, and in seventh grade students also meet the other side of it: the duty of an engineer to check the numbers, admit a mistake and protect the people who trust the work. The old Latin saying *Fabricando fit faber*, “by making, one becomes a maker,” is the method of this course.

Most videos come from museums, NASA and trusted engineering teaching channels such as Practical Engineering, The Engineering Mindset, The Efficient Engineer, Branch Education, Jared Owen and

Flipping Physics, chosen lesson by lesson and checked in preview for content and accuracy. Seventh-grade videos are sometimes longer (up to about 20 minutes) and use real equations; pause and work the numbers together. Some channels end with a sponsor message or an invitation to subscribe; stop the video when the teaching ends. Parent notes on a few lessons point out anything worth skipping.

Start with Lesson 1.1 →

WHO IT IS FOR

Written for students in grade 7 (about ages 12–13) who read independently, are comfortable with decimals, fractions, ratios and percentages, and can substitute numbers into a simple formula. Square roots and a calculator are used in a few lessons. A parent or teacher reads along, helps with the builds and supervises plaster, hot water, hot glue and the one soldering lesson. No kits are required: every build uses household or inexpensive craft-store materials, plus a basic digital multimeter and a few electronic parts. Optional kits are listed in some units for families who want them.

HOW TO USE THIS COURSE

1. **The weekly rhythm.** The year has 32 lessons, one a week. Session 1 (50–60 minutes) is the warm-up, the video, the teaching and the picture study. Session 2 (50–60 minutes) is the build and the engineer's notebook. In the last week of each unit, add a third session for the unit review and the portfolio build.
2. **Story, then physics, then engineering.** The core ideas are written for the student to read, with a parent reading along. *The story* and *How they figured it out* tell what happened; *The physics* explains why it works, usually with one equation and a worked example; *The engineering* explains how people turn the idea into a real, safe thing. After each paragraph, have the student tell it back, and have the student rework each worked example on paper with the numbers covered.
3. **Equations and units.** Every calculation is written with its units, and the student should do the same. A number without a unit is not an answer. Most lessons use newtons (N), meters (m), joules (J), watts (W), volts (V), ohms (Ω) and seconds (s). A useful rule of thumb: on Earth, a mass of 1 kilogram weighs about 9.8 newtons, so 100 grams weighs about 1 newton.

4. **Picture study.** Each lesson has one historic photograph, engineering drawing, patent or painting. Look at it quietly for two minutes. Then put it away and have the student tell everything he or she remembers. Bring it back and work through the “look for” items and questions, which point to the physics and engineering in the picture.
5. **The engineer’s notebook.** Use a graph-paper composition book for the whole year. For every build, write a prediction first, then record measurements in a table with units, then graph the results when there are several trials, calculate, and write what happened and what you would change. Date every page. Honest records matter more than perfect results: “a just weight is his delight” (Proverbs 11:1).
6. **Fair tests and improvement.** Most builds change only one variable at a time and repeat each trial at least three times so the student can average them. Every build ends with an “improve it” round. Compare your measured result with the predicted one and explain the difference; real engineers call this the error, and finding its causes is part of the work.
7. **Optional kits.** Some units list kits such as an Arduino starter kit, Snap Circuits, a balsa bridge kit, a BBC micro:bit or a small indoor drone. They are extras for families who enjoy them. Every lesson can be completed without them; the Arduino lesson can be done in the free Tinkercad Circuits simulator.
8. **Unit review and portfolio.** Each unit ends with a review worth 100 points, including two or three short calculations and one or two written explanations, and a portfolio build that pulls the unit together, such as a roller-coaster energy report, a predicted-and-tested truss, a tuned-mass-damper tower or a quadcopter thrust test. Keep the portfolio pages and photographs in a folder for the year.
9. **Safety.** Read the safety box before each build. Electricity in this course comes only from AA, C, D or 9-volt batteries and USB-powered boards, never from the outlets in the wall, and no appliance is ever opened. An adult handles hot glue guns, craft knives, plaster, hot water and the soldering iron. Wear safety glasses for anything that flies, snaps, spins or is under tension.
10. **The family engineering fair.** In the last week, set out the best build from each unit with its notebook pages and let the student explain them to family and guests, including one calculation for each build. Explaining your work clearly to someone else is part of being an engineer.

11. **The Toy Lab (optional).** Unit 9 is a bonus unit on the physics and engineering of toys: pinball machines, slot cars, motion-sensing game controllers and how plastic toys are designed for manufacture and safety. Use it after the engineering fair, over the summer, or any week that needs something fun.

SCOPE AND SEQUENCE

UNIT 1 • WEEKS 1–4

Energy and Engines

Work, energy, power and efficiency with Joule’s paddle wheel; Newcomen and Watt’s steam engines; the four-stroke internal-combustion engine of Otto and Diesel; and conservation of energy measured on a foam roller coaster.

- 1.1 Work, Energy and Efficiency: Joule’s Paddle Wheel
- 1.2 James Watt and the Steam Engine
- 1.3 The Internal-Combustion Engine: Otto and Diesel
- 1.4 Conservation of Energy on a Roller Coaster

UNIT 2 • WEEKS 5–8

Bridges

Free-body diagrams and equilibrium tested on two kitchen scales; the method of joints worked by hand on a 3-4-5 truss; cables, catenaries and Robert Hooke’s hanging chain; and the Quebec Bridge collapses, buckling and the engineer’s duty.

- 2.1 Free-Body Diagrams and Equilibrium: Simon Stevin’s Wreath of Spheres
- 2.2 The Method of Joints: Wendel Bollman’s Truss
- 2.3 Cables, Chains and Catenaries: Hooke’s Hanging Chain
- 2.4 The Quebec Bridge: Buckling, Safety Factors and the Engineer’s Duty

UNIT 3 • WEEKS 9–12

Architecture and Structures

Stress, strain and Hooke's law with David Kirkaldy's testing machine; reinforced and prestressed concrete from Monier to Freyssinet; foundations and soil pressure at the Leaning Tower of Pisa; and wind engineering, from the Citicorp Center to Taipei 101's tuned mass damper.

- 3.1 Stress, Strain and Strength: Hooke's Springs and Kirkaldy's Testing Machine
- 3.2 Reinforced and Prestressed Concrete: From Monier's Flowerpots to the Walnut Lane Bridge
- 3.3 Foundations and Soils: Saving the Leaning Tower of Pisa
- 3.4 Wind Engineering: The Citicorp Center and Taipei 101's Damper

UNIT 5 • WEEKS 17–20

Public Utilities

AC versus DC and the transformer: Edison, Tesla, Westinghouse and William Stanley; dams and hydroelectric power at Hoover Dam; the biology of wastewater treatment and activated sludge; and radio waves, Marconi and the cell tower.

- 5.1 AC versus DC: Edison, Tesla, Westinghouse and the Transformer
- 5.2 Dams and Hydroelectric Power: Building Hoover Dam
- 5.3 Wastewater Treatment: Activated Sludge and the Microbes That Clean Water
- 5.4 Radio Waves and Cell Towers: From Marconi to the Mobile Phone

UNIT 4 • WEEKS 13–16

Electronics

Resistors, capacitors, diodes and LEDs with the Leyden jar and the RC time constant; the transistor as a switch from Bell Labs to today; inputs and outputs on an Arduino (real or in the free Tinkercad simulator); and soldering basics with an adult.

- 4.1 Resistors, Capacitors, Diodes and LEDs: From the Leyden Jar to the LED
- 4.2 The Transistor as a Switch: Bell Labs, 1947
- 4.3 Arduino Inputs and Outputs: Sense, Decide, Act
- 4.4 Soldering Basics with an Adult

UNIT 6 • WEEKS 21–24

Ships

Naval architecture: the center of buoyancy, the metacenter and an inclining experiment; iron ships and Brunel's *Great Eastern*; the locks of the Panama Canal; and Malcom McLean's shipping container and the modern port.

- 6.1 Naval Architecture: The Metacenter and the Inclining Experiment
- 6.2 Iron Ships and Brunel's Great Eastern
- 6.3 The Panama Canal: Lifting Ships over a Mountain Range
- 6.4 Container Ships and Ports: Malcom McLean's Steel Box

UNIT 7 • WEEKS 25–28

Flight

Airfoils measured on a kitchen-scale lift balance, from Langley’s wind tunnels to the NACA airfoils; stability and control from Cayley to the modern tail; Whittle, von Ohain and the jet engine; and Chuck Yeager, the Bell X-1 and the speed of sound.

7.1 Airfoils and Wind-Tunnel Testing: From Langley to the NACA Airfoils

7.2 Stability and Control: Cayley, Pénaud and the Tail

7.3 The Jet Engine: Frank Whittle and Hans von Ohain

7.4 Breaking the Sound Barrier: Chuck Yeager and the Bell X-1

UNIT 9 • WEEKS 33–36

Toy Lab: The Engineering of Play

Optional bonus unit, the Toy Lab: solenoids and switches in the pinball machine; motors, friction and banked curves in slot cars; the MEMS accelerometers and gyroscopes in game controllers; and designing a toy for injection molding and safety.

9.1 The Pinball Machine: Solenoids, Switches and Scoring

9.2 Slot Cars: Motors, Friction and the Banked Curve

9.3 Game Controllers: Accelerometers and Gyroscopes

9.4 Designing a Toy for Manufacture: Injection Molding and Toy Safety

UNIT 8 • WEEKS 29–32

Robotics

Degrees of freedom and end effectors on the Space Shuttle’s Canadarm; feedback control from Sperry’s autopilot to a coded cruise control; sensors and autonomous vehicles from Sojourner to the DARPA challenges; and how a quadcopter flies, ending with the family engineering fair.

8.1 Degrees of Freedom and End Effectors: The Canadarm

8.2 Feedback Control: Sperry’s Autopilot and a Coded Cruise Control

8.3 Sensors and Autonomous Vehicles: From Sojourner to the DARPA Challenge

8.4 How a Quadcopter Flies, and the Family Engineering Fair

WEEKLY PACING CALENDAR

WEEK	PLAN
1	• Session 1: Lesson 1.1 Work, Energy and Efficiency: Joule's Paddle Wheel: warm-up, video, teaching and picture study • Session 2: Lesson 1.1 build project and engineer's notebook <i>Two sessions a week is the usual rhythm. Younger children can split a long session in two; older students can do both sessions in one sitting.</i>
2	• Session 1: Lesson 1.2 James Watt and the Steam Engine: warm-up, video, teaching and picture study • Session 2: Lesson 1.2 build project and engineer's notebook
3	• Session 1: Lesson 1.3 The Internal-Combustion Engine: Otto and Diesel: warm-up, video, teaching and picture study • Session 2: Lesson 1.3 build project and engineer's notebook
4	• Session 1: Lesson 1.4 Conservation of Energy on a Roller Coaster: warm-up, video, teaching and picture study • Session 2: Lesson 1.4 build project and engineer's notebook • Session 3: Unit 1 review and portfolio project
5	• Session 1: Lesson 2.1 Free-Body Diagrams and Equilibrium: Simon Stevin's Wreath of Spheres: warm-up, video, teaching and picture study • Session 2: Lesson 2.1 build project and engineer's notebook
6	• Session 1: Lesson 2.2 The Method of Joints: Wendel Bollman's Truss: warm-up, video, teaching and picture study • Session 2: Lesson 2.2 build project and engineer's notebook
7	• Session 1: Lesson 2.3 Cables, Chains and Catenaries: Hooke's Hanging Chain: warm-up, video, teaching and picture study • Session 2: Lesson 2.3 build project and engineer's notebook
8	• Session 1: Lesson 2.4 The Quebec Bridge: Buckling, Safety Factors and the Engineer's Duty: warm-up, video, teaching and picture study • Session 2: Lesson 2.4 build project and engineer's notebook • Session 3: Unit 2 review and portfolio project

WEEK	PLAN
9	• Session 1: Lesson 3.1 Stress, Strain and Strength: Hooke's Springs and Kirkaldy's Testing Machine: warm-up, video, teaching and picture study • Session 2: Lesson 3.1 build project and engineer's notebook
10	• Session 1: Lesson 3.2 Reinforced and Prestressed Concrete: From Monier's Flowerpots to the Walnut Lane Bridge: warm-up, video, teaching and picture study • Session 2: Lesson 3.2 build project and engineer's notebook
11	• Session 1: Lesson 3.3 Foundations and Soils: Saving the Leaning Tower of Pisa: warm-up, video, teaching and picture study • Session 2: Lesson 3.3 build project and engineer's notebook
12	• Session 1: Lesson 3.4 Wind Engineering: The Citicorp Center and Taipei 101's Damper: warm-up, video, teaching and picture study • Session 2: Lesson 3.4 build project and engineer's notebook • Session 3: Unit 3 review and portfolio project
13	• Session 1: Lesson 4.1 Resistors, Capacitors, Diodes and LEDs: From the Leyden Jar to the LED: warm-up, video, teaching and picture study • Session 2: Lesson 4.1 build project and engineer's notebook
14	• Session 1: Lesson 4.2 The Transistor as a Switch: Bell Labs, 1947: warm-up, video, teaching and picture study • Session 2: Lesson 4.2 build project and engineer's notebook
15	• Session 1: Lesson 4.3 Arduino Inputs and Outputs: Sense, Decide, Act: warm-up, video, teaching and picture study • Session 2: Lesson 4.3 build project and engineer's notebook
16	• Session 1: Lesson 4.4 Soldering Basics with an Adult: warm-up, video, teaching and picture study • Session 2: Lesson 4.4 build project and engineer's notebook • Session 3: Unit 4 review and portfolio project
17	• Session 1: Lesson 5.1 AC versus DC: Edison, Tesla, Westinghouse and the Transformer: warm-up, video, teaching and picture study • Session 2: Lesson 5.1 build project and engineer's notebook

WEEK	PLAN
18	• Session 1: Lesson 5.2 Dams and Hydroelectric Power: Building Hoover Dam: warm-up, video, teaching and picture study • Session 2: Lesson 5.2 build project and engineer's notebook
19	• Session 1: Lesson 5.3 Wastewater Treatment: Activated Sludge and the Microbes That Clean Water: warm-up, video, teaching and picture study • Session 2: Lesson 5.3 build project and engineer's notebook
20	• Session 1: Lesson 5.4 Radio Waves and Cell Towers: From Marconi to the Mobile Phone: warm-up, video, teaching and picture study • Session 2: Lesson 5.4 build project and engineer's notebook • Session 3: Unit 5 review and portfolio project
21	• Session 1: Lesson 6.1 Naval Architecture: The Metacenter and the Inclining Experiment: warm-up, video, teaching and picture study • Session 2: Lesson 6.1 build project and engineer's notebook
22	• Session 1: Lesson 6.2 Iron Ships and Brunel's Great Eastern: warm-up, video, teaching and picture study • Session 2: Lesson 6.2 build project and engineer's notebook
23	• Session 1: Lesson 6.3 The Panama Canal: Lifting Ships over a Mountain Range: warm-up, video, teaching and picture study • Session 2: Lesson 6.3 build project and engineer's notebook
24	• Session 1: Lesson 6.4 Container Ships and Ports: Malcom McLean's Steel Box: warm-up, video, teaching and picture study • Session 2: Lesson 6.4 build project and engineer's notebook • Session 3: Unit 6 review and portfolio project
25	• Session 1: Lesson 7.1 Airfoils and Wind-Tunnel Testing: From Langley to the NACA Airfoils: warm-up, video, teaching and picture study • Session 2: Lesson 7.1 build project and engineer's notebook
26	• Session 1: Lesson 7.2 Stability and Control: Cayley, Pénaud and the Tail: warm-up, video, teaching and picture study • Session 2: Lesson 7.2 build project and engineer's notebook

WEEK	PLAN
27	- Session 1: Lesson 7.3 The Jet Engine: Frank Whittle and Hans von Ohain: warm-up, video, teaching and picture study - Session 2: Lesson 7.3 build project and engineer's notebook
28	- Session 1: Lesson 7.4 Breaking the Sound Barrier: Chuck Yeager and the Bell X-1: warm-up, video, teaching and picture study - Session 2: Lesson 7.4 build project and engineer's notebook - Session 3: Unit 7 review and portfolio project
29	- Session 1: Lesson 8.1 Degrees of Freedom and End Effectors: The Canadarm: warm-up, video, teaching and picture study - Session 2: Lesson 8.1 build project and engineer's notebook
30	- Session 1: Lesson 8.2 Feedback Control: Sperry's Autopilot and a Coded Cruise Control: warm-up, video, teaching and picture study - Session 2: Lesson 8.2 build project and engineer's notebook
31	- Session 1: Lesson 8.3 Sensors and Autonomous Vehicles: From Sojourner to the DARPA Challenge: warm-up, video, teaching and picture study - Session 2: Lesson 8.3 build project and engineer's notebook
32	- Session 1: Lesson 8.4 How a Quadcopter Flies, and the Family Engineering Fair: warm-up, video, teaching and picture study - Session 2: Lesson 8.4 build project and engineer's notebook - Session 3: Unit 8 review and portfolio project <i>Last week. Hold a family engineering fair: set out the best build from each unit with its notebook pages, and let the student show guests how one of them works.</i>
33	- Session 1: Lesson 9.1 The Pinball Machine: Solenoids, Switches and Scoring: warm-up, video, teaching and picture study - Session 2: Lesson 9.1 build project and engineer's notebook <i>Optional bonus unit: Toy Lab. Do it after the fair, over the summer, or slip a lesson in whenever a week needs something fun.</i>
34	- Session 1: Lesson 9.2 Slot Cars: Motors, Friction and the Banked Curve: warm-up, video, teaching and picture study - Session 2: Lesson 9.2 build project and engineer's notebook

WEEK	PLAN
35	• Session 1: Lesson 9.3 Game Controllers: Accelerometers and Gyroscopes: warm-up, video, teaching and picture study • Session 2: Lesson 9.3 build project and engineer's notebook
36	• Session 1: Lesson 9.4 Designing a Toy for Manufacture: Injection Molding and Toy Safety: warm-up, video, teaching and picture study • Session 2: Lesson 9.4 build project and engineer's notebook • Session 3: Unit 9 review and portfolio project

MATERIALS

Engineer's notebook (graph-paper composition book) and a calculator

One notebook for the whole year: predictions, data tables with units, graphs, calculations and “what I would change.”

Ruler, tape measure, protractor, kitchen scale that reads in grams, and a smartphone stopwatch

Measuring is the heart of every build. Two kitchen scales (borrow one) are needed for Lesson 2.1.

Cardboard, card stock, masking tape, clear tape, white glue, string, rubber bands, paper clips, binder clips

The main building materials all year.

Craft sticks (about 200), wooden skewers, straws, dowels, toothpicks

For trusses, columns, arms and towers.

About 300 pennies, paper cups, zip-top bags and a small bucket

Standard weights for load tests. A U.S. penny made since 1983 has a mass of 2.5 grams.

Foam pipe insulation (about 2 meters, split lengthwise) and marbles

For the roller coaster in Lesson 1.4 and the energy portfolio.

Plastic syringes (10 mL and 60 mL), clear plastic tubing to fit, two plastic bottles, modeling clay

For the syringe heat engine, the engine model and the canal lock.

Plaster of Paris (a small bag), a dust mask, a quart milk carton, thin wire or string

For the reinforced-beam test in Lesson 3.2. An adult mixes the plaster.

A basic digital multimeter (about \$10–20)

Used throughout Units 4 and 5 to measure voltage, current, resistance and continuity.

Electronics parts: 9-volt and AA batteries with snaps and holders, a small solderless breadboard, jumper wires, alligator clip leads, red and green LEDs, resistors (100 Ω to 100 k Ω), two 1,000 μ F electrolytic capacitors (16 V or higher), 1N4001 diodes, two NPN transistors (2N2222 or 2N3904), a push button and a potentiometer

For Unit 4. Batteries only; never the outlets in the wall.

Magnet wire (about 26 gauge), two iron nails or bolts, a compass and strong magnets

For the transformer model in Lesson 5.1.

A box fan

The wind tunnel for airfoil, glider, tower and wind-load tests.

A small hobby motor (1.5–3 volt) with a propeller, and a battery holder for 2–3 AA cells

For the thrust tests in Units 7 and 8.

Free software: Tinkercad Circuits (tinkercad.com), Scratch (scratch.mit.edu) or

Microsoft MakeCode (makecode.microbit.org), and the free phyphox app

For the Arduino, feedback-control and sound-speed lessons. A parent sets up any accounts.

Safety glasses

For load tests, rubber bands, spinning propellers, soldering and anything else that can snap or fly.

Optional: a soldering iron with a stand, lead-free solder and a small perfboard, used only with an adult; and one kit, such as an Arduino Uno starter kit

Never required. See Lesson 4.4 and the kits listed in each unit.

GRADING

Grades come mostly from the builds and the engineer's notebook, because engineering is learned by doing, measuring and recording. In seventh grade, calculations count too: the student should show each formula, the numbers with units, and the answer. A build that fails but is honestly recorded, analyzed and improved earns full credit.

PART	%
Builds (fair testing, measurement and the improve round)	35
Engineer's notebook (predictions, data tables, graphs, calculations, conclusions)	20
Unit reviews	20
Portfolio builds and reports	25

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

- Grade the process, not just the result. Did the student predict, test fairly, repeat trials, measure carefully, calculate correctly with units, record honestly and try an improvement?
- A notebook page earns full marks when it has a date, a labeled sketch, a data table with units, a worked calculation, and a sentence about what to change.
- On calculation questions in the unit reviews, give most of the credit for a correct setup with units even if the arithmetic slips.
- Keep each unit's portfolio pages and photographs in one folder. They make a fine record of the year and the centerpiece of the family engineering fair.

A NOTE TO PARENTS

You do not need to be an engineer to teach this course. Read the story together, watch the video, and then be the student's lab partner: hold the ruler, check the units, and ask "What do you predict?", "How will you make it a fair test?" and "Why do you think the measured number was different from the predicted one?" Those questions are most of what a good engineering teacher does.

Expect things to fail. Beams will crack, gliders will dive and circuits will refuse to light. James Watt worked for years before his engine was ready, and the course is built to show that failure, carefully studied and honestly reported, is how engineers learn. Praise careful testing, clear units and honest records more than a winning result. *Fabricando fit faber*: by making, one becomes a maker.

This year several lessons deal with engineering failures and responsibility: the Quebec Bridge, the Citicorp Center and the dangers of building the Panama Canal. They are told plainly and briefly, with the focus on what engineers learned, and on the truth that an engineer's first duty is to the safety of the people who will use the work. One lesson (4.4) introduces soldering; it must be done with an adult at the bench, and an alternative without soldering is given.

UNIT 1

ENERGY AND ENGINES

Every machine runs on energy, and every engineer must answer the same three questions: How much work does this job take? How fast must it be done? And how much of the energy we put in comes out as useful work? In this unit you will learn the words and equations engineers use to answer them, work, energy, power and efficiency, and you will measure them yourself with a ramp, a syringe and a foam roller-coaster track.

The stories run from a quiet laboratory to the factories and roads of the modern world. James Joule measured how falling weights warm water and showed that work and heat are two forms of the same thing. Thomas Newcomen and James Watt turned steam into the first useful engines, and Watt's separate condenser cut their coal use by about three quarters. Nicolaus Otto and Rudolf Diesel put the fire inside the cylinder. Last, you will follow the energy of a marble down a roller coaster and find out where every joule goes.

PREREQUISITES

- Can multiply and divide decimals and use a calculator
- Knows that a force is a push or a pull, measured in newtons
- Has kept a dated engineer's notebook with predictions and data tables (Grades 5–6)

MASTERY CHECKLIST

- ☐ I can calculate work ($W = F \times d$), power ($P = W \div t$) and efficiency, with correct units.
- ☐ I can explain how Watt's separate condenser made the steam engine far more efficient.
- ☐ I can name the four strokes of an internal-combustion engine and calculate an engine's displacement.
- ☐ I can use conservation of energy to predict the speed of a marble or a roller-coaster car and explain where the "lost" energy went.
- ☐ I can run a fair test, repeat trials, average them and compare measured results with predictions.

OPTIONAL KITS FOR THIS UNIT

- **Thames & Kosmos physics and engine kits:** Ages 10 and up. Several kits build working models of engines, gears and machines with clear manuals; a good extra for Lessons 1.2 and 1.3.
- **LEGO Technic:** Ages vary by set. Many Technic cars include a model piston engine with a crankshaft and connecting rods that move as the wheels turn, a fine way to see the four strokes in Lesson 1.3.

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	Work, Energy and Efficiency: Joule's Paddle Wheel	2 sessions of 50–60 minutes
1.2	James Watt and the Steam Engine	2 sessions of 50–60 minutes
1.3	The Internal-Combustion Engine: Otto and Diesel	2 sessions of 50–60 minutes
1.4	Conservation of Energy on a Roller Coaster	2 sessions of 50–60 minutes

UNIT 1 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Define work and give its unit. Does a waiter do work on a tray while carrying it level across a room at a steady speed? Explain.

2. **10 pts**

Calculation: You pull a 6 N box up a ramp with a force of 2.5 N. The ramp is 2.0 m long and 0.60 m high. Find the work in, the useful work out, and the efficiency.

3. **8 pts**

What did James Joule show with his paddle-wheel experiment, and why was careful measurement so important to it?

4. (8 pts)

In Newcomen's engine, what actually pushed the piston down?

5. (10 pts)

Explain the problem James Watt found in Newcomen's engine and how his separate condenser solved it.

6. (10 pts)

Calculation: A pump lifts 2,000 N of water up 15 m in 20 s. How much work does it do, and what is its power in watts and in horsepower ($1 \text{ hp} \approx 746 \text{ W}$)?

7. (8 pts)

Name the four strokes of a four-stroke engine in order and say what the piston does in each.

8. (8 pts)

Why does compressing the fuel and air before lighting it make an engine more efficient? What limits how far engineers can raise the compression?

9. (10 pts)

Calculation: A marble is released from rest at the top of a 0.45 m drop. Predict its speed at the bottom, ignoring friction ($g = 9.8 \text{ m/s}^2$).

10. (8 pts)

Your measured marble speed was only 85% of the predicted speed. Give two reasons.

11. (12 pts)

Written answer: Explain, using the words potential energy, kinetic energy and friction, why the first hill of a roller coaster must be the tallest.

ANSWER KEY

1. Work is force times the distance moved in the direction of the force ($W = F \times d$), measured in joules. Carrying the tray level does almost no work on it, because the upward force is at right angles to the sideways motion.
2. $W_{\text{in}} = 2.5 \text{ N} \times 2.0 \text{ m} = 5.0 \text{ J}$. $W_{\text{out}} = 6 \text{ N} \times 0.60 \text{ m} = 3.6 \text{ J}$. Efficiency = $3.6 \div 5.0 = 0.72 = 72\%$.
3. He showed that a definite amount of work always produces the same amount of heat, so heat is a form of energy, not a fluid. The temperature change was tiny, so only very careful measurement and corrections for losses could prove it.
4. The pressure of the outside air (atmospheric pressure), pushing into the partial vacuum left when the steam was condensed.
5. Each spray of cold water cooled the cylinder, so much of the next charge of steam was wasted just reheating it. Watt condensed the steam in a separate vessel kept cold, so the cylinder could stay hot all the time. His engines used about a quarter of the coal.
6. $W = 2,000 \text{ N} \times 15 \text{ m} = 30,000 \text{ J}$. $P = 30,000 \text{ J} \div 20 \text{ s} = 1,500 \text{ W}$. $1,500 \div 746 \approx 2.0 \text{ hp}$.
7. Intake (moves down, pulls in air and fuel); compression (moves up, squeezes it); power (pushed down by the burning gas); exhaust (moves up, pushes burned gas out).
8. The burned gas can then expand more, so more of its heat is turned into work. If compression is too high for the fuel, it can ignite too early (knock) and damage the engine; higher compression also needs a heavier, stronger engine.
9. $v = \sqrt{(2gh)} = \sqrt{(2 \times 9.8 \times 0.45)} = \sqrt{8.82} \approx 3.0 \text{ m/s}$.
10. Any two: friction with the track; air drag; energy lost at bumps and joints; part of the energy went into making the marble spin; timing error.
11. At the top of the first hill the train has its most potential energy. As it rolls, potential energy changes to kinetic energy and back, but friction and drag keep turning some of it into heat, so the total mechanical energy only goes down. The train can never climb higher than its starting point, so every later hill must be lower than the first.

PORTFOLIO PIECE: AN ENERGY AUDIT OF A ROLLER COASTER

Design and build a foam-track roller coaster with at least one drop, one hill and one loop, and carry out a full energy audit of it. Measure the marble's mass and the height of each point, predict the speed at three points with $v = \sqrt{2gh}$, measure the real speeds, and calculate the percent of energy kept at each point. Write a one-page engineer's report with a scale drawing, your data table and graph, an explanation of the losses, and one improvement you built and tested.

LOOK FOR	WHAT IT MEANS
Design drawing	Scale drawing with heights, the loop size and the timing points labeled with units.
Predictions	Speeds calculated correctly with $v = \sqrt{2gh}$ before testing, with the work shown.
Fair, repeated measurements	Marble released from rest; at least three trials at each point; averages recorded.
Energy analysis	Percent of energy kept calculated, and the losses explained using friction, drag and spin.
Improvement	One change made for a specific reason, tested the same way, and the result reported honestly.

1.1 WORK, ENERGY AND EFFICIENCY:

JOULE’S PADDLE WHEEL

OBJECTIVES

- Define work, energy and efficiency and calculate each with correct units.
- Explain what James Joule’s paddle-wheel experiment showed about work and heat.
- Measure the efficiency of a ramp by comparing the work put in with the useful work that comes out.

Warm-up. Lift a 1-liter bottle of water (about 1 kilogram) from the floor to a table. Now carry it across the room at the same height. Which of those two actions do you think a physicist would call “work”? Rub your hands together hard for ten seconds. Where did the energy of your moving hands go?

WATCH

Introduction to Work with Examples

Flipping Physics • 7:09

<https://www.youtube.com/watch?v=0Oeywu5IR6s>

WHEN TO WATCH

After the physics paragraph. Pause at each example and work it yourself before the answer appears.

BACKUP VIDEO

Historical Didactical Video on Joule's Paddlewheel Experiment

HistoLab EUF • 4:41

<https://www.youtube.com/watch?v=oP5ET5uxPow>

Optional, to see a working copy of Joule’s apparatus.

KEY TERMS

work

Energy transferred when a force moves something through a distance: $W = F \times d$. Measured in joules (J).

joule (J)

The unit of work and energy. One joule is the work done by a force of 1 newton acting through 1 meter.

energy

The ability to do work. It comes in forms such as motion (kinetic), height (gravitational potential), heat, chemical and electrical energy.

conservation of energy

Energy is never created or destroyed by a machine; it only changes form or moves from one place to another.

efficiency

Useful energy out ÷ energy in, usually written as a percentage. No real machine is 100% efficient.

CORE IDEAS

The story. In the 1840s a young Englishman named James Prescott Joule set out to answer a question that puzzled the scientists of his day: what is heat? Many believed heat was an invisible fluid, called “caloric,” that flowed from hot things to cold ones. Joule, who had been taught by the chemist John Dalton, suspected instead that heat was a kind of motion, and that a certain amount of work would always make the same amount of heat. In 1845 he built the apparatus that made him famous: a brass paddle wheel inside a closed can of water, turned by two weights falling slowly on strings.

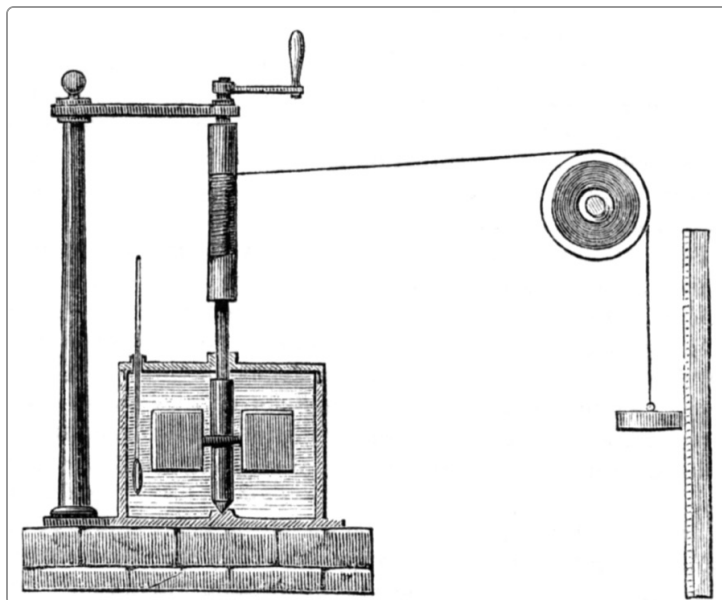
How they figured it out. The temperature rise was tiny, a fraction of a degree, so Joule used extremely sensitive thermometers that he could read to about one two-hundredth of a degree Fahrenheit. He measured exactly how far the weights fell, wound them up again, let them fall twenty times, and took the water’s temperature before and after. He corrected for heat lost to the air and for the energy the weights still had when they hit the floor. After years of careful work he announced in 1850 that 772 foot-pounds of work would warm one pound of water by one degree Fahrenheit, very close to the modern value of about 778. Other scientists at first doubted him, but his measurements were so careful that they were finally convinced. Today the unit of energy is named the **joule** in his honor.

The physics. In physics, **work** is done when a force moves something through a distance: $W = F \times d$. If you lift a 1-kilogram bottle (weight about 9.8 newtons) up 0.75 meters onto a table, you do $W = 9.8 \text{ N} \times 0.75 \text{ m} \approx 7.4$ joules of work. Carrying it level across the room does almost no work on the bottle, because the force (up) and the motion (sideways) are at right angles. Work is a transfer of **energy**, and energy is

conserved: it is never used up, only changed into other forms. Joule showed that when it seems to disappear, it has usually become heat. That is why **efficiency** matters: $\text{efficiency} = \text{useful work out} \div \text{work in} \times 100\%$. If you pull a toy cart up a ramp with 1.8 N of force over 1.0 m (1.8 J in) and the cart, weighing 4.9 N, rises 0.30 m ($4.9 \times 0.30 = 1.47$ J of useful work out), the ramp's efficiency is $1.47 \div 1.8 \approx 0.82$, or 82%. The other 18% became heat in the wheels and axles.

The engineering. Every engineer keeps an energy budget. A ramp, a pulley, a gearbox or an engine can make a job easier by trading force for distance, but none of them can give back more work than was put in; the difference is lost to friction, mostly as heat. Engineers raise efficiency by reducing friction (bearings, lubrication, smooth surfaces), by recapturing waste heat, and by choosing the right machine for the job. A good electric motor can be more than 90% efficient, while an old steam locomotive turned well under 10% of its coal's energy into motion. Saving energy is not only about cost; it means smaller fuel bills for families and less wear on every part.

PICTURE STUDY



Joule's Paddle-Wheel Apparatus, Unknown engraver, for a science book by Jacob Abbott, 1869 ·
Engraving · Published by Harper & Brothers, New York
Image: [Wikimedia Commons](#), public domain

This engraving shows the kind of apparatus Joule used to measure how much work makes a certain amount of heat. Look for the path the energy takes, from the weights to the water.

Look closely

- Find the weights. What kind of energy do they have before they fall?
- Follow the strings over the pulleys to the axle of the paddle wheel. Which way does the axle turn as the weights fall?
- Find the vessel that holds the water and paddles. Why is it closed and insulated?
- Look for the place where a thermometer could be put in.

Talk about it

1. Why did Joule let the weights fall twenty times before reading the thermometer, instead of just once?
2. Some energy went into the pulleys and the floor instead of the water. How would that affect his answer, and why did he try to measure it?

3. How does this machine show that work and heat are two forms of the same thing?

Safety first. Wear safety glasses if you use rubber bands in the pulling string. Keep the ramp on the floor or a low table so the cart cannot fall far.

BUILD

Measuring the Efficiency of a Ramp

You will pull a toy car up a ramp with a hanging bag of pennies and measure how much work goes in and how much useful work comes out. Then you will change the ramp's surface or angle (one variable at a time) and find which ramp is most efficient.

You will need

- A toy car or small wheeled cart with a little modeling clay or a few coins taped on to make it heavier (about 200–500 g)
- A smooth board, shelf or stiff cardboard about 1 meter long, and books to prop it up
- String, a thread spool and a pencil (the spool on the pencil makes a pulley at the top of the ramp)
- A zip-top sandwich bag and about 100 pennies (2.5 g each)
- Kitchen scale, meter stick or tape measure, calculator
- A towel or sheet of sandpaper to change the ramp surface

Steps

1. Weigh the car on the kitchen scale. Convert to newtons: $\text{weight (N)} = \text{mass (kg)} \times 9.8$. A 400 g car weighs $0.400 \times 9.8 = 3.92$ N.
2. Prop up the board so its top end is 0.20 m above the floor. Measure the length of the ramp surface, L , from bottom to top.
3. Push the pencil through the spool and tape the pencil ends to the top of the ramp so the spool can turn. Tie the string to the car, run it over the spool and tie the bag to the other end.
4. **Predict.** Calculate the useful work, $W_{\text{out}} = \text{car weight} \times \text{height}$. Write how many pennies you think it will take to pull the car up the ramp.
5. **Test.** Add pennies one at a time until the car, given a tiny nudge, creeps up the ramp at a slow, steady speed. Weigh the bag with its pennies and convert to newtons. That is your pulling force, F .

6. Calculate $W_{\text{in}} = F \times L$ and efficiency $= W_{\text{out}} \div W_{\text{in}} \times 100\%$. Repeat three times and average.
7. **Fair test.** Change only the surface: lay the towel over the ramp and repeat steps 5–6. Then try a steeper ramp (0.30 m high) on the bare board.
8. Record everything in a table: ramp surface, height, length, pulling force, W_{in} , W_{out} , efficiency.
9. **Improve.** Find one way to raise the efficiency of your best ramp (clean wheels, a drop of oil on the axles, a smoother surface, a lighter string) and test it. Did the efficiency go up?

Tips

- The spool pulley has friction too, so your efficiency includes the pulley. That is fine as long as you use the same pulley in every trial.
- If the car jerks instead of creeping, add or remove one penny at a time and give it the same small nudge each trial.
- A spring scale or luggage scale, if you have one, can replace the penny bag.

Check your work

- ☐ I can calculate work in, work out and efficiency with correct units.
- ☐ I can explain where the missing energy went.
- ☐ I can name the one variable I changed and show that I kept everything else the same.

ENGINEER'S NOTEBOOK

1. Draw your ramp with arrows for the pulling force, the car's weight, the height and the ramp length. Label each with its value and unit.
2. Make a data table and a bar graph of efficiency for each ramp you tested.
3. Write two sentences: Which ramp was most efficient, and why? Where did the lost energy go?

From history. Joule worked closely with the young Scottish physicist William Thomson, later Lord Kelvin, and together they discovered that a gas cools when it expands through a small opening, the effect that makes refrigerators work. Kelvin, a sincere Christian, saw the exactness of nature's laws as a mark of the Creator's wisdom.

COMMON MISTAKES

- Using grams as if they were newtons. Convert: newtons = kilograms $\times$ 9.8.
- Multiplying the pulling force by the height instead of the ramp length. The force acts along the ramp.
- Reading efficiency greater than 100%. That means a measurement error, usually a car that was nudged too hard.

Make it a game • Efficiency Estimation Duel. Your parent names a pretend machine, such as 500 joules in and 350 joules of useful work out. Calculate efficiency as a percentage and say where the rest went. Five rounds, thirty seconds each. Then explain what Joule's paddle wheel showed about work and heat. Closest answers win points, and correct units earn a bonus.

Scripture. “A false balance is abomination to the LORD: but a just weight is his delight.” (Proverbs 11:1, KJV)

Joule became famous not for a new machine but for honest, careful measurement. An engineer's numbers must be as true as a just weight.

1.2 JAMES WATT AND THE STEAM ENGINE

OBJECTIVES

- Explain how Newcomen’s atmospheric engine worked and why it wasted so much fuel.
- Describe Watt’s separate condenser and how it raised efficiency.
- Calculate power in watts and horsepower, and measure the work done by a simple heat engine.

Warm-up. Hold an empty plastic bottle (cap off) under hot tap water for a minute, then quickly put on the cap and run cold water over it. Watch and listen. What pushed the bottle in? (Keep the water hot from the tap, not boiling.)

WATCH

What is the First Engine Ever?

Branch Education • 9:10

<https://www.youtube.com/watch?v=GMgP-4O99qU>

WHEN TO WATCH

After the story. Watch for the moment the cylinder is cooled, and ask why that wastes steam.

BACKUP VIDEO

The power of atmospheric pressure, the power behind the Newcomen Steam Engine of 1712

New England Wireless & Steam Museum • 8:16

https://www.youtube.com/watch?v=wPcSQ1IS_hs

Optional, from a steam museum: a museum test of the atmospheric pressure behind Newcomen’s engine.

KEY TERMS

atmospheric pressure

The push of the air around us, about 101,000 newtons on every square meter (about 10 N on every square centimeter) at sea level.

cylinder and piston

A tube and a close-fitting plug that slides in it. Gas pressure on the piston turns heat into motion.

condenser

A cold chamber where steam turns back into water, leaving a partial vacuum behind it.

power

How fast work is done: $P = W \div t$.
Measured in watts (W); 1 watt = 1 joule per second.

horsepower

Watt's unit of power, 33,000 foot-pounds per minute, about 746 watts.

heat engine

Any machine that turns heat into work, such as a steam engine, a car engine or a jet engine.

CORE IDEAS

The story. In 1712 an English ironmonger named Thomas Newcomen set up the first successful steam engine near Dudley Castle, to pump water out of a coal mine. A great wooden beam rocked on a pivot like a seesaw. One end held the pump rods down in the mine; the other was chained to a piston in a big cylinder. Steam filled the cylinder, then a spray of cold water condensed it, leaving a partial vacuum. The air outside pushed the piston down, pulling the beam and lifting water from the mine. Newcomen engines worked for more than sixty years, but they burned enormous amounts of coal. In 1763 a young instrument maker at the University of Glasgow, James Watt, was asked to repair the university's small model Newcomen engine, and he could not stop wondering why it needed so much steam.

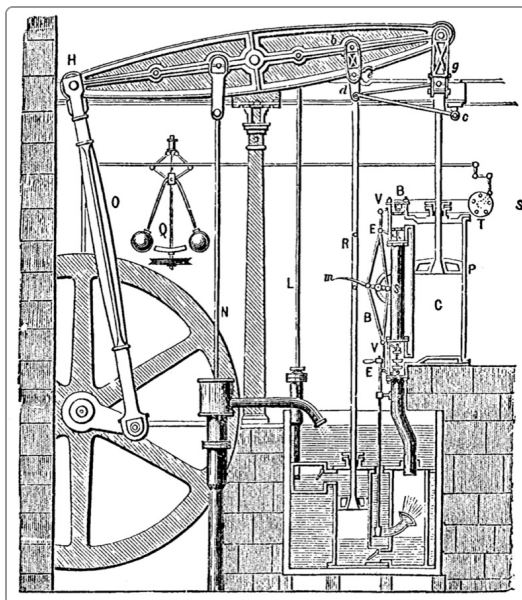
How they figured it out. Watt measured. He found that most of the steam was wasted simply warming the cylinder back up after each spray of cold water had chilled it. The cylinder had to be hot to keep steam from condensing too early, and cold to make the vacuum. It could not be both. In 1765, walking on Glasgow Green on a Sunday afternoon, Watt saw the answer: condense the steam in a **separate** vessel, connected to the cylinder but kept cold, while the cylinder stayed hot all the time. He patented the idea in 1769. It took years to make it work, until Matthew Boulton became his partner and John Wilkinson's new boring machine could cut cylinders round and true. From 1776 Boulton & Watt engines used only about a quarter of the coal of a Newcomen engine doing the same work.

The physics. Newcomen's engine was really pushed by the air. Atmospheric pressure is about 10 newtons on every square centimeter. A piston with an area of $2,000 \text{ cm}^2$ (about 50 cm across) feels up to $2,000 \times 10 = 20,000 \text{ N}$, the weight of about two tonnes, when there is a good vacuum underneath it. Heat made the steam; cooling the steam

made the vacuum; the air did the work. That is a **heat engine**: heat flows from something hot to something cold, and part of it is turned into work. **Power** is how fast the work is done: $P = W \div t$. An engine that lifts 1,000 N of mine water up 10 m in 5 seconds does 10,000 J of work, so its power is $10,000 \text{ J} \div 5 \text{ s} = 2,000 \text{ W}$, or about 2.7 horsepower. Watt invented the horsepower so that mine owners could compare his engines with the horses they replaced.

The engineering. Watt kept improving. He made the engine double-acting (steam pushed on both sides of the piston), added the sun-and-planet gears and later a crank to turn wheels, and fitted a spinning centrifugal governor that kept the speed steady. Rotating steam engines powered mills, factories, ships and railways. Watt engines were still only a few percent efficient by today's standards, but each improvement meant more work from each ton of coal. Modern power plants still use steam turbines and condensers, the direct heirs of Watt's idea, and the unit of power on every light bulb is named the watt in his honor.

PICTURE STUDY



A Boulton & Watt Steam Engine, Robert Henry Thurston, Published 1878 (engine design of 1784) · Engraving · From Thurston's A History of the Growth of the Steam-Engine

Image: [Wikimedia Commons](#), public domain

This engraving shows a rotating Boulton & Watt engine of the kind built from the 1780s. Every part has a job: making steam, using it, condensing it, and turning the motion into a spinning wheel.

Look closely

- Find the boiler, where the fire makes steam.
- Find the cylinder and the great rocking beam above it.
- Look for the separate condenser, a vessel near the cylinder kept in cold water.
- Find the large flywheel and the governor with its two spinning balls.

Talk about it

1. Why does keeping the condenser apart from the cylinder save coal?
2. What is the flywheel for? What would happen to the speed without it?
3. How does the governor keep the engine from running too fast?

Safety first. Use hot tap water only, never boiling water, for the syringe engine. If an adult does the optional can-crush test on the stove, the adult uses tongs and oven mitts, everyone wears safety glasses, and children stand back.

BUILD

A Syringe Heat Engine That Lifts a Load

You will build a tiny heat engine from a bottle, a tube and a syringe. Warming the air in the bottle pushes the syringe plunger up and lifts a load of pennies; cooling it brings the plunger back down. You will measure the work it does and test how the temperature difference changes the result.

You will need

- A small, stiff plastic bottle or glass jar (about 250–500 mL) with a cap
- A 10 mL or 20 mL plastic syringe and about 30 cm of tubing that fits its tip snugly
- Modeling clay or hot glue (adult) to seal the tubing through a hole in the cap
- A drop of cooking oil for the plunger, a small paper cup and pennies
- Two bowls: one of hot tap water and one of ice water, and a kitchen thermometer if you have one
- Tape, a ruler, a clamp or stack of books to hold the syringe upright

Steps

1. An adult makes a hole in the bottle cap, pushes the tubing through, and seals it airtight with clay or hot glue. Attach the other end of the tube to the syringe.
2. Wipe a drop of oil on the plunger's rubber so it slides easily. Push the plunger almost all the way in, then attach the tube. Fix the syringe upright with the plunger on top and tape a ruler beside it.
3. Tape the paper cup to the top of the plunger. Put 10 pennies (25 g) in it. Record the plunger height.
4. **Predict.** How many millimeters will the plunger rise when the bottle goes into hot water?
5. **Test.** Lower the bottle into the bowl of hot water and hold it there. Record how high the plunger rises (in meters) and how long it takes. Move the bottle to the ice water and record what happens.

6. Calculate the work done on the load: $W = \text{weight} \times \text{height}$. Ten pennies weigh $0.025 \text{ kg} \times 9.8 = 0.245 \text{ N}$. A rise of 0.02 m gives $W = 0.245 \times 0.02 \approx 0.005 \text{ J}$.
7. **Fair test.** Change only the temperature difference: try warm water (not hot) and then hot water, using the same load each time. Repeat each trial three times and average.
8. **Improve.** Try one change to get more work per cycle: a bigger bottle, less tubing, a better seal or a lighter-sliding plunger. Test it the same way.
9. Compare: how many cycles would your engine need to lift the pennies 1 meter? What does that tell you about why Watt cared so much about each stroke?

Tips

- A leak anywhere stops the engine. Test the seal by pressing the plunger: it should spring back.
- Plastic syringes have friction. If the plunger sticks, a heavier load sometimes helps it slide smoothly.
- The bottle must be the part that is heated and cooled, not the syringe.

Check your work

- ☐ I can explain how heating and cooling the air makes my engine do work.
- ☐ I can calculate the work my engine did on its load.
- ☐ I can explain why Watt's separate condenser saved so much fuel.

ENGINEER'S NOTEBOOK

1. Draw and label Newcomen's engine: beam, piston, cylinder, cold-water spray, pump rods. Then draw Watt's improvement beside it with the separate condenser circled.
2. Make a table of your engine trials: water temperature, load, rise, work done. Graph rise against temperature difference.
3. Calculate the power of a person who climbs 3 m of stairs in 4 s with a weight of 500 N. Show the formula, the numbers with units, and the answer in watts.

From history. Watt was a thorough and modest man who worried constantly about safety and preferred low-pressure steam. In 1800, after his patent expired, Richard Trevithick built high-pressure engines that were small enough to put on wheels, and within thirty years the steam locomotive had arrived.

COMMON MISTAKES

- Thinking the steam pushed the piston down in Newcomen's engine. It was the air pressure outside, pushing into the vacuum.
- Forgetting that power depends on time. Two engines can do the same work, but the faster one has more power.
- Letting the bottle warm up in your hands between trials, which changes the starting temperature.

Make it a game • Newcomen's Steam Trial. Take turns as Newcomen and Watt in a mock engineering hearing. Newcomen explains the atmospheric engine, Watt points out the wasted heat and introduces the separate condenser. Each side gets sixty seconds, then your parent asks one question about the cylinder and piston. Switch roles. The clearest explainer takes the point.

1.3 THE INTERNAL-COMBUSTION ENGINE: OTTO AND DIESEL

OBJECTIVES

- Name and explain the four strokes of a four-stroke engine.
- Explain why compressing the fuel and air raises an engine's efficiency.
- Build a crank-and-syringe model, measure its stroke and calculate its displacement.

Warm-up. Hold your finger tightly over the tip of a syringe and push the plunger in as far as you can. What do you feel? Let go of the plunger. What happens? Write one sentence about what the air inside is doing.

WATCH

How a Car Engine Works

Animagraffs • 7:55

<https://www.youtube.com/watch?v=ZQvfHyfgBtA>

WHEN TO WATCH

After the physics paragraph. Pause on each stroke and name it before the narrator does.

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>

Optional: a see-through engine filmed in slow motion, so you can watch the burning in the cylinder.

KEY TERMS

internal-combustion engine

An engine that burns its fuel inside the cylinder, so the hot gases push directly on the piston.

four-stroke cycle

Intake, compression, power and exhaust: the four piston movements that make one full cycle of most car engines.

crankshaft

A shaft with offset arms that turns the up-and-down motion of the pistons into rotation.

stroke

The distance the piston travels from top to bottom. It equals twice the crank radius.

displacement

The volume the pistons sweep through: $\text{area of the piston} \times \text{stroke} \times \text{number of cylinders}$.

compression ratio

The volume in the cylinder when the piston is at the bottom divided by the volume when it is at the top.

CORE IDEAS

The story. Steam engines needed a boiler, a firebox and a tall chimney. Inventors dreamed of an engine that burned its fuel inside the cylinder itself. In 1860 the Belgian-French engineer Étienne Lenoir built a gas engine that worked, but it burned its fuel without squeezing it first and turned only about 4% of the fuel's energy into work. In Cologne, Germany, a traveling salesman named Nicolaus Otto began experimenting with engines of his own, and in 1876, working with the engineers Gottlieb Daimler and Wilhelm Maybach at the Deutz company, he built the first successful four-stroke engine. Within ten years Karl Benz had put a small engine on a three-wheeled carriage (1886), and the automobile was born.

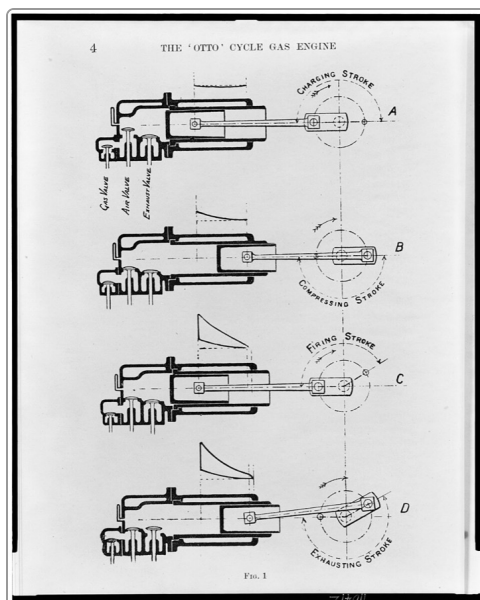
How they figured it out. Otto's key step was to **compress** the fuel and air before lighting it. He tried many arrangements and measured the power and the gas used by each. The engine that worked best needed four strokes of the piston for each power stroke: draw the mixture in, squeeze it, burn it, push the burned gas out. Otto's engine was quieter and used far less fuel for its power than Lenoir's. (A Frenchman, Alphonse Beau de Rochas, had described the same four-stroke idea on paper in 1862, but had never built it.) In the 1890s Rudolf Diesel asked whether squeezing the air even harder would make it so hot that fuel sprayed into it would light by itself, without a spark. His test engine of 1897 turned about a quarter of its fuel's energy into work, the most efficient engine of its day.

The physics. A four-stroke engine repeats four steps. **Intake:** the piston moves down and pulls in air and fuel. **Compression:** it moves up and squeezes the mixture into a small space. **Power:** a spark lights it, and the hot, high-pressure gas pushes the piston down hard. **Exhaust:** the piston moves up and pushes the burned gas out. Only one stroke in four does work; a heavy flywheel carries the engine through the

other three. Squeezing the mixture before burning lets the gas expand more afterward, so more of its heat becomes work. The **displacement** of a cylinder is its piston area times its stroke. A piston 8.6 cm across has a radius of 4.3 cm and an area of $\pi \times 4.3^2 \approx 58 \text{ cm}^2$; with a stroke of 8.6 cm it sweeps $58 \times 8.6 \approx 500 \text{ cm}^3$. Four such cylinders make a “2.0-liter” engine.

The engineering. An engine is a balance of trade-offs. A higher compression ratio raises efficiency, but if it is too high for the fuel, the mixture can ignite too early and knock, damaging the engine; that is why diesel engines are built heavier. More cylinders make a smoother engine but add cost and weight. Engineers also had to add cooling (water jackets and radiators), lubrication, fuel injection and, today, computer control. Even so, most car engines turn only about a quarter to a third of their fuel’s energy into motion; the rest leaves as heat in the exhaust and the radiator. Diesel engines, being more efficient, power most ships, trains, tractors and trucks.

PICTURE STUDY



The Four Strokes of the Otto-Cycle Engine, William Norris, 1896 · Diagram (photomechanical print) · Library of Congress, Prints and Photographs Division

Image: [Wikimedia Commons](#), public domain

This diagram from an 1896 book on the Otto-cycle gas engine shows one cylinder at each of its four strokes. Early engineers called them the charging, compressing, firing and exhausting strokes; we call them intake, compression, power and exhaust.

Look closely

- Find the four drawings and their labels. Match each to intake, compression, power and exhaust.
- Follow the crank on the right of each drawing. How far does it turn from one stroke to the next?
- Find the gas valve, air valve and exhaust valve at the left. Which are open in each stroke?
- Look at the small graphs beside each drawing. Where is the pressure highest?

Talk about it

1. Why does the crank turn twice for every power stroke?
2. Why is the pressure highest at the start of the firing stroke?

3. What would happen if the exhaust valve stayed shut during the exhausting stroke?

Safety first. Real engines are hot and have moving parts: never reach into a running engine or touch an exhaust pipe. In this build, an adult cuts any cardboard with a craft knife.

BUILD

A Crank-and-Syringe Engine Model

You will build a cardboard crank that pushes and pulls a syringe plunger, just as a crankshaft moves a piston. You will measure how the crank radius sets the stroke, calculate the displacement, and compare it with the syringe's own markings.

You will need

- A 10 mL or 20 mL syringe (the cylinder and piston)
- Corrugated cardboard, a brass paper fastener or a short bolt, craft sticks, a wooden skewer
- Hot glue (adult) or strong tape, a ruler, a compass for drawing circles
- Calculator and engineer's notebook

Steps

1. Cut a cardboard disk about 10 cm across (the crank). Push a skewer through its center as an axle and mount it on a cardboard stand so it turns freely.
2. Make three holes in the disk at 1.0 cm, 1.5 cm and 2.0 cm from the center. These are three possible crank radii.
3. Glue the syringe barrel firmly to the stand, in line with the center of the disk. Make a connecting rod from a craft stick: one end fastens to the crank hole with the paper fastener, the other end is glued to the plunger.
4. **Predict.** For each crank radius, predict the stroke (stroke = $2 \times$ crank radius).
5. **Test.** Attach the rod at the 1.0 cm hole. Turn the crank one full turn and read the syringe's volume at the top and bottom of the stroke. Measure the stroke in centimeters with the ruler. Repeat for 1.5 cm and 2.0 cm.
6. Measure the inside diameter of the syringe barrel and calculate its piston area ($\pi \times r^2$). Then calculate displacement = area $\times$ stroke and compare it with the change in the syringe's markings.
7. Mark the four strokes on your crank disk with a pencil: intake, compression, power, exhaust. How many turns of the crank does one full four-stroke cycle take?

8. **Compression ratio.** Cover the syringe tip with your finger at the bottom of the stroke (largest volume), turn the crank, and record the volumes at bottom and top. Ratio = bottom volume $\div$ top volume.
9. **Improve.** Make the model run more smoothly: add a cardboard flywheel with a few coins taped near the rim and see whether it keeps turning longer after a push.

Tips

- If the plunger binds, check that the syringe points exactly at the crank's axle.
- Real engines measure displacement in cubic centimeters (cc). One milliliter equals one cubic centimeter, so your syringe markings are already in cc.

Check your work

- ☐ I can name and describe the four strokes in order.
- ☐ I can explain why the stroke is twice the crank radius.
- ☐ I can calculate the displacement of a cylinder from its diameter and stroke.

ENGINEER'S NOTEBOOK

1. Draw four small pictures of one cylinder, one for each stroke, with arrows for the piston's motion and labels for the valves and spark plug.
2. Make a table: crank radius, predicted stroke, measured stroke, calculated displacement, displacement from the syringe markings. Explain any differences.
3. A lawn-mower engine has one cylinder with a bore of 6.5 cm and a stroke of 4.5 cm. Calculate its displacement in cubic centimeters.

From history. Bertha Benz, Karl Benz's wife, made the first long-distance drive in the Benz Motorwagen in 1888, about 106 kilometers from Mannheim to Pforzheim, buying fuel at a pharmacy along the way. Her report of the trip helped her husband improve the brakes and add a lower gear for hills.

COMMON MISTAKES

- Using the diameter instead of the radius in $\pi \times r^2$.
- Thinking every stroke makes power. Only one stroke in four does.
- Confusing displacement (the volume swept) with the total volume of the cylinder.

Make it a game • Four Stroke Charades. Act out the four strokes of an engine with your whole body: intake, compression, power and exhaust. Your parent guesses which stroke you show. Then rank three engine ideas by compression ratio and explain why squeezing the air and fuel raises efficiency. Swap roles. Fewest wrong guesses over two rounds wins.

1.4 CONSERVATION OF ENERGY ON A ROLLER COASTER

OBJECTIVES

- Calculate gravitational potential energy ($PE = mgh$) and kinetic energy ($KE = \frac{1}{2}mv^2$).
- Use conservation of energy to predict a speed and compare it with a measurement.
- Explain where the “missing” energy goes and what that means for roller-coaster design.

Warm-up. Drop a ball from shoulder height and watch it bounce. Does it ever bounce higher than where it started? Why not? Write one sentence about where the energy went.

WATCH

Introduction to Conservation of Mechanical Energy with Demonstrations

Flipping Physics · 8:25

<https://www.youtube.com/watch?v=AnuLW0ZX7-Q>

WHEN TO WATCH

After the physics paragraph. Pause before the calculation and predict the answer.

BACKUP VIDEO

The Physics of Roller Coasters

SciShow · 3:39

<https://www.youtube.com/watch?v=J8pJiV44hVM>

Optional, after the build: a short look at how real roller coasters use the same ideas.

KEY TERMS

gravitational potential energy

Energy stored by height: $PE = m \times g \times h$,
where $g \approx 9.8 \text{ m/s}^2$.

kinetic energy

Energy of motion: $KE = \frac{1}{2} \times m \times v^2$.

mechanical energy

The total of potential and kinetic energy.

friction and drag

Forces that oppose motion and turn mechanical energy into heat and sound.

clothoid loop

A teardrop-shaped loop, tighter at the top than at the bottom, used on modern roller coasters to keep forces on riders comfortable.

CORE IDEAS

The story. On June 16, 1884, LaMarcus Adna Thompson opened his Switchback Railway at Coney Island in New York. Riders climbed a tower, sat sideways in a car and rolled down a gentle wooden track at about 6 miles per hour to a second tower, where workers pushed the car up for the return trip. It cost a nickel and was so popular that it paid for itself within weeks. Builders soon raced to make coasters steeper, faster and loopier. The first loop coasters of the 1890s used perfectly circular loops, and riders felt the forces so strongly that the rides were soon closed.

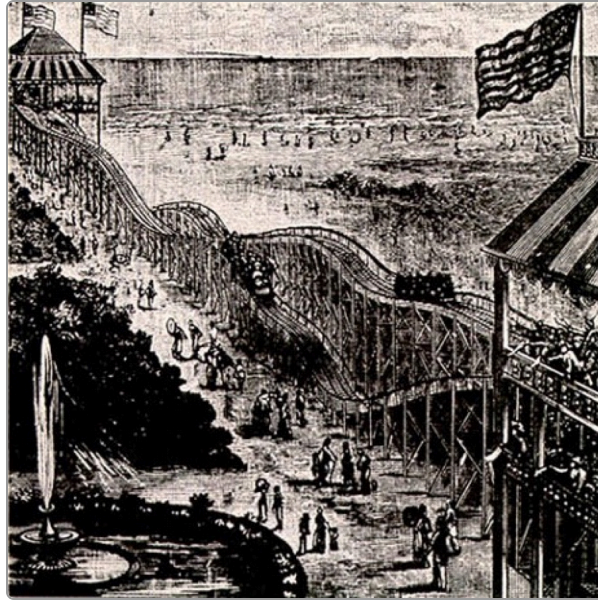
How they figured it out. Coaster designers had to answer two questions before building: how fast will the train be going at each point, and how strong will the forces on the riders be? The answer to the first comes from energy. The chain lift gives the train all its energy at the top of the first hill; after that, the train coasts. Engineers calculate the speed at every point from the height, then subtract a little for friction and air drag, and test the train on the finished track with weights in the seats before anyone rides. In the 1970s the German engineer Werner Stengel and others introduced the teardrop-shaped **clothoid loop**, which keeps the forces at the bottom of the loop gentle while giving enough speed at the top.

The physics. At the top of a hill the train has **potential energy**, $PE = mgh$. As it falls, that energy becomes **kinetic energy**, $KE = \frac{1}{2}mv^2$. If no energy were lost, $mgh = \frac{1}{2}mv^2$, and the mass cancels: $v = \sqrt{2gh}$. A coaster that drops 60 m could reach $v = \sqrt{2 \times 9.8 \times 60} = \sqrt{1,176} \approx 34$ m/s, about 77 miles per hour, whether it is full or empty. In real life friction and air drag turn some energy into heat and sound, so the true speed is a little less and each hill must be lower than the one before. A rolling

marble loses something else too: part of its energy goes into spinning, so it travels about 15% slower than the simple formula predicts.

The engineering. A roller coaster is an energy budget laid out in steel. The first hill must be the highest, because the train can never climb above its starting height. Brakes at the end remove the remaining energy safely. Engineers use the speed at each point to work out the forces on riders and design the track so those forces stay within safe limits for ordinary people, with wheels above, below and beside the rail so the train can never leave the track. Safety factors, daily inspections and test runs before opening each morning are part of the design. The same energy thinking is used in cars, elevators and even hydroelectric dams.

PICTURE STUDY



Thompson's Switchback Railway, Unknown engraver, 1884 · Engraving · Coney Island, Brooklyn, New York

Image: [Wikimedia Commons](#), public domain

This is the ride that started the American roller coaster. Look at how gentle it is compared with a modern coaster, and see whether you can find where the energy came from.

Look closely

- Find the raised platform at the start. What gave the car its energy?
- Follow the track. Does it go up and down? Is any hill higher than the starting point?
- Find the wooden trestle that holds the track up. What kind of structure is it?
- Find the car and its riders. Which way are they facing?

Talk about it

1. Why did workers have to push the car up the second tower for the return trip?
2. Why is every hill on the track lower than the starting point?
3. If you were redesigning this ride to go faster, what would you change, and what new safety problem would that create?

Safety first. Keep marbles away from small children (choking hazard). Tape the track firmly so it cannot fall, and do not stand on chairs that might tip.

BUILD

A Foam Roller Coaster Energy Test

You will build a marble roller coaster from foam pipe insulation, predict the marble's speed at the bottom of the first drop with $v = \sqrt{2gh}$, measure the real speed, and find how much energy was lost. Then you will add a loop and find the lowest starting height that carries the marble through it.

You will need

- About 2 m of foam pipe insulation, cut in half lengthwise to make two open tracks
- Masking tape, a wall or door, chairs or a tall bookshelf to hold the track
- Marbles (a few of the same size), a meter stick and tape measure
- A smartphone that records slow-motion video, or a stopwatch
- Calculator and engineer's notebook

Steps

1. Tape the track so it starts high, drops steeply, and then runs flat along the floor for at least 1 meter. Mark two lines on the flat part exactly 0.50 m apart.
2. Mark three starting points on the drop at heights of 0.40 m, 0.60 m and 0.80 m above the flat section.
3. **Predict.** For each height, calculate $v = \sqrt{2gh}$. For $h = 0.80$ m, $v = \sqrt{2 \times 9.8 \times 0.80} = \sqrt{15.7} \approx 4.0$ m/s.
4. **Test.** Release the marble from rest (do not push). Film it crossing the two lines in slow motion, or time it with a stopwatch. $\text{Speed} = 0.50 \text{ m} \div \text{time}$.
5. Repeat three times at each height and average the times.
6. Calculate the percent of the predicted speed that you measured. Then calculate the fraction of energy kept: $(\text{measured } v \div \text{predicted } v)^2$.
7. **Add a loop.** Curl the second track into a vertical loop about 20 cm across at the bottom of the drop. Find the lowest start height that carries the marble all the way around. Compare it with $2.7 \times$ the loop radius, the ideal value for a rolling ball.

8. **Improve.** Change one thing to lose less energy (smoother joints, a steeper or shorter drop, a heavier marble) and test again. Did more energy reach the bottom?

Tips

- Joints in the track steal energy. Tape them smooth on the outside, not across the inside.
- Slow-motion video is far more accurate than a hand stopwatch. Count frames if your phone tells you the frame rate.
- If the marble jumps off at the bottom, the curve at the bottom of the drop is too sharp.

Check your work

- ☐ I can predict a speed from a height using conservation of energy.
- ☐ I can explain why my measured speed was lower than my prediction.
- ☐ I can explain why the first hill of a roller coaster must be the highest.

ENGINEER'S NOTEBOOK

1. Draw your coaster to scale on graph paper. Label the start height, the timing lines and the loop.
2. Make a table: start height, predicted speed, three measured times, average speed, percent of predicted, fraction of energy kept. Graph measured speed against height.
3. A 500 kg coaster car starts at rest 30 m high. Calculate its potential energy at the top and its speed at the bottom, ignoring friction.

From history. Thompson went on to build scenic railways, coasters with painted scenery and tunnels along the route, across America and in Europe, and he received many patents for improvements to amusement rides.

COMMON MISTAKES

- Pushing the marble at the start, which adds energy you did not measure.
- Forgetting the square root when calculating speed.
- Measuring the height along the track instead of straight up and down.

Make it a game • Conservation Contest. Roll a marble down a ramp 0.2 m high. Predict its speed at the bottom using $v = \text{the square root of } 2gh$, with g near 10. Then predict a different height. Your parent times a short run to check. Closest predictions win. Say where the lost energy went in terms of friction and drag.

Scripture. “And he is before all things, and by him all things consist.” (Colossians 1:17, KJV)

Conservation of energy holds for every coaster, every engine and every star. Its steadiness is one way the orderly world God upholds can be measured and trusted.

UNIT 1

ENERGY AND ENGINES

Every machine runs on energy, and every engineer must answer the same three questions: How much work does this job take? How fast must it be done? And how much of the energy we put in comes out as useful work? In this unit you will learn the words and equations engineers use to answer them, work, energy, power and efficiency, and you will measure them yourself with a ramp, a syringe and a foam roller-coaster track.

The stories run from a quiet laboratory to the factories and roads of the modern world. James Joule measured how falling weights warm water and showed that work and heat are two forms of the same thing. Thomas Newcomen and James Watt turned steam into the first useful engines, and Watt's separate condenser cut their coal use by about three quarters. Nicolaus Otto and Rudolf Diesel put the fire inside the cylinder. Last, you will follow the energy of a marble down a roller coaster and find out where every joule goes.

PREREQUISITES

- Can multiply and divide decimals and use a calculator
- Knows that a force is a push or a pull, measured in newtons
- Has kept a dated engineer's notebook with predictions and data tables (Grades 5–6)

MASTERY CHECKLIST

- ☐ I can calculate work ($W = F \times d$), power ($P = W \div t$) and efficiency, with correct units.
- ☐ I can explain how Watt's separate condenser made the steam engine far more efficient.
- ☐ I can name the four strokes of an internal-combustion engine and calculate an engine's displacement.
- ☐ I can use conservation of energy to predict the speed of a marble or a roller-coaster car and explain where the "lost" energy went.
- ☐ I can run a fair test, repeat trials, average them and compare measured results with predictions.

OPTIONAL KITS FOR THIS UNIT

- **Thames & Kosmos physics and engine kits:** Ages 10 and up. Several kits build working models of engines, gears and machines with clear manuals; a good extra for Lessons 1.2 and 1.3.
- **LEGO Technic:** Ages vary by set. Many Technic cars include a model piston engine with a crankshaft and connecting rods that move as the wheels turn, a fine way to see the four strokes in Lesson 1.3.

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	Work, Energy and Efficiency: Joule's Paddle Wheel	2 sessions of 50–60 minutes
1.2	James Watt and the Steam Engine	2 sessions of 50–60 minutes
1.3	The Internal-Combustion Engine: Otto and Diesel	2 sessions of 50–60 minutes
1.4	Conservation of Energy on a Roller Coaster	2 sessions of 50–60 minutes

UNIT 1 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Define work and give its unit. Does a waiter do work on a tray while carrying it level across a room at a steady speed? Explain.

2. 10 pts

Calculation: You pull a 6 N box up a ramp with a force of 2.5 N. The ramp is 2.0 m long and 0.60 m high. Find the work in, the useful work out, and the efficiency.

3. 8 pts

What did James Joule show with his paddle-wheel experiment, and why was careful measurement so important to it?

4. (8 pts)

In Newcomen's engine, what actually pushed the piston down?

5. (10 pts)

Explain the problem James Watt found in Newcomen's engine and how his separate condenser solved it.

6. (10 pts)

Calculation: A pump lifts 2,000 N of water up 15 m in 20 s. How much work does it do, and what is its power in watts and in horsepower ($1 \text{ hp} \approx 746 \text{ W}$)?

7. (8 pts)

Name the four strokes of a four-stroke engine in order and say what the piston does in each.

8. (8 pts)

Why does compressing the fuel and air before lighting it make an engine more efficient? What limits how far engineers can raise the compression?

9. (10 pts)

Calculation: A marble is released from rest at the top of a 0.45 m drop. Predict its speed at the bottom, ignoring friction ($g = 9.8 \text{ m/s}^2$).

10. (8 pts)

Your measured marble speed was only 85% of the predicted speed. Give two reasons.

11. (12 pts)

Written answer: Explain, using the words potential energy, kinetic energy and friction, why the first hill of a roller coaster must be the tallest.

ANSWER KEY

1. Work is force times the distance moved in the direction of the force ($W = F \times d$), measured in joules. Carrying the tray level does almost no work on it, because the upward force is at right angles to the sideways motion.
2. $W_{\text{in}} = 2.5 \text{ N} \times 2.0 \text{ m} = 5.0 \text{ J}$. $W_{\text{out}} = 6 \text{ N} \times 0.60 \text{ m} = 3.6 \text{ J}$. Efficiency = $3.6 \div 5.0 = 0.72 = 72\%$.
3. He showed that a definite amount of work always produces the same amount of heat, so heat is a form of energy, not a fluid. The temperature change was tiny, so only very careful measurement and corrections for losses could prove it.
4. The pressure of the outside air (atmospheric pressure), pushing into the partial vacuum left when the steam was condensed.
5. Each spray of cold water cooled the cylinder, so much of the next charge of steam was wasted just reheating it. Watt condensed the steam in a separate vessel kept cold, so the cylinder could stay hot all the time. His engines used about a quarter of the coal.
6. $W = 2,000 \text{ N} \times 15 \text{ m} = 30,000 \text{ J}$. $P = 30,000 \text{ J} \div 20 \text{ s} = 1,500 \text{ W}$. $1,500 \div 746 \approx 2.0 \text{ hp}$.
7. Intake (moves down, pulls in air and fuel); compression (moves up, squeezes it); power (pushed down by the burning gas); exhaust (moves up, pushes burned gas out).
8. The burned gas can then expand more, so more of its heat is turned into work. If compression is too high for the fuel, it can ignite too early (knock) and damage the engine; higher compression also needs a heavier, stronger engine.
9. $v = \sqrt{(2gh)} = \sqrt{(2 \times 9.8 \times 0.45)} = \sqrt{8.82} \approx 3.0 \text{ m/s}$.
10. Any two: friction with the track; air drag; energy lost at bumps and joints; part of the energy went into making the marble spin; timing error.
11. At the top of the first hill the train has its most potential energy. As it rolls, potential energy changes to kinetic energy and back, but friction and drag keep turning some of it into heat, so the total mechanical energy only goes down. The train can never climb higher than its starting point, so every later hill must be lower than the first.

PORTFOLIO PIECE: AN ENERGY AUDIT OF A ROLLER COASTER

Design and build a foam-track roller coaster with at least one drop, one hill and one loop, and carry out a full energy audit of it. Measure the marble's mass and the height of each point, predict the speed at three points with $v = \sqrt{2gh}$, measure the real speeds, and calculate the percent of energy kept at each point. Write a one-page engineer's report with a scale drawing, your data table and graph, an explanation of the losses, and one improvement you built and tested.

LOOK FOR	WHAT IT MEANS
Design drawing	Scale drawing with heights, the loop size and the timing points labeled with units.
Predictions	Speeds calculated correctly with $v = \sqrt{2gh}$ before testing, with the work shown.
Fair, repeated measurements	Marble released from rest; at least three trials at each point; averages recorded.
Energy analysis	Percent of energy kept calculated, and the losses explained using friction, drag and spin.
Improvement	One change made for a specific reason, tested the same way, and the result reported honestly.

BRIDGES

In earlier years you learned that bridges carry loads by compression and tension. This year you will learn to calculate those forces the way bridge engineers do. You will draw free-body diagrams, use the two rules of equilibrium to predict the forces on a bridge's supports, and then check your predictions with two kitchen scales. You will work out the forces in every member of a simple truss by the method of joints, and you will see why a hanging chain takes the shape it does and how much a suspension cable must pull to hold up a deck.

The unit ends with one of the most important stories in engineering. The Quebec Bridge fell twice before it finally stood, and the lessons learned there changed how engineers check their work and how seriously they take their duty to the public. Canadian engineers still wear an iron ring on the little finger of their working hand to remember it.

PREREQUISITES

- Can calculate work and energy with units (Unit 1)
- Knows compression, tension, and why triangles are rigid (Grades 5–6)
- Can use a ratio and solve a simple equation such as $2x = 600$

MASTERY CHECKLIST

- ☐ I can draw a free-body diagram and use $\Sigma F = 0$ and $\Sigma \text{moments} = 0$ to find support forces.
- ☐ I can find the forces in a simple truss by the method of joints and say which members are in tension and which in compression.
- ☐ I can explain the shapes of hanging cables and arches and calculate how cable tension changes with sag.
- ☐ I can explain what went wrong at the Quebec Bridge, what buckling is, and what a safety factor is for.
- ☐ I can describe an engineer's duty to the public and give an example of an engineer acting on it.

OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits:** Ages 12 and up with an adult. Balsa sticks, plans and gussets for building a truss bridge that can be weighed and load-tested; a fine portfolio extension for Lesson 2.2.
- **K’NEX building sets:** Ages vary by set. Rods and connectors make quick trusses, arches and suspension models for testing many shapes in one afternoon.

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 Free-Body Diagrams and Equilibrium: Simon Stevin’s Wreath of Spheres

2 sessions of 50–60 minutes

2.2 The Method of Joints: Wendel Bollman’s Truss

2 sessions of 50–60 minutes

2.3 Cables, Chains and Catenaries: Hooke’s Hanging Chain

2 sessions of 50–60 minutes

2.4 The Quebec Bridge: Buckling, Safety Factors and the Engineer’s Duty

2 sessions of 50–60 minutes

UNIT 2 REVIEW

Answer each question. For calculations, draw a small free-body diagram, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

State the two conditions an object must meet to be in equilibrium.

2. **10 pts**

Calculation: A 6 m plank rests on supports at each end. A 600 N load sits 2 m from the left end. Find the force on each support (ignore the plank’s weight).

3. **8 pts**

What did Simon Stevin’s wreath of spheres show, and how did he reason it out?

4. (12 pts)

Calculation: A simple roof truss has a half-base of 4 m and a height of 3 m (each slope 5 m). A load of 1,200 N acts at the peak. Find the force in each sloping member and in the bottom chord, and say whether each is in tension or compression.

5. (8 pts)

Why can the tension members of a truss be thinner than its compression members?

6. (8 pts)

What is the difference between a catenary and a parabola, and which shape does a suspension-bridge main cable take?

7. (10 pts)

Calculation: A model cable spans 2.0 m and carries 10 N per meter of span. Find the horizontal pull if the sag is 0.25 m. What happens to the pull if the sag is halved?

8. (8 pts)

What did Robert Hooke mean by “As hangs the flexible line, so but inverted will stand the rigid arch”?

9. (8 pts)

Calculation: A column will buckle at 90 kN and carries a working load of 36 kN. What is its safety factor?

10. (10 pts)

Give two technical causes of the 1907 Quebec Bridge collapse.

11. (10 pts)

Written answer: What did engineers change after the Quebec Bridge disaster, and what does the Iron Ring remind Canadian engineers of?

ANSWER KEY

1. The forces must balance ($\Sigma F = 0$: up equals down, left equals right), and the moments must balance ($\Sigma \text{moments} = 0$ about any point).
2. Moments about the left support: $R_{\text{right}} \times 6 = 600 \times 2$, so $R_{\text{right}} = 200$ N. $R_{\text{left}} = 600 - 200 = 400$ N.
3. That forces along slopes balance: a few balls on a steep slope balance more on a gentle one. He reasoned that if they did not balance, the loop would move forever by itself, which is impossible.
4. Each support pushes up 600 N. Sloping member: $600 \times 5/3 = 1,000$ N in compression. Bottom chord: $600 \times 4/3 = 800$ N in tension.
5. A pull straightens a member, so a slender rod is fine in tension; a push can make a slender member buckle sideways, so compression members must be stockier or braced.
6. A catenary is the shape of a chain hanging under its own weight alone; a parabola is the shape of a cable carrying a load spread evenly along the level span. A suspension-bridge cable, which mostly carries the deck, is very close to a parabola.
7. $H = wL^2 \div 8d = 10 \times 2.0^2 \div (8 \times 0.25) = 40 \div 2 = 20$ N. Halving the sag doubles the pull, to 40 N.
8. A hanging chain takes the shape that carries its load in pure tension; turned upside down, the same shape carries the load in pure compression, which is the best shape for a stone or brick arch.
9. $90 \div 36 = 2.5$.
10. The span was lengthened but the dead load was not properly recalculated, so the bridge was much heavier than designed; and the lacing on the built-up lower chords was too weak, so the chords buckled.
11. Engineers began to be licensed so a qualified person is legally responsible for each design; they recalculate loads when a design changes, test details of built-up members, and give inspectors authority to stop work. The Iron Ring reminds engineers of their obligation to honest, careful work and to public safety, in memory of failures like Quebec.

PORTFOLIO PIECE: A PREDICTED-AND-TESTED TRUSS

Design a craft-stick or balsa truss bridge to span 40 cm and carry a load at its center. Before you build, draw it full size, and use the method of joints to calculate the force in every member for a 20 N center load, marking each member as tension or compression. Size your members to match: double or brace the compression members. Build it, weigh it, and load-test it to failure. Write a one-page engineer's report with your calculations, the load at failure, the efficiency (load $\div$ mass), where it failed, whether that member was in compression or tension, and what you would change.

LOOK FOR	WHAT IT MEANS
Calculations	Free-body diagrams and method-of-joints calculations for every member, with units and tension or compression marked.
Design follows the analysis	Compression members are doubled or braced; tension members are lighter; joints are well glued.
Fair test and data	Bridge weighed; load added evenly at the center; failure load and efficiency recorded correctly.
Failure analysis	Explains where and why it failed, using buckling, compression, tension or joint, and compares with the calculation.
Honest report	Report states what went wrong as clearly as what went right, and proposes a specific improvement.

2.1 FREE-BODY DIAGRAMS AND EQUILIBRIUM: SIMON STEVIN'S WREATH OF SPHERES

OBJECTIVES

- Draw a free-body diagram showing every force on an object.
- Use the two conditions of equilibrium ($\Sigma F = 0$ and $\Sigma \text{moments} = 0$) to calculate the forces on a beam's supports.
- Test the predictions with a board resting on two kitchen scales.

Warm-up. Hold a ruler level with one finger under each end. Have someone set a heavy book near your left hand. Which finger feels more of the weight? Slide the book toward the middle. What changes? Predict what each finger would feel if the book were exactly in the middle.

WATCH

What Are Free Body Diagrams? | Physics in Motion

GPB Education · 6:41

<https://www.youtube.com/watch?v=LXr1sLi3fL8>

WHEN TO WATCH

After the physics paragraph, before drawing your own diagrams.

BACKUP VIDEO

Introduction to Free Body Diagrams

Flipping Physics · 6:56

<https://www.youtube.com/watch?v=29YPIvj1zjc>

Optional: another clear introduction with worked examples.

KEY TERMS

free-body diagram

A sketch of one object by itself, with an arrow for every force acting on it, drawn from the point where the force acts.

equilibrium

The state of an object that is not speeding up, slowing down or starting to turn. All the forces and all the turning effects balance.

moment (torque)

The turning effect of a force: force $\times$ perpendicular distance from the pivot.
Measured in newton-meters (N·m).

reaction force

The force a support pushes back with, such as the upward push of a bridge pier on the beam.

statics

The branch of engineering that studies objects in equilibrium, such as bridges and buildings.

CORE IDEAS

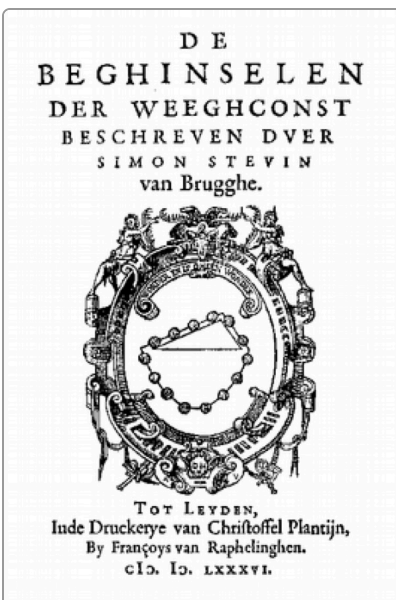
The story. In 1586 the Flemish engineer and mathematician Simon Stevin published a book called *The Principles of the Art of Weighing*. Stevin built dikes, windmills and fortifications in the Netherlands and wanted engineers to be able to calculate, not guess, the forces in their works. On the title page he put a strange picture: a loop of fourteen balls on a string, draped over a triangular block with one long and one short sloping side. Beneath it he wrote, in Dutch, “A wonder is no wonder.”

How they figured it out. Stevin reasoned like this. If the four balls on the long slope pulled harder than the two on the short slope, the loop would start sliding around by itself, and it would keep sliding forever, a perpetual-motion machine. He knew that was impossible. So the forces must balance: two balls on a steep slope pull along it just as hard as four on a gentle slope. From this one picture he worked out how forces on slopes combine, which led to the “triangle of forces” engineers still use. He also stated clearly the law of the lever that Archimedes had found: a small weight far from the pivot balances a large weight close to it.

The physics. An object is in **equilibrium** when two things are true. First, the forces balance: all the upward forces equal all the downward forces, and the leftward forces equal the rightward ones ($\Sigma F = 0$). Second, the turning effects balance ($\Sigma \text{moments} = 0$). A **moment** is force $\times$ distance from a pivot. Picture a 1.0 m plank resting on a support at each end, with a 2.0 kg weight (19.6 N) placed 0.25 m from the left end. Take moments about the left support: the right support’s push $\times$ 1.0 m must equal $19.6 \text{ N} \times 0.25 \text{ m}$, so the right support pushes up with 4.9 N. The two supports together must hold 19.6 N, so the left support pushes up with $19.6 - 4.9 = 14.7 \text{ N}$. The support nearer the load carries more of it, just as your hand felt.

The engineering. Every bridge calculation starts with a **free-body diagram**. An engineer draws the deck alone, with arrows for its own weight (the dead load), the trucks and people on it (the live load) and the push of each pier, and then uses the two rules of equilibrium to find what each pier and foundation must carry. Then the engineer draws a free-body diagram of each pier, each beam and each joint in turn, following the load all the way to the ground. This load path tells the engineer how big every part must be. Getting a free-body diagram wrong, by leaving out a force or putting it in the wrong place, is one of the most common ways a structure is under-designed.

PICTURE STUDY



Title Page of The Principles of the Art of Weighing, Simon Stevin, 1586 · Woodcut title page · Published in Leiden by Christoffel Plantijn

Image: [Wikimedia Commons](#), public domain

This is the title page of Stevin's book. He was so proud of his wreath-of-spheres argument that he put it on the cover, and later used it as his personal emblem.

Look closely

- Find the triangular block. Which side is longer, and which is steeper?
- Count the balls on each sloping side and the balls hanging below.
- Find the motto, "Wonder en is gheen wonder."
- Notice that the hanging part of the loop is balanced. Why can Stevin ignore it?

Talk about it

1. Why did Stevin say the loop could not start moving by itself?
2. Two balls on the steep side balance four on the gentle side. What does that tell you about how hard a slope pulls compared with straight down?
3. Why might an engineer call a careful calculation "a wonder that is no wonder"?

Safety first. Keep your feet clear when adding heavy weights to the board, and make sure the board cannot slide off the scales.

BUILD

Predicting Support Forces with Two Kitchen Scales

You will make a model bridge deck from a board resting on two kitchen scales, place loads at measured positions, predict what each scale will read using the rules of equilibrium, and then check your predictions.

You will need

- Two kitchen scales that read in grams (borrow one if needed) and books to make them the same height
- A stiff board, shelf or meter stick about 1 m long
- Two pencils or dowels to set across the scales as knife-edge supports, so you know exactly where the support is
- Loads: a bag of 100 pennies (250 g), a filled water bottle, a can of food
- Ruler, tape, calculator, engineer's notebook

Steps

1. Set the two scales the same height, with a pencil taped across the top of each. Lay the board on the pencils and measure the distance between the pencils (the span, L).
2. Read both scales with the board alone. Each should show about half the board's mass. Record both, then press the "zero" or "tare" button on each scale so you measure only the added load.
3. Draw a free-body diagram of the board with one load at a measured distance x from the left support.
4. **Predict.** Using moments about the left support, right reading = load $\times x \div L$. Then left reading = load – right reading.
5. **Test.** Place the 250 g bag at $x = 0.25 L$. Read both scales. Repeat at $x = 0.5 L$ and $x = 0.75 L$, and at a point beyond the right support (an overhang).
6. Record a table of position, predicted left and right readings, measured readings and the difference.
7. **Two loads.** Place the bag and the water bottle at two different measured points. Predict both readings by adding the moments, then test.

8. **Improve.** Find the biggest source of error in your test (the scale's precision, the knife-edge position, the board bending) and change one thing to reduce it. Repeat one trial and compare.

Tips

- Kitchen scales read mass in grams. Because both sides of every equation have the same g , you can work in grams throughout, but write newtons on your free-body diagram.
- Measure distances to the center of each load, not its edge.
- When the load overhangs past a support, one scale may read less than zero: the board is trying to lift off it. Hold that end down gently with a known weight.

Check your work

- ☐ I can draw a complete free-body diagram of a loaded beam.
- ☐ I can calculate support forces using $\Sigma F = 0$ and $\Sigma \text{moments} = 0$.
- ☐ I can compare my predictions with measurements and explain the differences.

ENGINEER'S NOTEBOOK

1. Draw free-body diagrams of the board for each test, with every force labeled in newtons and every distance in meters.
2. Make a table of predicted and measured readings and calculate the percent difference for each.
3. A 12 m footbridge rests on piers at each end. A 900 N person stands 3 m from the left pier. Find the push of each pier (ignore the bridge's own weight).

From history. Stevin also introduced decimal fractions to ordinary people in a little book called *The Tenth* (1585), and he urged that measures, weights and money all be divided by tens. Two centuries later the metric system did just that.

COMMON MISTAKES

- Forgetting the weight of the beam itself. Zero the scales or include it as a force at the middle.
- Measuring the distance from the wrong point. Moments are always measured from the pivot you chose.
- Leaving a force off the free-body diagram because it seems small.

Make it a game • Draw the Forces. Your parent places a book across two supports and puts a weight on it. Draw a free-body diagram in under a minute, with every force as an arrow. Then predict how the load shifts as the weight moves closer to one support. Check with two kitchen scales. Closest prediction wins the round.

Scripture. “Who hath measured the waters in the hollow of his hand, and meted out heaven with the span, and comprehended the dust of the earth in a measure, and weighed the mountains in scales, and the hills in a balance?” (Isaiah 40:12, KJV)

Stevin’s book was about “the art of weighing.” God weighs the mountains; we weigh pennies and bridges, and find that His world balances exactly.

2.2 THE METHOD OF JOINTS: WENDEL BOLLMAN'S TRUSS

OBJECTIVES

- Explain why a truss can be analyzed one joint at a time.
- Use the method of joints and similar triangles to find the forces in a simple truss.
- Build a truss whose bottom chord is a calibrated rubber-band gauge and compare measured and predicted chord forces.

Warm-up. Lay two craft sticks in an upside-down V on the table with their top ends touching and press down on the peak. Watch what the bottom ends do. Now tie a string across the bottom ends and press again. What job is the string doing?

WATCH

Understanding and Analysing Trusses

The Efficient Engineer · 17:40

https://www.youtube.com/watch?v=Hn_iozUo9m4

WHEN TO WATCH

Watch the first 8 minutes after the physics paragraph; the rest is optional and more advanced.

Note: Longer and more mathematical than most videos in this course; pause often and work along.

BACKUP VIDEO

Truss analysis by method of joints explained

Engineer4Free · 5:11

<https://www.youtube.com/watch?v=08ChRvOt9il>

Optional: one complete method-of-joints example worked step by step.

KEY TERMS

truss

A frame of straight members joined in triangles, so each member is only pushed or pulled along its length.

method of joints

Finding the forces in a truss by applying $\Sigma F = 0$ at each joint in turn, starting where only two forces are unknown.

panel point

A joint on a truss where members meet and where loads are applied.

chord

The long top or bottom member of a truss.

statically determinate

A structure whose member forces can all be found from the rules of equilibrium alone.

CORE IDEAS

The story. In the 1840s the Baltimore and Ohio Railroad was pushing west across Maryland, and it needed iron bridges that it could trust under heavy locomotives. Wendel Bollman had started as a carpenter on the railroad with little schooling. He taught himself engineering, became the B&O's master of road, and in 1852 patented a new kind of iron truss. Bollman bridges were built all along the line. One of them, built in 1869 and moved in 1887 to carry a branch line over the Little Patuxent River at Savage, Maryland, still stands, the last of its kind. In 1966 the American Society of Civil Engineers named it one of the first National Historic Civil Engineering Landmarks.

How they figured it out. Early wooden bridges were built by experience, and builders could not say exactly what force each piece carried. Bollman designed his truss so that the load at each panel point was carried by its own pair of iron rods running straight up to the tops of the end towers. That made every force easy to calculate: a pair of rods, a known angle, a known load. Engineers of the time, such as Squire Whipple and Herman Haupt, showed that any truss built of triangles could be solved the same way, one joint at a time. If a joint is not moving, every force on it must balance. Start at a joint with only two unknown forces, solve them, and move to the next joint.

The physics. Here is the method of joints on the simplest truss: two sloping members meeting at a peak, tied together by a bottom chord, like a roof. Let the bottom chord be 8 m long and the peak 3 m high, so each sloping member is a 3-4-5 triangle (half the base is 4 m, the height is 3 m, the slope is 5 m long). Put a 600 N load at the peak. By symmetry, each support pushes up 300 N. At the left support joint, the sloping member must supply that 300 N of upward force. In a 3-4-5 triangle

the force in the sloping member is to its vertical part as 5 is to 3, so the member carries $300 \times 5/3 = 500 \text{ N}$ **in compression**. Its horizontal part is $300 \times 4/3 = 400 \text{ N}$, pushing outward, so the bottom chord must pull inward with **400 N of tension**. Make the truss taller (half-base 3 m, height 4 m) and the chord tension drops to $300 \times 3/4 = 225 \text{ N}$. Taller trusses have smaller chord forces.

The engineering. Once every member force is known, the engineer chooses a size for each one. Members in tension can be slender rods or cables, because a pull straightens them. Members in compression must be stocky or braced, because a push can make them buckle sideways. That is why Bollman used thin iron rods for his diagonals and heavy cast-iron posts for his towers, and why modern trusses use stout box or I-shaped sections for compression and lighter sections for tension. Today computers solve trusses with thousands of members, but engineers still check key joints by hand with the same method, because a computer gives the wrong answer just as confidently as the right one if the input is wrong.

PICTURE STUDY



The Bollman Truss Bridge at Savage, Maryland, William E. Barrett, Historic American Engineering Record, 1970 (bridge built 1869) · Photograph · Library of Congress, Prints and Photographs Division
Image: [Wikimedia Commons](#), public domain

The Historic American Engineering Record photographed this bridge in 1970. It is the last surviving Bollman truss, and you can still walk across it today.

Look closely

- Find the tall end towers. Are they in compression or tension?
- Find the thin rods that slant down from the top of each tower. Follow one to the panel point where it ends.
- Count the panel points along the bottom of the bridge.
- Compare the thickness of the rods with the thickness of the towers and the top chord.

Talk about it

1. Why can the slanting rods be so thin?
2. Each panel point hangs from its own pair of rods. Why did that make the bridge easy to calculate?
3. If one rod broke, what do you think would happen to the load at its panel point?

Safety first. Wear safety glasses when stretching rubber bands under load. An adult cuts any sticks or dowels.

BUILD

A Truss with a Built-In Force Gauge

You will build a simple roof truss from two sticks and a bottom chord made of a rubber band. First you will calibrate the rubber band so its stretch tells you the force in it. Then you will load the peak, predict the chord tension by the method of joints, and measure it. Last, you will change the height of the truss (one variable) and see whether the chord force changes as predicted.

You will need

- Two rulers, paint stirrers or flat sticks about 30 cm long, joined at one end with a bolt, a brass fastener or a strong tape hinge
- Two small toy-car wheels, bottle caps or plastic straws taped under the bottom ends so the feet can slide on a smooth table
- A rubber band and two paper clips (the bottom chord), plus string
- A cup and pennies (2.5 g each) for calibration and loading
- Ruler, graph paper, calculator

Steps

1. **Calibrate the gauge.** Hang the rubber band from a hook with a cup below it. Measure its length with the cup empty, then after adding 20, 40, 60, 80 and 100 pennies. Make a table and a graph of stretch against force (newtons = $\text{kg} \times 9.8$). This graph turns stretch into force.
2. Join the two sticks at the top to make the peak. Hook the rubber-band chord between the two bottom ends with paper clips, adjusting with string so the truss stands with half-base 16 cm and height 12 cm (a 3-4-5 shape: each sloping side is 20 cm from foot to peak).
3. Set the truss on a smooth table so the feet can slide freely. The table pushes up on each foot, just like bridge supports.
4. **Predict.** For a load W at the peak, chord tension = $(W \div 2) \times (\text{half-base} \div \text{height}) = (W \div 2) \times 16/12$.
5. **Test.** Hang a cup from the peak and add pennies in steps of 40. At each step measure the rubber band's length, adjust the string so the height stays at 12

cm if needed, and use your calibration graph to find the chord force. Record predicted and measured force.

6. **Change one variable.** Shorten the chord so the truss is taller (half-base 12 cm, height 16 cm). Predict the new chord tension and test with the same loads.
7. Graph predicted and measured chord tension against load for both trusses.
8. **Improve.** Find one source of error (friction at the feet, the weight of the sticks, a sagging hinge) and reduce it. Test again and compare.

Tips

- The feet must slide easily on the table, not your chord, will carry the outward push. Wheels or straws under the feet help.
- Rubber bands stretch a little more each time. Calibrate just before testing and do not leave it stretched for long.
- Your sticks also push on the peak and the feet; include their weight only if your measured forces are consistently off.

Check your work

- ☐ I can find the forces in a simple truss by the method of joints.
- ☐ I can say which members of my truss were in tension and which in compression.
- ☐ I can explain why a taller truss has a smaller chord force.

ENGINEER'S NOTEBOOK

1. Draw free-body diagrams of the peak joint and one foot joint, with every force labeled in newtons.
2. Make a table and a graph of predicted and measured chord tension for both truss shapes.
3. A roof truss has a half-base of 6 m and a height of 2.5 m (so each slope is 6.5 m). A load of 2,600 N sits at the peak. Find the force in each sloping member and in the bottom chord, and say which is tension and which is compression.

From history. Bollman's fellow B&O engineer Albert Fink designed a similar truss, and the two systems carried trains across much of the eastern United States. Both were later replaced by Pratt and Warren trusses, which use less iron, as engineers became confident calculating any truss by the method of joints.

COMMON MISTAKES

- Using the whole load at each support instead of half.
- Mixing up the ratios. The sloping member force is always larger than either of its parts; check that your answer makes sense.
- Letting the feet stick to the table, which takes load away from the chord.

Make it a game • Joint by Joint. Draw a simple truss with a load on it. Your parent covers all joints but one. Call out which forces meet at the exposed joint and solve it with the method of joints, using similar triangles. Then reveal another joint. Teach it back and see whether your parent catches the planted wrong sign.

2.3 CABLES, CHAINS AND CATENARIES:

HOOKE’S HANGING CHAIN

OBJECTIVES

- Explain the difference between a catenary and a parabola and when each shape appears.
- Explain Hooke’s insight that an arch is a hanging chain turned upside down.
- Measure how the pull at the end of a loaded cable changes with its sag and compare with $H = wL^2 \div 8d$.

Warm-up. Hold a necklace or light chain by its two ends and let it hang. Move your hands closer together and farther apart. Then pull them as far apart as you can. What happens to the shape, and how hard do you have to pull to make the chain almost straight?

WATCH

3. Arches and Chains

Engineering Models · 9:27

<https://www.youtube.com/watch?v=JIL6ZHChhQE>

WHEN TO WATCH

After the story. Watch for the moment the hanging shape is turned upside down.

BACKUP VIDEO

4. Suspension Bridges

Engineering Models · 7:02

<https://www.youtube.com/watch?v=caTaBeKUUh-U>

Optional, after the physics paragraph: the same models applied to suspension bridges.

KEY TERMS

catenary

The curve a chain or cable makes when it hangs under its own weight alone.

parabola

The curve a cable makes when it carries a load spread evenly along the level span, as a suspension-bridge cable does.

sag

The vertical distance from the line between the cable's supports down to its lowest point.

anchorage

The massive block at each end of a suspension bridge that holds the main cables.

thrust

The outward horizontal push at the foot of an arch, the mirror image of the inward pull of a hanging cable.

CORE IDEAS

The story. In 1675 the English scientist Robert Hooke, who was helping his friend Christopher Wren rebuild London after the Great Fire, published a riddle: a Latin sentence with its letters scrambled out of order. The solution, published after his death, read: “As hangs the flexible line, so but inverted will stand the rigid arch.” Hooke had seen that a hanging chain is pulled into exactly the shape that has no bending in it, only tension. Turn that shape upside down, and you have an arch that carries its own weight in pure compression. Wren used the idea for the hidden brick cone that holds up the lantern on top of St Paul’s Cathedral.

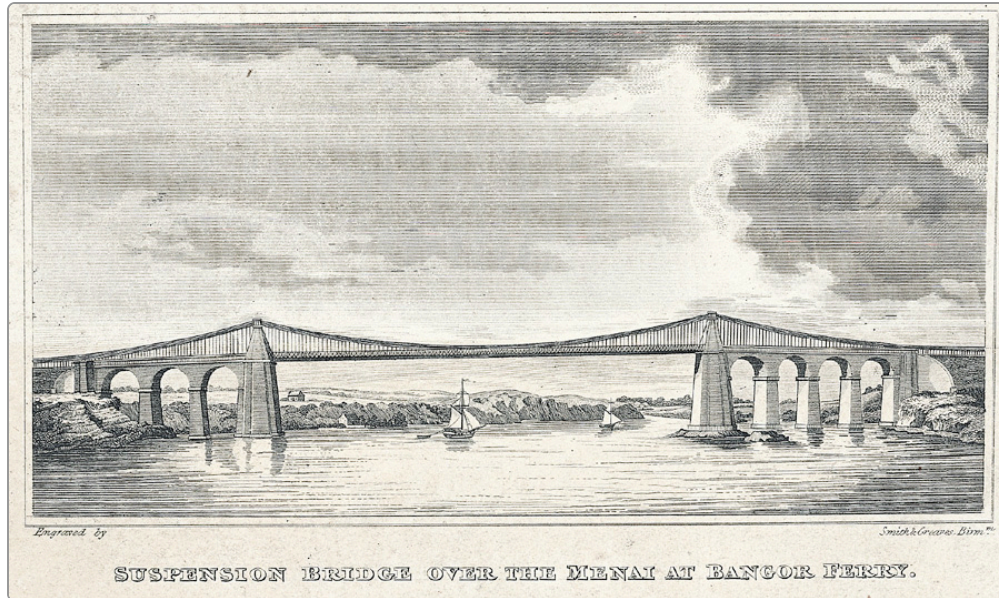
How they figured it out. Galileo had guessed in 1638 that a hanging chain forms a parabola, the curve of a thrown ball. In 1669 Joachim Jungius showed by careful measurement that it does not. In 1690 Jacob Bernoulli challenged the mathematicians of Europe to find the true shape, and the next year three of them, Christiaan Huygens, Gottfried Leibniz and Johann Bernoulli, each published the answer. Huygens named it the **catenary**, from the Latin for chain. Engineers then noticed an important difference: a cable carrying a heavy, level bridge deck is pulled into a **parabola** after all, because its load is spread evenly along the span, not along the curve.

The physics. A cable can only pull, so at every point it bends just enough for the tension to balance the loads hanging from it. The flatter you try to make it, the harder it must pull. For a cable carrying a load w (newtons per meter of span) across a span L with sag d , the horizontal pull at each end is $H = wL^2 \div (8d)$. Suppose a model cable spans 1.0 m and carries 20 N spread evenly ($w = 20$ N/m). With a sag of 0.10 m, $H = 20 \times 1.0^2 \div (8 \times 0.10) = 25$ N. Halve the sag to 0.05 m and H doubles to 50 N.

A perfectly straight cable would need infinite tension, which is why no cable can be pulled perfectly straight.

The engineering. Suspension-bridge designers choose a sag of about one-ninth to one-twelfth of the main span. A deeper sag means less cable tension but taller towers; a shallower sag means shorter towers but thicker cables and bigger anchorages. The Golden Gate Bridge (1937) has two main cables, each made of 27,572 steel wires bundled together, and anchorages of solid concrete that hold the enormous horizontal pull. Arch designers use the same idea in reverse: they shape the arch to follow the inverted hanging line of its loads, so the stone or concrete stays in compression, and they build heavy abutments to resist the outward thrust.

PICTURE STUDY



The Menai Suspension Bridge, Unknown engraver, About 1830 (bridge opened 1826) · Engraving ·
Published in Britain soon after the bridge opened

Image: [Wikimedia Commons](#), public domain

Thomas Telford's bridge over the Menai Strait in Wales, opened in 1826, was the longest suspension bridge in the world at the time. Its deck hung from iron chains high enough for tall sailing ships to pass beneath.

Look closely

- Follow the main chains from one end to the other. Where is the sag greatest?
- Find the vertical hangers that connect the chains to the deck.
- Find the stone towers and the arches beside them. Which parts are in compression?
- Look for where the chains go into the ground at each end (the anchorages).

Talk about it

1. Is the chain's curve a catenary or a parabola? Why?
2. If Telford had made the chains sag only half as much, what would have happened to the pull on the anchorages?
3. Why did this bridge need to be so high above the water?

Safety first. Wear safety glasses if you pull a cable very tight. Do not stand on chairs that might tip when attaching the cable.

BUILD

Sag and Tension in a Model Suspension Cable

You will hang a string cable across a 1-meter span, load it with five evenly spaced cups of pennies, and pull one end over a spool with a counterweight bag. By changing the counterweight you change the pull, and you will measure how the sag responds and compare it with $H = wL^2 \div 8d$.

You will need

- Strong, thin string about 2 m long
- A table edge or two chairs, with a thread spool on a pencil as a pulley at one end and a firm tie-off point at the other, exactly 1.0 m apart and at the same height
- Five small paper cups with paper-clip hangers, and pennies
- A zip-top bag for the counterweight and more pennies
- Kitchen scale, meter stick, graph paper and a calculator

Steps

1. Tie one end of the string firmly. Run the other end over the spool and tie on the counterweight bag. Hang the five cups at 1/6, 2/6, 3/6, 4/6 and 5/6 of the span.
2. Put 20 pennies in each cup. Weigh the five cups with their pennies and calculate $w = \text{total weight (N)} \div 1.0 \text{ m}$.
3. **Predict.** Rearrange the formula to find the sag: $d = wL^2 \div (8H)$. For counterweights of 1.0 N, 2.0 N and 3.0 N, predict the sag.
4. **Test.** Load the bag to 1.0 N (about 102 g). Let the cable settle and measure the sag at the middle cup, from the level line between the supports down to the string. Repeat with 2.0 N and 3.0 N.
5. Do each trial three times and average. Record predicted and measured sag.
6. Graph sag against counterweight. Describe the shape of the graph: when you double the pull, what happens to the sag?
7. **Catenary check.** Remove the cups and hang a light chain between the supports. Trace both the loaded string and the chain onto a large sheet of

paper taped behind them. Are the curves exactly the same shape?

8. **Improve.** Add a sixth and seventh cup so the load is spread more evenly. Does the measurement come closer to the prediction?

Tips

- Tap the table lightly after each change so friction in the spool does not hold the string in the wrong place.
- A paper “level line” taped between the two supports makes the sag easy to measure.
- The formula assumes the load is spread evenly; with only five cups it is a close approximation.

Check your work

- ☐ I can explain why a flatter cable needs more tension.
- ☐ I can use $H = wL^2 \div 8d$ to predict a sag or a pull.
- ☐ I can explain how Hooke’s hanging chain tells us the best shape for an arch.

ENGINEER’S NOTEBOOK

1. Draw your cable with the five loads, the sag and the end pull. Draw a small free-body diagram of the middle of the cable.
2. Make a table and graph of counterweight, predicted sag and measured sag.
3. A footbridge cable spans 40 m and carries 500 N per meter of span. Find the horizontal pull if the sag is 4 m, and again if the sag is 2 m.

From history. The Spanish architect Antoni Gaudí designed his churches in Barcelona with upside-down hanging models: strings loaded with little bags of shot, photographed and flipped over to give the shapes of arches and vaults that would stand in pure compression.

COMMON MISTAKES

- Measuring the sag from the floor instead of from the line between the supports.
- Thinking a tighter cable is always better. Tighter means much more force on the anchorages.
- Mixing up the catenary (own weight only) and the parabola (load spread along the level span).

Make it a game • Parabola or Catenary? Hang a chain from two points to see a catenary. Then imagine a cable carrying a bridge deck, which forms a parabola. Your parent names a hanging object: free chain, loaded cable or an arch. You say which shape it forms and why. Explain Hooke's upside-down chain idea. Fewest wrong calls wins.

2.4 THE QUEBEC BRIDGE: BUCKLING, SAFETY FACTORS AND THE ENGINEER'S DUTY

OBJECTIVES

- Tell what went wrong at the Quebec Bridge and why.
- Explain buckling, lacing and the safety factor, and calculate a safety factor.
- Test how lacing changes the strength of a built-up compression member.

Warm-up. Stand a drinking straw on end on the table and press down gently on top with one finger. Press harder until it bends. Did it crush, or did it bow out sideways? Try again with a straw cut to half the length. Which held more?

WATCH

Ego in Engineering: The Quebec Bridge Collapse

Brick Immortal · 14:47

<https://www.youtube.com/watch?v=e4DTMe0huXM>

WHEN TO WATCH

After the story paragraph. Watch for the moment the inspector sees the bent chord.

BACKUP VIDEO

The Iron Ring - What it Means to be a Canadian Engineer

Daniel Moy · 3:56

https://www.youtube.com/watch?v=fYn9C_ixIPA

After the engineering paragraph: a Canadian engineer explains the Iron Ring.

KEY TERMS

buckling

Sudden sideways bending of a long, slender member under compression, at a load far below what would crush it.

lacing

Small diagonal bars that tie the separate parts of a built-up member together so they act as one stiff member.

dead load

The weight of the structure itself.

safety factor

The load that would cause failure divided by the load the part is expected to carry. A safety factor of 2 means the part could hold twice its working load.

professional engineer

An engineer licensed by law to approve designs, who has a legal and moral duty to protect public safety.

CORE IDEAS

The story. At the beginning of the 1900s, Canada set out to build the longest bridge span in the world across the St. Lawrence River near Quebec City: a steel cantilever bridge with a main span of 1,800 feet (549 m). The consulting engineer was Theodore Cooper of New York, one of the most respected bridge engineers in America, who had helped build the Eads Bridge in St. Louis. In 1900 Cooper lengthened the main span from 1,600 feet to 1,800 feet. By the summer of 1907 the two great arms were reaching out over the river. In August an inspector, Norman McLure, noticed that some of the huge lower compression chords near the south pier were slightly bent, and the bend was growing. He reported it. On August 29, 1907, before the warnings led to any action on site, the south arm buckled and fell into the river. Seventy-five of the eighty-six workers on the bridge died, including thirty-three Mohawk ironworkers from the Kahnawake community.

How they figured it out. A Royal Commission investigated. It found that when Cooper lengthened the span, the weight of the steel was not properly recalculated, so the bridge was much heavier than the design assumed, and the stresses in the lower chords were far higher than planned. Worse, the chords were built up from four separate steel plates tied together only by light lacing bars. The commission's tests showed that this lacing was too weak to make the four parts act as one, so the chord could buckle at a load well below what it was meant to carry. Cooper, elderly and in poor health, had rarely visited the site. Many people had seen the danger, but no one person had the authority and clear responsibility to stop the work. The bridge was redesigned with much heavier members. In 1916 a casting failed while the center span was being lifted into place, and it fell, and thirteen more men died.

The bridge was finally finished in 1917, and its 549-meter cantilever span is still the longest in the world.

The physics. A short, stocky post fails by crushing, but a long, slender one fails by **buckling**: it suddenly bows sideways. The buckling load falls very quickly as a member gets longer; if you double the length of a column, it buckles at only one-quarter of the load. The cure is to make the member stiffer against bending, by spreading its material out away from its center and tying the parts firmly together with lacing or solid plates so they act as one. Engineers protect against uncertainty with a **safety factor**: $\text{safety factor} = \text{failure load} \div \text{working load}$. If a chord would buckle at 30,000 kN and is expected to carry 20,000 kN, its safety factor is $30,000 \div 20,000 = 1.5$. At Quebec, the extra dead load and the weak lacing together used up the whole safety factor.

The engineering. The Quebec disaster changed engineering. Canadian provinces began licensing engineers, so that a named, qualified person is legally responsible for each design. Engineers learned to recalculate the dead load whenever a design changes, to test the details of built-up members, and to give inspectors the authority to stop work. In 1922 a group of Canadian engineers asked the author Rudyard Kipling to write a ceremony for new graduates. Since 1925, every new Canadian engineer has taken an obligation of honesty and care and received an iron ring, worn on the little finger of the working hand, where it brushes the paper as the engineer writes. A popular story says the first rings were made from the fallen bridge; that is not true, but the ring does remind engineers of Quebec. In the United States many new engineers receive a similar steel ring in the Order of the Engineer.

PICTURE STUDY



The Quebec Bridge under Construction, F. E. Cudworth, 1907 · Photograph · Library and Archives Canada

Image: [Wikimedia Commons](#), public domain

This photograph was taken in 1907, during construction of the south arm of the first Quebec Bridge. It shows the scale of what the engineers were attempting, and the great lower chords that carried the compression.

Look closely

- Find the pier and the long arm reaching out from it over the river. That reaching arm is the cantilever.
- Find the bottom chords running out from the pier. Are they being pushed or pulled?
- Look at the size of the people or the cranes compared with the steel.
- Find the slanting members that make triangles in the arm.

Talk about it

1. The bottom chords near the pier carried the most compression. Why there?
2. Why does a long compression member need lacing or bracing?
3. If you had been the inspector who saw a chord beginning to bend, what would you have done, and who would you have told?

Safety first. Wear safety glasses during the column tests; straws and sticks can pop out sideways when they buckle. Add weights gently and keep fingers clear of the falling load.

BUILD

Laced Columns: A Buckling Test

You will build model compression members from pairs of straws, some loose and some tied together with paper lacing at different spacings, and load each until it buckles. Then you will calculate a safety factor for your best design.

You will need

- Plastic drinking straws (all the same kind), cut to 18 cm
- Index cards or card stock cut into 1 cm × 3 cm lacing strips, and clear tape
- Two squares of stiff cardboard as end plates
- A paper cup and pennies, or a small bag of rice, and a kitchen scale
- Safety glasses, ruler, engineer's notebook

Steps

1. Build column A: two straws standing side by side, 2 cm apart, taped to the end plates at top and bottom but not tied to each other in between.
2. Build column B: the same, but with card lacing strips taped across the two straws every 6 cm. Build column C with lacing every 3 cm. Build column D with lacing every 3 cm and also diagonal strips between them.
3. **Predict.** Rank the columns from weakest to strongest and write why.
4. **Test.** Stand a column on the table and balance the cup on the top plate. Add pennies a few at a time until the column buckles. Weigh the cup and pennies. Record the buckling load in newtons and sketch the buckled shape.
5. Build and test a second copy of each column, and average.
6. Make a bar graph of average buckling load for A, B, C and D.
7. **Safety factor.** Suppose each column must carry a working load of 2 N. Calculate the safety factor of each: buckling load ÷ 2 N. Which designs meet a required safety factor of 2?
8. **Improve.** Using what you learned, design the strongest column you can from two straws and four lacing strips, and test it.

Tips

- Keep the load centered. An off-center load bends the column and makes it fail early.
- Look carefully at the buckled shape of the unlaced column. Did the two straws bend separately or together?
- Tape the straws to the end plates the same way every time.

Check your work

- ☐ I can explain what buckling is and why lacing makes a built-up member stronger.
- ☐ I can calculate a safety factor.
- ☐ I can explain what went wrong at Quebec and what engineers changed afterward.

ENGINEER'S NOTEBOOK

1. Draw each column and its buckled shape. Label the lacing spacing and the buckling load.
2. Write a paragraph from the point of view of a young engineer at Quebec in August 1907 who has just seen the bent chords. What would you do, and why?
3. A steel post will buckle at 120 kN. It must carry 45 kN. What is its safety factor? Would it meet a code that requires a safety factor of 2.5?

From history. The idea for the ring ceremony came from Professor Herbert Haultain of the University of Toronto, who wrote to Rudyard Kipling in 1922. The first ceremony was held in Montreal in 1925, and the rings are still given privately to each new class of engineers, with older engineers present to welcome them.

COMMON MISTAKES

- Thinking a compression member fails only by crushing. Long, slender members buckle first.
- Believing a big safety factor means a design can be careless. Safety factors cover uncertainty, not mistakes.
- Blaming one person only. At Quebec, many people and a weak system of responsibility let the danger grow.

Make it a game • The Engineer's Duty. Take turns as the engineer and the chief inspector at the Quebec Bridge. The chief states a worry about a compression chord, and the engineer replies with a calculation or a decision, using the words buckling, lacing and safety factor. Calculate a safety factor from 12000 N strength and 4000 N load. Argue for stopping work.

Scripture. “A prudent man foreseeeth the evil, and hideth himself; but the simple pass on, and are punished.” (Proverbs 27:12, KJV)

The bending chords at Quebec were seen weeks before the collapse. An engineer must be the prudent man who sees the danger and acts on it, for the sake of everyone who trusts the work.

UNIT 2

BRIDGES

In earlier years you learned that bridges carry loads by compression and tension. This year you will learn to calculate those forces the way bridge engineers do. You will draw free-body diagrams, use the two rules of equilibrium to predict the forces on a bridge's supports, and then check your predictions with two kitchen scales. You will work out the forces in every member of a simple truss by the method of joints, and you will see why a hanging chain takes the shape it does and how much a suspension cable must pull to hold up a deck.

The unit ends with one of the most important stories in engineering. The Quebec Bridge fell twice before it finally stood, and the lessons learned there changed how engineers check their work and how seriously they take their duty to the public. Canadian engineers still wear an iron ring on the little finger of their working hand to remember it.

PREREQUISITES

- Can calculate work and energy with units (Unit 1)
- Knows compression, tension, and why triangles are rigid (Grades 5–6)
- Can use a ratio and solve a simple equation such as $2x = 600$

MASTERY CHECKLIST

- ☐ I can draw a free-body diagram and use $\Sigma F = 0$ and $\Sigma \text{moments} = 0$ to find support forces.
- ☐ I can find the forces in a simple truss by the method of joints and say which members are in tension and which in compression.
- ☐ I can explain the shapes of hanging cables and arches and calculate how cable tension changes with sag.
- ☐ I can explain what went wrong at the Quebec Bridge, what buckling is, and what a safety factor is for.
- ☐ I can describe an engineer's duty to the public and give an example of an engineer acting on it.

OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits:** Ages 12 and up with an adult. Balsa sticks, plans and gussets for building a truss bridge that can be weighed and load-tested; a fine portfolio extension for Lesson 2.2.
- **K’NEX building sets:** Ages vary by set. Rods and connectors make quick trusses, arches and suspension models for testing many shapes in one afternoon.

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 Free-Body Diagrams and Equilibrium: Simon Stevin’s Wreath of Spheres

2 sessions of 50–60 minutes

2.2 The Method of Joints: Wendel Bollman’s Truss

2 sessions of 50–60 minutes

2.3 Cables, Chains and Catenaries: Hooke’s Hanging Chain

2 sessions of 50–60 minutes

2.4 The Quebec Bridge: Buckling, Safety Factors and the Engineer’s Duty

2 sessions of 50–60 minutes

UNIT 2 REVIEW

Answer each question. For calculations, draw a small free-body diagram, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

State the two conditions an object must meet to be in equilibrium.

2. **10 pts**

Calculation: A 6 m plank rests on supports at each end. A 600 N load sits 2 m from the left end. Find the force on each support (ignore the plank’s weight).

3. **8 pts**

What did Simon Stevin’s wreath of spheres show, and how did he reason it out?

4. (12 pts)

Calculation: A simple roof truss has a half-base of 4 m and a height of 3 m (each slope 5 m). A load of 1,200 N acts at the peak. Find the force in each sloping member and in the bottom chord, and say whether each is in tension or compression.

5. (8 pts)

Why can the tension members of a truss be thinner than its compression members?

6. (8 pts)

What is the difference between a catenary and a parabola, and which shape does a suspension-bridge main cable take?

7. (10 pts)

Calculation: A model cable spans 2.0 m and carries 10 N per meter of span. Find the horizontal pull if the sag is 0.25 m. What happens to the pull if the sag is halved?

8. (8 pts)

What did Robert Hooke mean by “As hangs the flexible line, so but inverted will stand the rigid arch”?

9. (8 pts)

Calculation: A column will buckle at 90 kN and carries a working load of 36 kN. What is its safety factor?

10. (10 pts)

Give two technical causes of the 1907 Quebec Bridge collapse.

11. (10 pts)

Written answer: What did engineers change after the Quebec Bridge disaster, and what does the Iron Ring remind Canadian engineers of?

ANSWER KEY

1. The forces must balance ($\Sigma F = 0$: up equals down, left equals right), and the moments must balance ($\Sigma \text{moments} = 0$ about any point).
2. Moments about the left support: $R_{\text{right}} \times 6 = 600 \times 2$, so $R_{\text{right}} = 200$ N. $R_{\text{left}} = 600 - 200 = 400$ N.
3. That forces along slopes balance: a few balls on a steep slope balance more on a gentle one. He reasoned that if they did not balance, the loop would move forever by itself, which is impossible.
4. Each support pushes up 600 N. Sloping member: $600 \times 5/3 = 1,000$ N in compression. Bottom chord: $600 \times 4/3 = 800$ N in tension.
5. A pull straightens a member, so a slender rod is fine in tension; a push can make a slender member buckle sideways, so compression members must be stockier or braced.
6. A catenary is the shape of a chain hanging under its own weight alone; a parabola is the shape of a cable carrying a load spread evenly along the level span. A suspension-bridge cable, which mostly carries the deck, is very close to a parabola.
7. $H = wL^2 \div 8d = 10 \times 2.0^2 \div (8 \times 0.25) = 40 \div 2 = 20$ N. Halving the sag doubles the pull, to 40 N.
8. A hanging chain takes the shape that carries its load in pure tension; turned upside down, the same shape carries the load in pure compression, which is the best shape for a stone or brick arch.
9. $90 \div 36 = 2.5$.
10. The span was lengthened but the dead load was not properly recalculated, so the bridge was much heavier than designed; and the lacing on the built-up lower chords was too weak, so the chords buckled.
11. Engineers began to be licensed so a qualified person is legally responsible for each design; they recalculate loads when a design changes, test details of built-up members, and give inspectors authority to stop work. The Iron Ring reminds engineers of their obligation to honest, careful work and to public safety, in memory of failures like Quebec.

PORTFOLIO PIECE: A PREDICTED-AND-TESTED TRUSS

Design a craft-stick or balsa truss bridge to span 40 cm and carry a load at its center. Before you build, draw it full size, and use the method of joints to calculate the force in every member for a 20 N center load, marking each member as tension or compression. Size your members to match: double or brace the compression members. Build it, weigh it, and load-test it to failure. Write a one-page engineer's report with your calculations, the load at failure, the efficiency (load $\div$ mass), where it failed, whether that member was in compression or tension, and what you would change.

LOOK FOR	WHAT IT MEANS
Calculations	Free-body diagrams and method-of-joints calculations for every member, with units and tension or compression marked.
Design follows the analysis	Compression members are doubled or braced; tension members are lighter; joints are well glued.
Fair test and data	Bridge weighed; load added evenly at the center; failure load and efficiency recorded correctly.
Failure analysis	Explains where and why it failed, using buckling, compression, tension or joint, and compares with the calculation.
Honest report	Report states what went wrong as clearly as what went right, and proposes a specific improvement.

UNIT 3

ARCHITECTURE AND STRUCTURES

A building is a structure first: before it can be beautiful or useful, it must stand. In this unit you will learn how engineers describe the strength of materials with stress and strain, why concrete needs steel inside it, how the ground under a building carries its weight, and how tall buildings are designed to stand up to the wind. You will load paper strips until they tear, cast and break small plaster beams, sink model footings into sand, and tune a pendulum damper to calm a swaying tower.

The stories include Robert Hooke and his springs, David Kirkaldy and his giant testing machine, Joseph Monier's reinforced flowerpots, the engineers who saved the Leaning Tower of Pisa after eight hundred years, and William LeMessurier, who discovered a hidden weakness in his own skyscraper and chose to tell the truth about it.

PREREQUISITES

- Can draw free-body diagrams and find support forces (Unit 2)
- Knows compression, tension and buckling (Unit 2)
- Can calculate an area in square centimeters and square meters

MASTERY CHECKLIST

- ☐ I can calculate stress ($\sigma = F \div A$) and strain ($\epsilon = \Delta L \div L$) and explain Hooke's law.
- ☐ I can explain why concrete is reinforced with steel and where the steel must go, and how prestressing helps.
- ☐ I can calculate the pressure a foundation puts on the soil and explain why the Tower of Pisa leans and how it was stabilized.
- ☐ I can explain resonance, natural frequency and how a tuned mass damper works.
- ☐ I can tell the Citicorp Center story and explain what it teaches about an engineer's honesty.

OPTIONAL KITS FOR THIS UNIT

- **KEVA planks:** All ages. Identical maple planks for building towers, arches and cantilevers without glue; good for testing foundations and wind loads in Lessons 3.3 and 3.4.
- **Thames & Kosmos structural engineering kits:** Ages 8 and up. Kits such as Structural Engineering: Bridges & Skyscrapers build towers and frames for load and stability tests; useful alongside Lessons 3.1 and 3.4.

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

3.1 Stress, Strain and Strength: Hooke's Springs and Kirkaldy's Testing Machine

2 sessions of 50–60 minutes

3.2 Reinforced and Prestressed Concrete: From Monier's Flowerpots to the Walnut Lane Bridge

2 sessions of 50–60 minutes

3.3 Foundations and Soils: Saving the Leaning Tower of Pisa

2 sessions of 50–60 minutes

3.4 Wind Engineering: The Citicorp Center and Taipei 101's Damper

2 sessions of 50–60 minutes

UNIT 3 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Define stress and strain and give the unit of each.

2. (10 pts)

Calculation: A steel bar with a cross-sectional area of 200 mm^2 carries 30,000 N. Find the stress. If steel's Young's modulus is $200,000 \text{ N/mm}^2$, find the strain, and the stretch of a 3 m bar.

3. (8 pts)

What did David Kirkaldy's motto "Facts not Opinions" mean for engineering?

4. (8 pts)

Explain the difference between elastic and permanent (plastic) stretching.

5. (8 pts)

Why is reinforcing steel placed near the bottom of a simply supported concrete beam?

6. (8 pts)

How does prestressing help a concrete beam?

7. (10 pts)

Calculation: A column puts 900 kN on a square footing $2 \text{ m} \times 2 \text{ m}$. What is the bearing pressure? If the soil can safely carry 150 kN/m^2 , is the footing big enough?

8. (10 pts)

Why does the Tower of Pisa lean, and how did engineers reduce the lean between 1999 and 2001?

9. (10 pts)

Calculation: A model tower sways with a period of 1.0 s. Calculate the length of a pendulum damper tuned to it ($g = 9.8 \text{ m/s}^2$, $2\pi \approx 6.28$).

10. (8 pts)

What is resonance, and why must tall buildings be designed to avoid it?

11. (12 pts)

Written answer: What did William LeMessurier discover about the Citicorp Center in 1978, what did he do, and why is his choice taught to engineering students?

ANSWER KEY

1. Stress is force divided by the area carrying it ($\sigma = F \div A$), in pascals or N/mm^2 . Strain is change in length divided by original length ($\epsilon = \Delta L \div L$); it has no unit.
2. $\sigma = 30,000 \div 200 = 150 \text{ N/mm}^2$. $\epsilon = 150 \div 200,000 = 0.00075$. Stretch = $0.00075 \times 3,000 \text{ mm} = 2.25 \text{ mm}$.
3. That the strength of materials should be found by careful, honest testing and measurement, not assumed or guessed; engineers should design from recorded test data.
4. In the elastic region, a material springs back to its original length when unloaded, and stretch is proportional to force. Past the elastic limit, it stays permanently stretched (it has yielded).
5. When the beam bends under load, its bottom is stretched (in tension). Concrete is weak in tension, so the steel is placed there to carry the tension.
6. Tightened steel tendons squeeze the concrete before it is loaded, so the load must first cancel that compression before the bottom goes into tension; the beam stays uncracked and can be thinner and longer.
7. Area = 4 m^2 . $p = 900 \div 4 = 225 \text{ kN/m}^2$. No, 225 is greater than 150; the footing must be larger (at least 6 m^2 , about 2.45 m square).
8. It stands on soft clay and silt that compressed more on the south side, so the tower sank more there, and the lean put even more weight on that side. Engineers carefully drilled out small amounts of soil from under the north side so it settled gently, reducing the lean by about 45 cm at the top.
9. $L = g \times (T \div 2\pi)^2 = 9.8 \times (1.0 \div 6.28)^2 = 9.8 \times 0.0254 \approx 0.25 \text{ m}$.
10. Resonance is the growth of motion when pushes come at the same rhythm as the structure's natural frequency. Wind gusts or vortices in rhythm with a building's sway could make it sway dangerously or uncomfortably.
11. He found that winds hitting the building diagonally greatly raised the forces in some braces, and that the joints had been bolted instead of welded, so a strong storm could tear them apart. He told the owners and the city, and crews secretly welded steel plates over the joints while emergency plans were prepared. It is taught because he put public safety ahead of his own reputation and told the truth about his own mistake.

PORTFOLIO PIECE: A WIND-TESTED TOWER WITH A TUNED DAMPER

Design and build a tower at least 60 cm tall from card stock, straws or craft sticks, with a mass on top to stand for the upper floors. Measure its natural period, then design, tune and install a pendulum damper. Test the tower in front of a box fan on low and high, and with a flick test, with and without the damper. Write a one-page engineer's report with a drawing, your period measurement and damper calculation, a data table and graph of the sway with and without the damper, and one improvement.

LOOK FOR	WHAT IT MEANS
Structure	Tower stands at least 60 cm, is braced with triangles, and carries its top mass without buckling.
Measurement	Natural period measured by timing at least ten swings, repeated and averaged.
Calculation	Damper length calculated correctly from $L = g \times (T \div 2\pi)^2$, with units.
Fair test	Tower tested with and without the damper under the same fan setting and flick, with the results recorded honestly.
Report	Explains resonance and damping in the student's own words and proposes a specific improvement.

3.1 STRESS, STRAIN AND STRENGTH: HOOKE'S SPRINGS AND KIRKALDY'S TESTING MACHINE

OBJECTIVES

- Define stress, strain, elastic behavior and ultimate strength, and calculate stress and strain with units.
- Explain Hooke's law and find a spring constant from a graph.
- Test paper strips to failure and show that strength depends on cross-sectional area.

Warm-up. Hang a rubber band from a hook and add coins one at a time to a cup hanging from it. After each coin, guess how much it will stretch with the next. Does each coin stretch it the same amount? What happens when you take all the coins off?

WATCH

An Introduction to Stress and Strain

The Efficient Engineer • 10:01

<https://www.youtube.com/watch?v=aQf6Q8t1FQE>

WHEN TO WATCH

After the physics paragraph. Pause on the stress-strain graph and find the elastic region.

BACKUP VIDEO

The Kirkaldy Testing Museum

Londonist Ltd • 3:50

<https://www.youtube.com/watch?v=S221OB0Bv5c>

After the story: a visit to David Kirkaldy's testing works in London, with his machine still in place.

KEY TERMS

stress

Force divided by the area that carries it: $\sigma = F \div A$. Measured in pascals (N/m²) or, for engineers, newtons per square millimeter (N/mm², the same as megapascals).

Hooke's law

For many materials, the stretch is proportional to the force, as long as the load is not too large: $F = k \times x$.

ultimate strength

The greatest stress a material can carry before it breaks.

strain

The change in length divided by the original length: $\epsilon = \Delta L \div L$. It has no unit.

elastic limit

The greatest stress a material can take and still spring back to its original shape.

Young's modulus

A material's stiffness: stress $\div$ strain in the elastic region. Steel's is about 200,000 N/mm².

CORE IDEAS

The story. In 1678 Robert Hooke published a short book called *Lectures de Potentia Restitutiva, or Of Spring*. He had hung weights on coiled wires, watch springs and long straight wires, measured how far each stretched, and found a simple rule, which he first published as a scrambled Latin riddle: *ut tensio, sic vis*, “as the extension, so the force.” Two centuries later, as railways and iron ships were built everywhere, a Scottish engineer named David Kirkaldy decided that engineers needed real numbers for the strength of real iron and steel, not guesses. He tested hundreds of samples at the Napier shipyard in Glasgow, published his results in 1862, and then designed an enormous hydraulic testing machine, about 47 feet long, which could pull, push, bend or twist a sample with a force of up to about a million pounds. In 1866 he opened his testing works in London. Over the door he carved his motto: “Facts not Opinions.”

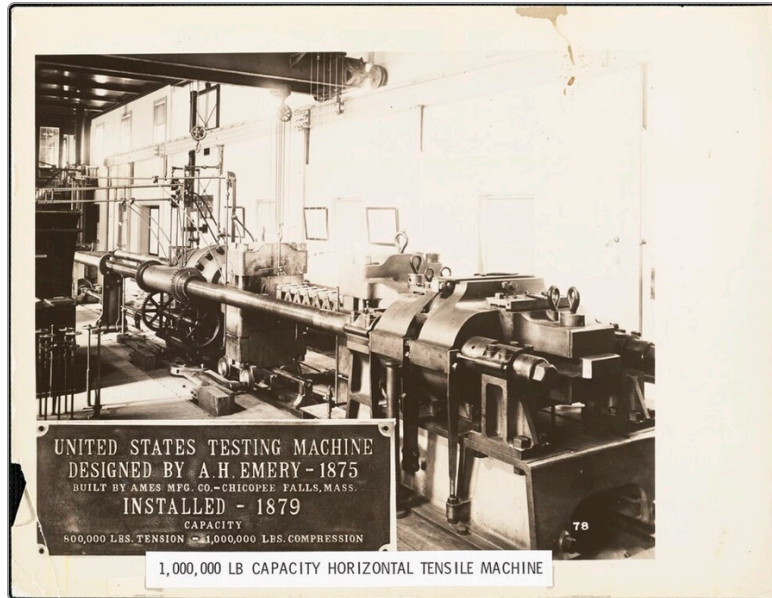
How they figured it out. Kirkaldy's method was to test, measure and record without favor. Manufacturers and railway companies sent him samples, and he reported exactly what each one did: how much it stretched under each load, the load at which it stopped springing back, the load at which it broke, and what the broken surface

looked like. His careful reports showed that iron and steel varied far more than people believed, and that the shape and treatment of a part mattered as much as its material. When the Tay Bridge in Scotland collapsed in 1879, his works tested parts recovered from the wreck for the official inquiry. His machine still stands in Southwark, London, as a museum.

The physics. A thick rope holds more than a thin one, so engineers compare materials by **stress**, the force on each unit of area: $\sigma = F \div A$. A steel rod 10 mm across has an area of $\pi \times 5^2 \approx 78.5 \text{ mm}^2$. If it carries 15,700 N, its stress is $15,700 \div 78.5 = 200 \text{ N/mm}^2$. **Strain** is the fraction a part stretches: $\epsilon = \Delta L \div L$. In the **elastic** region, stress and strain are proportional (Hooke's law), and the part springs back when unloaded. For steel, stress $\div$ strain is about $200,000 \text{ N/mm}^2$, so a stress of 200 N/mm^2 gives a strain of $200 \div 200,000 = 0.001$: a 2 m rod stretches 2 mm. Load it past the elastic limit and it stretches permanently (it yields); load it further and it reaches its **ultimate strength** and breaks.

The engineering. Engineers design so that the working stress in every part stays well inside the elastic region, with a safety factor between the working stress and the stress that would cause yielding or breaking. Different materials suit different jobs: steel is strong in both tension and compression and stretches a great deal before breaking (it is ductile), which gives warning; cast iron and concrete are strong in compression but crack suddenly in tension (they are brittle). Today every batch of structural steel and concrete is tested in machines that are direct descendants of Kirkaldy's, and the results are recorded so that anyone can check them. Facts, not opinions.

PICTURE STUDY



The United States Testing Machine at Watertown Arsenal, U.S. Army, Watertown Arsenal, Designed 1875, installed 1879 · Photograph · U.S. Army Materials and Mechanics Research Center, Watertown, Massachusetts

Image: [Wikimedia Commons](#), public domain

Inspired by the need for trustworthy numbers that Kirkaldy had shown in Britain, the United States government had its own great testing machine built, designed by Albert Emery and installed at Watertown Arsenal in 1879. Its plaque says it could pull with 800,000 pounds and push with 1,000,000 pounds, and measure the force precisely.

Look closely

- Find where a sample would be gripped at each end.
- Find the part that does the pulling. Is it a screw, a hydraulic cylinder, or both?
- Read the plaque. What is the machine's capacity in tension and in compression?
- Look at how massive the frame is. Why must it be so strong?

Talk about it

1. Why must the frame of a testing machine be far stiffer than any sample it tests?

2. Why would the government want its own testing machine instead of trusting manufacturers' claims?
3. What would you measure besides the breaking force?

Safety first. Wear safety glasses when loading strips and rubber bands. Keep feet clear of the falling cup.

BUILD

Tensile Tests: Rubber Bands and Paper Strips

You will make two kinds of tensile test, the same kind Kirkaldy made on iron. First you will test a rubber band and a spring to see whether they obey Hooke's law. Then you will pull paper strips of different widths until they tear and find whether the stress at failure stays the same.

You will need

- A rubber band and, if you have one, a spring from a ballpoint pen or a toy
- A hook or a pencil taped firmly across the edge of a table
- A paper cup with a string handle, pennies, and a kitchen scale
- Plain copy paper, scissors, a ruler and binder clips
- Graph paper, calculator

Steps

1. **Hooke's law.** Hang the rubber band with the cup below it. Measure the length after each 10 pennies, up to 100. Then remove the pennies 10 at a time and measure again on the way down.
2. Graph stretch (y) against force in newtons (x). Is the line straight? Does the unloading line match the loading line? Find the spring constant $k = \text{force} \div \text{stretch}$ from the straight part.
3. **Paper strips.** Cut strips of copy paper 15 cm long and 1 cm, 2 cm and 3 cm wide, three of each, all cut in the same direction from the sheet.
4. Measure the paper's thickness: stack 100 sheets (or a pad), measure the stack and divide by 100. Copy paper is usually about 0.1 mm thick.
5. **Predict.** If a 1 cm strip breaks at a certain load, what do you predict for 2 cm and 3 cm strips?
6. **Test.** Clip the top of a strip to the hook with a binder clip and the cup to the bottom with another. Add pennies gently until the strip tears. Weigh the cup and pennies. Record the force in newtons.
7. Calculate the area (width $\times$ thickness in mm^2) and the failure stress (force $\div$ area) for each strip. Average each width.

8. Compare: is the failure stress about the same for every width? Why might narrow strips fail at a lower stress?
9. **Improve.** Cut three new 2 cm strips with very clean, straight edges using a sharp blade and ruler (adult), and test them. Did clean edges raise the strength?

Tips

- Add pennies one at a time near the end, or the jolt will break the strip early.
- Paper is stronger along its grain. Cut all strips the same way so that is not a hidden variable.
- Most strips tear at a nick or at the clip. Note where each one tore.

Check your work

- ☐ I can calculate stress and strain with units.
- ☐ I can tell from my graph whether a material follows Hooke's law.
- ☐ I can explain why engineers compare stress, not just force.

ENGINEER'S NOTEBOOK

1. Graph the rubber band's loading and unloading. Label the elastic region and any place where the line curves.
2. Make a table of strip width, area, failure force and failure stress, and a bar graph of the average stress for each width.
3. A steel cable 20 mm in diameter carries 60,000 N. Calculate its stress in N/mm^2 . If steel yields at 250 N/mm^2 , what is the safety factor against yielding?

From history. Kirkaldy's son and grandson kept the testing works running until 1965. Volunteers now look after the building and its great machine as the Kirkaldy Testing Museum in Southwark, London, where visitors can still see it.

COMMON MISTAKES

- Using the diameter instead of the radius when finding the area of a round rod.
- Comparing failure forces instead of failure stresses.
- Forgetting to convert grams to newtons.

Make it a game • Stress and Strain Race. Your parent calls out a force and a cross-section area, such as 100 newtons on 0.5 square centimeters. Calculate the stress with units. Then give a stretch and original length and find the strain. Five rounds against a timer. Then find a spring constant from two points and say Hooke's law out loud.

Scripture. “Through wisdom is an house builded; and by understanding it is established:” (Proverbs 24:3, KJV)

Kirkaldy’s motto, “Facts not Opinions,” is a kind of wisdom. A house stands on understanding: knowing, by honest test, what each material can really carry.

3.2 REINFORCED AND PRESTRESSED CONCRETE: FROM MONIER'S FLOWERPOTS TO THE WALNUT LANE BRIDGE

OBJECTIVES

- Explain why concrete is strong in compression but weak in tension.
- Explain where steel reinforcement goes in a beam and why.
- Cast and test plain and reinforced plaster beams, and explain how prestressing works.

Warm-up. Take a bar of dry soap or a stick of chalk and try to crush it by squeezing the ends together. Then bend it between your hands until it snaps. Which was easier? Which side of the stick broke first when you bent it, the side being stretched or the side being squeezed?

WATCH

Why Concrete Needs Reinforcement

Practical Engineering · 8:11

<https://www.youtube.com/watch?v=cZINeaDjisY>

WHEN TO WATCH

After the physics paragraph, before you cast your beams.

BACKUP VIDEO

What is Prestressed Concrete?

Practical Engineering · 8:46

<https://www.youtube.com/watch?v=P13Mau2VUWw>

After the engineering paragraph: how prestressing works.

KEY TERMS

concrete

A stone-like material made by mixing cement, sand, gravel and water, which hardens by a chemical reaction.

reinforced concrete

Concrete with steel bars (rebar) inside it to carry the tension that concrete cannot.

prestressed concrete

Concrete squeezed by tightened steel tendons before it is loaded, so that it stays in compression even under load.

tendon

A high-strength steel wire, strand or bar used to prestress concrete.

neutral axis

The line through a bending beam that is neither stretched nor squeezed, between the compression zone and the tension zone.

CORE IDEAS

The story. Joseph Monier was a gardener in Paris who was tired of clay flowerpots that cracked and wooden tubs that rotted. In the 1860s he began making large planters of cement mortar with a mesh of iron wire inside them, and in 1867 he patented his reinforced tubs. He went on to patent reinforced pipes, tanks, panels and, in 1873, a bridge. Others took the idea further: François Hennebique in France developed a complete building system of reinforced columns, beams and floors in the 1890s, and soon reinforced concrete was being used for bridges, factories and houses around the world. In the 1920s the French bridge engineer Eugène Freyssinet asked a new question: what if the steel were stretched tight before the concrete was loaded? He patented prestressing in 1928.

How they figured it out. Engineers learned by testing beams to failure and studying the cracks. A plain concrete beam cracks on its bottom face and snaps suddenly at a small load. Put steel bars near the bottom and the beam still cracks, but the steel holds the cracks closed and carries the tension, and the beam can carry many times more. Put the steel near the top instead and it does almost nothing. Freyssinet found that ordinary steel was not good enough for prestressing, because concrete slowly shrinks and squashes over the years and the tension in the steel would be lost. He used very high-strength steel wire stretched far enough that it kept its pull. In 1950 the Walnut Lane Memorial Bridge in Philadelphia, designed with the help of the Belgian engineer Gustave Magnel, became the first major prestressed concrete bridge in the United States.

The physics. Concrete is strong in compression (a good mix can carry about 30 N/mm²) but weak in tension, only about one-tenth as much. When a beam bends, its

top is squeezed and its bottom is stretched, and between them lies the **neutral axis**, which is neither. So the bottom of a concrete beam cracks first. Steel is strong in tension (rebar yields at about 400 N/mm^2), so placing it near the bottom puts the strong material where the tension is. Steel and concrete work well together because they expand almost the same amount when heated, and concrete protects the steel from rust. In prestressed concrete, tendons are stretched and anchored so they squeeze the beam before any load arrives; the load must first undo that squeeze before the bottom goes into tension, so the beam stays uncracked.

The engineering. Reinforced concrete can be poured into almost any shape, is fireproof, and uses cheap local materials, which is why it is the most used building material in the world. Engineers must decide how much steel to use and exactly where: rebar along the bottom of beams, over the supports where the beam bends the other way, in stirrups to resist shear near the supports, and with enough concrete cover to keep out water and salt. Prestressing lets engineers build longer, thinner beams, bridge girders, parking garages and floor slabs with fewer columns. The price is care: tendons must be protected from rust for the whole life of the structure.

PICTURE STUDY



The Walnut Lane Memorial Bridge, A. Pierce Bounds, Historic American Engineering Record, 1998
(bridge opened 1950) · Photograph · Library of Congress, Prints and Photographs Division
Image: [Wikimedia Commons](#), public domain

The Historic American Engineering Record photographed this bridge because of its place in engineering history: it was the first major prestressed concrete bridge in the United States. Look at how thin the girders are for their length.

Look closely

- Find the long, straight girders that carry the deck. Estimate how many times longer than they are deep they are.
- Find the piers. What do they carry?
- Look for any visible cracks or patches on the concrete.
- Compare this bridge with the stone arches and iron trusses you have seen. What is different about its shape?

Talk about it

1. Why could prestressed girders be made thinner than ordinary reinforced ones?
2. Where in the girder would the tendons be placed, and why?
3. What would an inspector look for to make sure the tendons inside are not rusting?

Safety first. An adult mixes the plaster. Wear a dust mask while handling dry plaster powder and safety glasses during the breaking tests. Plaster warms as it sets; never put hands or any body part into setting plaster. Never pour plaster down a sink or drain; scrape leftovers into the trash.

BUILD

Plaster Beams: Where Should the Steel Go?

You will cast small plaster beams, some plain and some reinforced with wire or string at the bottom or at the top, and break them with a measured load. Plaster of Paris behaves much like concrete: strong when squeezed, weak when pulled.

You will need

- Plaster of Paris (craft store), water, a disposable mixing bowl and stick
- A quart milk carton cut in half lengthwise, with cardboard dividers taped in, to make molds about 15 cm × 2 cm × 2 cm (or several small boxes)
- Reinforcement: thin craft wire, paper-clip wire straightened, or strong string, cut to 14 cm
- Two stacks of books to make a 10 cm span, a cup with a string handle, pennies or sand, kitchen scale
- Dust mask, safety glasses, petroleum jelly or cooking oil to coat the molds

Steps

1. Coat the molds lightly with oil. Plan six beams: two plain, two with wire 0.5 cm from the bottom, two with wire 0.5 cm from the top. Label each mold.
2. An adult mixes the plaster with water (about 2 parts plaster to 1 part water, following the package). Pour each mold half full, lay the wire in for the bottom-reinforced beams, then fill. For the top-reinforced beams, fill almost to the top, then lay in the wire and cover it.
3. Let the beams harden for at least 24 hours, then remove them and let them dry another day or two.
4. **Predict.** Rank the three kinds of beam by the load each will hold. Write why, using the words tension, compression and neutral axis.
5. **Test.** Lay a beam across the 10 cm span, wire side down for the bottom-reinforced beams. Hang the cup from the middle with a loop of string. Add pennies or sand slowly until the beam cracks. Weigh the load. Then keep adding: does the reinforced beam fall apart or hang together?
6. Test all six and record the first-crack load and the final failure load for each.

7. Turn one bottom-reinforced beam upside down (wire on top) and test it. What happens?
8. **Prestress model.** Thread a string through a row of ten empty spools, beads or sponge blocks. Try to lift the row by its ends. Then tie the string tightly so the row is squeezed together, and lift it again. Explain what changed.
9. **Improve.** Cast one more beam with a change you think will help most (two wires, a mesh, or a hooked end on the wire) and test it.

Tips

- Make all beams from the same batch of plaster so the mix is not a hidden variable.
- Mark the middle of each beam with a pencil so you load each one at the same spot.
- Plaster is weak; loads of a few hundred grams to a few kilograms are typical.

Check your work

- ☐ I can explain why concrete beams need steel near the bottom.
- ☐ I can describe how my reinforced beams failed differently from the plain ones.
- ☐ I can explain how prestressing keeps a beam in compression.

ENGINEER'S NOTEBOOK

1. Draw a bending beam with the compression zone, the tension zone and the neutral axis labeled, and show where the rebar goes.
2. Make a table of beam type, first-crack load and final failure load. Draw how each kind of beam broke.
3. A concrete beam carries a tension stress of 4 N/mm^2 on its bottom face, but the concrete can only take 3 N/mm^2 . What will happen without steel? Explain in two sentences how rebar or prestressing solves it.

From history. Roman engineers built the dome of the Pantheon from unreinforced concrete about AD 125, and it still stands, because a dome of the right shape is in compression everywhere. Reinforced concrete lets modern engineers build beams, slabs and cantilevers that the Romans could not.

COMMON MISTAKES

- Putting the reinforcement in the middle of the beam, where the neutral axis is and it does little.
- Testing beams before they are fully dry.
- Loading reinforced beams with the wire side facing up.

Make it a game • Steel Placement Quiz. Draw a beam on paper and sketch where tension and compression occur when it bends. Your parent suggests three places for the steel bars. Choose the best one and explain why the neutral axis matters. Then explain why concrete is strong when squeezed but weak when pulled. Right answers earn points, wrong spots earn a cracked-beam doodle.

3.3 FOUNDATIONS AND SOILS: SAVING THE LEANING TOWER OF PISA

OBJECTIVES

- Calculate the pressure a foundation puts on the ground ($p = F \div A$).
- Explain why the Tower of Pisa leans and how engineers stabilized it between 1990 and 2001.
- Test how footing size and load position affect how far a model footing sinks.

Warm-up. Press the eraser end of a pencil into a lump of clay or soft butter. Then press the flat side of a ruler into it with the same push. Which sinks deeper? Why?

WATCH

How Engineers Straightened the Leaning Tower of Pisa

Practical Engineering • 13:16

<https://www.youtube.com/watch?v=0ZhHoyqQEhA>

WHEN TO WATCH

After the story paragraph. Watch for the soil extraction drills.

BACKUP VIDEO

Soil Bearing Capacity Failure: Classroom Demonstration from Grounded!

ASCELibrary • 2:48

<https://www.youtube.com/watch?v=HkjVWkyLfig>

Before the build: a short classroom test of a soil bearing failure from the American Society of Civil Engineers.

KEY TERMS

foundation

The part of a structure that carries its weight into the ground.

bearing pressure

The weight on a foundation divided by its area: $p = F \div A$, in newtons per square meter (pascals) or kilonewtons per square meter (kPa).

bearing capacity

The greatest pressure a soil can carry without failing or sinking too much.

settlement

The downward movement of a foundation as the soil beneath it is squeezed.

consolidation

The slow squeezing of water out of clay under a load, which makes it settle and grow stronger over time.

geotechnical engineer

An engineer who studies soil and rock and designs foundations, tunnels and earthworks.

CORE IDEAS

The story. In 1173 the people of Pisa began a marble bell tower beside their cathedral. When the builders reached the third story, about five years later, the tower began to lean. War with neighboring cities halted the work for almost a century. When building resumed, the builders made the upper stories slightly curved, taller on the low side, to correct the lean. The tower was finished, with its bell chamber, around 1372. It kept leaning, a little more every year. By 1990 the top overhung the base by about 4.5 meters and the lean was about 5.5 degrees. Engineers calculated that it was close to toppling, and the tower was closed to visitors.

How they figured it out. An international committee of engineers, including the British soil engineer John Burland, drilled into the ground and studied the soil. They found the tower stood on layers of soft clay and silt that had been squeezed more on the south side, so the tower had sunk more on that side; the heavier it leaned, the more weight pressed on the south, and the faster it leaned. The long pause in construction had probably saved it, because it let the clay consolidate and grow stronger before more weight was added. First the engineers placed about 600 tonnes of lead weights on the north side as a temporary measure (later increased to about 900 tonnes). Then, from 1999 to 2001, they used long, slanted drills to remove small amounts of soil from under the north side, a little at a time, measuring the tower every day. The north side settled gently, and the lean was reduced by about 45 centimeters at the top, back to where it had been around 1838. The tower reopened in December 2001, and it has been stable since.

The physics. A foundation spreads a building's weight over the ground. The **bearing pressure** is $p = F \div A$. The Tower of Pisa weighs about 14,500 tonnes, a force of about

142,000 kN, resting on a ring-shaped foundation of about 285 m². Its average bearing pressure is $142,000 \div 285 \approx 500$ kN/m², about five times the pressure of the air around us, all on soft clay. A bigger footing spreads the same weight over more area and lowers the pressure. When a tall structure leans, its weight shifts toward the low side, raising the pressure there; if the soil gives way under that extra pressure, the lean grows. Engineers call this “leaning instability.”

The engineering. Before any large building is designed today, a geotechnical engineer drills boreholes, takes soil samples and tests them. If the soil near the surface is strong, a spread footing (a wide, shallow pad) may be enough. If it is soft, engineers use deep foundations: piles driven or drilled down to firm soil or rock, or a thick mat under the whole building. They also predict how much the building will settle and make sure it settles evenly. Pisa taught engineers a gentle lesson: with patience, measurement and small, careful steps, even an eight-hundred-year-old mistake can be put right.

PICTURE STUDY



The Leaning Tower, Pisa, Detroit Publishing Company (Photochrom Print Collection), Between 1890 and 1900 · Photochrom print · Library of Congress, Prints and Photographs Division

Image: [Wikimedia Commons](#), public domain

Photochrom prints were black-and-white photographs colored by a special printing process in the 1890s. This one shows the tower about a hundred years before engineers had to close it.

Look closely

- Find which way the tower leans. Which side of the ground has sunk more?
- Count the stories. Can you see where the upper stories bend slightly back toward vertical?
- Look at the ground and buildings around the tower. Is the ground flat?
- Look for the bell chamber at the top.

Talk about it

1. Why did the builders' long pause in the 1200s probably save the tower?
2. Why does leaning more make the tower lean faster?
3. Why did the engineers remove soil from the north side instead of pushing on the tower?

Safety first. If you use sand from outside, wash your hands afterward. Keep the sand box on the floor so it cannot fall.

BUILD

Footings in Sand

You will press model footings of different sizes into damp sand with the same load, measure how far each sinks, and find how bearing pressure controls settlement. Then you will load a footing off-center and watch it tilt, just as the Tower of Pisa did.

You will need

- A plastic tub or shoebox lined with plastic, filled with at least 10 cm of damp sand (play sand works), packed evenly
- Three square footings cut from stiff cardboard or thin wood: 3 cm, 5 cm and 8 cm on a side, each with a short dowel or pencil glued upright in the center
- A paper cup or small plastic container that can rest on the dowel, and pennies or a bag of rice of known mass
- Ruler with millimeters, a straight stick laid across the box as a reference line, calculator

Steps

1. Pack the sand the same way before every test: smooth it, press it with a flat board, and smooth it again.
2. Calculate the area of each footing in m^2 ($5 \text{ cm} \times 5 \text{ cm} = 0.0025 \text{ m}^2$).
3. **Predict.** For a load of 500 g (4.9 N), calculate the bearing pressure under each footing ($p = F \div A$). Predict which will sink most and roughly how much more.
4. **Test.** Set the 5 cm footing on the sand, place the cup on the dowel, and add the load. Wait 30 seconds and measure how far the footing sank below the reference stick.
5. Repeat for the 3 cm and 8 cm footings with the same load and the same packing. Test each three times and average.
6. Graph settlement against bearing pressure.

7. **Leaning instability.** Set the 5 cm footing with a tall cardboard tube (a model tower) on it. Shift a small weight toward one edge and watch. Measure the tilt with a protractor and plumb line after each step.
8. **Rescue it.** Try to straighten your tilted tower the Pisa way: use a spoon to remove a little sand from under the high side, a spoonful at a time, measuring after each. Record what happens.

Tips

- Damp sand gives much more repeatable results than dry sand.
- Measure to the same corner of the footing each time.
- Small differences in packing make big differences in results; that is why real engineers test the soil at many points.

Check your work

- ☐ I can calculate bearing pressure from a load and a footing area.
- ☐ I can explain why a wider footing sinks less.
- ☐ I can explain why the Tower of Pisa leaned and how engineers reduced the lean.

ENGINEER'S NOTEBOOK

1. Draw the Tower of Pisa with arrows for its weight, the soil's push and the extra pressure on the low side. Label the soft clay layer.
2. Make a table of footing size, area, pressure and average settlement, and graph settlement against pressure.
3. A house wall puts 60 kN on each meter of its strip footing. The soil can safely carry 150 kN/m². How wide must the footing be? (Hint: $A = F \div p$ for one meter of length.)

From history. Galileo was born in Pisa in 1564, and a famous story says he dropped balls of different weights from the tower to show they fall together. The story may not be true, but Galileo did study falling bodies with ramps, and his student Vincenzo Viviani is the source of the tale.

COMMON MISTAKES

- Using centimeters squared in one place and meters squared in another. Convert before dividing.
- Packing the sand differently for each test.

- Thinking a bigger footing carries less weight. It carries the same weight at a lower pressure.

Make it a game · Pressure Footing Duel. Your parent names a load and a footing area, such as 6000 newtons on a 0.5 square meter pad. Calculate the pressure in pascals with $p = F$ divided by A . Then redo it with a wider footing. Five rounds. Explain why the Tower of Pisa leans and how engineers stabilized it. Fastest correct answers win.

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)

Jesus used foundations to teach about obedience, and every engineer knows He was right about soil, too: what lies beneath decides whether a building stands.

3.4 WIND ENGINEERING: THE CITICORP CENTER AND TAIPEI 101'S DAMPER

OBJECTIVES

- Explain natural frequency and resonance in tall buildings.
- Explain how a tuned mass damper works and calculate the length of a pendulum with a given period.
- Tell the Citicorp Center story and explain what it shows about an engineer's honesty.

Warm-up. Hold a ruler flat on a table with most of it hanging over the edge, and flick the free end. Count how many times it wiggles in five seconds. Now slide it so less hangs over and flick again. What changed? Every structure has its own natural rhythm.

WATCH

What is a Tuned Mass Damper?

Practical Engineering • 9:37

<https://www.youtube.com/watch?v=f1U4SAgy60c>

WHEN TO WATCH

After the physics paragraph, before the build.

BACKUP VIDEO

Citicorp Center | NYC skyscraper saved by a student's question

Tyler Ley • 8:24

<https://www.youtube.com/watch?v=Bv2YQnT6pSo>

After the story paragraph: an engineering professor tells the Citicorp Center story.

KEY TERMS

natural frequency

The rate at which a structure sways back and forth by itself when disturbed. Its inverse is the period, the time for one full sway.

resonance

The growth of motion when pushes come at the same rhythm as a structure's natural frequency.

tuned mass damper

A heavy mass, often a pendulum, mounted high in a building and tuned to its natural frequency, which moves against the building's sway and soaks up its energy.

quartering wind

Wind blowing diagonally against a building, hitting two faces at once.

damping

Anything that removes energy from a vibration so it dies away.

CORE IDEAS

The story. The Citicorp Center in New York City opened in 1977, 59 stories tall. Because a church stood on one corner of the site, the structural engineer, William LeMessurier, set the tower on four giant columns placed at the middle of each side rather than at the corners, with a system of diagonal braces carrying the loads down to them. He also put a 400-ton concrete block on top, sliding on a film of oil, as a tuned mass damper to reduce swaying. In 1978, after an engineering student asked questions about the building's columns, LeMessurier reworked his calculations for winds striking the building diagonally, and he discovered two things. The diagonal winds raised the forces in some braces much more than he had assumed, and the braces' joints had been bolted instead of welded, a change his own office had approved to save money. A storm strong enough to tear the joints apart could come to New York, he calculated, about once every sixteen years.

How they figured it out. LeMessurier later said he considered keeping silent. Instead, he told the building's owners and the city, at the risk of his career. Working quickly and quietly, crews welded heavy two-inch-thick steel plates over more than two hundred bolted joints, working at night while people worked in the offices by day. The city prepared emergency evacuation plans, weather services sent wind forecasts several times a day, and engineers kept the damper running. In early September 1978 Hurricane Ella moved up the coast toward New York, and then turned out to sea. The repairs were finished in October. The building is now among the strongest in the city. LeMessurier's honesty earned him more respect than before, and his story is taught in engineering schools as a lesson in professional responsibility.

The physics. A tall building sways in the wind like a tree. It has a natural period: tall buildings sway back and forth once every few seconds. Gusts that push in rhythm with that period can cause **resonance**, and wind blowing past a building can also shed swirling vortices from alternate sides that push it back and forth. A **tuned mass damper** is a large mass, often hung as a pendulum, whose natural period matches the building's. When the building sways one way, the damper lags behind and pulls the other way, and dampers (like shock absorbers) turn its motion into heat. A pendulum's period is $T = 2\pi\sqrt{L \div g}$, so the length needed for a period T is $L = g \times (T \div 2\pi)^2$. For a model tower that sways once every 0.80 s, $L = 9.8 \times (0.80 \div 6.28)^2 \approx 0.16$ m.

The engineering. Today tall buildings are tested in boundary-layer wind tunnels before they are built, with scale models surrounded by models of the neighboring city. Engineers shape the tower to confuse the vortices (rounded or stepped corners, tapering, openings near the top) and add damping where needed. Taipei 101 in Taiwan, completed in 2004 and 508 meters tall, hangs a 660-tonne steel sphere 5.5 meters across from cables between its 92nd and 87th floors, with large hydraulic dampers around it. In typhoons and earthquakes it swings by up to a meter or more, and it reduces the building's sway by as much as 40 percent. It is also open to visitors, so the public can see the engineering at work.

PICTURE STUDY



The Eiffel Tower under Construction, Louis-Émile Durandelle, November 23, 1888 · Albumen photograph · From Durandelle's photographs of the tower's construction

Image: [Wikimedia Commons](#), public domain

Gustave Eiffel was a bridge engineer, and he shaped his tower almost entirely by calculating the force of the wind. The curve of its legs follows the line of the wind's turning effect, so that the iron is used where it is needed. Later in life Eiffel built wind tunnels and studied wind on wings and buildings.

Look closely

- Follow one of the four legs from the ground up. Is it straight or curved?
- Look at the iron lattice. Why is the tower made of a lacework of thin members instead of solid plates?
- Find the cranes at the top. How did the builders lift each piece?
- Look at the wide base. Why must a tall tower be wide at the bottom?

Talk about it

1. Why does open latticework catch less wind than a solid wall?
2. The wind pushes hardest high up, where it is fastest. Why does that make the base need to be so wide?
3. How might a modern skyscraper, which must have solid walls and windows, deal with the same wind?

Safety first. Clamp the tower firmly so it cannot fall. Keep faces clear of the flicked tower and the swinging pendulum.

BUILD

Tuning a Mass Damper

You will make a model tower from a flexible strip with a weight on top, measure its natural period, and then hang a pendulum damper from it. You will test dampers of the wrong length and of the tuned length and compare how quickly the tower's swaying dies away.

You will need

- A thin, flexible strip about 60–80 cm long: a wooden yardstick, a strip of thin plywood or a stack of two or three flat rulers taped together
- A clamp or heavy books to hold the bottom of the strip upright at the table edge
- A lump of modeling clay (about 100 g) for the top of the tower
- String, a few large metal washers or a small bag of pennies (about 30–50 g) for the pendulum bob, and a paper cup of water
- Stopwatch or phone with slow-motion video, ruler, calculator

Steps

1. Clamp the strip upright and press the clay onto the top. Push the top 3 cm to one side and let go.
2. **Measure the period.** Time 10 full swings and divide by 10. Repeat three times and average. This is the tower's natural period, T .
3. **Calculate.** Find the tuned pendulum length: $L = 9.8 \times (T \div 6.28)^2$. Write it in centimeters.
4. **Test with no damper.** Push the top 3 cm aside, let go, and count how many swings it takes until the motion is less than about half a centimeter (or time it). Repeat three times.
5. **Test a tuned damper.** Hang the washers on a string of the calculated length from a small hook or tape at the top of the tower, with the bob hanging inside the cup of water (the water provides damping). Repeat the test.
6. **Test untuned dampers.** Change only the string length: try half the tuned length and double the tuned length. Repeat the test for each.

7. Make a table and a bar graph: damper length against swings (or seconds) to settle.
8. **Improve.** Try a heavier bob, or a different liquid (water versus no liquid), changing one thing at a time. Which gives the fastest settling?
9. **Resonance test.** Remove the damper. Give the tower tiny pushes exactly once per period. Watch the sway grow. Then push at the wrong rhythm and compare.

Tips

- The damper bob should be about 2–5% of the total moving mass; very light bobs do little.
- If your tower swings too fast to time, add more clay on top or use a longer strip.
- Slow-motion video makes counting swings much easier.

Check your work

- ☐ I can measure a natural period and calculate a tuned pendulum length.
- ☐ I can explain why a tuned damper works better than a wrong-length one.
- ☐ I can tell the Citicorp Center story and explain why LeMessurier's choice mattered.

ENGINEER'S NOTEBOOK

1. Draw your tower and damper, with the string length, the bob and the cup labeled. Draw arrows for which way the bob moves when the tower sways.
2. Make a table and bar graph of settling time for each damper.
3. A building sways with a period of 5.0 s. What length of pendulum would have the same period? Show $L = g \times (T \div 2\pi)^2$ with units.

From history. The engineering student whose questions started LeMessurier's review was Diane Hartley, who was writing an undergraduate thesis about the building at Princeton. She did not learn until years later how important her questions had been.

COMMON MISTAKES

- Timing only one swing. Time ten and divide, to reduce stopwatch error.
- Changing two things at once, such as the bob and the string length.
- Thinking a damper stops the wind. It reduces the motion by soaking up energy.

Make it a game • Pendulum Period Pick. Your parent names a period, such as 2 seconds. Use $T = 2\pi \sqrt{L/g}$ to find the pendulum length needed, with a calculator. Check by timing a string pendulum of the right length. Closest to the target period wins. Explain how a tuned mass damper cancels sway in Taipei 101.

UNIT 3

ARCHITECTURE AND STRUCTURES

A building is a structure first: before it can be beautiful or useful, it must stand. In this unit you will learn how engineers describe the strength of materials with stress and strain, why concrete needs steel inside it, how the ground under a building carries its weight, and how tall buildings are designed to stand up to the wind. You will load paper strips until they tear, cast and break small plaster beams, sink model footings into sand, and tune a pendulum damper to calm a swaying tower.

The stories include Robert Hooke and his springs, David Kirkaldy and his giant testing machine, Joseph Monier's reinforced flowerpots, the engineers who saved the Leaning Tower of Pisa after eight hundred years, and William LeMessurier, who discovered a hidden weakness in his own skyscraper and chose to tell the truth about it.

PREREQUISITES

- Can draw free-body diagrams and find support forces (Unit 2)
- Knows compression, tension and buckling (Unit 2)
- Can calculate an area in square centimeters and square meters

MASTERY CHECKLIST

- ☐ I can calculate stress ($\sigma = F \div A$) and strain ($\epsilon = \Delta L \div L$) and explain Hooke's law.
- ☐ I can explain why concrete is reinforced with steel and where the steel must go, and how prestressing helps.
- ☐ I can calculate the pressure a foundation puts on the soil and explain why the Tower of Pisa leans and how it was stabilized.
- ☐ I can explain resonance, natural frequency and how a tuned mass damper works.
- ☐ I can tell the Citicorp Center story and explain what it teaches about an engineer's honesty.

OPTIONAL KITS FOR THIS UNIT

- **KEVA planks:** All ages. Identical maple planks for building towers, arches and cantilevers without glue; good for testing foundations and wind loads in Lessons 3.3 and 3.4.
- **Thames & Kosmos structural engineering kits:** Ages 8 and up. Kits such as Structural Engineering: Bridges & Skyscrapers build towers and frames for load and stability tests; useful alongside Lessons 3.1 and 3.4.

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

3.1 Stress, Strain and Strength: Hooke's Springs and Kirkaldy's Testing Machine

2 sessions of 50–60 minutes

3.2 Reinforced and Prestressed Concrete: From Monier's Flowerpots to the Walnut Lane Bridge

2 sessions of 50–60 minutes

3.3 Foundations and Soils: Saving the Leaning Tower of Pisa

2 sessions of 50–60 minutes

3.4 Wind Engineering: The Citicorp Center and Taipei 101's Damper

2 sessions of 50–60 minutes

UNIT 3 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Define stress and strain and give the unit of each.

2. (10 pts)

Calculation: A steel bar with a cross-sectional area of 200 mm^2 carries 30,000 N. Find the stress. If steel's Young's modulus is $200,000 \text{ N/mm}^2$, find the strain, and the stretch of a 3 m bar.

3. (8 pts)

What did David Kirkaldy's motto "Facts not Opinions" mean for engineering?

4. (8 pts)

Explain the difference between elastic and permanent (plastic) stretching.

5. (8 pts)

Why is reinforcing steel placed near the bottom of a simply supported concrete beam?

6. (8 pts)

How does prestressing help a concrete beam?

7. (10 pts)

Calculation: A column puts 900 kN on a square footing $2 \text{ m} \times 2 \text{ m}$. What is the bearing pressure? If the soil can safely carry 150 kN/m^2 , is the footing big enough?

8. (10 pts)

Why does the Tower of Pisa lean, and how did engineers reduce the lean between 1999 and 2001?

9. (10 pts)

Calculation: A model tower sways with a period of 1.0 s. Calculate the length of a pendulum damper tuned to it ($g = 9.8 \text{ m/s}^2$, $2\pi \approx 6.28$).

10. (8 pts)

What is resonance, and why must tall buildings be designed to avoid it?

11. (12 pts)

Written answer: What did William LeMessurier discover about the Citicorp Center in 1978, what did he do, and why is his choice taught to engineering students?

ANSWER KEY

1. Stress is force divided by the area carrying it ($\sigma = F \div A$), in pascals or N/mm². Strain is change in length divided by original length ($\epsilon = \Delta L \div L$); it has no unit.
2. $\sigma = 30,000 \div 200 = 150 \text{ N/mm}^2$. $\epsilon = 150 \div 200,000 = 0.00075$. Stretch = $0.00075 \times 3,000 \text{ mm} = 2.25 \text{ mm}$.
3. That the strength of materials should be found by careful, honest testing and measurement, not assumed or guessed; engineers should design from recorded test data.
4. In the elastic region, a material springs back to its original length when unloaded, and stretch is proportional to force. Past the elastic limit, it stays permanently stretched (it has yielded).
5. When the beam bends under load, its bottom is stretched (in tension). Concrete is weak in tension, so the steel is placed there to carry the tension.
6. Tightened steel tendons squeeze the concrete before it is loaded, so the load must first cancel that compression before the bottom goes into tension; the beam stays uncracked and can be thinner and longer.
7. Area = 4 m^2 . $p = 900 \div 4 = 225 \text{ kN/m}^2$. No, 225 is greater than 150; the footing must be larger (at least 6 m^2 , about 2.45 m square).
8. It stands on soft clay and silt that compressed more on the south side, so the tower sank more there, and the lean put even more weight on that side. Engineers carefully drilled out small amounts of soil from under the north side so it settled gently, reducing the lean by about 45 cm at the top.
9. $L = g \times (T \div 2\pi)^2 = 9.8 \times (1.0 \div 6.28)^2 = 9.8 \times 0.0254 \approx 0.25 \text{ m}$.
10. Resonance is the growth of motion when pushes come at the same rhythm as the structure's natural frequency. Wind gusts or vortices in rhythm with a building's sway could make it sway dangerously or uncomfortably.
11. He found that winds hitting the building diagonally greatly raised the forces in some braces, and that the joints had been bolted instead of welded, so a strong storm could tear them apart. He told the owners and the city, and crews secretly welded steel plates over the joints while emergency plans were prepared. It is taught because he put public safety ahead of his own reputation and told the truth about his own mistake.

PORTFOLIO PIECE: A WIND-TESTED TOWER WITH A TUNED DAMPER

Design and build a tower at least 60 cm tall from card stock, straws or craft sticks, with a mass on top to stand for the upper floors. Measure its natural period, then design, tune and install a pendulum damper. Test the tower in front of a box fan on low and high, and with a flick test, with and without the damper. Write a one-page engineer's report with a drawing, your period measurement and damper calculation, a data table and graph of the sway with and without the damper, and one improvement.

LOOK FOR	WHAT IT MEANS
Structure	Tower stands at least 60 cm, is braced with triangles, and carries its top mass without buckling.
Measurement	Natural period measured by timing at least ten swings, repeated and averaged.
Calculation	Damper length calculated correctly from $L = g \times (T \div 2\pi)^2$, with units.
Fair test	Tower tested with and without the damper under the same fan setting and flick, with the results recorded honestly.
Report	Explains resonance and damping in the student's own words and proposes a specific improvement.

UNIT 4

ELECTRONICS

Electricity lights a bulb; electronics makes decisions. In this unit you will meet the four parts that every electronic device is built from, the resistor, the capacitor, the diode and the transistor, and you will learn what each one does and how to calculate with it. You will time a capacitor charging and discharging, use a transistor to let a tiny current switch a larger one, write a program that reads a button and a knob and controls a light, and, with an adult at the bench, make your first soldered circuit.

The stories run from the Leyden jar of 1745, the first device that could store electric charge, to the transistor invented at Bell Labs in 1947, which made the modern world of computers and phones possible. Along the way you will see the room-sized ENIAC computer and the keyboard and display of the Apollo Guidance Computer that helped men fly to the Moon.

PREREQUISITES

- Can build series and parallel circuits and use $V = IR$ (Grades 5–6)
- Can read a simple circuit diagram
- Has used a multimeter to measure voltage, or is ready to learn

MASTERY CHECKLIST

- ☐ I can identify resistors, capacitors, diodes, LEDs and transistors and explain what each does.
- ☐ I can calculate an LED's current-limiting resistor and a capacitor's time constant ($\tau = RC$).
- ☐ I can explain how a transistor lets a small current switch a larger one, and why that matters for computers.
- ☐ I can write an Arduino program that reads a digital and an analog input and controls an output.
- ☐ I can explain how solder makes a joint and make or inspect a good soldered joint safely, with an adult.

OPTIONAL KITS FOR THIS UNIT

- **Arduino Uno and the Arduino Starter Kit**: Ages 12 and up. The board used in Lesson 4.3, powered by USB, with a breadboard, parts and a project book in the starter kit. Lesson 4.3 can also be done free in the Tinkercad Circuits simulator.
- **Snap Circuits**: Ages 8 and up. Snap-together parts include capacitors, transistors and LEDs, a no-solder way to try the circuits in Lessons 4.1 and 4.2.
- **BBC micro:bit**: Ages 8 and up. A small USB-powered board with built-in buttons, lights and sensors, programmed in the free MakeCode editor; an easier alternative to the Arduino for Lesson 4.3.

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 Resistors, Capacitors, Diodes and LEDs: From the Leyden Jar to the LED

2 sessions of 50–60 minutes

4.2 The Transistor as a Switch: Bell Labs, 1947

2 sessions of 50–60 minutes

4.3 Arduino Inputs and Outputs: Sense, Decide, Act

2 sessions of 50–60 minutes

4.4 Soldering Basics with an Adult

2 sessions of 50–60 minutes

UNIT 4 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Name the job of each of these parts in a circuit: resistor, capacitor, diode, LED.

2. **10 pts**

Calculation: A green LED needs 2.2 V and 15 mA. Your battery is 6 V. What resistor do you need?

3. **10 pts**

Calculation: Find the time constant of a $470\ \mu\text{F}$ capacitor discharging through a $2,000\ \Omega$ resistor. What happens to τ if the resistor is halved?

4. **8 pts**

What was the Leyden jar, and what did Benjamin Franklin find about where it stored its charge?

5. **8 pts**

Why did the transistor replace the vacuum tube?

6. **10 pts**

Calculation: A transistor lets $40\ \text{mA}$ flow through its collector when its base current is $0.25\ \text{mA}$. What is its current gain?

7. **8 pts**

In an NPN transistor switch, what must happen at the base for the LED on the collector to light?

8. **8 pts**

What is the difference between a digital input and an analog input on an Arduino?

9. **8 pts**

An Arduino analog input reads 300. About what voltage is on the pin? (Use $5\ \text{V} \div 1023$ per step.)

10. **10 pts**

Why does a button input need a pull-down resistor?

11. **12 pts**

Written answer: Describe how to make a good soldered joint and how to tell it from a cold joint. Give two safety rules for soldering.

ANSWER KEY

1. Resistor: limits current. Capacitor: stores charge. Diode: lets current flow only one way. LED: a diode that gives off light when current flows the right way.
2. The resistor must drop $6 - 2.2 = 3.8$ V. $R = V \div I = 3.8 \div 0.015 \approx 253 \Omega$; use the next standard value up, such as 270Ω .
3. $\tau = RC = 2,000 \times 0.000470 = 0.94$ s. Halving R halves τ , to 0.47 s.
4. The first capacitor: a glass jar with conductors inside and outside (water, then foil). Franklin showed the charge was stored in the glass between the conductors.
5. Transistors are much smaller, use far less power, make little heat, switch faster and almost never wear out, while tubes were large, hot and burned out often.
6. Gain = $40 \div 0.25 = 160$.
7. A small current must flow into the base (with about 0.7 V between base and emitter); this lets a larger current flow from collector to emitter through the LED.
8. A digital input reads only HIGH or LOW (on or off). An analog input measures a voltage from 0 to 5 V and reports it as a number from 0 to 1023.
9. $300 \times 5 \div 1023 \approx 1.47$ V.
10. Without it, the pin is not connected to anything when the button is not pressed, so it “floats” and may read HIGH or LOW at random; the resistor holds it LOW until the button connects it to 5 V.
11. Clean, tinned tip; heat both the pad and the leg for a few seconds; touch solder to the joint (not the iron) so it flows; remove solder, then iron; do not move it while it cools. A good joint is shiny, smooth and cone-shaped; a cold joint is dull, lumpy, balled or cracked and may fail a continuity test. Safety (any two): adult present; iron always in its stand; safety glasses; lead-free solder; ventilation; never touch the tip or catch a falling iron; wash hands.

PORTFOLIO PIECE: A SENSE-DECIDE-ACT ELECTRONIC DEVICE

Design and build a small useful device that senses something, decides, and acts, using parts from this unit. Examples: a water-level alarm using a transistor and LED, a night light that turns on in the dark using a light sensor, or an Arduino reaction-time tester with a button and LEDs. Include at least one calculation (a resistor value, a time constant or a gain) that you check with a measurement. Write a one-page engineer's report with your circuit diagram, your calculation and measurement, a photograph, the tests you ran, and what you would improve.

LOOK FOR	WHAT IT MEANS
Working device	The device reliably senses, decides and acts as intended, powered only by batteries or USB.
Circuit diagram	Clear, correct diagram with standard symbols, polarity marked and every value labeled.
Calculation checked	At least one calculation done with units and compared honestly with a measurement.
Testing	The device was tested under several conditions, and failures were recorded and fixed.
Craftsmanship and safety	Neat wiring or soldering; every safety rule followed.

4.1 RESISTORS, CAPACITORS, DIODES AND LEDs: FROM THE LEYDEN JAR TO THE LED

OBJECTIVES

- Explain what a resistor, a capacitor, a diode and an LED do in a circuit.
- Calculate the current-limiting resistor for an LED and the time constant $\tau = RC$.
- Time a capacitor discharging through an LED and test how the resistor changes it.

Warm-up. Look at a flashlight, a TV remote or a phone charger and list every light, button and plug you see. For each light, guess: is it an old-style bulb with a glowing wire, or an LED? How can you tell?

WATCH

Capacitors Explained - The basics how capacitors work working principle

The Engineering Mindset · 8:42

<https://www.youtube.com/watch?v=X4EUwTwZ110>

WHEN TO WATCH

After the physics paragraph on capacitors.

BACKUP VIDEO

How Capacitors Work

National MagLab · 3:33

<https://www.youtube.com/watch?v=5hFC9ugTGLs>

Optional: a short explanation from the National High Magnetic Field Laboratory.

KEY TERMS

resistor

A part that limits current. Its resistance is measured in ohms (Ω) and marked with colored bands.

capacitor

A part that stores electric charge on two conducting plates separated by an insulator. Its capacitance is measured in farads (F); most are microfarads (μF).

time constant (τ)

$\tau = R \times C$, the time in seconds for a capacitor to charge or discharge most of the way (about 63%) through a resistor.

diode

A part that lets current flow in only one direction.

LED (light-emitting diode)

A diode that gives off light when current flows through it the right way. It needs a resistor to limit its current.

polarity

Which way round a part must go. LEDs, diodes and electrolytic capacitors have a + side and a – side.

CORE IDEAS

The story. In 1745 a German clergyman, Ewald Georg von Kleist, and in 1746 a Dutch professor, Pieter van Musschenbroek of Leiden, each tried to store electricity in a glass jar of water held in the hand, with a wire dipping into the water from an electrostatic machine. When Musschenbroek’s assistant touched the wire, he received a jolt so strong that Musschenbroek wrote he would not try it again for the whole kingdom of France. The “Leyden jar,” soon made with metal foil inside and outside the glass, was the first capacitor. Benjamin Franklin studied it and showed that the charge was stored in the glass between the two conductors, not in the water.

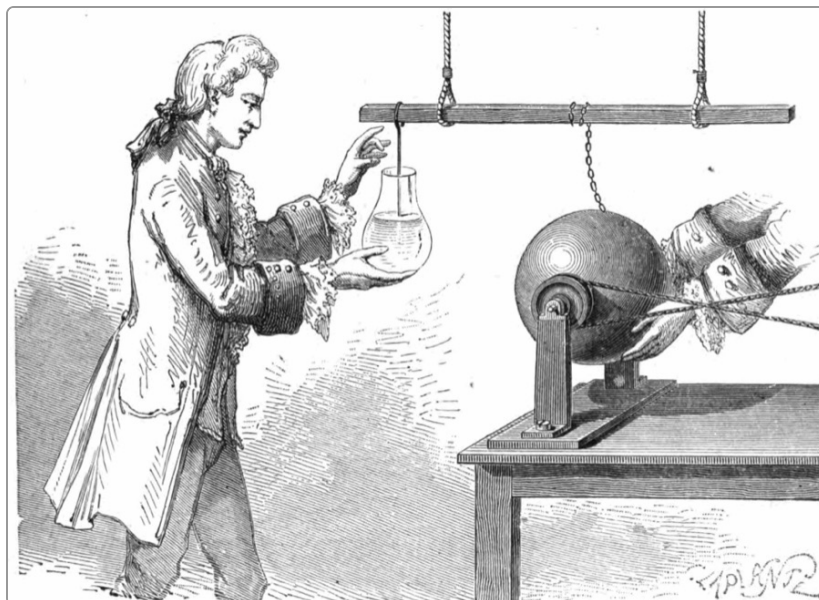
How they figured it out. Over the next two centuries, experimenters learned to control electricity with ever smaller parts. Georg Ohm showed in 1827 that current is proportional to voltage and that each wire has a resistance. Engineers made resistors of carbon or metal film to set currents exactly. In 1874 Ferdinand Braun discovered that certain crystals let current pass one way but not the other, the first diodes, used in early radios. In 1962 Nick Holonyak Jr., working at General Electric, made the first practical LED that gave visible red light. It took until the 1990s for engineers in Japan to make a bright blue LED, and blue plus a yellow coating gave white LEDs, which now light homes and streets while using a small fraction of the energy of a glowing-wire bulb.

The physics. A **resistor** obeys $V = IR$. A red LED needs about 2 V across it and a current of about 15–20 mA (0.015–0.020 A). With a 9 V battery, the resistor must drop the other 7 V: $R = V \div I = 7 \text{ V} \div 0.015 \text{ A} \approx 470 \text{ } \Omega$. A **capacitor** stores charge: $Q = C \times V$. A 1,000 μF capacitor charged to 9 V holds $Q = 0.001 \text{ F} \times 9 \text{ V} = 0.009$ coulombs. When it discharges through a resistor, the voltage falls quickly at first and then more slowly;

the **time constant** $\tau = RC$ tells how fast. With 1,000 μF and 1,000 Ω , $\tau = 0.001 \times 1,000 = 1$ second; double the resistance and it takes twice as long. A **diode** is a one-way valve for current, and an **LED** is a diode that turns some of its energy into light.

The engineering. These four parts are everywhere. Resistors set currents and divide voltages. Capacitors smooth out the ripples from power supplies, store energy for a camera flash, filter signals in radios and set the timing in blinking circuits. Diodes protect circuits from batteries put in backward and turn alternating current into direct current. LEDs have replaced bulbs because they last tens of thousands of hours and waste far less energy as heat. Every circuit designer must respect each part's ratings: the most current a resistor can carry without overheating, the most voltage a capacitor can stand, and which way round each polarized part goes.

PICTURE STUDY



The Discovery of the Leyden Jar, Laplante (engraver), Nineteenth century · Engraving · From a nineteenth-century French book on the history of electricity

Image: [Wikimedia Commons](#), public domain

This engraving imagines the moment in Musschenbroek's laboratory in Leiden when Andreas Cunaeus, holding the jar, touched the conductor and received the first shock from a capacitor.

Look closely

- Find the electrostatic machine. What is being turned, and what is rubbing against it?
- Follow the path of the charge from the machine to the jar.
- Find the jar. Where are the two conductors, and where is the insulator between them?
- Look at the man's hands. Why did his touching the wire make a complete circuit?

Talk about it

1. Why does a capacitor need an insulator between its two conductors?
2. Why did Cunaeus get a shock only when he touched the wire with his other hand?
3. How is a modern 1,000 μF capacitor like this jar, and how is it different?

Safety first. Use only batteries. Electrolytic capacitors must go in the right way round (the stripe marks the – leg) and must be rated at least 16 V; a backward or overloaded capacitor can swell or burst. Never connect a capacitor straight across a battery without a resistor, and never touch the legs of a charged capacitor to your tongue or lips.

BUILD

Timing a Capacitor

You will charge a 1,000 μF capacitor from a battery, then let it discharge through an LED and a resistor and time how long the LED glows. By changing only the resistor, you will test whether the glow time follows $\tau = RC$.

You will need

- A 9 V battery with a snap connector (or 3 AA cells in a holder, 4.5 V)
- A solderless breadboard and jumper wires, or alligator clip leads
- A 1,000 μF electrolytic capacitor rated 16 V or more
- A red LED; resistors of 220 Ω , 470 Ω , 1 k Ω and 2.2 k Ω
- A digital multimeter and a stopwatch or phone timer

Steps

1. Read the color bands on each resistor, then check its value with the multimeter on the ohms setting. Record both.
2. **LED circuit.** Build battery $\rightarrow$ 470 Ω resistor $\rightarrow$ LED (long leg toward the resistor) $\rightarrow$ back to the battery. The LED should light. Turn the LED around: what happens? Measure the voltage across the LED and across the resistor and use $I = V \div R$ to find the current.
3. **Charge.** Disconnect the LED. Connect the capacitor through a 100–220 Ω resistor to the battery, + leg to + (the stripe to –), for 10 seconds. Measure its voltage with the multimeter.
4. **Predict.** Calculate $\tau = RC$ for each of the four resistors you will use for discharging. Predict which will make the LED glow longest.
5. **Test.** Disconnect the battery. Connect the charged capacitor to the LED and the 470 Ω resistor in a loop (capacitor + to resistor, to LED long leg, LED short leg back to capacitor –). Start the timer as you make the last connection and stop it when you can no longer see any glow in a dim room.
6. Recharge and repeat three times. Then test with 220 Ω , 1 k Ω and 2.2 k Ω , changing nothing else.
7. Graph glow time against τ . Is it close to a straight line?

8. **Improve.** Make the LED glow as long as possible with the parts you have: try two capacitors in parallel (+ to +, - to -), which doubles C. Predict, then test.

Tips

- “Dim room, same eyes” is part of a fair test: the person timing and the lighting should be the same each trial.
- The LED stops glowing when the capacitor falls below about 1.8 V, so glow time is a few time constants, not exactly τ .
- If nothing lights, check the LED’s direction first.

Check your work

- ☐ I can calculate the resistor an LED needs.
- ☐ I can calculate $\tau = RC$ and explain what it tells me.
- ☐ I can explain my graph of glow time against τ .

ENGINEER’S NOTEBOOK

1. Draw the circuit diagram for the charging circuit and the discharging circuit, with the correct symbols and polarity marks.
2. Make a table of resistor value, τ , three glow times and average, and graph the results.
3. A blue LED needs 3.0 V and 20 mA. You have a 9 V battery. Calculate the resistor needed, and the time constant if that resistor is used with a 470 μF capacitor.

From history. Nick Holonyak Jr., the son of a coal miner, later taught for decades at the University of Illinois. In 1963 he predicted in a magazine article that LEDs would one day replace the light bulb. It took about fifty years, but he was right.

COMMON MISTAKES

- Putting an LED in without a resistor, which can burn it out in a moment.
- Putting an electrolytic capacitor in backward.
- Forgetting to convert microfarads to farads ($1,000 \mu\text{F} = 0.001 \text{ F}$) and milliamps to amps.

Make it a game • Time Constant Guess. Your parent names a resistor and a capacitor, such as 10 kilohms and 100 microfarads. Calculate the time constant τ equals RC in seconds before anyone checks a clock. Then calculate an LED resistor for a 9 volt supply and 20 milliamp LED with a 2 volt drop. Closest answers win each round.

4.2 THE TRANSISTOR AS A SWITCH: BELL LABS, 1947

OBJECTIVES

- Explain what a transistor does and why it replaced the vacuum tube.
- Describe how a small base current controls a larger collector current in an NPN transistor, and calculate the current gain.
- Build a transistor touch switch and test how the base resistor changes it.

Warm-up. Think of a garden hose with a tap. Your hand turns the tap with a small force, but it controls a big flow of water. Can you name two other machines where a small action controls a much bigger one?

WATCH

Electronic Basics #22: Transistor (BJT) as a Switch

GreatScott! · 6:05

<https://www.youtube.com/watch?v=WRm2oUw4owE>

WHEN TO WATCH

After the physics paragraph, before you build. Pause at each circuit and find the base, collector and emitter.

BACKUP VIDEO

How the first transistor worked

engineerguy · 4:46

<https://www.youtube.com/watch?v=RdYHljZi7ys>

After the story: an engineering professor shows how the very first transistor worked.

KEY TERMS

semiconductor

A material, such as silicon, whose ability to conduct can be controlled by adding tiny amounts of other elements.

transistor

A semiconductor device in which a small current or voltage controls a much larger current. It can act as a switch or an amplifier.

base, collector, emitter

The three legs of a bipolar transistor. A small current into the base lets a larger current flow from the collector to the emitter.

current gain (β)

Collector current $\div$ base current. For common small transistors it is often 100 or more.

vacuum tube

The glass-bulb switch and amplifier used in radios and early computers before the transistor; hot, large and short-lived.

CORE IDEAS

The story. In the 1940s, telephone calls crossing America were boosted along the way by vacuum tubes, glowing glass bulbs that used a lot of power, ran hot and burned out. The first general-purpose electronic computer, ENIAC, finished in 1945, used about 17,500 of them and filled a large room. At Bell Telephone Laboratories in New Jersey, a team led by William Shockley was searching for a solid replacement. On December 16, 1947, John Bardeen and Walter Brattain pressed two thin gold contacts very close together onto a slab of the semiconductor germanium and found that a small current at one contact could control a larger current at the other. A week later they showed it to the laboratory's managers by amplifying a voice. They called it the transistor. Bardeen, Brattain and Shockley shared the Nobel Prize in Physics in 1956.

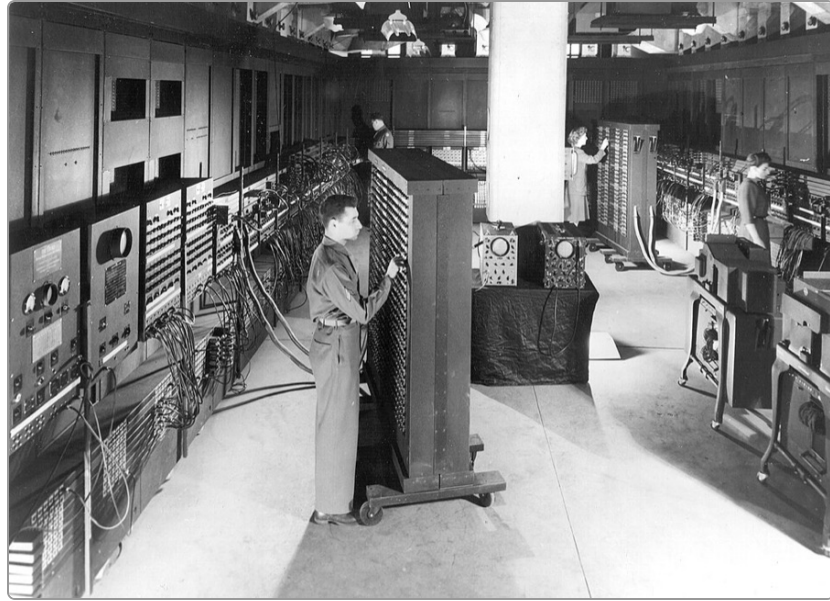
How they figured it out. The road was not straight. Shockley's first idea, using an electric field to control the current in a thin layer of semiconductor, did not work, and for two years the team could not see why. Bardeen worked out that electric charges trapped at the surface of the crystal were blocking the field. Brattain built experiment after experiment to get around the surface, until the point-contact transistor worked. Shockley, spurred on, then worked out the theory of the sturdier junction transistor, built in layers, and it became the type made by the billions. Each step depended on careful measurement and on admitting when an idea had failed.

The physics. A common transistor such as the 2N2222 or 2N3904 is an **NPN** transistor: three layers of silicon, treated differently, called the emitter, base and collector. When no current flows into the base, almost no current can flow from

collector to emitter: the switch is off. When a small current flows into the base (which needs about 0.7 V between base and emitter), a much larger current is allowed to flow from collector to emitter: the switch is on. The ratio is the **current gain**: if a base current of 0.1 mA allows a collector current of 20 mA, the gain is $20 \div 0.1 = 200$. The base current is set by a resistor: with 9 V, a 47 k Ω base resistor gives about $(9 - 0.7) \div 47,000 \approx 0.00018$ A, or 0.18 mA, which is plenty to switch an LED fully on.

The engineering. Transistors switch in billionths of a second, use very little power and almost never wear out. Engineers use them to let a weak signal, like a sensor or a microcontroller pin, turn on a motor, a buzzer or a bright light. Even more important, transistors can switch each other, so they can be built into logic gates, memory and processors. In 1958 and 1959 Jack Kilby and Robert Noyce found ways to build many transistors on a single chip, the integrated circuit. A modern phone processor holds billions of transistors on a piece of silicon the size of a fingernail.

PICTURE STUDY



Programming the ENIAC, U.S. Army photographer, 1946 · Photograph · U.S. Army; Moore School of Electrical Engineering, University of Pennsylvania

Image: [Wikimedia Commons](#), public domain

ENIAC, built for the U.S. Army and finished in 1945, was the first general-purpose electronic computer. Every one of its decisions was made by a vacuum tube. This photograph shows why engineers wanted something smaller.

Look closely

- Look at how far the panels stretch. Estimate the size of the room.
- Find the rows of switches and the cables plugged between panels. That is how ENIAC was programmed.
- Look for any sign of the heat the tubes produced, such as ventilation.
- Find the two people. What is each one doing?

Talk about it

1. ENIAC used about 17,500 vacuum tubes, and tubes burned out often. Why was that a serious problem?
2. How did the transistor change the size, power use and reliability of computers?
3. Programming ENIAC meant moving cables by hand. How is programming different today?

Safety first. Use only a 9 V or AA battery. Touching the two touch wires with your fingers is safe at battery voltage; never do this experiment with any other power source.

BUILD

A Transistor Touch Switch

You will build a circuit in which the tiny current through your fingertip turns on an LED, by using a transistor to amplify it. Then you will test how the base resistor changes the current, and measure the transistor's gain.

You will need

- A 9 V battery with a snap, or 3 AA cells in a holder
- A breadboard and jumper wires
- One NPN transistor (2N2222 or 2N3904) and its pin diagram
- A red LED and a 470 Ω resistor
- Base resistors: 1 k Ω , 10 k Ω , 100 k Ω and 1 M Ω
- Two short bare wires or paper clips as touch pads, a cup of water and a pinch of salt
- A digital multimeter

Steps

1. Look up the pin diagram for your transistor and identify the emitter, base and collector. Write them in your notebook.
2. **Build.** Battery + $\rightarrow$ 470 Ω $\rightarrow$ LED (long leg first) $\rightarrow$ transistor collector. Transistor emitter $\rightarrow$ battery -. Base $\rightarrow$ 10 k Ω resistor $\rightarrow$ a touch pad. The second touch pad connects to battery +.
3. Touch both pads with one finger. The LED should light. Try one finger of each hand, a damp finger, and a pencil-lead line on paper bridging the pads.
4. **Predict.** Which base resistor (1 k Ω , 10 k Ω , 100 k Ω , 1 M Ω) will light the LED most brightly when the pads are joined by a wire? Which will barely light it?
5. **Test.** Join the pads with a wire. For each base resistor, measure the LED current (set the meter to mA and put it in series with the LED) and the base current (meter in series with the base resistor). Record both.
6. Calculate the gain (collector current $\div$ base current) for each trial where the LED is not fully on.

7. **A water sensor.** Put the two touch pads into a cup of tap water, then salt water. Does the LED light? Measure the currents. What could this circuit be used for?
8. **Improve.** Use a second transistor so the first one drives the base of the second (a Darlington pair). Can it now switch on with a much weaker touch? Explain why.

Tips

- When the LED is fully on, the transistor is “saturated” and the gain calculation no longer applies; use the trials where the LED is dim to measure gain.
- Keep the meter on the mA setting only while it is in series. Never put it across the battery on the current setting.
- If the LED will not light, check the transistor’s pin order first.

Check your work

- ☐ I can identify the base, collector and emitter and explain what each does.
- ☐ I can calculate a transistor’s current gain from measurements.
- ☐ I can explain why transistors replaced vacuum tubes.

ENGINEER’S NOTEBOOK

1. Draw the circuit diagram of your touch switch with the correct transistor symbol and label the base, collector and emitter.
2. Make a table of base resistor, base current, LED current and gain.
3. A transistor has a gain of 150. How much base current is needed to allow a collector current of 60 mA? Give the answer in milliamps.

From history. John Bardeen later won a second Nobel Prize in Physics, in 1972, for explaining superconductivity; he is the only person to have won the physics prize twice.

COMMON MISTAKES

- Connecting the LED without its $470\ \Omega$ resistor.
- Getting the emitter and collector backward.
- Thinking the transistor creates current. The current comes from the battery; the transistor only controls it.

Make it a game • Transistor Switch Story. Be the transistor. Your parent holds a small base signal, a tiny push, and you use it to hold open a large collector flow with your arms wide. Name the base, collector and emitter. Calculate a current gain of 100 for a 0.2 mA base current. Then explain why transistors replaced vacuum tubes.

4.3 ARDUINO INPUTS AND OUTPUTS: SENSE, DECIDE, ACT

OBJECTIVES

- Explain the difference between digital and analog inputs and outputs.
- Write a program that reads a button and a potentiometer and controls an LED.
- Convert an analog reading to a voltage and check it with a meter.

Warm-up. List three machines at home that sense something and then do something by themselves (for example, a refrigerator light, an automatic door, a thermostat). For each, what is the input, what is the decision, and what is the output?

WATCH

Introduction to Tinkercad Circuits (Lesson #4)

[Science Buddies](#) • 5:21

https://www.youtube.com/watch?v=9RF_BZ1Cg4k

WHEN TO WATCH

Before the build, to learn how to place parts in the Tinkercad simulator.

BACKUP VIDEO

How to Use a Button with an Arduino (Lesson #5)

[Science Buddies](#) • 20:57

<https://www.youtube.com/watch?v=yBgMJssXqHY>

During the build: a full lesson on wiring and coding a button.

KEY TERMS

microcontroller

A small computer on a single chip, with its own memory and input and output pins, that runs one program over and over.

analog input

A pin that measures a voltage between 0 and 5 V and reports it as a number from 0 to 1023.

digital input/output

A pin that is either HIGH (about 5 V, “on”) or LOW (0 V, “off”).

potentiometer

A variable resistor with a knob, used as a voltage divider to give a voltage that changes as the knob turns.

pull-down resistor

A resistor that holds an input LOW when a button is not pressed, so it does not float and give random readings.

CORE IDEAS

The story. In 2005, at a small design school in Ivrea, Italy, the teacher Massimo Banzi and his colleagues wanted their students to be able to build interactive projects without years of electronics training. The microcontroller boards of the day were expensive and hard to program. So they designed their own simple, inexpensive board, wrote free software that made programming it easy, and published the designs openly so anyone could build one. They named it Arduino, after a café in Ivrea that was named for Arduin, a king of Italy a thousand years earlier. Within a few years millions of students, hobbyists and engineers were using Arduino boards for everything from weather stations to robots.

How they figured it out. The team kept asking what got in the way of beginners, and removed it. Programs would be called “sketches” and have just two parts: *setup*, which runs once, and *loop*, which repeats forever. Simple commands such as *digitalRead*, *digitalWrite* and *analogRead* would hide the complicated details of the chip. The board would be powered and programmed through one USB cable. Every choice was tested with real students and changed when it confused them.

The physics. Every automatic machine follows the same pattern: **sense, decide, act**. A **digital input** sees only two states. A button connects a pin to 5 V when pressed; a **pull-down resistor** (often 10 kΩ) connects it to 0 V when not pressed. An **analog input** measures a voltage and turns it into a number from 0 to 1023, so each step is $5\text{ V} \div 1023 \approx 0.0049\text{ V}$. A reading of 512 means about $512 \times 0.0049 \approx 2.5\text{ V}$. A **potentiometer** with its ends on 5 V and 0 V gives any voltage in between at its middle pin. An output pin can supply about 5 V and a small current, enough for an LED through a 220 Ω resistor; larger loads, such as motors, need a transistor, as in Lesson 4.2.

The engineering. Microcontrollers are hidden inside almost every modern machine: microwave ovens, cars (which may have a hundred or more), washing machines, toys, medical pumps and traffic lights. Engineers who design them must think about what happens when something goes wrong: a button that bounces and seems to be

pressed twice, a sensor wire that breaks, or a program that gets stuck. Good designs check their inputs, fail safely and are tested far more than seems necessary. The Apollo Guidance Computer of the 1960s, with its keypad input and number display, was an early ancestor of today's microcontrollers.

PICTURE STUDY



The Apollo Guidance Computer's Display and Keyboard, NASA, 1960s · Photograph · NASA

Image: [Wikimedia Commons](#), public domain

Astronauts flying to the Moon talked to their guidance computer through this panel, called the DSKY (“display and keyboard”). It is a set of inputs and outputs, like the ones you will program in this lesson.

Look closely

- Find the keys. Which are digits, and which are commands such as VERB and NOUN?
- Find the number displays. How many digits can each line show?
- Find the warning and status lights at the upper left.
- Count the keys. Are there any letters?

Talk about it

1. Which parts of this panel are inputs and which are outputs?
2. Why would engineers make the astronauts type two-digit codes instead of words?
3. What should the computer do if an astronaut pressed a wrong key?

Safety first. An Arduino is powered only by its USB cable or a battery pack. Never connect anything on the board to any other power source. Unplug the USB cable before changing wiring.

BUILD

Button, Knob and Light

You will program an Arduino, a real one or the free simulator in Tinkercad Circuits, to sense two inputs and control an output. First a button will turn an LED on and off. Then a knob will set how fast the LED blinks. You will measure the knob's voltage two ways and compare.

You will need

- Free Tinkercad Circuits account (a parent sets it up) with a computer, or an Arduino Uno with a USB cable
- A breadboard, a push button, a 10 k Ω resistor (pull-down), an LED and a 220 Ω resistor, a 10 k Ω potentiometer, jumper wires
- A multimeter (Tinkercad has one built in)

Steps

1. **Wire the output.** Pin 13 $\rightarrow$ 220 Ω resistor $\rightarrow$ LED long leg; LED short leg $\rightarrow$ GND. Upload a test sketch: in setup, `pinMode(13, OUTPUT);` in loop, `digitalWrite(13, HIGH); delay(500); digitalWrite(13, LOW); delay(500);`. The LED should blink.
2. **Wire the button.** One side of the button to 5V. The other side to pin 2, and also through the 10 k Ω pull-down resistor to GND.
3. **Program it.** In setup add `pinMode(2, INPUT);`. In loop write: `if (digitalRead(2) == HIGH) { digitalWrite(13, HIGH); } else { digitalWrite(13, LOW); }`. Test it.
4. **Test the pull-down.** Remove the 10 k Ω resistor and watch the LED as you move your hand near the wires. Explain what happens, then put it back.
5. **Wire the knob.** Potentiometer outer legs to 5V and GND, middle leg to A0. Add `Serial.begin(9600)` to setup and in loop `read int value = analogRead(A0); Serial.println(value);`. Open the Serial Monitor.
6. **Measure.** Set the knob to five positions. For each, record the reading, calculate the voltage ($\text{reading} \times 5 \div 1023$), and measure the middle-pin voltage with the multimeter. Compare.

7. **Decide and act.** Make the blink delay depend on the knob: `delay(value)`; so turning the knob changes the blink speed. Then add the button so the LED blinks only while the button is pressed.
8. **Improve.** Add a second LED that lights only when the reading is above 800, a “warning light.” Test it at readings just below and just above 800.

Tips

- Every line of Arduino code ends with a semicolon, and every opening brace { needs a closing brace }.
- If the simulator says there is an error, read the line number it gives and check that line and the one above it.
- Save a copy of each working version before you change it, so you can always go back.

Check your work

- ☐ I can explain the difference between a digital and an analog input.
- ☐ I can convert an analog reading to a voltage.
- ☐ I can write a program that senses, decides and acts.

ENGINEER'S NOTEBOOK

1. Draw the circuit diagram of your finished project, with the Arduino as a box and each pin labeled.
2. Make a table of knob position, analog reading, calculated voltage and measured voltage.
3. Write your finished sketch out by hand and add a comment (a note after `//`) beside each line explaining what it does.

From history. The Arduino team published every board design under an open license, so anyone may copy and improve it. Many companies now make compatible boards, and the free Arduino software runs on all of them.

COMMON MISTAKES

- Leaving out the pull-down resistor, so the button input floats.
- Forgetting `pinMode` in `setup`.
- Using `=` (which sets a value) instead of `==` (which compares) inside an `if`.

Make it a game • Code Reader Challenge. Your parent writes a short program on paper with a button, a potentiometer and an LED, hiding one bug. Read it line by line like a microcontroller and say what the LED does. Find the bug. Name digital and analog inputs and the pull-down resistor's job. Swap and try again, fastest bug hunter wins.

4.4 SOLDERING BASICS WITH AN ADULT

OBJECTIVES

- Explain how solder joins metals and why flux and heat are needed.
- Follow every safety rule for soldering with an adult at the bench.
- Make and inspect soldered joints and test them with a multimeter.

Warm-up. Look closely at the inside of an old, already-opened toy or a circuit-board photograph online (never open anything that plugs into the wall). Find the shiny silver bumps where parts meet the board. Count how many there are on one small board.

WATCH

iFixit's Soldering 101: Beginners Guide

iFixit • 6:46

<https://www.youtube.com/watch?v=rK38rpUy568>

WHEN TO WATCH

Before the build, with the adult who will supervise. Watch it twice.

BACKUP VIDEO

How to Solder Through-Hole Components - Another Teaching Moment | DigiKey Electronics

DigiKey • 3:47

<https://www.youtube.com/watch?v=DJH7VLGJ4fs>

Just before you start: a close-up of soldering parts through a circuit board.

KEY TERMS

solder

A metal alloy that melts at a fairly low temperature and joins other metals. Electronics solder is usually tin with small amounts of silver and copper (lead-free).

flux

A cleaning chemical, often in the core of the solder wire, that removes the oxide film from metal so the solder can flow and bond.

wetting

Solder flowing smoothly over a clean, hot metal surface and bonding to it, like water on clean glass.

cold joint

A bad joint where the solder did not get hot enough or the part moved; it looks dull, lumpy or cracked and may not conduct.

printed circuit board (PCB)

A board with copper paths printed on it that connect the parts soldered to it.

continuity

An unbroken path for current. A multimeter's continuity setting beeps when it finds one.

CORE IDEAS

The story. Metalworkers have joined metals with solder for thousands of years. Goldsmiths in the ancient world soldered tiny gold beads onto jewelry, and Roman plumbers soldered lead water pipes; our word “plumber” comes from *plumbum*, the Latin word for lead. In the electrical age, every telegraph and telephone connection had to be soldered or screwed by hand. In 1936 Paul Eisler, an engineer from Austria who had moved to England, made the first printed circuit board for a radio: instead of a tangle of wires, the connections were copper paths printed on a board. Printed boards made it possible to build electronics by the millions, and nearly every one of their joints is soldered.

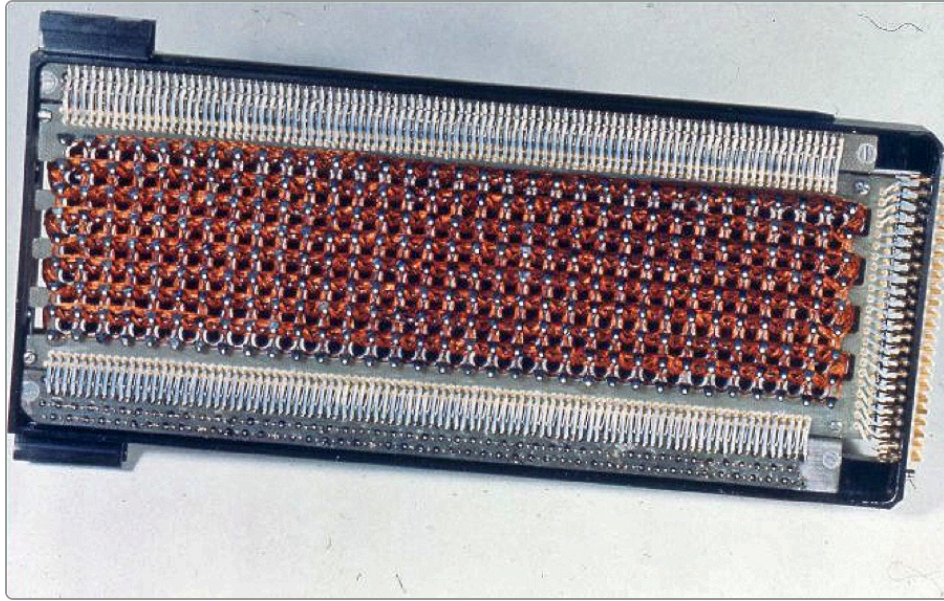
How they figured it out. Engineers learned that a soldered joint is not glue. When it is done right, the melted solder dissolves a very thin layer of the copper and forms a true metal bond. That only happens if the copper is clean and hot enough. Copper exposed to air grows an invisible oxide skin that solder will not stick to, so **flux** was added to clean it at the moment of soldering. Workers who built the Apollo Guidance Computer in the 1960s were trained and inspected joint by joint, because one bad joint could fail on the way to the Moon. Today's inspectors use magnifiers and X-rays, and they still look for the same signs: a smooth, shiny, cone-shaped fillet.

The physics. A soldering iron's tip runs at about 330–370 °C. Lead-free electronics solder melts at about 217–220 °C. (Older tin-lead solder melts at 183 °C, but it contains lead, which is poisonous, so we use lead-free.) The iron must heat both metal parts above the melting point, and then the solder is touched to the parts, not to the iron, so it melts on the joint and flows in. A good joint has very low resistance, a small fraction of an ohm. A cold joint may have high resistance or none at all, or

may work at first and fail when it is bumped or warms up. A multimeter on its continuity or ohms setting finds the bad ones.

The engineering. Factories solder whole boards at once by passing them over a wave of molten solder or by heating them in an oven, while robots place tiny parts with great precision. Hand soldering remains essential for repairs, prototypes and repairs in the field, and many electronics technicians and engineers learned it as teenagers. The habits of a good solderer are the habits of a good engineer: prepare carefully, work cleanly, inspect every joint, test before power is applied, and never rush.

PICTURE STUDY



Core Rope Memory from the Apollo Guidance Computer, NASA, 1960s · Photograph · NASA

Image: [Wikimedia Commons](#), public domain

The Apollo Guidance Computer's programs were stored in "core rope memory": wires threaded by hand through or around tiny magnetic rings, then soldered into modules. A wire passing through a ring stood for a 1; a wire passing around it stood for a 0.

Look closely

- Find the tiny rings (cores).
- Look for the very fine wires and how they pass through or around the cores.
- Find the rows of connections along the edge where the wires were soldered.
- Notice how neatly the module is laid out.

Talk about it

1. Why would one cold solder joint in this module be so serious?
2. Why do you think the workers who wove and soldered these modules were inspected so carefully?
3. What does this picture tell you about the patience and care engineering requires?

Safety first. Soldering is done only with an adult at the bench the whole time. The adult sets up the iron, places it in its stand, and turns it off at the end; the student never handles the cord or plug. Wear safety glasses. Use lead-free solder, work in a ventilated room with a small fan blowing the fumes away from your face, and wash your hands afterward. The tip is hotter than an oven: always return the iron to its stand, never touch the metal end, and never try to catch a falling iron. Keep drinks and food off the bench. A USB-powered soldering iron is a good choice for beginners.

BUILD

Solder a Battery-Powered LED Light

With an adult beside you, you will solder a small, useful circuit: a 9 V battery snap, a switch (or a pair of wires), a resistor and an LED on a piece of perfboard. You will inspect and test every joint, fix any bad ones, and measure the finished circuit. If you do not have a soldering iron, use the no-solder alternative in step 9.

You will need

- A soldering iron (25–40 W, or a USB-powered iron) with a stand and a damp sponge or brass tip cleaner, used only with an adult
- Lead-free rosin-core solder, about 0.8 mm thick
- A small piece of perfboard (a board with holes and copper pads)
- A 9 V battery snap, a small slide switch (optional), a 470 Ω resistor and a red or white LED
- Small wire cutters, safety glasses, a small fan, a magnifying glass
- A digital multimeter

Steps

1. **Practice first.** With the adult, practice on spare wire: heat two twisted wire ends with the tip for 2–3 seconds, touch solder to the wires (not the iron), let it flow, remove the solder, then the iron. Let it cool without moving. Make five practice joints.
2. **Plan.** Draw the circuit diagram and a full-size layout of where each part will go on the perfboard.
3. Push the resistor's legs through the holes and bend them slightly outward so it stays put. Solder each leg to its pad, then trim the extra leg.
4. Mount the LED (long leg toward the resistor) and solder it. Add the switch if you have one, and the battery snap wires (red to the resistor side, black to the LED's short leg).
5. **Inspect.** Look at every joint with the magnifier. A good joint is shiny, smooth and shaped like a small volcano around the leg. Mark any dull, lumpy, balled

or bridged joints.

6. **Test before power.** With the multimeter on continuity, check every connection that should be joined, and check that the two battery wires are not shorted to each other.
7. Connect the battery. Measure the voltage across the LED and the resistor and calculate the current.
8. **Improve.** Reheat any bad joint, add a touch of fresh solder, and test again. Record what was wrong and how you fixed it.
9. **No-solder alternative.** Twist the leads together tightly and cover each joint with electrical tape, or use a small screw terminal block. Test the same way and compare how solid the joints are.

Tips

- Heat the joint, not the solder. Solder flows toward heat.
- Wipe the tip on the damp sponge often and keep a thin coat of solder on it (tinning) so heat flows well.
- Most beginners use too much solder. A small, neat fillet is stronger than a blob.

Check your work

- ☐ I can explain why flux and enough heat are needed for a good joint.
- ☐ I can tell a good joint from a cold joint by looking and by testing.
- ☐ I followed every safety rule while soldering.

ENGINEER'S NOTEBOOK

1. Draw the circuit diagram and the perfboard layout of your light.
2. Draw a good joint and a cold joint side by side in cross-section and label the differences.
3. Make a checklist of the safety rules you followed and the inspection results for each joint.

From history. After the Second World War, printed circuit boards spread to radios, televisions and eventually everything electronic. Paul Eisler held many patents for printed circuits but earned little from them in his lifetime.

COMMON MISTAKES

- Melting solder on the iron and dripping it onto the joint, which makes a cold joint.
- Moving the part before the solder has hardened.
- Leaving the iron lying on the bench instead of in its stand.

Make it a game · Solder Safety Drill. Run a safety briefing without touching any hot tool. Tell your parent every rule for soldering at the bench: protective glasses, ventilation, holder, tip resting, and no touching the iron. Then explain why flux and heat matter for wetting, and describe a cold joint. Miss none to win a point.

Scripture. “And I have filled him with the spirit of God, in wisdom, and in understanding, and in knowledge, and in all manner of workmanship, To devise cunning works, to work in gold, and in silver, and in brass, And in cutting of stones, to set them, and in carving of timber, to work in all manner of workmanship.” (Exodus 31:3-5, KJV)

God gave Bezalel skill to work in metals for the tabernacle. Careful handwork with metal, even a single soldered joint, can be done as worship, with wisdom and understanding.

UNIT 4

ELECTRONICS

Electricity lights a bulb; electronics makes decisions. In this unit you will meet the four parts that every electronic device is built from, the resistor, the capacitor, the diode and the transistor, and you will learn what each one does and how to calculate with it. You will time a capacitor charging and discharging, use a transistor to let a tiny current switch a larger one, write a program that reads a button and a knob and controls a light, and, with an adult at the bench, make your first soldered circuit.

The stories run from the Leyden jar of 1745, the first device that could store electric charge, to the transistor invented at Bell Labs in 1947, which made the modern world of computers and phones possible. Along the way you will see the room-sized ENIAC computer and the keyboard and display of the Apollo Guidance Computer that helped men fly to the Moon.

PREREQUISITES

- Can build series and parallel circuits and use $V = IR$ (Grades 5–6)
- Can read a simple circuit diagram
- Has used a multimeter to measure voltage, or is ready to learn

MASTERY CHECKLIST

- ☐ I can identify resistors, capacitors, diodes, LEDs and transistors and explain what each does.
- ☐ I can calculate an LED's current-limiting resistor and a capacitor's time constant ($\tau = RC$).
- ☐ I can explain how a transistor lets a small current switch a larger one, and why that matters for computers.
- ☐ I can write an Arduino program that reads a digital and an analog input and controls an output.
- ☐ I can explain how solder makes a joint and make or inspect a good soldered joint safely, with an adult.

OPTIONAL KITS FOR THIS UNIT

- **Arduino Uno and the Arduino Starter Kit:** Ages 12 and up. The board used in Lesson 4.3, powered by USB, with a breadboard, parts and a project book in the starter kit. Lesson 4.3 can also be done free in the Tinkercad Circuits simulator.
- **Snap Circuits:** Ages 8 and up. Snap-together parts include capacitors, transistors and LEDs, a no-solder way to try the circuits in Lessons 4.1 and 4.2.
- **BBC micro:bit:** Ages 8 and up. A small USB-powered board with built-in buttons, lights and sensors, programmed in the free MakeCode editor; an easier alternative to the Arduino for Lesson 4.3.

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 Resistors, Capacitors, Diodes and LEDs: From the Leyden Jar to the LED

2 sessions of 50–60 minutes

4.2 The Transistor as a Switch: Bell Labs, 1947

2 sessions of 50–60 minutes

4.3 Arduino Inputs and Outputs: Sense, Decide, Act

2 sessions of 50–60 minutes

4.4 Soldering Basics with an Adult

2 sessions of 50–60 minutes

UNIT 4 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Name the job of each of these parts in a circuit: resistor, capacitor, diode, LED.

2. **10 pts**

Calculation: A green LED needs 2.2 V and 15 mA. Your battery is 6 V. What resistor do you need?

3. 10 pts

Calculation: Find the time constant of a $470\ \mu\text{F}$ capacitor discharging through a $2,000\ \Omega$ resistor. What happens to τ if the resistor is halved?

4. 8 pts

What was the Leyden jar, and what did Benjamin Franklin find about where it stored its charge?

5. 8 pts

Why did the transistor replace the vacuum tube?

6. 10 pts

Calculation: A transistor lets $40\ \text{mA}$ flow through its collector when its base current is $0.25\ \text{mA}$. What is its current gain?

7. 8 pts

In an NPN transistor switch, what must happen at the base for the LED on the collector to light?

8. 8 pts

What is the difference between a digital input and an analog input on an Arduino?

9. 8 pts

An Arduino analog input reads 300. About what voltage is on the pin? (Use $5\ \text{V} \div 1023$ per step.)

10. 10 pts

Why does a button input need a pull-down resistor?

11. 12 pts

Written answer: Describe how to make a good soldered joint and how to tell it from a cold joint. Give two safety rules for soldering.

ANSWER KEY

1. Resistor: limits current. Capacitor: stores charge. Diode: lets current flow only one way. LED: a diode that gives off light when current flows the right way.
2. The resistor must drop $6 - 2.2 = 3.8$ V. $R = V \div I = 3.8 \div 0.015 \approx 253 \Omega$; use the next standard value up, such as 270Ω .
3. $\tau = RC = 2,000 \times 0.000470 = 0.94$ s. Halving R halves τ , to 0.47 s.
4. The first capacitor: a glass jar with conductors inside and outside (water, then foil). Franklin showed the charge was stored in the glass between the conductors.
5. Transistors are much smaller, use far less power, make little heat, switch faster and almost never wear out, while tubes were large, hot and burned out often.
6. $\text{Gain} = 40 \div 0.25 = 160$.
7. A small current must flow into the base (with about 0.7 V between base and emitter); this lets a larger current flow from collector to emitter through the LED.
8. A digital input reads only HIGH or LOW (on or off). An analog input measures a voltage from 0 to 5 V and reports it as a number from 0 to 1023 .
9. $300 \times 5 \div 1023 \approx 1.47$ V.
10. Without it, the pin is not connected to anything when the button is not pressed, so it “floats” and may read HIGH or LOW at random; the resistor holds it LOW until the button connects it to 5 V.
11. Clean, tinned tip; heat both the pad and the leg for a few seconds; touch solder to the joint (not the iron) so it flows; remove solder, then iron; do not move it while it cools. A good joint is shiny, smooth and cone-shaped; a cold joint is dull, lumpy, balled or cracked and may fail a continuity test. Safety (any two): adult present; iron always in its stand; safety glasses; lead-free solder; ventilation; never touch the tip or catch a falling iron; wash hands.

PORTFOLIO PIECE: A SENSE-DECIDE-ACT ELECTRONIC DEVICE

Design and build a small useful device that senses something, decides, and acts, using parts from this unit. Examples: a water-level alarm using a transistor and LED, a night light that turns on in the dark using a light sensor, or an Arduino reaction-time tester with a button and LEDs. Include at least one calculation (a resistor value, a time constant or a gain) that you check with a measurement. Write a one-page engineer's report with your circuit diagram, your calculation and measurement, a photograph, the tests you ran, and what you would improve.

LOOK FOR	WHAT IT MEANS
Working device	The device reliably senses, decides and acts as intended, powered only by batteries or USB.
Circuit diagram	Clear, correct diagram with standard symbols, polarity marked and every value labeled.
Calculation checked	At least one calculation done with units and compared honestly with a measurement.
Testing	The device was tested under several conditions, and failures were recorded and fixed.
Craftsmanship and safety	Neat wiring or soldering; every safety rule followed.

UNIT 5

PUBLIC UTILITIES

Turn on a light, run the tap, flush the toilet or make a phone call, and you are using engineering systems so large and so reliable that most people never think about them. In this unit you will learn how they work, with the physics and arithmetic underneath. You will see why the electric grid uses alternating current and transformers, measure the power of falling water, watch microbes at work the way a wastewater plant uses them, and find out how radio waves carry your voice to a cell tower and why a metal box can stop them.

The stories include Edison, Tesla, Westinghouse and William Stanley in the contest between direct and alternating current, the building of Hoover Dam, two English chemists who discovered activated sludge in 1914, and Guglielmo Marconi listening for a signal from across the Atlantic. Every one of these systems is a way of serving neighbors: light, clean water and communication for millions of people.

PREREQUISITES

- Can use $V = IR$ and $P = W \div t$ (Units 1 and 4)
- Knows that a moving magnet near a coil makes a current (Grades 5–6)
- Can calculate pressure and work with units

MASTERY CHECKLIST

- ☐ I can explain the difference between AC and DC and why the grid transmits power at high voltage, using $P = I^2R$.
- ☐ I can explain how a transformer changes voltage, and why it only works with changing current.
- ☐ I can calculate the power available from falling water with $P = \rho g Q h \times \text{efficiency}$.
- ☐ I can describe the stages of wastewater treatment and the job of the microbes in activated sludge.
- ☐ I can use $c = f\lambda$ to find the wavelength of a radio signal and explain how cell towers and Faraday cages work.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (including the AM/FM radio sets):** Ages 8 and up. Several sets build a working AM or FM radio receiver and simple transmitters without soldering; a fine extension of Lesson 5.4.

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

5.1 AC versus DC: Edison, Tesla, Westinghouse and the Transformer

2 sessions of 50–60 minutes

5.2 Dams and Hydroelectric Power: Building Hoover Dam

2 sessions of 50–60 minutes

5.3 Wastewater Treatment: Activated Sludge and the Microbes That Clean Water

2 sessions of 50–60 minutes

5.4 Radio Waves and Cell Towers: From Marconi to the Mobile Phone

2 sessions of 50–60 minutes

UNIT 5 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

What is the difference between AC and DC? Give one source of each.

2. **10 pts**

Calculation: A line with $4\ \Omega$ of resistance delivers 20,000 W. Find the power lost at 2,000 V and at 20,000 V.

3. **8 pts**

Why can a transformer not work with steady DC?

4. **8 pts**

A transformer has 100 turns on its primary and 2,000 turns on its secondary. If 120 V goes in, what voltage comes out? Is it a step-up or step-down transformer?

5. **8 pts**

How did engineers keep the concrete of Hoover Dam from cracking as it cooled?

6. **10 pts**

Calculation: Water flows at $50 \text{ m}^3/\text{s}$ through turbines with a head of 80 m. Find the power available, and the output if the plant is 90% efficient ($\rho = 1,000 \text{ kg/m}^3$, $g = 9.8 \text{ m/s}^2$).

7. **8 pts**

Why is a dam much thicker at the bottom than at the top?

8. **10 pts**

Name the main stages of a wastewater treatment plant in order and say what each removes or does.

9. **8 pts**

What did Arden and Lockett discover in 1914, and why did it work?

10. **10 pts**

Calculation: Find the wavelength of an AM radio station at 1,000 kHz (1,000,000 Hz), using $c = 300,000,000 \text{ m/s}$.

11. **12 pts**

Written answer: Explain how the cellular idea lets millions of people use phones at the same time, and why a closed metal tin blocks a phone signal.

ANSWER KEY

1. DC flows one way all the time (a battery); AC reverses direction many times a second (the grid, a generator at a power plant).
2. At 2,000 V: $I = 10 \text{ A}$, $\text{loss} = 10^2 \times 4 = 400 \text{ W}$. At 20,000 V: $I = 1 \text{ A}$, $\text{loss} = 1^2 \times 4 = 4 \text{ W}$.
3. A transformer needs a changing magnetic field to make a voltage in the second coil. Steady DC makes a steady field, so there is a voltage only for an instant when it is switched on or off.
4. $V = 120 \times 2,000 \div 100 = 2,400 \text{ V}$. Step-up.
5. They built it as many separate columns poured in thin layers, cooled with water (and then chilled water) running through embedded steel pipes, and filled the gaps with grout once it had shrunk.
6. $P = 1,000 \times 9.8 \times 50 \times 80 = 39,200,000 \text{ W}$ (39.2 MW). $\times 0.90 \approx 35.3 \text{ MW}$.
7. Water pressure increases with depth ($p = \rho gh$), so the push on the dam is greatest at the bottom.
8. Screens (trash and rags); grit chambers (sand and gravel); primary clarifier (settling solids and floating grease); aeration basin with activated sludge (microbes eat dissolved pollution); secondary clarifier (microbes settle and are returned); disinfection (destroys remaining germs).
9. That returning the settled sludge from aeration to the next batch made cleaning much faster, because the sludge was full of microbes already adapted to eating sewage.
10. $\lambda = c \div f = 300,000,000 \div 1,000,000 = 300 \text{ m}$.
11. A region is divided into small cells, each with low-power antennas; neighboring cells use different frequencies and the same frequencies are reused in distant cells, so many calls share the limited frequencies; phones are handed from cell to cell as they move. A closed metal tin is a Faraday cage: the radio waves move the electrons in the metal, which rearrange to cancel the field inside, so the waves cannot get in.

PORTFOLIO PIECE: A UTILITY ENGINEER'S REPORT

Choose one utility that serves your home: electricity, water, wastewater or communications. Find out (with a parent, from the utility's website or a public tour) where it comes from or goes to, and draw a labeled map or flow diagram of the whole system from source to your house or from your house to the river. Include at least two calculations with real or reasonable numbers (for example, your family's daily water use in cubic meters, the power lost on a line, or the wavelength of your nearest radio station). Then build and test one small model from this unit that shows a key part of the system, and write a one-page report that ends with a thank-you note to the people who keep that system running.

LOOK FOR	WHAT IT MEANS
System diagram	Complete, labeled diagram of the utility from source to home or from home to the environment.
Calculations	At least two calculations, each with the formula, numbers with units and a sensible answer.
Model and test	A working model from this unit, tested fairly, with results recorded.
Explanation	Explains the physics of the system in the student's own words, including one trade-off engineers must make.
Service	The report recognizes the workers and engineers who keep the system safe and running.

5.1 AC VERSUS DC: EDISON, TESLA, WESTINGHOUSE AND THE TRANSFORMER

OBJECTIVES

- Explain the difference between direct and alternating current.
- Use $P = I^2R$ to show why power is sent over long distances at high voltage.
- Show with a two-coil model that a transformer works only when the current changes.

Warm-up. Look at the label on a phone charger or laptop power brick (do not plug or unplug anything). Find the “input” and “output” lines. What voltages do you see? Why do you think the charger changes one into the other?

WATCH

How does a Transformer work - Working Principle electrical engineering

The Engineering Mindset • 6:30

<https://www.youtube.com/watch?v=UchitHGF4n8>

WHEN TO WATCH

After the physics paragraph, before the build.

BACKUP VIDEO

How Transformers Work

Northwest Lineman College • 2:05

https://www.youtube.com/watch?v=n_KO_g9HNKE

Optional: a short explanation from a school that trains lineworkers.

KEY TERMS

direct current (DC)

Current that flows one way all the time, as from a battery.

alternating current (AC)

Current that reverses direction many times a second; 60 times a second (60 hertz) in North America.

transformer

Two coils of wire around an iron core. A changing current in one coil makes a voltage in the other; the ratio of the turns sets the ratio of the voltages.

power loss (I^2R)

The power wasted as heat in a wire: current squared times the wire's resistance.

transmission line

A high-voltage power line that carries electricity long distances from power plants to cities.

CORE IDEAS

The story. On September 4, 1882, Thomas Edison's Pearl Street Station in New York City began sending direct current to customers in about a square mile of lower Manhattan. Edison's system worked well, but it had a serious limit: low-voltage DC lost so much power in the wires that a power station could only serve customers within about a mile. Meanwhile, in Europe, Lucien Gaulard and John Gibbs were experimenting with alternating current and early transformers. The American inventor George Westinghouse bought the rights to their transformer, and his engineer William Stanley improved it. In March 1886 Stanley lit up the shops and offices of Great Barrington, Massachusetts, with alternating current stepped up for transmission and stepped down by transformers for use. In 1888 Nikola Tesla patented a practical AC motor, and Westinghouse bought those patents too.

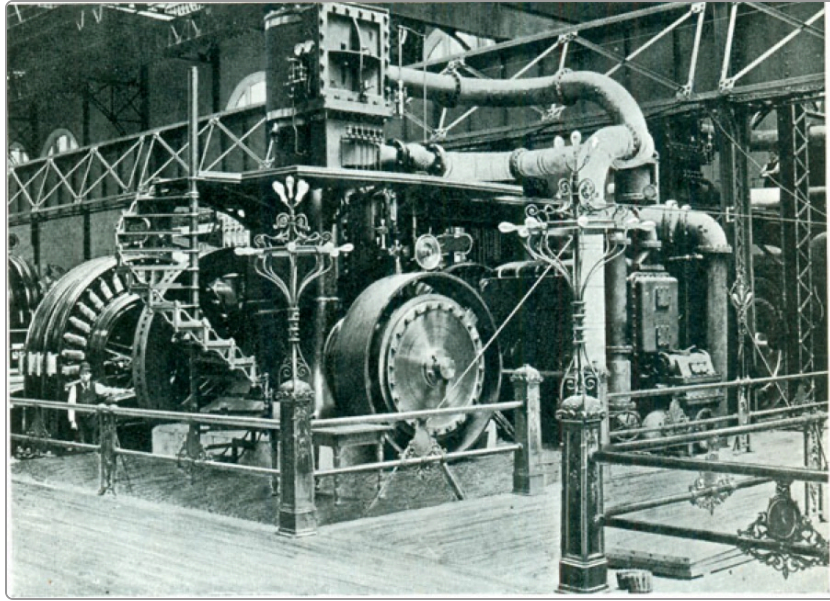
How they figured it out. For several years Edison's and Westinghouse's companies competed fiercely, and the newspapers called it the "war of the currents." The engineering decided it. In 1893 Westinghouse lit the World's Columbian Exposition in Chicago with alternating current, and that year his company won the contract to build generators at Niagara Falls. In November 1896 power from Niagara began flowing to Buffalo, about 26 miles away, by AC transmission at high voltage. Engineers had measured and calculated the losses, and the numbers showed that only AC, with transformers, could carry large amounts of power over long distances cheaply. Edison's own company soon began building AC systems as well.

The physics. The power delivered by a line is $P = V \times I$, but the power wasted heating the wire is $P_{\text{loss}} = I^2R$. Suppose a town needs 10,000 W through a line with a

resistance of $5\ \Omega$. At 1,000 V, the current is $10,000 \div 1,000 = 10\ \text{A}$, and the loss is $10^2 \times 5 = 500\ \text{W}$, 5% of the power. At 10,000 V, the current is only 1 A, and the loss is $1^2 \times 5 = 5\ \text{W}$. Ten times the voltage means one-hundredth of the loss. A **transformer** changes voltage by the ratio of its turns: $V_{\text{secondary}} \div V_{\text{primary}} = N_{\text{secondary}} \div N_{\text{primary}}$. It works because a **changing** current in the first coil makes a changing magnetic field in the iron core, and a changing magnetic field makes a voltage in the second coil, as Michael Faraday discovered in 1831. Steady DC makes no change after it is switched on, so a transformer cannot work with it. AC changes all the time.

The engineering. Today's grid uses transformers at every step. Generators make power at perhaps 20,000 V; step-up transformers at the plant raise it to 115,000 V to 765,000 V for long transmission lines; substations step it down for local distribution lines; and the gray can on a pole or the green box in a yard steps it down to the 120 and 240 volts used in homes. Interestingly, modern electronics can now convert very high-voltage DC efficiently, so some of the longest lines in the world, including undersea cables, now carry high-voltage DC. Both Edison and Tesla were right about something. Lineworkers who build and repair these lines do some of the most skilled and dangerous work in the country so that the rest of us have light.

PICTURE STUDY



A Westinghouse Alternator at the 1893 World's Fair, Unknown photographer, 1893 · Photograph · World's Columbian Exposition, Chicago
Image: [Wikimedia Commons](#), public domain

Westinghouse lit the 1893 World's Fair with alternating current from machines like this one, and the lights of the fair convinced many visitors that AC was the future.

Look closely

- Find the large spinning part. What turned it?
- Look for the coils and the iron frame around them.
- Find any belts, shafts or wires leading away from the machine.
- Look for people in the picture to judge its size.

Talk about it

1. Why did lighting the World's Fair with AC help Westinghouse win the Niagara Falls contract?
2. Where in this machine is the moving magnetic field that makes the voltage?
3. Why would the electricity from this generator need a transformer before it traveled far?

Safety first. Use only batteries. Never touch or go near power lines, substations, transformer boxes or anything connected to the outlets in the wall. If you ever see a fallen power line, stay far away and tell an adult to call the power company. Disconnect the battery after each short test so the wire does not get hot.

BUILD

Two Experiments: Line Loss and a Model Transformer

First you will feed a small bulb through a long, thin wire and measure how much voltage is lost in the line. Then you will wind a model transformer on an iron bolt and find out when it makes a voltage in its second coil and how the number of turns matters.

You will need

- A D-cell or 2 AA cells in a holder, and a 6 V lantern battery or 4 AA cells (optional, for the higher-voltage comparison)
- A small flashlight bulb in a holder (or an LED with a resistor)
- About 10 m of thin magnet wire (about 30 gauge) for the long line, and short alligator clip leads
- A large iron bolt or two iron nails taped together, and more magnet wire (about 26 gauge) for the coils
- A digital multimeter, fine sandpaper, a compass, masking tape

Steps

1. **Line loss.** Connect the bulb to the battery with short clip leads. Measure the voltage at the bulb. Then connect it through the 10 m of thin wire (sand the enamel off the ends). Measure the voltage at the battery and at the bulb. The difference is the voltage lost in the line.
2. Measure the line's resistance with the multimeter, and calculate the current ($I = V_{\text{lost}} \div R_{\text{line}}$) and the power lost (I^2R).
3. **Predict.** If you could send the same power at a higher voltage, would the line lose more or less? Explain with $P = I^2R$.
4. **Model transformer.** Wind 30 turns of magnet wire around one end of the bolt (the primary) and 30 turns around the other end (the secondary). Sand the wire ends.
5. Connect the secondary to the multimeter on its lowest DC millivolt setting. Touch the primary's wires to the battery and hold them there, watching the

meter. Then disconnect. Record what the meter shows at the moment of connecting, while connected, and at the moment of disconnecting.

6. **Fair test.** Change only the number of secondary turns: 30, 60 and 90. For each, tap the battery connection on and off quickly several times and record the largest reading you see.
7. Graph the largest reading against the number of secondary turns.
8. **Improve.** Find a way to make a bigger, steadier reading: more primary turns, a closed iron loop (bend a coat hanger into a ring), or tapping faster. Change one thing at a time.

Tips

- The meter only shows a voltage at the instant the current changes; watch closely or film it in slow motion.
- Do not leave the primary connected for more than a second or two; it is nearly a short circuit and the wire and battery will warm.
- Magnet wire has a thin enamel coating; the ends must be sanded bright to make contact.

Check your work

- ☐ I can explain why high-voltage transmission wastes less power.
- ☐ I can explain why a transformer needs a changing current.
- ☐ I can describe how the number of turns affected my transformer's output.

ENGINEER'S NOTEBOOK

1. Draw the grid from the generator to your house, with each transformer, its job (step up or step down) and an approximate voltage.
2. Make a table of your line-loss measurements and calculations, and a graph of transformer output against turns.
3. A city receives 50,000 W through lines with a total resistance of 2 Ω . Calculate the power lost at 5,000 V and at 50,000 V.

From history. Michael Faraday, who discovered the induction that makes transformers and generators work, was a devout Christian and an elder in his small church in London. He refused most honors and spent his life explaining science to ordinary people, including famous Christmas lectures for children.

COMMON MISTAKES

- Thinking high voltage means more power is lost. For the same power, higher voltage means lower current and much less loss.
- Expecting a transformer to work with steady DC.
- Forgetting that a transformer cannot create power: if it raises the voltage, it lowers the current.

Make it a game • Line Loss Numbers. Your parent names a current and a line resistance, such as 10 amps and 2 ohms. Calculate power loss with $P \text{ equals } I \text{ squared times } R$. Then halve the current and recalculate. Say what happened. Explain why transmission lines run at high voltage, and the difference between AC and DC. Highest accuracy over five rounds wins.

5.2 DAMS AND HYDROELECTRIC POWER: BUILDING HOOVER DAM

OBJECTIVES

- Explain how water pressure increases with depth ($p = \rho gh$) and why dams are thicker at the bottom.
- Calculate the power available from falling water with $P = \rho g Q h \times \text{efficiency}$.
- Build a small water turbine and test how the height of the water (the head) changes its power.

Warm-up. Poke three small holes one above another in the side of a plastic bottle (an adult can use a pushpin). Cover them with tape, fill the bottle with water over a sink, and pull off the tape. Which jet shoots farthest? Why?

WATCH

Building the Hoover Dam

The B1M • 6:50

https://www.youtube.com/watch?v=n9Gy_1Ppw5U

WHEN TO WATCH

After the story paragraph.

KEY TERMS

head

The height the water falls from the reservoir surface to the turbine. More head means more pressure and more power.

penstock

A large pipe that carries water from the reservoir down to the turbines.

flow rate (Q)

The volume of water passing per second, in cubic meters per second (m^3/s).

turbine

A wheel with curved blades that the moving water spins, turning a generator.

arch-gravity dam

A dam that holds back water both by its great weight and by arching upstream so that the water's push is carried into the canyon walls.

CORE IDEAS

The story. The Colorado River flooded farms in the spring and dried to a trickle in late summer. In 1931 the United States government began building a dam in Black Canyon on the border of Nevada and Arizona to tame the river, store water for farms and cities, and generate electricity. Six construction companies joined together for the job. Workers first dug four tunnels, each about 50 feet across, through the canyon walls to carry the river around the site. Then they cleared the canyon floor down to solid rock and began placing concrete in June 1933. The dam was finished in 1936, two years ahead of schedule. It rises 726 feet (221 meters), is about 660 feet thick at the base and 45 feet thick at the top, and holds back Lake Mead, one of the largest reservoirs in the country.

How they figured it out. The engineers faced a problem no one had met on this scale: concrete gets hot as it hardens, and a dam this size poured in one piece would have taken well over a century to cool, cracking as it shrank. The Bureau of Reclamation's engineers solved it by building the dam as hundreds of separate interlocking columns, poured in layers about 5 feet deep, with steel pipes laid through the concrete carrying first river water and then chilled water from a refrigeration plant. When each part had cooled and shrunk, the gaps between columns were filled with grout under pressure, making one solid dam. They tested concrete mixes, models and the canyon rock before trusting their design with the safety of everyone downstream.

The physics. Water pressure grows with depth: $p = \rho gh$, where ρ (rho) is water's density, $1,000 \text{ kg/m}^3$. At 10 m deep, $p = 1,000 \times 9.8 \times 10 = 98,000 \text{ Pa}$, about the same as the air pressure at the surface. At the base of Hoover Dam, about 180 m below the lake surface, the pressure is roughly 1.8 million pascals, which is why the dam is so thick at the bottom. That pressure is also stored energy. The power of falling water is $P = \rho g Q h$. If 100 m^3 of water falls 150 m every second, $P = 1,000 \times 9.8 \times 100 \times 150 = 147,000,000 \text{ W}$, or 147 megawatts. Good turbines and generators are about 90% efficient, so about 132 MW would reach the grid.

The engineering. Water from the reservoir enters intake towers, falls through penstocks 30 feet across, and spins the turbines in the powerhouse at the foot of the dam. Hoover Dam's generators can produce about 2,000 megawatts at full output. Hydroelectric power has great advantages: it uses no fuel, can start up in minutes when demand rises, and the reservoir stores water for dry seasons. It also has costs: a dam floods a valley, changes the river downstream, blocks fish and slowly fills with silt. Engineers weigh these trade-offs, and they inspect dams constantly, because a dam must be safe for as long as it stands.

PICTURE STUDY



Excavating the Nevada Powerhouse at Hoover Dam, U.S. Bureau of Reclamation, 1932 · Photograph · National Archives and Records Administration

Image: [Wikimedia Commons](#), public domain

This photograph, from the government's own construction albums, looks down into the place where the Nevada-side powerhouse would stand. The tunnel openings in the rock would later hold the penstocks carrying water to the turbines.

Look closely

- Find the tunnel openings in the canyon wall. What would later flow through them?
- Find the trucks and roads at the bottom. How big are they compared with the tunnels?
- Look at the rock. Why did engineers want to build on solid rock?
- Look for anything that tells you how the workers got in and out of the canyon.

Talk about it

1. Why are the turbines placed at the bottom of the dam rather than near the top?
2. Why must the penstocks be so strong?

3. What dangers did workers face in a deep canyon like this, and what would you do to keep them safe?

Safety first. Do the turbine test outdoors or over a sink or tub with an adult nearby. Never play near real dams, spillways or canals: currents and water released without warning are dangerous.

BUILD

A Water Turbine and the Power of Head

You will build a small water turbine from a cork or bottle cap and plastic spoons, let water fall on it from different heights, and measure how fast it can lift a load. You will calculate the power output and find how the head changes it.

You will need

- A cork or a thick bottle cap, 6–8 plastic spoons, a wooden skewer for the axle, and a cardboard or plastic frame to hold it
- A 2-liter bottle with a hole about 1 cm wide near the bottom, covered with tape until ready (the reservoir), and a bucket or tub to catch the water
- Thread, a paper clip hook and a small load (10 pennies, 25 g)
- A ruler, tape measure, stopwatch and measuring cup

Steps

1. Push the spoons into the cork evenly around its edge, all with their bowls facing the same way. Push the skewer through the center as an axle and mount it on the frame so it spins freely over the tub.
2. Tape one end of a 60 cm thread to the axle and hang the 25 g load from the other end. When the turbine turns, the thread winds up and lifts the load.
3. **Measure the flow.** Fill the bottle to a marked line and time how long it takes to empty a measured 500 mL through the hole. Calculate Q in m^3/s (500 mL = 0.0005 m^3).
4. **Predict.** Hold the bottle so the hole is 20 cm, 40 cm and 60 cm above the turbine. Predict which head will lift the load fastest.
5. **Test.** For each head, refill the bottle to the same line, pull the tape, and time how long the turbine takes to lift the load 0.50 m. Repeat three times and average.
6. Calculate the power output: $P_{\text{out}} = (\text{load weight} \times 0.50 \text{ m}) \div \text{time}$. Calculate the power available: $P_{\text{in}} = \rho g Q h$. Find the efficiency.
7. Make a table and graph power output against head.

8. **Improve.** Change one thing about the turbine to raise its efficiency (more spoons, bigger spoons, aiming the stream at the spoon bowls, a nozzle to make the jet narrower) and test it at the best head.

Tips

- Keep the water level in the bottle the same at the start of each trial; it changes the flow.
- Your efficiency will be very low, probably well under 5%. Real turbines are carefully shaped to catch nearly all the water's energy.
- A friend should hold the bottle steady at each height while you time.

Check your work

- ☐ I can calculate water pressure at a depth.
- ☐ I can calculate the power of falling water and the efficiency of my turbine.
- ☐ I can explain why more head gives more power.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of a hydroelectric dam: reservoir, intake, penstock, turbine, generator and the river downstream. Label the head.
2. Make a table and graph of head, time to lift, power out, power in and efficiency.
3. A small hydro plant has a head of 40 m and a flow of $20 \text{ m}^3/\text{s}$. Calculate the power available, and the electrical power if it is 88% efficient.

From history. Hoover Dam was the work of thousands of men during the hard years of the 1930s, when jobs were scarce. In 1984 the American Society of Civil Engineers named it a National Historic Civil Engineering Landmark, and in 1994 one of the Seven Wonders of the modern civil-engineering world.

COMMON MISTAKES

- Measuring the head from the wrong point. It is the height from the water surface to the turbine.
- Forgetting to convert milliliters to cubic meters.
- Thinking a dam makes energy. It converts the energy the water already has because of its height.

Make it a game • Head and Power. Your parent names a flow rate and a head, such as 2 cubic meters per second and 30 m. Estimate the power using P equals ρ times g times Q times h times efficiency, with 1000 kg per cubic meter. Do three rounds. Then calculate the pressure at the base of a dam and explain why it is thicker there.

Scripture. “All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.” (Ecclesiastes 1:7, KJV)

The water cycle lifts water back up to the mountains again and again. A hydroelectric dam borrows a little of that energy on the water’s way back to the sea.

5.3 WASTEWATER TREATMENT: ACTIVATED SLUDGE AND THE MICROBES THAT CLEAN WATER

OBJECTIVES

- Describe the main stages of a wastewater treatment plant.
- Explain how microbes in activated sludge remove pollution, and why they need oxygen.
- Measure settling over time and test how temperature affects how fast microbes work.

Warm-up. Stir a spoonful of garden soil into a clear glass of water and set it down. Watch for two minutes. What happens first, and what is still floating at the end? Write a prediction of how it will look in an hour.

WATCH

Zurich Werdhoelzli: How does a sewage treatment plant work?

Stadt Zürich · 12:53

<https://www.youtube.com/watch?v=XjEuWlr78b8>

WHEN TO WATCH

After the physics paragraph: a tour of the city of Zurich's treatment plant, stage by stage.

BACKUP VIDEO

Wastewater Instructional Video: Introduction to Activated Sludge

Pennsylvania DEP · 17:59

https://www.youtube.com/watch?v=0Zfj8Vg_3HM

Optional and longer: a state environmental agency's training video on activated sludge. Watch the first 8 minutes.

KEY TERMS

wastewater

Used water from homes and businesses: from sinks, showers, washing machines and toilets.

primary clarifier

A large, calm tank where solids settle to the bottom and grease floats to the top.

activated sludge

A mixture of wastewater and living microbes, kept stirred and supplied with air, in which the microbes eat the dissolved pollution.

aeration

Bubbling air through water to supply oxygen to the microbes.

biochemical oxygen demand (BOD)

A measure of how much organic pollution is in water: the oxygen microbes would use up eating it.

disinfection

The final step that destroys remaining germs, using chlorine or ultraviolet light, before the water is returned to a river.

CORE IDEAS

The story. In the early 1900s many cities had sewers, but they simply carried the wastewater into the nearest river. Engineers knew how to let solids settle out, but the dissolved pollution, the part that uses up the oxygen in a river and suffocates its fish, was much harder to remove. In Manchester, England, two chemists named Edward Ardern and William Lockett were testing ways to clean sewage at the city's Davyhulme works. They knew that air bubbled through sewage helped bacteria break it down, but it took weeks. In 1914 they tried something new: they let the brown, fluffy solids that formed during aeration settle out, and instead of throwing them away, they added them back to the next batch. Each time they did this, the cleaning went faster. They called the reused solids "activated sludge."

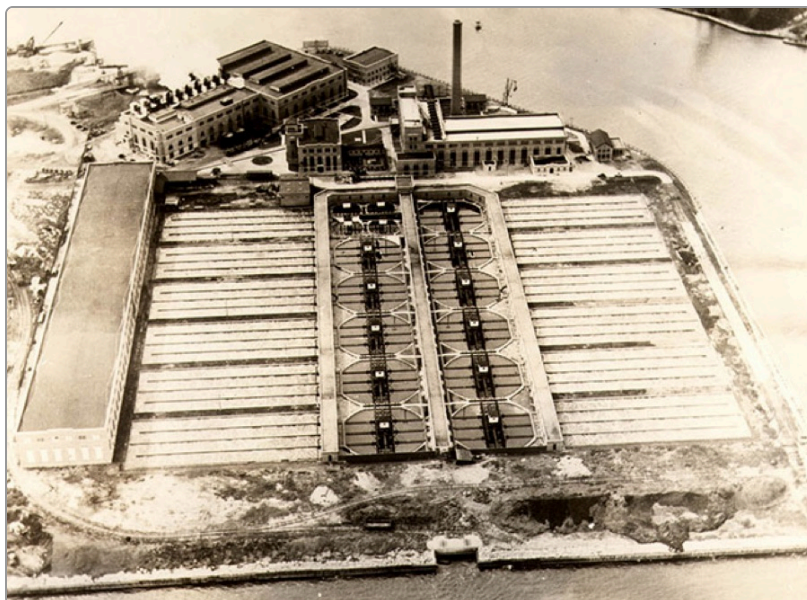
How they figured it out. Ardern and Lockett measured the pollution in every batch and the time it took to clean. They found that the settled sludge was a thriving community of microbes that had already learned, in a sense, to feed on sewage. Returning it meant each new batch began with a huge, hungry population instead of a few. Within ten years cities were building large activated-sludge plants. Milwaukee, Wisconsin, opened one of the first big ones in America at Jones Island in 1925, and found a use for its leftover sludge: dried and heat-treated, it was sold as a garden fertilizer, which it still is today.

The physics. A treatment plant uses physics first and biology second. **Screens** catch rags and trash. In **grit chambers**, the water slows down so sand and gravel settle. In the **primary clarifier**, the water moves so slowly that heavier solids sink, according to how fast each particle falls compared with how fast the water carries it. Then

comes the **aeration basin**, where blowers force air through the water. The microbes, mostly bacteria with tiny animals called protozoa that eat them, use the oxygen to break down dissolved food into carbon dioxide, water and more microbes, just as your body uses oxygen to burn food. Warm water and plenty of oxygen make them work faster. In the **secondary clarifier**, the microbes clump together and settle out, and most are pumped back to the start. Finally the clear water is disinfected and returned to a river.

The engineering. Running a wastewater plant is like caring for a living thing. Operators test the water every day, adjust the air, measure how well the sludge settles, look at the microbes under a microscope and remove extra sludge as the population grows. Engineers size the tanks for the city's flow on its busiest days and for heavy rains, and design backup pumps and power so the plant never stops. A modern plant can remove more than 90% of the pollution, so rivers that were once open sewers now have fish again. Wastewater operators are some of the least thanked public servants, and some of the most important.

PICTURE STUDY



The Jones Island Sewage Plant, Milwaukee, Unknown photographer, 1926 · Photograph · Milwaukee, Wisconsin

Image: [Wikimedia Commons](#), public domain

Milwaukee's Jones Island plant, opened in 1925, was one of the first large activated-sludge plants in the United States. It is still in service, much enlarged.

Look closely

- Find the long rectangular tanks. Which might be aeration basins and which clarifiers?
- Find the buildings. What machines might be inside them (hint: think about where the air comes from)?
- Look at where the plant is placed. Why would it be built near the lake and at the low end of the city?
- Look for pipes or channels connecting the tanks.

Talk about it

1. Why are the tanks so large and so shallow compared with their length?
2. Why must the blowers that supply air run day and night?
3. Why do you think cities waited so long to treat wastewater, and what changed their minds?

Safety first. Never handle real sewage or water from storm drains, and never go near manholes or treatment tanks. Use only clean soil and kitchen ingredients. Wash your hands after the build. Do not drink any of the test water.

BUILD

Settling and Microbes at Work

You will run two small tests of the two key processes in a treatment plant. First you will measure how fast solids settle out of muddy water, as in a clarifier. Then you will use yeast, a harmless microbe, to test how temperature changes how fast microbes eat their food, measuring the gas they give off.

You will need

- Two tall, clear jars or bottles of the same size, garden soil, a ruler and a marker
- Three small plastic bottles (about 500 mL), three balloons, three teaspoons of active dry yeast and three tablespoons of sugar
- Three bowls of water: cold (with ice), room temperature and warm from the tap (about 40 °C, not hot), and a kitchen thermometer if you have one
- String or a tape measure for balloon size, a stopwatch, graph paper

Steps

1. **Settling.** Fill a jar with water and stir in three spoonfuls of soil until it is evenly cloudy. Start the stopwatch when you stop stirring.
2. Every 2 minutes for 20 minutes, then at 30 and 60 minutes, measure the height of the clear layer at the top (or the height of the settled layer at the bottom). Record each reading.
3. Graph the clear-layer height against time. When was settling fastest?
4. **Fair test.** Repeat with the second jar, but stir in a pinch of alum from the spice aisle or a teaspoon of salt (change only that). Does it change how fast it settles?
5. **Microbes.** Into each small bottle put 1 teaspoon of yeast, 1 tablespoon of sugar and 200 mL of water at room temperature. Stretch a balloon over each mouth.
6. **Predict.** Stand one bottle in the cold bowl, one at room temperature and one in the warm bowl. Predict which balloon will grow fastest.

7. **Test.** Every 5 minutes for 30 minutes, measure the balloon's circumference with string. Record a table.
8. Graph circumference against time for all three. Explain the result: what does it mean for a treatment plant in a cold winter?
9. **Improve.** Repeat the warm bottle with twice as much sugar, or with no sugar, changing only that. What does the result tell you about microbes and their food?

Tips

- Use the same kind of jar for both settling tests so the depth is the same.
- Yeast makes carbon dioxide when it eats sugar without much air; wastewater microbes use oxygen instead, but temperature and food matter for both.
- Measure the balloons at the same point (their widest part) each time.

Check your work

- ☐ I can name the stages of a wastewater treatment plant in order.
- ☐ I can explain what the microbes in activated sludge do and what they need.
- ☐ I can graph and explain my settling and microbe results.

ENGINEER'S NOTEBOOK

1. Draw a flow diagram of a treatment plant from the sewer pipe to the river, with each stage labeled and one sentence on what it removes.
2. Make graphs of your settling test and your balloon test, with titles, labeled axes and units.
3. A city of 50,000 people sends about 380 liters of wastewater per person to the plant each day. How many liters is that per day? How many cubic meters ($1 \text{ m}^3 = 1,000 \text{ L}$)?

From history. Edward Ardern and William Lockett published their discovery in 1914 and did not patent it, so cities everywhere could use it freely. More than a hundred years later, activated sludge is still the most common way of treating wastewater in the world.

COMMON MISTAKES

- Thinking treatment plants mainly use chemicals. Most of the cleaning is done by settling and by microbes.

- Measuring the settling at different heights each time.
- Changing two things at once in the yeast test.

Make it a game · Microbe Menu. Make a menu for activated sludge microbes: what they eat, what they need, and what they leave behind. Your parent plays a plant manager who asks why oxygen matters, what a primary clarifier does and what BOD measures. Answer in full sentences. Name the stages in order, ending with disinfection.

5.4 RADIO WAVES AND CELL TOWERS: FROM MARCONI TO THE MOBILE PHONE

OBJECTIVES

- Explain what radio waves are and use $c = f\lambda$ to find a wavelength.
- Explain how cell towers divide a region into cells so many phones can share the airwaves.
- Test which materials block a phone's signal and explain the Faraday cage.

Warm-up. Make a list of every device in your home that sends or receives radio waves without a wire (think about phones, routers, remote car keys, garage door openers, baby monitors and radios). How many did you find?

WATCH

How Information Travels Wirelessly

MITK12Videos • 7:55

<https://www.youtube.com/watch?v=Ax7dYaRiY6o>

WHEN TO WATCH

After the physics paragraph.

BACKUP VIDEO

How Cell Towers Work: Hands-On!

MrMobile [Michael Fisher] • 9:28

<https://www.youtube.com/watch?v=Ct0wFde9Xcl>

After the engineering paragraph: a close look at real cell-tower equipment.

KEY TERMS

electromagnetic wave

A wave of changing electric and magnetic fields that travels at the speed of light, $c = 300,000,000$ m/s. Radio, microwaves and light are all electromagnetic waves.

frequency (f)

How many waves pass each second, measured in hertz (Hz). 1 MHz is a million hertz; 1 GHz is a billion.

wavelength (λ)

The distance from one wave crest to the next. For electromagnetic waves, $\lambda = c \div f$.

antenna

A conductor shaped and sized to send or receive radio waves, usually a fraction (often one-quarter or one-half) of the wavelength long.

cell

The area served by one tower antenna. Neighboring cells use different frequencies, and the same frequencies are reused farther away.

Faraday cage

A conducting enclosure that blocks electric fields and radio waves from getting in or out.

CORE IDEAS

The story. In 1865 the Scottish physicist James Clerk Maxwell, a man of deep Christian faith, wrote down four equations describing electricity and magnetism, and from them predicted that waves of electric and magnetic force should travel through space at the speed of light. In 1887 the German physicist Heinrich Hertz made a spark jump across a gap and detected the waves it sent across his laboratory. A young Italian, Guglielmo Marconi, read about Hertz's waves and wondered how far they could go. Working first in his family's attic and garden, he sent signals farther and farther. On December 12, 1901, sitting in a room at Signal Hill in St. John's, Newfoundland, with an antenna wire held up by a kite, Marconi heard three faint clicks, the letter S in Morse code, sent from Poldhu in Cornwall, England, more than 3,000 kilometers away across the Atlantic.

How they figured it out. Marconi was not the deepest scientist of his day, but he was a tireless experimenter. He found that taller antennas and a connection to the ground carried signals much farther, and he kept records of every test. Many scientists believed the waves would travel in straight lines and be lost into space because of the curve of the Earth; his transatlantic test showed that some waves follow the Earth's curve or bounce from the upper atmosphere. Radio quickly saved lives at sea, because ships could call for help. Decades later, engineers at Bell Labs proposed the cellular idea (1947), and on April 3, 1973, Martin Cooper of Motorola stood on a New York street and made the first call from a handheld mobile phone.

The physics. All electromagnetic waves travel at $c = 300,000,000$ m/s, and their speed equals frequency times wavelength: $c = f\lambda$. An FM radio station at 100 MHz has a

wavelength of $\lambda = 300,000,000 \div 100,000,000 = 3$ meters. A phone signal at 1.9 GHz has $\lambda = 300,000,000 \div 1,900,000,000 \approx 0.16$ m, or 16 cm, so the phone's antenna can be only a few centimeters long (often a quarter of the wavelength, about 4 cm). An antenna works because the alternating current in it pushes electrons back and forth, sending out waves; in a receiving antenna, arriving waves push electrons back and forth, making a tiny current. A metal box or mesh blocks radio waves because the waves push the electrons in the metal, which move to cancel the field inside; holes much smaller than the wavelength do not let the waves through.

The engineering. There are only so many radio frequencies, and millions of people want to use them at once. The cellular idea solves this by dividing a region into small areas called cells, each served by low-power antennas on a tower. Neighboring cells use different frequencies; cells far enough apart reuse the same ones. When you move, your phone is handed from one cell to the next without dropping the call. Towers are placed to cover roads and towns, and more cells are added where many people gather. Engineers must also make sure each tower's radio power stays within safety limits for people nearby, and that tower structures are strong enough for wind and ice.

PICTURE STUDY



Marconi at Signal Hill, James Vey, December 12, 1901 · Photograph · Cabot Tower, Signal Hill, St. John's, Newfoundland

Image: [Wikimedia Commons](#), public domain

This photograph was taken on the day Marconi heard the first radio signal sent across the Atlantic Ocean. His receiving equipment is on the table in front of him.

Look closely

- Find the receiving instruments on the table. Can you see coils of wire?
- Look for the wire leading to the antenna outside.
- Look at the room. What kind of building is this?
- Notice Marconi's expression and posture. What do you think he was listening for?

Talk about it

1. Why did Marconi need a very tall antenna, held up by a kite, for this test?
2. Many scientists thought radio waves could not follow the curve of the Earth. Why does that matter for a signal crossing an ocean?
3. How did radio change safety at sea?

Safety first. Do not open any phone, router or radio. Do not stand near the base of cell towers or climb any tower or fence. Do not put a phone in a microwave oven or turn on a microwave oven to test it.

BUILD

Which Materials Block a Phone Signal?

You will place a phone inside different containers and wrappings and call it or send it a message from another phone, to find which materials block radio waves. You will also test how the size of the gaps in a metal wrapping matters, and connect it to the wavelength.

You will need

- A phone that can receive calls (with a parent's permission), and a second phone to call it
- Containers and wrappings: a cardboard box, a plastic food container, a towel, a metal cookie tin with a lid, a metal cooking pot with a lid, aluminum foil
- A ruler, scissors, tape and a calculator

Steps

1. Calculate the wavelength of a typical phone signal (use 1.9 GHz) and of an FM radio station (use 100 MHz). Write both down.
2. **Predict.** List each container and predict: will the phone ring inside it?
3. **Test.** Put the phone in the first container and close it. Call it from the second phone and record whether it rings, and how many signal bars it showed just before you closed it (if you can see). Repeat three times for each container.
4. **Test:** cardboard, plastic, towel, one sheet of foil wrapped loosely, foil wrapped tightly with all edges folded, metal tin with lid, metal pot with lid.
5. **Gap test.** Wrap the phone completely in foil so it does not ring. Then cut a slit in the foil 1 cm long and test. Lengthen the slit to 4 cm, 8 cm and 15 cm, testing each time. At what slit length does the signal get through?
6. Compare the slit length that let the signal through with your calculated wavelength.
7. Record all results in a table.
8. **Improve.** Using what you learned, design the smallest, simplest wrapping that reliably blocks the signal, and test it three times.

Tips

- Some phones keep a signal through thin wrappings. The sealing of the edges matters more than the thickness of the foil.
- Test in the same spot in the house each time; signal strength changes from room to room.
- Take the phone out right after each test so it does not keep searching for a signal and drain its battery.

Check your work

- ☐ I can use $c = f\lambda$ to calculate a wavelength.
- ☐ I can explain why metal blocks radio waves and why small gaps matter less than large ones.
- ☐ I can explain how cells let many phones share the airwaves.

ENGINEER'S NOTEBOOK

1. Draw a map of a town divided into hexagonal cells, with a tower in each and a different color for each group of frequencies, showing how colors are reused.
2. Make a table of materials and results, and a second table of slit length and result.
3. A Wi-Fi router uses 2.4 GHz. Calculate the wavelength in centimeters, and the length of a quarter-wave antenna.

From history. When the *Titanic* sank in April 1912, its Marconi radio operators sent distress calls that brought the ship *Carpathia* to rescue the survivors. Afterward, new laws required ships to keep a radio operator on duty day and night.

COMMON MISTAKES

- Using the wrong power of ten. Write out mega (million) and giga (billion) carefully.
- Thinking radio waves are sound. They are electromagnetic waves and travel at the speed of light.
- Leaving one edge of the foil open and concluding foil does not block signals.

Make it a game • Wavelength Quick Draw. Your parent calls a frequency in megahertz. Use $c = f\lambda$ with c as 300 million meters per second to find wavelength in meters, with a calculator if needed. Race through five problems. Then draw a cell grid showing how towers share frequencies. Explain what a Faraday cage does.

Scripture. “Canst thou send lightnings, that they may go, and say unto thee, Here we are?” (Job 38:35, KJV)

God asked Job a question that seemed impossible. Today we send electromagnetic signals around the world in an instant, and we can only do it because God made a world whose laws Maxwell could write down and Marconi could test.

UNIT 5

PUBLIC UTILITIES

Turn on a light, run the tap, flush the toilet or make a phone call, and you are using engineering systems so large and so reliable that most people never think about them. In this unit you will learn how they work, with the physics and arithmetic underneath. You will see why the electric grid uses alternating current and transformers, measure the power of falling water, watch microbes at work the way a wastewater plant uses them, and find out how radio waves carry your voice to a cell tower and why a metal box can stop them.

The stories include Edison, Tesla, Westinghouse and William Stanley in the contest between direct and alternating current, the building of Hoover Dam, two English chemists who discovered activated sludge in 1914, and Guglielmo Marconi listening for a signal from across the Atlantic. Every one of these systems is a way of serving neighbors: light, clean water and communication for millions of people.

PREREQUISITES

- Can use $V = IR$ and $P = W \div t$ (Units 1 and 4)
- Knows that a moving magnet near a coil makes a current (Grades 5–6)
- Can calculate pressure and work with units

MASTERY CHECKLIST

- ☐ I can explain the difference between AC and DC and why the grid transmits power at high voltage, using $P = I^2R$.
- ☐ I can explain how a transformer changes voltage, and why it only works with changing current.
- ☐ I can calculate the power available from falling water with $P = \rho g Q h \times \text{efficiency}$.
- ☐ I can describe the stages of wastewater treatment and the job of the microbes in activated sludge.
- ☐ I can use $c = f\lambda$ to find the wavelength of a radio signal and explain how cell towers and Faraday cages work.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (including the AM/FM radio sets):** Ages 8 and up. Several sets build a working AM or FM radio receiver and simple transmitters without soldering; a fine extension of Lesson 5.4.

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

5.1 AC versus DC: Edison, Tesla, Westinghouse and the Transformer

2 sessions of 50–60 minutes

5.2 Dams and Hydroelectric Power: Building Hoover Dam

2 sessions of 50–60 minutes

5.3 Wastewater Treatment: Activated Sludge and the Microbes That Clean Water

2 sessions of 50–60 minutes

5.4 Radio Waves and Cell Towers: From Marconi to the Mobile Phone

2 sessions of 50–60 minutes

UNIT 5 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

What is the difference between AC and DC? Give one source of each.

2. **10 pts**

Calculation: A line with $4\ \Omega$ of resistance delivers 20,000 W. Find the power lost at 2,000 V and at 20,000 V.

3. **8 pts**

Why can a transformer not work with steady DC?

4. **8 pts**

A transformer has 100 turns on its primary and 2,000 turns on its secondary. If 120 V goes in, what voltage comes out? Is it a step-up or step-down transformer?

5. **8 pts**

How did engineers keep the concrete of Hoover Dam from cracking as it cooled?

6. **10 pts**

Calculation: Water flows at $50 \text{ m}^3/\text{s}$ through turbines with a head of 80 m. Find the power available, and the output if the plant is 90% efficient ($\rho = 1,000 \text{ kg/m}^3$, $g = 9.8 \text{ m/s}^2$).

7. **8 pts**

Why is a dam much thicker at the bottom than at the top?

8. **10 pts**

Name the main stages of a wastewater treatment plant in order and say what each removes or does.

9. **8 pts**

What did Arden and Lockett discover in 1914, and why did it work?

10. **10 pts**

Calculation: Find the wavelength of an AM radio station at 1,000 kHz (1,000,000 Hz), using $c = 300,000,000 \text{ m/s}$.

11. **12 pts**

Written answer: Explain how the cellular idea lets millions of people use phones at the same time, and why a closed metal tin blocks a phone signal.

ANSWER KEY

1. DC flows one way all the time (a battery); AC reverses direction many times a second (the grid, a generator at a power plant).
2. At 2,000 V: $I = 10 \text{ A}$, $\text{loss} = 10^2 \times 4 = 400 \text{ W}$. At 20,000 V: $I = 1 \text{ A}$, $\text{loss} = 1^2 \times 4 = 4 \text{ W}$.
3. A transformer needs a changing magnetic field to make a voltage in the second coil. Steady DC makes a steady field, so there is a voltage only for an instant when it is switched on or off.
4. $V = 120 \times 2,000 \div 100 = 2,400 \text{ V}$. Step-up.
5. They built it as many separate columns poured in thin layers, cooled with water (and then chilled water) running through embedded steel pipes, and filled the gaps with grout once it had shrunk.
6. $P = 1,000 \times 9.8 \times 50 \times 80 = 39,200,000 \text{ W}$ (39.2 MW). $\times 0.90 \approx 35.3 \text{ MW}$.
7. Water pressure increases with depth ($p = \rho gh$), so the push on the dam is greatest at the bottom.
8. Screens (trash and rags); grit chambers (sand and gravel); primary clarifier (settling solids and floating grease); aeration basin with activated sludge (microbes eat dissolved pollution); secondary clarifier (microbes settle and are returned); disinfection (destroys remaining germs).
9. That returning the settled sludge from aeration to the next batch made cleaning much faster, because the sludge was full of microbes already adapted to eating sewage.
10. $\lambda = c \div f = 300,000,000 \div 1,000,000 = 300 \text{ m}$.
11. A region is divided into small cells, each with low-power antennas; neighboring cells use different frequencies and the same frequencies are reused in distant cells, so many calls share the limited frequencies; phones are handed from cell to cell as they move. A closed metal tin is a Faraday cage: the radio waves move the electrons in the metal, which rearrange to cancel the field inside, so the waves cannot get in.

PORTFOLIO PIECE: A UTILITY ENGINEER'S REPORT

Choose one utility that serves your home: electricity, water, wastewater or communications. Find out (with a parent, from the utility's website or a public tour) where it comes from or goes to, and draw a labeled map or flow diagram of the whole system from source to your house or from your house to the river. Include at least two calculations with real or reasonable numbers (for example, your family's daily water use in cubic meters, the power lost on a line, or the wavelength of your nearest radio station). Then build and test one small model from this unit that shows a key part of the system, and write a one-page report that ends with a thank-you note to the people who keep that system running.

LOOK FOR	WHAT IT MEANS
System diagram	Complete, labeled diagram of the utility from source to home or from home to the environment.
Calculations	At least two calculations, each with the formula, numbers with units and a sensible answer.
Model and test	A working model from this unit, tested fairly, with results recorded.
Explanation	Explains the physics of the system in the student's own words, including one trade-off engineers must make.
Service	The report recognizes the workers and engineers who keep the system safe and running.

SHIPS

Naval architects, the engineers who design ships, must answer two questions before any others: will it float, and will it stay upright? In this unit you will learn the answer to the second question with the same ideas naval architects use, the center of gravity, the center of buoyancy and the metacenter, and you will measure the stability of your own model with a real inclining experiment.

Then you will follow ships from wood to iron with Isambard Kingdom Brunel's gigantic *Great Eastern*, watch the Panama Canal lift ships 26 meters over a mountain range using nothing but gravity, and see how one trucker's idea, the steel shipping container, changed the way the whole world moves its goods.

PREREQUISITES

- Knows Archimedes' principle and density (Grades 5–6)
- Can find a center of gravity by balancing
- Can calculate volume and use a ratio

MASTERY CHECKLIST

- ☐ I can explain how the center of gravity, the center of buoyancy and the metacenter decide whether a ship is stable.
- ☐ I can carry out an inclining experiment and calculate a metacentric height.
- ☐ I can explain how an iron ship floats and how watertight compartments protect it.
- ☐ I can explain how canal locks raise and lower ships using gravity, and calculate the water a lock uses.
- ☐ I can explain how containerization changed shipping and how a ship must be loaded to stay stable.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Eureka and Tinker crates:** Ages vary by crate (Tinker 9–16, Eureka 14 and up). Some crates build boats, hydraulic machines and models with clear engineering notes; check the current list for a boat or water project.

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 Naval Architecture: The Metacenter and the Inclining Experiment

2 sessions of 50–60 minutes

6.2 Iron Ships and Brunel’s Great Eastern

2 sessions of 50–60 minutes

6.3 The Panama Canal: Lifting Ships over a Mountain Range

2 sessions of 50–60 minutes

6.4 Container Ships and Ports: Malcom McLean’s Steel Box

2 sessions of 50–60 minutes

UNIT 6 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Define the center of gravity (G), the center of buoyancy (B) and the metacenter (M) of a ship.

2. **8 pts**

Why does a ship capsize if its center of gravity rises above its metacenter?

3. **10 pts**

Calculation: In an inclining experiment, 10 tonnes is moved 8 m across the deck of a 4,000-tonne ship, and it heels 1° ($\tan 1^\circ \approx 0.0175$). Find GM.

4. (8 pts)

Who introduced the metacenter, and in what book?

5. (8 pts)

Iron is denser than water. How can an iron ship float?

6. (10 pts)

Calculation: A box-shaped barge is 12 m long, 5 m wide and 2 m deep and has a mass of 30 tonnes. How much cargo can it carry before the water reaches the deck edge in fresh water (1 tonne per m^3)?

7. (8 pts)

Name two features of the *Great Eastern* that made it safer than other ships of its time, and what happened when it struck a rock in 1862.

8. (10 pts)

Explain how a lock raises a ship from a lower level to a higher level without pumps.

9. (10 pts)

Calculation: A lock chamber is 300 m long and 30 m wide. How much water does it take to raise a ship 9 m? Give the answer in m^3 and in liters.

10. (8 pts)

Give two reasons the shipping container made shipping cheaper.

11. (12 pts)

Written answer: Explain how you would load heavy and light containers on a ship to keep it stable and level, and what can go wrong if you do not.

ANSWER KEY

1. G: the point where the ship's whole weight acts. B: the center of the underwater volume, where buoyancy acts. M: where the line of buoyancy crosses the centerline when the ship heels slightly.
2. When the ship heels, weight (down through G) and buoyancy (up through the moved B) then form a turning pair that rolls the ship farther over instead of back upright.
3. $GM = (w \times d) \div (W \times \tan \theta) = (10 \times 8) \div (4,000 \times 0.0175) = 80 \div 70 \approx 1.14 \text{ m}.$
4. Pierre Bouguer, in *Traité du navire* (1746).
5. The hull is shaped to enclose a large volume of air, so its average density is less than water's; it displaces a weight of water equal to its own weight before it is submerged.
6. Volume = $12 \times 5 \times 2 = 120 \text{ m}^3$, so it can displace 120 tonnes. Cargo = $120 - 30 = 90$ tonnes (in practice less, to keep freeboard).
7. A double iron hull and watertight bulkheads (also its iron box-girder structure). When it tore an 83-foot gash in its outer hull, the inner hull held and the ship reached port safely.
8. The ship enters the chamber and the lower gates close. Valves open culverts that let water flow by gravity from the higher level into the chamber. The water and ship rise until the levels match; then the upper gates open and the ship moves on.
9. $300 \times 30 \times 9 = 81,000 \text{ m}^3 = 81,000,000 \text{ liters}.$
10. Any two: goods are not handled piece by piece; cranes load ships in hours instead of days; the same box moves by ship, train and truck; less theft and damage; ships spend more time at sea and less in port.
11. Put heavy containers low and near the middle, light ones high; balance the weight side to side and end to end; follow the order of ports. If heavy ones are high, G rises and the ship may roll dangerously or capsize; if weight is unbalanced, the ship heels or trims, which can overload parts of the hull or let water over the deck.

PORTFOLIO PIECE: A STABLE, TESTED CARGO SHIP

Design and build a model cargo ship (from foam, plastic or a carton) to carry at least 500 grams of cargo. Before testing, calculate its maximum load from its dimensions and mass. Fit it with a mast and pendulum and carry out an inclining experiment to find GM, empty and loaded. Then write a stowage plan, load it, and measure its draft, trim and heel. Write a one-page naval architect's report with your drawings, calculations, data and one improvement you made.

LOOK FOR	WHAT IT MEANS
Design and drawings	Profile and cross-section drawings with dimensions, waterline and freeboard marked.
Capacity prediction	Maximum load calculated from volume and mass, then compared with the test.
Inclining experiment	GM measured correctly with the formula, empty and loaded, with units.
Loading plan	A clear stowage plan that keeps heavy cargo low and balanced; draft, trim and heel recorded.
Improvement	One specific change made and tested, with honest results.

6.1 NAVAL ARCHITECTURE: THE METACENTER AND THE INCLINING EXPERIMENT

OBJECTIVES

- Explain the center of gravity, the center of buoyancy and the metacenter.
- Explain why a ship with a high center of gravity can capsize.
- Carry out an inclining experiment on a model and calculate its metacentric height.

Warm-up. Float an empty plastic food container in a sink and push down on one edge, then let go. Now stack a few coins in a tall pile on the middle of its floor and try again. Then tape the same coins flat along the bottom. Which way is the boat most stable, and why do you think so?

WATCH

WHY DON'T CRUISE SHIPS TIP OVER? | An introduction to ship stability.

Casual Navigation · 5:41

https://www.youtube.com/watch?v=DPV_VjzU9kE

WHEN TO WATCH

After the physics paragraph. Pause on each diagram and find G, B and M.

KEY TERMS

center of gravity (G)

The point where the whole weight of the ship and its cargo can be thought of as acting, straight down.

metacenter (M)

The point where the line of the buoyant force crosses the ship's centerline when the ship heels slightly. A ship is stable if M is above G.

center of buoyancy (B)

The center of the underwater volume of the hull, where the upward buoyant force acts.

metacentric height (GM)

The distance from G up to M. A larger GM means a stiffer ship that rights itself more strongly.

righting moment

The turning effect of weight and buoyancy that pushes a heeled ship back upright.

heel

A sideways tilt of a ship.

CORE IDEAS

The story. For thousands of years, shipbuilders learned what made a ship stable by experience, and some lessons were costly: in 1628 the Swedish warship *Vasa*, built too tall and too narrow, capsized on its first voyage. The first person to put ship stability on a mathematical footing was the French scientist Pierre Bouguer. He spent nearly ten years in the Andes of Peru on an expedition to measure the shape of the Earth, and there, far from any ocean, he wrote his great book on ships. *Traité du navire*, published in 1746, introduced the **metacenter** and showed how to calculate, from a ship's drawings, whether it would stand upright.

How they figured it out. Bouguer imagined a ship heeled over by a small angle. The weight still acts straight down through the center of gravity, G. But the shape of the underwater part of the hull has changed: more of it is now on the low side, so the center of buoyancy, B, moves toward the low side. The buoyant force acts straight up through the new B. Bouguer saw that the line of that force crosses the ship's centerline at a point he called the metacenter, M. If M is above G, the pair of forces twists the ship back upright. If G is above M, the same forces roll it farther over. Later engineers found a simple way to measure this on a real ship: the **inclining experiment**, in which known weights are moved across the deck and the angle of heel is measured with a long pendulum.

The physics. When a weight w is moved a distance d across the deck of a ship that weighs W , the ship heels to an angle θ , and $GM = (w \times d) \div (W \times \tan \theta)$. Here is a worked example. A 10,000-tonne ship has 20 tonnes of weights moved 10 m across its deck, and it heels 2° . Since $\tan 2^\circ \approx 0.035$, $GM = (20 \times 10) \div (10,000 \times 0.035) \approx 0.57$ m. Naval architects want GM to be positive and comfortable: too small and the ship can capsize; too large and it snaps back so quickly that the rolling is violent for crew and cargo. A wide hull raises M; heavy weights placed low lower G. Both increase GM.

The engineering. Every new ship has an inclining experiment before it enters service, and the result is used to check every loading plan for the rest of its life. Naval architects calculate stability for every condition: full and empty, with fuel

tanks half full (liquid sloshing in a tank raises the effective G), with ice on the decks, and with water in a damaged compartment. Ships carry heavy machinery low in the hull and may pump seawater into ballast tanks to keep G low when they are lightly loaded. Officers on board run stability calculations, now on computers, before every voyage, because the sea will test them.

PICTURE STUDY



Title Engraving of Bouguer's Traité du navire, Pierre-Quentin Chedel (engraver), 1746 · Engraving · From Pierre Bouguer, Traité du navire, Paris
Image: [Wikimedia Commons](#), public domain

This engraving opens Bouguer's book on the ship, its construction and its motions. It shows a hull being built in a shipyard. Bouguer showed that, from the drawings of a hull like this one, an engineer could calculate where the metacenter would be before the ship was launched.

Look closely

- Find the hull on the building stocks. Can you see its ribs (frames)?
- Find the workers and their tools.
- Find the crane and the ships at sea in the distance.
- Read the title. What three things did Bouguer promise to explain?

Talk about it

1. Why is it better to find the metacenter on paper than by launching the ship and seeing whether it tips?
2. How might the shape of the hull being built here affect its stability?
3. Why would shipbuilders in 1746 welcome a mathematical method?

Safety first. An adult should be present whenever you work with a tub or sink full of water. Wipe up spills so no one slips.

BUILD

An Inclining Experiment on a Model Ship

You will build a model ship from a plastic container or a foam block, fit it with a mast and a pendulum to measure heel, and carry out a real inclining experiment: move a known weight across the deck, measure the angle, and calculate the metacentric height. Then you will raise the center of gravity and see GM shrink, and find the point where the model capsizes.

You will need

- A rectangular plastic food container about 20 cm × 12 cm, or a block of foam the same size
- A wooden skewer for a mast, modeling clay, and a piece of thread with a small bead for a pendulum
- A protractor taped to the mast, or a paper scale marked in degrees
- Weights: 10 pennies in a small bag (25 g) to move across the deck, and extra pennies or clay for ballast
- A kitchen scale, a ruler, a tub or sink of water, and a calculator with a tan button (or a table of tangents)

Steps

1. Fix the mast upright in the middle of the model with clay. Hang the pendulum from the top of the mast so it hangs in front of the protractor scale.
2. Add pennies as ballast, spread evenly and low, until the model floats level with a few centimeters of freeboard. Weigh the whole model with the moving weight on board: this is W .
3. **Inclining experiment.** Put the 25 g bag on the centerline. Then move it to a point $d = 5$ cm toward one side, let the model settle, and read the heel angle θ . Move it 5 cm to the other side and read again. Average the two angles.
4. Calculate $GM = (w \times d) \div (W \times \tan \theta)$. Use grams for both weights and centimeters for d , so GM comes out in centimeters.
5. **Predict.** If you move 50 g of ballast from the bottom to the top of the mast, will GM grow or shrink? Will the angle for the same weight shift be larger or

smaller?

6. **Test.** Move the ballast up in three steps (bottom, middle of mast, top of mast). At each step repeat the inclining experiment and calculate GM.
7. Graph GM against the height of the ballast. Extend the line: at what height would GM reach zero? Test it carefully. Does the model capsize near there?
8. **Improve.** Keep the ballast high but change one thing about the hull to make it stable again (for example, widen it by taping on side floats). Measure GM again.

Tips

- Make every angle reading with the model at rest; wait for the rocking to stop.
- Small angles are hard to read; a longer pendulum gives a bigger scale.
- If your model heels before you move the weight, adjust the ballast until it floats level.

Check your work

- ☐ I can explain where G, B and M are on a floating ship.
- ☐ I can calculate a metacentric height from an inclining experiment.
- ☐ I can explain why raising the center of gravity makes a ship less stable.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of your model upright and heeled. Mark G, B (in both positions) and M, and draw arrows for weight and buoyancy.
2. Make a table of ballast height, heel angle and GM, and a graph of GM against ballast height.
3. A 5,000-tonne ship heels 1.5° ($\tan 1.5^\circ \approx 0.026$) when 15 tonnes is moved 12 m across the deck. Calculate GM.

From history. Bouguer also invented the heliometer for measuring the sizes of the Sun and planets and was a founder of photometry, the measurement of light. His expedition partner, Charles-Marie de La Condamine, brought back the first scientific report of rubber to Europe.

COMMON MISTAKES

- Mixing units: weights must both be in grams (or both in tonnes), and the answer comes out in the units of d.

- Reading the angle while the model is still rocking.
- Thinking a wider ship is always better. Too much stiffness makes a violent roll.

Make it a game • Metacenter Argument. Draw a ship on paper and mark G, B and M. Your parent asks, "Will it capsize if I lift the cargo high?" Predict and explain with righting moment and metacentric height. Then check using a toy boat in a basin with weight placed high and low. Best prediction accuracy wins.

Scripture. “And this is the fashion which thou shalt make it of: The length of the ark shall be three hundred cubits, the breadth of it fifty cubits, and the height of it thirty cubits.” (Genesis 6:15, KJV)

The ark’s length was six times its breadth and ten times its height, proportions well suited to a vessel built to float steadily and carry a heavy load rather than to sail fast.

6.2 IRON SHIPS AND BRUNEL'S GREAT EASTERN

OBJECTIVES

- Explain how a ship made of iron, which is denser than water, can float.
- Describe the engineering of Brunel's *Great Eastern*: its size, iron double hull and watertight bulkheads.
- Predict a model hull's load capacity from its dimensions, test it, and test how compartments protect it after damage.

Warm-up. Drop a steel paper clip and a steel jar lid into a bowl of water. One sinks and one may float. Both are made of steel. Write a sentence explaining the difference using the word “displace.”

WATCH

Great Eastern: Isambard Kingdom Brunel's Great Babe

The Great Big Move • 12:40

<https://www.youtube.com/watch?v=koP2Pv39mdc>

WHEN TO WATCH

After the story paragraph.

BACKUP VIDEO

Isambard Kingdom Brunel's 'Great Eastern'

Royal Museums Greenwich • 2:05

<https://www.youtube.com/watch?v=maAbHKjErL4>

Optional: Royal Museums Greenwich on the *Great Eastern*.

KEY TERMS

displacement

The weight of water a floating ship pushes aside, which equals the ship's whole weight. Also used to mean the ship's weight itself.

average density

The total mass of the ship and everything in it divided by its total volume, including the air inside. A ship floats if its average density is less than the water's.

bulkhead

A wall across the inside of a hull. A watertight bulkhead divides the hull into compartments so one leak cannot flood the whole ship.

double hull

A hull with an inner and an outer skin, so a hole in the outer skin need not let water inside the ship.

freeboard

The height of the hull above the waterline.

CORE IDEAS

The story. Isambard Kingdom Brunel was the most daring engineer of Victorian Britain. He built the Great Western Railway, then decided the line should continue across the Atlantic by steamship, and built the wooden paddle steamer *Great Western* (1838) and the iron, propeller-driven *Great Britain* (1843). His last ship was the biggest of all. The *Great Eastern*, begun in 1854 on the River Thames, was designed to carry 4,000 passengers all the way to Australia without stopping for coal. It was 692 feet (211 meters) long, nearly six times the tonnage of any ship afloat, and no larger ship was built for forty years. It was so big it had to be built sideways along the river bank and launched sideways. The first attempt, in November 1857, moved it only a few feet. Brunel needed hydraulic rams and three months of effort before it floated on January 31, 1858.

How they figured it out. Brunel and the shipbuilder John Scott Russell knew that a wooden ship that long would sag and break, so they built the hull of wrought-iron plates like a giant box girder, with long iron members running from bow to stern for strength. They gave it a double iron hull up to above the waterline and divided it with watertight bulkheads, ideas far ahead of their time. In 1862 the *Great Eastern* struck an uncharted rock off Long Island and tore a gash in its outer hull about 83 feet long; the inner hull held, and the ship reached port safely. It never made money as a passenger liner, but in 1866 it laid the first lasting telegraph cable across the Atlantic, because it was the only ship big enough to carry the whole cable.

The physics. Iron is about 7.8 times as dense as water, so a solid lump sinks. But a ship is mostly air. Archimedes' principle says the buoyant force equals the weight of the water displaced. A hull shaped like a box 10 m long, 4 m wide and 2 m deep can displace up to $10 \times 4 \times 2 = 80 \text{ m}^3$ of water, which weighs 80 tonnes (fresh water is 1

tonne per cubic meter). If the hull itself has a mass of 15 tonnes, it can carry up to about $80 - 15 = 65$ tonnes before the water reaches the top edge. In practice it must keep plenty of freeboard, so it carries less. A watertight compartment works because a flooded compartment only removes the buoyancy of that one part; the rest of the hull can still hold the ship up.

The engineering. Iron, and later steel, let ships become far larger, stronger and longer-lived than wooden ones, and they did not rot or leak at the seams. But iron brought new problems: rust, fouling by marine growth, and compasses thrown off by the iron hull, which had to be corrected with magnets. The lessons of the *Great Eastern's* double hull were slowly forgotten and then painfully relearned. After the *Titanic* in 1912, international rules required more watertight subdivision; after a series of oil-tanker spills, new tankers were required to have double hulls.

PICTURE STUDY



Brunel and the Launching Chains of the Great Eastern, Robert Howlett, 1857 · Albumen photograph · Metropolitan Museum of Art, New York (other prints in British collections)

Image: [Wikimedia Commons](#), public domain

This is one of the most famous photographs of an engineer ever taken. Robert Howlett photographed Brunel in front of the giant chains that controlled the *Great Eastern's* sideways launch.

Look closely

- Look at the size of the chain links compared with Brunel.
- Find the drum the chains are wrapped around.
- Look at Brunel's clothes and boots. Are they clean?
- Look at his face and stance. What does he seem to be thinking?

Talk about it

1. Why would the launching of such a heavy ship need huge chains to control it, not just to pull it?
2. What can you tell about the forces involved from the size of the links?
3. Why do you think this photograph became a symbol of the engineer?

Safety first. An adult should be present whenever you work with a tub of water. An adult makes any cuts in plastic containers with a craft knife.

BUILD

Predict, Load and Puncture: Compartments in a Model Hull

You will build two identical model hulls, one open and one divided into three watertight compartments. First you will predict each hull's maximum load from its dimensions and test it. Then you will punch a hole in one compartment of each and see how much load each can still carry.

You will need

- Two identical half-gallon milk or juice cartons, cut in half lengthwise (an adult cuts), or two identical rectangular foil pans
- Modeling clay to make bulkheads, and waterproof tape
- A ruler, kitchen scale, pennies (2.5 g each) or small bags of rice, and a tub of water
- A nail or pencil to punch holes (adult)

Steps

1. Measure the inside length, width and depth of one hull in centimeters. Calculate its volume in cm^3 . Weigh the hull in grams.
2. **Predict.** Maximum load (g) = volume (cm^3) $\times$ 1 g/ cm^3 – hull mass (g). Then decide a safe working load that leaves 1 cm of freeboard, and calculate it.
3. In the second hull, build two watertight clay bulkheads to make three equal compartments. Weigh it again.
4. **Test.** Float the open hull and add pennies evenly until the water reaches 1 cm below the rim. Weigh the load. Then add more until it sinks, and record the maximum. Repeat with the compartment hull.
5. Compare the measured maximum loads with your prediction.
6. **Damage test.** Punch a hole in the bottom at one end of each hull (in one compartment of the divided hull). Float each with your safe working load, spread evenly, and observe for two minutes. Record what happens.
7. Remove pennies from the damaged divided hull until it floats with 0.5 cm of freeboard at its lowest point. How much load can it still carry? How does it trim (tilt end to end)?

8. **Improve.** Add a double bottom: line one hull with a second skin of foil or plastic and tape it watertight. Punch the outer skin only. What happens?

Tips

- Spread the load evenly or the hull will tip before it fills.
- Clay bulkheads leak where they meet the hull; press them in firmly and seal with tape.
- Watch the trim: a flooded end makes the whole ship tip down at that end.

Check your work

- ☐ I can predict a hull's load capacity from its volume and mass.
- ☐ I can explain why watertight compartments help after damage.
- ☐ I can explain why an iron ship floats.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of the *Great Eastern's* double hull and a plan view showing the bulkheads.
2. Make a table of predicted and measured loads for both hulls, before and after damage.
3. A steel barge is a box 20 m long, 6 m wide and 3 m deep, with a mass of 60 tonnes. How much cargo could it carry in fresh water before the water reached the deck edge? If it must keep 0.5 m of freeboard, how much can it carry?

From history. Brunel suffered a stroke on board the *Great Eastern* just before its first voyage in 1859 and died a few days later, aged 53. The ship outlived its designer by thirty years and was finally broken up in 1889–90.

COMMON MISTAKES

- Forgetting to subtract the hull's own mass.
- Measuring the outside of the hull instead of the inside for volume, or vice versa without thinking about which matters.
- Thinking more compartments make a ship unsinkable. They help, but enough damage can still sink it.

Make it a game • Iron Can Float. Predict how many pennies a foil boat holds, then calculate average density from mass and volume. Add a bulkhead and puncture a compartment while your parent watches. Say how the Great Eastern's double hull and bulkheads mattered. Closest prediction wins. Explain why iron floats when shaped into a hull.

6.3 THE PANAMA CANAL: LIFTING SHIPS OVER A MOUNTAIN RANGE

OBJECTIVES

- Explain how canal locks raise and lower ships using only gravity.
- Calculate the volume of water a lock uses and estimate a filling time.
- Build a model lock and test how the size of the valve changes the filling time.

Warm-up. Fill a bowl with water and float a small toy boat in it. Lower an empty, larger tub next to it. Without lifting the boat, how could you get it from the bowl to the tub if both were connected by a short channel? Sketch your idea.

WATCH

The Surprising Efficiency of Canal Locks

Practical Engineering · 10:37

<https://www.youtube.com/watch?v=SBvclVcesEE>

WHEN TO WATCH

After the physics paragraph.

BACKUP VIDEO

How Does the Panama Canal Work?

The Panama Canal · 1:03

<https://www.youtube.com/watch?v=hoQ7RHyG-EA>

Optional: a one-minute animation from the Panama Canal itself.

KEY TERMS

lock

A chamber with gates at each end, used to raise or lower boats from one water level to another.

culvert

A large tunnel in the lock walls that carries water into or out of the chamber.

miter gates

Pairs of gates that close at an angle, like a V pointing upstream, so the water pressure pushes them tightly shut.

head

The difference in water height between two levels; it sets the pressure and the speed of the flowing water.

Gatun Lake

The large artificial lake, 26 meters above the sea, made by damming the Chagres River; ships cross Panama on it.

CORE IDEAS

The story. For centuries, ships sailing between the Atlantic and the Pacific had to go all the way around South America. In 1881 a French company led by Ferdinand de Lesseps, who had built the Suez Canal, began digging a sea-level canal across Panama. It failed. The mountains were higher, the rock and clay slid back into the cuts, the Chagres River flooded, and tropical diseases took the lives of an estimated 22,000 workers. In 1904 the United States took over. Its engineers made two decisions that changed everything. Chief engineer John Stevens convinced the government to build a canal with locks rather than at sea level, and Dr. William Gorgas showed that controlling mosquitoes would stop yellow fever and malaria. Colonel George Goethals, an Army engineer, led the work to completion, and the canal opened on August 15, 1914.

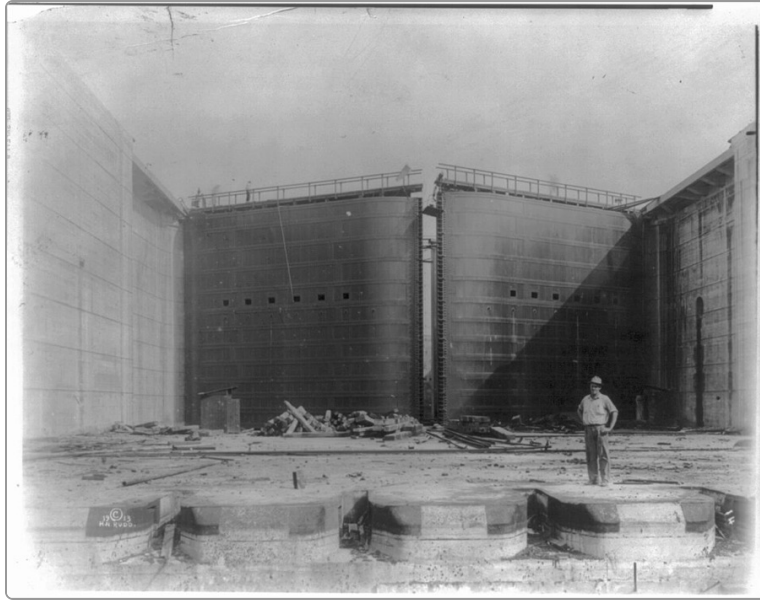
How they figured it out. Instead of digging the whole isthmus down to sea level, the engineers dammed the Chagres River at Gatun to make a huge lake 26 meters above the sea and used locks to lift ships up to it and down again. That turned the floods that had defeated the French into the canal's water supply. Through the mountain at the Culebra Cut, steam shovels and trains of dirt cars removed millions of cubic meters of rock and earth, and engineers kept adjusting the slopes as slides came down. The locks were among the largest concrete structures ever built: each chamber is 1,000 feet (305 m) long and 110 feet (33.5 m) wide, with steel miter gates 7 feet thick.

The physics. The locks need no pumps. To raise a ship, the gates behind it close and valves open in huge culverts, 18 feet across, that let water flow downhill from the

higher level into the chamber through holes in its floor. The water level and the ship rise together until they match the next level; then the front gates open. To lower a ship, water flows out to the lower level. Water flows faster when the head is greater, so a chamber fills quickly at first and more slowly as the levels approach each other. Each step uses a lot of water: a chamber 305 m long, 33.5 m wide, filled 8.5 m deeper, holds $305 \times 33.5 \times 8.5 \approx 86,800 \text{ m}^3$, about 87 million liters. That water comes from Gatun Lake and ends up in the sea, so the canal depends on rain.

The engineering. Lock engineering is about controlling enormous forces gently. The miter gates are hollow and partly buoyant, so their hinges do not carry their full weight, and they close in a V so the water pressure seals them. Electric locomotives on the lock walls hold each ship centered with steel cables. The whole system was designed with duplicate locks side by side, so ships can pass in both directions, and spare gates so one can be repaired. In 2016 a third, larger set of locks opened, with water-saving basins beside each chamber that reuse about 60% of the water, because fresh water from the lake is precious.

PICTURE STUDY



Building a Lock of the Panama Canal, Unknown photographer, 1913 · Photograph · Library of Congress, Prints and Photographs Division

Image: [Wikimedia Commons](#), public domain

This photograph was taken from the floor of a lock chamber before it was filled with water. The tiny figures of workers show how vast the locks are.

Look closely

- Find the lock gates at the far end. How many leaves do they have, and how do they meet?
- Look at the walls. Can you find any openings where water could enter the chamber?
- Find the workers. Use them to estimate the height of the walls.
- Look for cranes or scaffolding used to build the gates.

Talk about it

1. Why do the gates close in a V shape pointing toward the higher water?
2. Why are the lock walls so thick at the bottom?
3. How does water get into this chamber without any pumps?

Safety first. Do the build over a sink, tub or outdoors. Never play near real canals, locks or spillways: the water moves fast and walls are steep.

BUILD

A Model Canal Lock

You will build a model lock from three containers at different heights, connected by tubes with clamps as valves. You will raise and lower a small boat, measure how long each step takes, and test how the valve size changes the filling time.

You will need

- Three clear plastic containers or the bottoms of large bottles (upper level, lock chamber, lower level), set on stacks of books at three heights
- Clear plastic tubing in two sizes (for example 6 mm and 10 mm inside diameter), each about 30 cm long, and binder clips or clothespins as valves
- Modeling clay to seal the tubes into holes near the bottom of each container (an adult makes the holes)
- A small boat (a bottle cap or foil boat), a ruler, a stopwatch and a measuring cup

Steps

1. Set the upper container about 8 cm higher than the lock chamber and the chamber 8 cm higher than the lower container. Connect upper to chamber and chamber to lower with the 6 mm tubes, sealed with clay. Clamp both tubes shut.
2. Fill the upper container. Put a little water and the boat in the chamber.
3. **Calculate.** Measure the chamber's inside length and width. Calculate how many milliliters it takes to raise the level by 5 cm ($1 \text{ cm}^3 = 1 \text{ mL}$).
4. **Raise the boat.** Open the upper valve and time how long the chamber takes to rise 5 cm. Record the level every 10 seconds. Is the rise steady, or does it slow down?
5. **Lower the boat.** Close the upper valve, open the lower one and time how long it takes to fall back.

6. **Fair test.** Replace the tubes with the 10 mm tubes, change nothing else, and repeat. Then try a smaller head difference (4 cm). Repeat each trial three times.
7. Graph water level against time for each trial.
8. **Improve.** Real canals save water with side basins. Add a fourth container beside the lock at a middle height. Before emptying the lock to the lower level, drain half into the side basin; next time, fill from the basin first. How much water from the upper level did you save?

Tips

- Keep the upper container topped up to the same mark at the start of each trial.
- Mark the chamber's side with a ruler scale in centimeters.
- Air bubbles in the tube slow the flow; fill the tubes with water before starting.

Check your work

- ☐ I can explain how a lock raises a ship with no pumps.
- ☐ I can calculate the volume of water a lock uses.
- ☐ I can explain why the chamber fills more slowly near the end.

ENGINEER'S NOTEBOOK

1. Draw the Panama Canal in profile from the Atlantic to the Pacific, showing Gatun Locks, Gatun Lake, the Culebra Cut, Pedro Miguel Locks and Miraflores Locks, with heights.
2. Make graphs of level against time for each trial and a table of filling times.
3. A lock chamber is 200 m long and 25 m wide. How many cubic meters of water does it use to raise a boat 6 m? How many liters?

From history. Dr. William Gorgas's mosquito-control work in Panama eliminated yellow fever from the Canal Zone by 1906 and greatly reduced malaria. It was one of the greatest public-health achievements of its time, and without it the canal could not have been built.

COMMON MISTAKES

- Thinking locks use pumps to lift ships.

- Forgetting that the flow slows as the levels get closer.
- Changing the tube size and the head at the same time.

Make it a game • Lock Fill Estimate. Your parent names a lock size, such as 100 m long, 20 m wide and a 10 m lift. Calculate the volume of water in cubic meters. Then estimate how long a culvert flowing at 50 cubic meters per second takes to fill it. Do three problems. Explain miter gates and why gravity does the work.

6.4 CONTAINER SHIPS AND PORTS: MALCOM MCLEAN'S STEEL BOX

OBJECTIVES

- Explain how the shipping container changed the cost and speed of moving goods.
- Explain how a container ship must be loaded to stay stable and level (trim and heel).
- Plan and test the loading of a model container ship.

Warm-up. Look at the label on something in your home that came from overseas (a toy, shoes, a kitchen tool). Where was it made? Write down how many kilometers you think it traveled and how you think it got to your town.

WATCH

How a Steel Box Changed the World: A Brief History of Shipping

The Wall Street Journal · 4:06

<https://www.youtube.com/watch?v=0MUkgDIQdcM>

WHEN TO WATCH

After the story paragraph.

BACKUP VIDEO

Container port animation - how a shipping container port works - logistics training

Train Learn Grow · 4:45

<https://www.youtube.com/watch?v=DQM-4yZVe0c>

Before the build: an animation of how a container port works.

KEY TERMS

shipping container

A standard steel box, 8 feet wide and usually 20 or 40 feet long, that can be moved by ship, train and truck without unpacking.

TEU

Twenty-foot equivalent unit: one 20-foot container. A ship's size is often given in TEUs.

break-bulk cargo

Goods loaded piece by piece in bags, barrels and crates, as all cargo was before containers.

trim

The difference between a ship's draft at the bow and at the stern; a ship is "trimmed by the stern" if the stern sits deeper.

stowage plan

The plan that says where every container goes on a ship, with heavy ones low and the weight balanced.

twistlock

A locking device that fits into the corner castings of containers to fasten them to each other and to the ship.

CORE IDEAS

The story. Malcom McLean grew up in North Carolina and started a trucking business in the 1930s with one used truck. Waiting for hours at the docks while longshoremen unloaded his truck crate by crate onto a ship, he wondered why the whole trailer box could not simply be lifted aboard. In 1956 he bought an old tanker, the *Ideal X*, and fitted it with a deck to carry boxes. On April 26, 1956, cranes lifted 58 steel containers aboard at Port Newark, New Jersey, and the ship sailed to Houston, Texas, where trucks drove the same boxes away. McLean later calculated that loading the *Ideal X* cost about 16 cents a ton, compared with nearly \$6 a ton for ordinary cargo.

How they figured it out. The idea only worked if every box was the same and every crane, ship, truck and train could handle it. McLean's engineer, Keith Tantlinger, designed strong containers with steel corner fittings and a twistlock that could fasten boxes together and lock them to trucks and ships. Tantlinger's designs were released for others to use, and in the 1960s international standards set the sizes we use today. Ports built huge gantry cranes and wide, paved yards, and ships were designed with cell guides in their holds so containers slid into place. A ship that had taken a week to unload could be turned around in a day.

The physics. A container ship is a stability problem stacked many stories high. Every container's weight raises or lowers the center of gravity, G , depending on where it sits, and tilts the ship if the weight is not balanced. Moving a weight across the ship causes heel; moving it lengthwise causes trim. The heel angle can be found from the inclining formula you used in Lesson 6.1, rearranged: $\tan \theta = (w \times d) \div (W \times GM)$. Placing a 30-tonne container 15 m off center on a 60,000-tonne ship with $GM = 1.5$ m

gives $\tan \theta = (30 \times 15) \div (60,000 \times 1.5) = 0.005$, a heel of about 0.3° . Small, but hundreds of containers add up. So heavy containers go low and toward the middle, and the plan is balanced side to side and end to end.

The engineering. Today the largest container ships carry more than 24,000 TEU. Computer programs prepare the stowage plan, checking stability, the strength of the hull, the weight on each stack and the order in which containers will be unloaded at each port. Containers are lashed with steel rods and twistlocks to survive storms, and ships pump water between ballast tanks to correct heel and trim as they are loaded. Ports run around the clock with cranes, straddle carriers and, at some ports, self-driving vehicles. Because shipping is so cheap per item, a pair of shoes can cross an ocean for less than a dollar of freight cost.

PICTURE STUDY



The Coalmen (Men Unloading Coal), Claude Monet, 1875 · Oil on canvas · Musée d'Orsay, Paris

Image: [Wikimedia Commons](#), public domain

Before containers, almost every cargo was loaded and unloaded by hand, one bag, basket or crate at a time. Monet painted these men carrying coal off barges on the Seine near Paris. Look at how much human work each ton of cargo took.

Look closely

- Follow the line of men on the planks. How is each one carrying his load?
- Find the barges. Where are they in relation to the shore?
- Find the bridge in the background. Why might barges be unloaded here?
- Look at the color and light. What time of day and weather does Monet show?

Talk about it

1. How many trips do you think it took to unload one barge? How long might that take?
2. How would containers and cranes change this scene?
3. What did the container mean for dockworkers, and for the price of the things families buy?

Safety first. An adult should be present when using a tub of water. Keep small blocks and coins away from small children.

BUILD

Loading a Model Container Ship

You will load a model barge with “containers” of different weights following different stowage plans, and measure the heel, the trim and the stability. You will find the plan that carries the most cargo safely and level.

You will need

- A rectangular foam tray, a shallow plastic food container or a piece of thick foam board about 30 cm × 15 cm as the hull
- At least 16 identical small boxes or blocks as containers (dominoes, matchboxes or wooden blocks), some weighted with pennies taped inside to make “heavy” (about 25 g), the rest “light” (about 5 g)
- A ruler taped upright at the bow and the stern to read the draft, a protractor and pendulum or a phone level app
- A tub of water, a kitchen scale, paper for stowage plans

Steps

1. Draw a deck grid on paper: 4 rows across and 4 rows lengthwise per layer. Weigh every container and write its weight on it.
2. Float the empty hull and record the draft at bow and stern.
3. **Plan A.** Load all heavy containers on the top layer and light ones below. Record draft at bow and stern, the heel angle, and then push gently on one side and count how many seconds it takes to stop rocking.
4. **Plan B.** Load the heavy containers on the bottom layer, spread evenly. Record the same measurements.
5. **Plan C.** Load all heavy containers at one end. Measure the trim (stern draft – bow draft).
6. **Predict.** Before each new plan, write which will be most stable and level.
7. **Capacity test.** Using your best plan, keep adding layers until the freeboard is 1 cm or the ship becomes unstable. Record the maximum number of containers.

8. **Improve.** Fix Plan C without moving any containers by adding “ballast” (pennies) to one end of the hull. How much ballast did you need?

Tips

- Load one container at a time, alternating sides, or the hull may tip during loading, as real ships can.
- Read the draft with your eye level with the water surface.
- Stability can be judged by how quickly and smoothly the model returns upright after a push.

Check your work

- ☐ I can explain heel and trim and measure both.
- ☐ I can explain why heavy containers go low and toward the center.
- ☐ I can explain how containers made shipping cheaper and faster.

ENGINEER'S NOTEBOOK

1. Draw your stowage plans A, B and C as grids, with heavy containers shaded, and record the measurements under each.
2. Make a table comparing the plans: drafts, trim, heel and rocking time.
3. A 40,000-tonne ship with $GM = 1.2$ m has a 24-tonne container placed 10 m off its centerline. Calculate $\tan \theta$ and estimate the heel angle (for small angles, θ in degrees $\approx \tan \theta \times 57$).

From history. Within twenty-five years of the *Ideal X*, containers carried most of the world's manufactured goods. Many old harbor docks, where gangs of longshoremen once worked, were rebuilt as container terminals or turned into parks.

COMMON MISTAKES

- Loading all of one side first, which can tip the ship during loading.
- Ignoring trim; a ship can be level side to side but badly down at one end.
- Thinking only total weight matters. Where the weight sits matters as much.

Make it a game • Stowage Plan Puzzle. Use ten small boxes of different weights to load a toy ship in a tray of water. Make a stowage plan, explain trim and heel, and place them so the ship sits level. Your parent can swap one box and you must fix it. Add one fact about Malcom McLean's steel box.

Scripture. “They that go down to the sea in ships, that do business in great waters; These see the works of the LORD, and his wonders in the deep.” (Psalm 107:23-24, KJV)

Merchant sailors still “do business in great waters” every day, carrying the goods families use. Their work, and the engineering behind it, is part of how neighbors on opposite sides of the world serve one another.

SHIPS

Naval architects, the engineers who design ships, must answer two questions before any others: will it float, and will it stay upright? In this unit you will learn the answer to the second question with the same ideas naval architects use, the center of gravity, the center of buoyancy and the metacenter, and you will measure the stability of your own model with a real inclining experiment.

Then you will follow ships from wood to iron with Isambard Kingdom Brunel's gigantic *Great Eastern*, watch the Panama Canal lift ships 26 meters over a mountain range using nothing but gravity, and see how one trucker's idea, the steel shipping container, changed the way the whole world moves its goods.

PREREQUISITES

- Knows Archimedes' principle and density (Grades 5–6)
- Can find a center of gravity by balancing
- Can calculate volume and use a ratio

MASTERY CHECKLIST

- ☐ I can explain how the center of gravity, the center of buoyancy and the metacenter decide whether a ship is stable.
- ☐ I can carry out an inclining experiment and calculate a metacentric height.
- ☐ I can explain how an iron ship floats and how watertight compartments protect it.
- ☐ I can explain how canal locks raise and lower ships using gravity, and calculate the water a lock uses.
- ☐ I can explain how containerization changed shipping and how a ship must be loaded to stay stable.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Eureka and Tinker crates:** Ages vary by crate (Tinker 9–16, Eureka 14 and up). Some crates build boats, hydraulic machines and models with clear engineering notes; check the current list for a boat or water project.

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 Naval Architecture: The Metacenter and the Inclining Experiment

2 sessions of 50–60 minutes

6.2 Iron Ships and Brunel’s Great Eastern

2 sessions of 50–60 minutes

6.3 The Panama Canal: Lifting Ships over a Mountain Range

2 sessions of 50–60 minutes

6.4 Container Ships and Ports: Malcom McLean’s Steel Box

2 sessions of 50–60 minutes

UNIT 6 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Define the center of gravity (G), the center of buoyancy (B) and the metacenter (M) of a ship.

2. **8 pts**

Why does a ship capsize if its center of gravity rises above its metacenter?

3. **10 pts**

Calculation: In an inclining experiment, 10 tonnes is moved 8 m across the deck of a 4,000-tonne ship, and it heels 1° ($\tan 1^\circ \approx 0.0175$). Find GM.

4. (8 pts)

Who introduced the metacenter, and in what book?

5. (8 pts)

Iron is denser than water. How can an iron ship float?

6. (10 pts)

Calculation: A box-shaped barge is 12 m long, 5 m wide and 2 m deep and has a mass of 30 tonnes. How much cargo can it carry before the water reaches the deck edge in fresh water (1 tonne per m^3)?

7. (8 pts)

Name two features of the *Great Eastern* that made it safer than other ships of its time, and what happened when it struck a rock in 1862.

8. (10 pts)

Explain how a lock raises a ship from a lower level to a higher level without pumps.

9. (10 pts)

Calculation: A lock chamber is 300 m long and 30 m wide. How much water does it take to raise a ship 9 m? Give the answer in m^3 and in liters.

10. (8 pts)

Give two reasons the shipping container made shipping cheaper.

11. (12 pts)

Written answer: Explain how you would load heavy and light containers on a ship to keep it stable and level, and what can go wrong if you do not.

ANSWER KEY

1. G: the point where the ship's whole weight acts. B: the center of the underwater volume, where buoyancy acts. M: where the line of buoyancy crosses the centerline when the ship heels slightly.
2. When the ship heels, weight (down through G) and buoyancy (up through the moved B) then form a turning pair that rolls the ship farther over instead of back upright.
3. $GM = (w \times d) \div (W \times \tan \theta) = (10 \times 8) \div (4,000 \times 0.0175) = 80 \div 70 \approx 1.14 \text{ m}.$
4. Pierre Bouguer, in *Traité du navire* (1746).
5. The hull is shaped to enclose a large volume of air, so its average density is less than water's; it displaces a weight of water equal to its own weight before it is submerged.
6. Volume = $12 \times 5 \times 2 = 120 \text{ m}^3$, so it can displace 120 tonnes. Cargo = $120 - 30 = 90$ tonnes (in practice less, to keep freeboard).
7. A double iron hull and watertight bulkheads (also its iron box-girder structure). When it tore an 83-foot gash in its outer hull, the inner hull held and the ship reached port safely.
8. The ship enters the chamber and the lower gates close. Valves open culverts that let water flow by gravity from the higher level into the chamber. The water and ship rise until the levels match; then the upper gates open and the ship moves on.
9. $300 \times 30 \times 9 = 81,000 \text{ m}^3 = 81,000,000 \text{ liters}.$
10. Any two: goods are not handled piece by piece; cranes load ships in hours instead of days; the same box moves by ship, train and truck; less theft and damage; ships spend more time at sea and less in port.
11. Put heavy containers low and near the middle, light ones high; balance the weight side to side and end to end; follow the order of ports. If heavy ones are high, G rises and the ship may roll dangerously or capsize; if weight is unbalanced, the ship heels or trims, which can overload parts of the hull or let water over the deck.

PORTFOLIO PIECE: A STABLE, TESTED CARGO SHIP

Design and build a model cargo ship (from foam, plastic or a carton) to carry at least 500 grams of cargo. Before testing, calculate its maximum load from its dimensions and mass. Fit it with a mast and pendulum and carry out an inclining experiment to find GM, empty and loaded. Then write a stowage plan, load it, and measure its draft, trim and heel. Write a one-page naval architect's report with your drawings, calculations, data and one improvement you made.

LOOK FOR	WHAT IT MEANS
Design and drawings	Profile and cross-section drawings with dimensions, waterline and freeboard marked.
Capacity prediction	Maximum load calculated from volume and mass, then compared with the test.
Inclining experiment	GM measured correctly with the formula, empty and loaded, with units.
Loading plan	A clear stowage plan that keeps heavy cargo low and balanced; draft, trim and heel recorded.
Improvement	One specific change made and tested, with honest results.

FLIGHT

In earlier years you learned the four forces of flight and how the Wright brothers solved the problem of control. This year you will measure lift yourself on a kitchen-scale balance in front of a box fan, use the lift equation, and see how the engineers of NACA tested dozens of wing shapes to build the first families of airfoils. You will tune a glider's center of gravity to make it stable, measure the thrust of a homemade jet, and find the speed of sound with an echo.

The stories run from Sir George Cayley and Alphonse Pénauud, who first understood how to make an aircraft fly steadily by itself, to Frank Whittle and Hans von Ohain, who each invented the jet engine without knowing of the other, and to Chuck Yeager, who flew the rocket-powered Bell X-1 faster than sound on October 14, 1947.

PREREQUISITES

- Knows the four forces of flight and Newton's third law (Grades 5–6)
- Can find a center of gravity by balancing
- Can use a formula with squares and square roots

MASTERY CHECKLIST

- ☐ I can explain lift correctly, using both the turning of the air and the pressure difference, and use the lift equation.
- ☐ I can measure lift against angle of attack and find the stall.
- ☐ I can explain how the center of gravity, the tail and dihedral make an aircraft stable.
- ☐ I can explain how a jet engine makes thrust and calculate thrust from mass flow and speed change.
- ☐ I can calculate a Mach number and measure the speed of sound.

OPTIONAL KITS FOR THIS UNIT

- **Estes model rockets:** Grades 6 and up, only with an adult, outdoors in an open field, following the National Association of Rocketry safety code. A model rocket shows thrust, stability (center of pressure behind the center of gravity) and the effects of drag.
- **Guillow's balsa gliders and rubber-powered models:** Ages 8 and up for simple gliders, older for the stick-and-tissue kits. Inexpensive balsa models for testing center of gravity, dihedral and trim in Lesson 7.2.

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 Airfoils and Wind-Tunnel Testing: From Langley to the NACA Airfoils

2 sessions of 50–60 minutes

7.2 Stability and Control: Cayley, Pénaud and the Tail

2 sessions of 50–60 minutes

7.3 The Jet Engine: Frank Whittle and Hans von Ohain

2 sessions of 50–60 minutes

7.4 Breaking the Sound Barrier: Chuck Yeager and the Bell X-1

2 sessions of 50–60 minutes

UNIT 7 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. 10 pts

Explain how a wing makes lift. Why is the “equal transit time” explanation wrong?

2. 10 pts

Calculation: A wing of 20 m^2 flies at 40 m/s with $C_L = 0.6$ in air of density 1.2 kg/m^3 . Find the lift.

3. (8 pts)

What is a stall, and about what angle of attack does it happen at on most wings?

4. (8 pts)

What did the NACA engineers do with the Variable Density Tunnel that made their airfoil data so useful?

5. (10 pts)

Why must an airplane's center of gravity be ahead of its center of lift? What happens if it is too far back?

6. (8 pts)

How does dihedral help an airplane level its wings after a gust tips it?

7. (8 pts)

Name the four stages of a turbojet and what happens in each.

8. (10 pts)

Calculation: A jet engine takes in 80 kg of air per second at 150 m/s and expels it at 600 m/s. What is its thrust?

9. (10 pts)

Calculation: Find the speed of sound at -40°C and the Mach number of a jet flying at 280 m/s there.

10. (8 pts)

What problem did Chuck Yeager meet near Mach 0.94, and how did the X-1's design solve it?

11. (10 pts)

Written answer: Frank Whittle and Hans von Ohain both invented the jet engine. Explain what made it so hard to build a working one, and why turbofans are used on airliners today.

ANSWER KEY

1. The wing turns the passing air downward; by Newton's third law the air pushes the wing up. Turning the flow lowers the pressure on top and raises it below, and the pressure difference is the lift. The equal-transit idea is wrong because nothing forces the two flows to meet at the trailing edge; measurements show the air over the top arrives first.
2. $L = \frac{1}{2}\rho v^2 SC_L = 0.5 \times 1.2 \times 40^2 \times 20 \times 0.6 = 0.5 \times 1.2 \times 1,600 \times 20 \times 0.6 = 11,520 \text{ N}$.
3. A sudden loss of lift when the angle of attack is too large and the air separates from the top of the wing; about 15° .
4. They tested a family of related airfoils, changing one feature (thickness, camber, position of camber) at a time, in a tunnel pressurized so small models behaved like full-size wings, and published the results for designers to use.
5. So that a disturbance creates a moment that pushes the nose back (pitch stability), with the tail's lift helping. If the CG is too far back, a small nose-up disturbance grows until the airplane stalls; it is unstable.
6. The airplane slips sideways toward the lower wing, which then meets the air at a higher angle and makes more lift, rolling the airplane level.
7. Intake (air enters); compression (compressor squeezes it); combustion (fuel burns, raising temperature); exhaust (hot gas spins the turbine and rushes out the nozzle).
8. $F = \dot{m} \times (v_{\text{out}} - v_{\text{in}}) = 80 \times (600 - 150) = 80 \times 450 = 36,000 \text{ N}$.
9. $v \approx 331 + 0.6 \times (-40) = 331 - 24 = 307 \text{ m/s}$. $\text{Mach} = 280 \div 307 \approx 0.91$.
10. A shock wave on the tail made the elevator stop working, so he lost pitch control. The X-1's horizontal tail could be tilted as a whole (an all-moving tail), which kept control.
11. The turbine had to spin very fast in gas hotter than ordinary steel could stand, needing new alloys; the combustion had to be steady in a fast airstream; and the compressor had to be efficient enough for the turbine to drive it with energy left for thrust. Early engines overheated, ran away and shook apart. Turbofans move a large mass of air a little faster, which is more efficient and quieter than a turbojet's small, very fast jet.

PORTFOLIO PIECE: A TESTED, TUNED GLIDER

Design and build a glider (foam, card stock or balsa) that flies steadily and as far as possible from a measured launch height. Before testing, mark its center of lift and its center of gravity. Run a series of fair tests changing one thing at a time (CG position, dihedral, tail size), with at least three flights per setting, and measure the glide ratio for each. Write a one-page engineer's report with labeled drawings, your data tables and graphs, your best glide ratio, and an explanation of why your final design is stable.

LOOK FOR	WHAT IT MEANS
Design drawings	Side and front views with the CG, center of lift, tail and dihedral labeled and measured.
Fair tests	One variable changed at a time, at least three flights each, same launch height and method.
Data and calculation	Glide ratios calculated correctly and graphed against the variable tested.
Stability explanation	Explains pitch and roll stability using CG, tail and dihedral in the student's own words.
Improvement	Final design shows a measured improvement over the first, reported honestly.

7.1 AIRFOILS AND WIND-TUNNEL TESTING: FROM LANGLEY TO THE NACA AIRFOILS

OBJECTIVES

- Explain lift correctly: the wing turns air downward, and the pressure above the wing is lower than below.
- Use the lift equation $L = \frac{1}{2}\rho v^2 SC_L$ with numbers.
- Measure the lift of a model wing at different angles of attack on a kitchen-scale lift balance and find the stall.

Warm-up. Hold a sheet of paper by one short edge so it droops, and blow hard across the top. Then hold a flat piece of cardboard by its edge in front of a running box fan (keep fingers clear of the guard) and tilt it slowly up. When does it push up most strongly? When does it stop lifting and just push back?

WATCH

Understanding Aerodynamic Lift

The Efficient Engineer • 14:19

https://www.youtube.com/watch?v=E3i_XHIVCeU

WHEN TO WATCH

After the physics paragraph. Watch carefully for the part that explains why the “equal transit time” idea is wrong.

BACKUP VIDEO

Airflow across a wing

Cambridge University • 1:13

<https://www.youtube.com/watch?v=UqBmdZ-BNig>

A short smoke-tunnel film from the University of Cambridge showing air over a wing. Watch where the pulses of smoke above and below the wing end up.

KEY TERMS

airfoil

The cross-sectional shape of a wing, designed to turn the air smoothly and make lift with little drag.

angle of attack

The angle between the wing’s chord line and the oncoming air.

lift coefficient (C_L)

A number that describes how much lift a wing shape makes at a given angle of attack, measured in wind tunnels.

stall

The sudden loss of lift when the angle of attack is too great and the air can no longer follow the top of the wing.

wind tunnel

A tunnel where air is blown past a model at a measured speed so that its forces can be measured.

chord

The straight line from the front (leading edge) to the back (trailing edge) of an airfoil.

CORE IDEAS

The story. After the Wright brothers flew in 1903, airplanes spread quickly in Europe, and American engineers worried that their country was falling behind. In 1915 Congress created the National Advisory Committee for Aeronautics (NACA), and in 1917 it began building a laboratory at Langley Field in Virginia. NACA's engineers had a problem: a small model in a wind tunnel does not behave exactly like a full-size wing, because air flows differently around small and large objects. In the early 1920s the German engineer Max Munk designed Langley's Variable Density Tunnel, a steel tank in which the air could be squeezed to twenty times normal pressure, so that small models would behave like full-size wings.

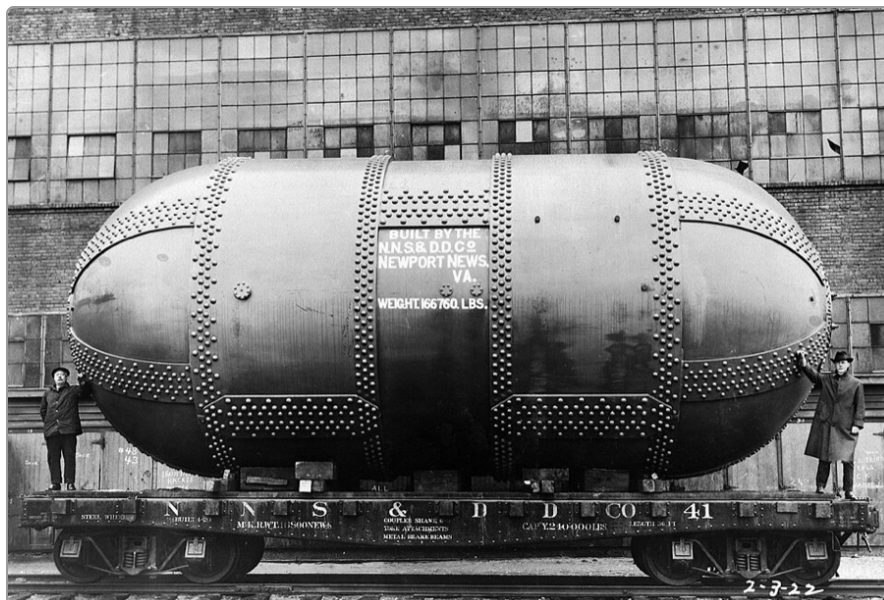
How they figured it out. Through the 1920s and early 1930s, Eastman Jacobs and his colleagues tested wing section after wing section in the Variable Density Tunnel. Instead of testing random shapes, they built a **family** of airfoils by changing one thing at a time: the thickness, the amount of curve (camber), and where along the chord the curve was highest. In 1933 they published the results for 78 related airfoils, each described by a four-digit number. A designer could now look up exactly how much lift and drag a wing would make at each angle. Some of these NACA airfoils, such as the NACA 2412, are still used on small airplanes today, nearly a century later.

The physics. A wing makes lift by turning the air that flows past it downward. By Newton's third law, if the wing pushes air down, the air pushes the wing up. Turning the flow also creates a pressure difference: the pressure on the upper surface is lower than the pressure on the lower surface, and that difference, acting over the whole wing, is the same lift force described another way. (The popular idea that air over the top must "catch up" with air underneath is false; in wind tunnels the air

over the top actually arrives at the trailing edge first.) Engineers sum this up in the **lift equation**: $L = \frac{1}{2}\rho v^2 S C_L$, where ρ is air density (about 1.2 kg/m^3), v is speed, S is wing area and C_L is the lift coefficient. A small plane with 16 m^2 of wing at 50 m/s and $C_L = 0.5$ makes $L = 0.5 \times 1.2 \times 50^2 \times 16 \times 0.5 = 12,000 \text{ N}$ of lift, enough for about 1,200 kg. Notice the v^2 : double the speed and the lift goes up four times.

The engineering. Raising the angle of attack raises C_L , up to a point. At about 15° for most wings, the air can no longer follow the curved top surface; it breaks away in swirls, lift drops suddenly and drag rises. This is the **stall**, and pilots are trained to recognize and recover from it. Engineers choose an airfoil for its job: thin, nearly symmetric sections for fast jets and aerobatic planes; thicker, more curved sections for slow planes and gliders that need high lift. Wind tunnels are still essential, along with computer simulations that must themselves be checked against wind-tunnel and flight measurements.

PICTURE STUDY



The Variable Density Tunnel Arrives at Langley, NACA photographer, February 3, 1922 · Photograph · NASA Langley Research Center

Image: [Wikimedia Commons](#), public domain

The heavy steel tank of the Variable Density Tunnel was built by a shipyard and delivered to Langley by rail. Inside it, air squeezed to twenty times normal pressure let small models behave like full-size wings.

Look closely

- Look at the rivets and thick steel plates. Why does the tank need to be so strong?
- Find the workers. Estimate the size of the tank.
- Look for the flatcar and rails. How else could such a heavy tank be moved?
- Look for any openings where models or instruments would go in.

Talk about it

1. Why would squeezing the air make a small model behave more like a full-size wing?
2. What dangers come with a tank full of air at twenty times normal pressure?
3. Why was testing a whole family of airfoils, changing one thing at a time, more useful than testing many unrelated shapes?

Safety first. Keep fingers, hair and loose clothing away from the fan. Do not reach behind the fan guard. Unplugging the fan is a job for an adult.

BUILD

A Kitchen-Scale Lift Balance

You will build a model wing, mount it on a stand on a kitchen scale in front of a box fan, and measure how the reading drops as the wing lifts. You will measure lift at angles of attack from 0° to 25° and find the stall, then compare two airfoil shapes.

You will need

- Card stock or a manila folder for the wing, about 30 cm span and 10 cm chord, bent over a pencil into a curved (cambered) airfoil and taped
- A second wing of the same size made flat
- A straw or dowel stand about 15 cm tall, fixed upright in a lump of clay, with the wing pinned to the top through a pivot so you can set its angle
- A kitchen scale that reads to 1 gram, a protractor, a box fan, a tape measure
- Optional: a phone anemometer app or a cheap anemometer to estimate the air speed

Steps

1. Build the cambered wing and fix it to the stand so its angle of attack can be set and locked with tape. Put the stand and clay on the scale and press tare (zero).
2. Set the fan about 50 cm from the wing, on its highest setting, aimed level at the wing. Mark the positions so every test is the same.
3. **Predict.** Sketch a graph of what you think lift will do as the angle of attack rises from 0° to 25° .
4. **Test.** At 0° , turn on the fan, wait for the reading to settle, and record it. The drop in the reading, in grams, is the lift; convert it to newtons ($\text{grams} \div 1,000 \times 9.8$). Repeat at 5° , 10° , 15° , 20° and 25° , three readings each.
5. Graph lift against angle of attack. Where is lift greatest? Where does it drop: the stall?

6. **Fair test.** Replace the cambered wing with the flat wing and repeat, changing nothing else. Compare the two curves.
7. **Calculate.** If you can estimate the air speed, use $L = \frac{1}{2}\rho v^2 SC_L$ to find C_L at your best angle: $C_L = L \div (0.5 \times 1.2 \times v^2 \times S)$.
8. **Improve.** Change one feature to get more lift at 10° (more camber, a rounded leading edge, a longer span), test it, and compare.

Tips

- Scales can drift with air blowing on them. Shield the scale itself with a cardboard box so only the wing is in the wind.
- Box-fan air is swirly; results vary. Repeat each reading and average.
- A tiny strip of tissue taped to the top of the wing near the back shows when the air separates at the stall.

Check your work

- ☐ I can explain lift with Newton's third law and the pressure difference.
- ☐ I can read lift from my balance and graph it against angle of attack.
- ☐ I can find the stall angle and explain what happens there.

ENGINEER'S NOTEBOOK

1. Draw an airfoil at a moderate angle of attack with streamlines showing the air turned downward, and label the low-pressure and high-pressure regions. Then draw the same wing stalled.
2. Make a table and graph of lift against angle for both wings.
3. A glider has 12 m^2 of wing, flies at 25 m/s and has $C_L = 0.9$. Calculate its lift. What mass could it carry? ($\rho = 1.2 \text{ kg/m}^3$.)

From history. In 1958 NACA became the core of the new National Aeronautics and Space Administration, NASA. The Variable Density Tunnel was retired after decades of service and is now a National Historic Landmark at NASA Langley.

COMMON MISTAKES

- Saying air over the top must meet the air underneath at the back. It does not; the top flow arrives first.
- Forgetting to square the speed in the lift equation.
- Letting the fan blow on the scale and reading that as lift.

Make it a game • Lift Equation Race. Your parent gives a wing area, speed and coefficient, such as air density 1.2, speed 20, area 0.5 and C_L of 0.8. Calculate L equals one half $\rho v^2 S C_L$. Then double the speed and calculate again. Say how much lift changed. Correct answers in under a minute earn a point.

Scripture. “they shall mount up with wings as eagles” (Isaiah 40:31, KJV)

Isaiah used flight as a picture of strength renewed by God. The NACA engineers learned slowly, measuring wing after wing, how men might mount up with wings of their own.

7.2 STABILITY AND CONTROL: CAYLEY, PÉNAUD AND THE TAIL

OBJECTIVES

- Explain why an aircraft's center of gravity must be ahead of its center of lift, and the job of the tail.
- Explain dihedral and how it gives roll stability.
- Test a glider's stability by moving its center of gravity and changing its dihedral, and measure its glide ratio.

Warm-up. Throw a plain sheet of paper flat across the room. Then fold a paper clip onto the front edge of another sheet and throw it. Then make a simple dart. Which ones fly steadily, and which tumble? What do the steady ones have in common?

WATCH

Airplane Stability Explained (Private Pilot Ground Lesson 6)

Free Pilot Training · 5:42

<https://www.youtube.com/watch?v=2ezQghY01bA>

WHEN TO WATCH

After the physics paragraph.

BACKUP VIDEO

What is DIHEDRAL?

flight-club · 1:29

<https://www.youtube.com/watch?v=WlwxH9SuH5M>

Before testing dihedral in the build: a short explanation of dihedral.

KEY TERMS

stability

An aircraft's tendency to return to steady flight by itself after being disturbed by a gust.

center of gravity (CG)

The balance point of the aircraft, where its weight acts.

center of lift (center of pressure)

The point where the total lift of the wing can be thought of as acting.

pitch, roll and yaw

Rotations about the three axes: nose up and down, wings tipping, nose left and right.

dihedral

The upward angle of the wings from root to tip, seen from the front, which gives roll stability.

glide ratio

The horizontal distance a glider travels divided by the height it loses.

CORE IDEAS

The story. In 1799 a young Yorkshire landowner, Sir George Cayley, engraved a small silver disc with a drawing of a flying machine with a fixed wing, a tail and a separate means of pushing it forward. It was the first design of a modern airplane. In 1804 he flew a model glider made from a kite for a wing, set at an angle on a pole, with a cross-shaped tail at the back, and he learned that a weight he could slide along the pole changed how it flew. In 1853, near the end of his life, his full-size glider carried his coachman across a small valley on his estate at Brompton. In France in 1871, the young engineer Alphonse Pénauud flew his Planophore, a little model powered by a twisted rubber band, in the Tuileries Gardens in Paris. It flew about 40 meters in 11 seconds and, most important, it flew steadily by itself.

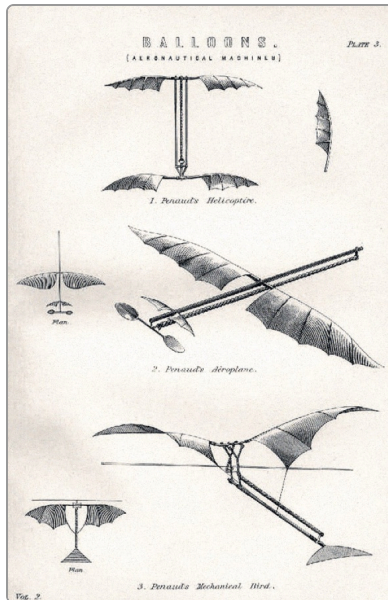
How they figured it out. Cayley found by experiment that a model whose weight was too far back would pitch up and stall, and one whose weight was too far forward would dive. With the weight in the right place, and a tail behind, a gust that pitched the nose up would increase the tail's angle of attack and push the tail up, bringing the nose back down. Pénauud worked out why: his tail was set at a slightly smaller angle than the wing, and the wings were bent upward toward the tips. Both features came to be used on nearly every airplane. (The Wright brothers deliberately made their Flyer unstable, with the elevator in front, because they wanted a responsive machine they could control; later designers went back to the stable arrangement Cayley and Pénauud had found.)

The physics. An aircraft is stable in **pitch** when its center of gravity is ahead of the point where lift acts. Then any disturbance creates a turning moment that pushes it back. The tail makes this work: it is a small wing far behind the CG, so even a small change in its lift has a large moment (force $\times$ distance). Move the CG too far back and

the airplane becomes unstable: a small nose-up disturbance grows until it stalls. Move it too far forward and the tail cannot lift the nose; the plane dives. In **roll**, dihedral helps: when one wing drops, the airplane slips sideways toward it, and the lower wing meets the air at a higher angle, makes more lift, and rolls the plane level again. A vertical tail fin works like a weathervane to keep it stable in **yaw**.

The engineering. Before every flight, pilots calculate the weight and balance of their airplane, to make sure the center of gravity lies inside the safe range set by the designers; loading baggage in the wrong place can make an airplane dangerous to fly. Designers choose how stable to make each airplane: training planes are very stable and forgiving, while fighter and aerobatic planes are made less stable so they turn quickly, and some modern jets are so unstable that computers must adjust the controls many times a second to keep them flying. Control surfaces, the elevator, ailerons and rudder, let the pilot command the airplane around all three axes.

PICTURE STUDY



Pénaud's Flying Models, Unknown engraver, 1875 · Engraving · From a French science publication of the 1870s

Image: [Wikimedia Commons](#), public domain

Alphonse Pénaud built several small flying models powered by twisted rubber bands. The middle one is the Planophore of 1871, the first model airplane that was stable on its own.

Look closely

- Find the Planophore. Locate its wing, tail and propeller.
- Look closely at the wing tips. Are they bent upward?
- Find the rubber band that powers it, running along the stick body.
- Compare the three models. Which kinds of flight is each one trying?

Talk about it

1. Why did Pénaud put the tail far behind the wing?
2. How would bending the wing tips upward make the model more stable in roll?
3. Where do you think the model's center of gravity was, compared with its wing?

Safety first. Fly gliders indoors in a clear room or outdoors away from people. Never aim a glider at anyone. Wear safety glasses if gliders have pointed noses.

BUILD

Tuning a Glider for Stability

You will build a simple glider from a foam plate or card stock, find its center of gravity, and test how moving the CG changes its flight. Then you will change the dihedral and measure the glide ratio. You are repeating Cayley's sliding-weight experiments.

You will need

- A foam plate or stiff card stock, a drinking straw or balsa stick for the body, tape, scissors
- Paper clips or small coins as movable nose weights
- A ruler, tape measure, protractor
- A launch spot at a measured height (standing on the floor, launching from shoulder height, or from a safe landing with an adult)

Steps

1. Cut a wing about 20 cm wide and 5 cm deep, a horizontal tail about 8 cm wide and 3 cm deep, and a vertical fin. Tape them to the straw body, wing near the front third, tail at the back.
2. Find the wing's center of lift: for a flat wing, about one-quarter of the way back from its front edge. Mark it on the body.
3. **Find the CG.** Balance the glider on your fingertip and mark the balance point. Record its distance ahead of or behind the center-of-lift mark.
4. **Predict.** What will the glider do with the CG behind the lift mark? Right on it? 1 cm ahead? 3 cm ahead?
5. **Test.** Adjust paper clips on the nose to set each CG position. Launch gently and level from the same height each time. Record the flight path (stall, dive, steady glide) and the distance. Three flights each.
6. **Glide ratio.** For the best CG, measure launch height and distance traveled and calculate glide ratio = distance $\div$ height.
7. **Dihedral.** Keeping the best CG, bend the wing tips up to 0°, 10° and 20° of dihedral. For each, launch with one wing tipped slightly down and observe

whether it rolls level. Record results.

8. **Improve.** Use what you learned to make your longest steady glide. Record the final CG position, dihedral and glide ratio.

Tips

- Launch gently. Throwing hard makes every glider loop or dive.
- Small changes matter: move the CG a few millimeters at a time near the best spot.
- If the glider turns, bend the trailing edge of the fin slightly, or check that both wings are the same.

Check your work

- ☐ I can find the center of gravity and explain where it must be for stability.
- ☐ I can explain how the tail and dihedral make a glider stable.
- ☐ I can calculate a glide ratio.

ENGINEER'S NOTEBOOK

1. Draw your glider from the side and from the front. Mark the CG, the center of lift, the tail's lift and the dihedral angle.
2. Make a table of CG position, flight behavior and distance, and a table of dihedral and roll behavior.
3. A glider launched from 2.0 m travels 9.0 m. What is its glide ratio? From 40 m, how far could the same glider travel in still air?

From history. Pénaud went on to design a full-size airplane with retractable landing gear and a glass-covered cockpit in 1876, decades before such things were built, but he could not find the money to build it. Cayley, meanwhile, is often called the “father of aeronautics” for being the first to separate lift, thrust and control in one design.

COMMON MISTAKES

- Changing two things at once, such as CG and dihedral.
- Throwing harder to fix a bad glide instead of fixing the balance.
- Forgetting that a nose-heavy glider can still be stable but will dive steeply.

Make it a game • CG Ahead of Lift. Make a paper glider and slide a paper clip along its nose. Predict whether it will dive, glide or stall for each position, with the center of gravity ahead of or behind the center of lift. Test each. Explain the tail's job and dihedral. Best predictions win.

7.3 THE JET ENGINE: FRANK WHITTLE AND HANS VON OHAIN

OBJECTIVES

- Describe the four stages of a jet engine: intake, compression, combustion, exhaust.
- Calculate jet thrust from mass flow rate and change in speed.
- Measure the thrust of a balloon jet on a kitchen scale and test how the nozzle size changes it.

Warm-up. Blow up a balloon and let it go. Now blow it up again and, holding the neck, feel the air rushing out. Which way does the air go, and which way does the balloon want to go? What would happen if the opening were smaller?

WATCH

How Jet Engines Work

[Animagraffs](#) • 5:01

<https://www.youtube.com/watch?v=L24Wf0VITE0>

WHEN TO WATCH

After the physics paragraph. Name each section of the engine as it appears.

BACKUP VIDEO

Inventing the Jet Engine Came With a Few Disasters

[Smithsonian Channel](#) • 2:56

<https://www.youtube.com/watch?v=LZglVV36bJU>

After the story: the setbacks Whittle and his team faced testing the first engines.

KEY TERMS

turbojet

A jet engine in which a compressor squeezes air, fuel burns in it, and the hot gas spins a turbine that drives the compressor before rushing out the back.

compressor

Spinning blades that squeeze incoming air to high pressure.

turbine

Blades spun by the hot exhaust gas; the turbine turns the shaft that drives the compressor.

thrust

The forward force an engine makes by pushing gas backward: $F = \dot{m} \times (v_{\text{out}} - v_{\text{in}})$.

mass flow rate ($\dot{m}$)

How many kilograms of gas pass through the engine each second.

turbofan

A jet engine with a large fan in front that pushes extra air around the core; quieter and more efficient, used on airliners.

CORE IDEAS

The story. In 1928 a young Royal Air Force cadet named Frank Whittle wrote a paper arguing that airplanes would one day fly very high and very fast, where propellers do not work well. By 1930 he had worked out how: an engine that sucked in air, squeezed it with a compressor, burned fuel in it, and blew it out the back as a jet, using a turbine in the hot gas to drive the compressor. He patented it in January 1930, but the Air Ministry was not interested, and he could not afford to renew the patent. In 1936, with private backers, he formed a small company, Power Jets, and on April 12, 1937, his first engine ran on a test stand. Meanwhile in Germany, a young physicist named Hans von Ohain had the same idea independently, and with the aircraft builder Ernst Heinkel he built an engine that powered the Heinkel He 178 on the first jet flight on August 27, 1939. Whittle's engine first flew in the Gloster E.28/39 on May 15, 1941.

How they figured it out. The hard part was not the idea but the materials and the details. Whittle's first engines raced out of control, glowed red-hot and shook themselves apart, and every test taught his small team something. The combustion chambers had to burn fuel steadily in a howling stream of air; the turbine blades had to spin thousands of times a minute while sitting in gas hotter than the melting point of ordinary steel, which needed new heat-resistant alloys. The compressor had to be efficient enough that the turbine could drive it and still leave energy to spare for thrust. After the Second World War, Whittle and von Ohain met and became friends, and they spoke together about their parallel work.

The physics. A jet engine works by Newton's second and third laws. It speeds up a large mass of air every second; pushing that air backward pushes the engine forward. $\text{Thrust} = \dot{m} \times (v_{\text{out}} - v_{\text{in}})$. Suppose an engine takes in 100 kg of air every second while flying at 200 m/s and blows it out at 500 m/s. $\text{Thrust} = 100 \times (500 - 200) = 30,000 \text{ N}$. The engine runs on a simple cycle, often summed up as suck, squeeze, burn, blow: the compressor raises the pressure many times, the burning fuel raises the temperature, and the hot, high-pressure gas expands through the turbine and the nozzle. The hotter and more squeezed the gas, the more work it can do, which is why engineers keep pushing turbine temperatures higher.

The engineering. Modern airliners use turbofan engines. A huge fan at the front pushes most of the air around the outside of the engine core. Moving a very large mass of air a little faster is more efficient and much quieter than moving a small mass very fast, so turbofans burn far less fuel than Whittle's turbojets. Jet engines are among the most carefully engineered machines in the world: turbine blades are grown as single crystals of special metal alloys, cooled by air flowing through tiny holes, and inspected regularly with cameras slipped inside. Thanks to this engineering, today's engines can run for tens of thousands of hours between overhauls.

PICTURE STUDY



The Gloster E.28/39, Britain's First Jet Airplane, Royal Air Force official photographer, About 1941 · Photograph · Imperial War Museum, London
Image: [Wikimedia Commons](#), public domain

The Gloster E.28/39 was built to test Frank Whittle's engine in the air. It first flew on May 15, 1941. Look for what is missing compared with every airplane before it.

Look closely

- Find the air intake. Where does the air enter the engine?
- Look for a propeller. Why is there none?
- Find where the hot exhaust leaves the airplane.
- Look at the size of the airplane compared with the pilot or ground crew.

Talk about it

1. Why was the intake put in the nose?
2. Why would the exhaust need to be kept away from the tail?
3. What advantages would a jet have over a propeller airplane at high speed and high altitude?

Safety first. Wear safety glasses when releasing balloons. Never point a balloon nozzle at anyone's face. Keep popped balloon pieces away from small children; they are a choking hazard.

BUILD

A Balloon-Jet Thrust Stand

You will measure the thrust of a balloon jet on a kitchen scale. With the nozzle pointing up, the escaping air pushes the balloon down onto the scale, and the increase in the reading is the thrust. You will test how the size of the nozzle changes the thrust and how long it lasts.

You will need

- Several identical round balloons
- Nozzles: short pieces of drinking straw of different widths (a thin coffee stirrer, a regular straw and a wide smoothie straw), each taped airtight into a balloon neck
- A paper cup taped upside down on the kitchen scale as a cradle, with a hole in the bottom for the nozzle
- A kitchen scale, a tape measure (to measure balloon size), a stopwatch or slow-motion video

Steps

1. Tape a nozzle airtight into a balloon. Blow it up to the same measured circumference each time (for example 60 cm) and pinch the nozzle.
2. Set the balloon in the cradle with the nozzle pointing straight up through the hole. Press tare to zero the scale while you hold the nozzle pinched (the balloon's weight is then removed).
3. **Predict.** Which nozzle will give the biggest thrust at the start? Which will last longest?
4. **Test.** Release the nozzle and film the scale display. Record the highest reading and the time until the balloon is empty.
5. Convert the peak reading to newtons ($\text{grams} \div 1,000 \times 9.8$). Repeat three times with each nozzle size and average.
6. Graph peak thrust and burn time against nozzle diameter.
7. **Total impulse.** Estimate the total push for each nozzle as average thrust $\times$ burn time (newton-seconds). Which nozzle gave the most total impulse, or

was it about the same?

8. **Improve.** Design the nozzle you think gives the best push for a balloon car that must travel as far as possible, and explain your choice using thrust and burn time.

Tips

- Inflate every balloon to the same size; a fuller balloon has more pressure and more air.
- Your hand must be off the balloon when you read the scale.
- Balloons stretch with use; use a fresh one if results start to change.

Check your work

- ☐ I can name and explain the four stages of a jet engine.
- ☐ I can calculate thrust from mass flow and speed change.
- ☐ I can explain how nozzle size changed my balloon jet's thrust and burn time.

ENGINEER'S NOTEBOOK

1. Draw a cutaway of a turbojet and label the intake, compressor, combustion chamber, turbine and nozzle, with arrows showing pressure and temperature rising and falling.
2. Make a table and graph of nozzle size, peak thrust and burn time.
3. A turbofan moves 600 kg of air per second, speeding it up from 250 m/s to 300 m/s. Calculate its thrust.

From history. Whittle was knighted in 1948 and later moved to the United States, where he taught at the U.S. Naval Academy. Von Ohain also moved to the United States after the war and worked for many years as a research scientist for the U.S. Air Force in Ohio, not far from where the Wright brothers had lived.

COMMON MISTAKES

- Thinking the jet pushes against the air behind it. It pushes the gas backward, and the gas pushes the engine forward, even in thin air.
- Forgetting to subtract the incoming air speed in the thrust formula.
- Comparing balloons inflated to different sizes.

Make it a game • Jet Thrust Quiz. Order the four jet engine stages on cards: intake, compression, combustion, exhaust. Race to arrange them, then say what each does. Your parent names a mass flow rate and a speed change, such as 20 kg per second and 300 m per second. Calculate thrust in newtons. Beat your best total.

7.4 BREAKING THE SOUND BARRIER: CHUCK YEAGER AND THE BELL X-1

OBJECTIVES

- Explain what the “sound barrier” was and why airplanes had trouble near the speed of sound.
- Calculate the speed of sound at different temperatures and a Mach number.
- Measure the speed of sound with an echo or with two phones.

Warm-up. Watch a distant worker hammering, a ball being kicked across a field, or a firework far away (only one set off by professionals). Do you see it before you hear it? Count the seconds between flash and sound in a thunderstorm (from indoors). What does the delay tell you?

WATCH

The Moment Chuck Yeager Flew His Plane Past the Sound Barrier | Smithsonian Channel

Smithsonian Channel Aviation Nation · 4:02

<https://www.youtube.com/watch?v=fJV12u81glo>

WHEN TO WATCH

After the story paragraph.

BACKUP VIDEO

Speed of sound activity - Measure the echo - Homemade Science with Bruce Yeany

Homemade Science with Bruce Yeany · 4:55

<https://www.youtube.com/watch?v=J97YSCnU4KM>

Before the build: a science teacher shows how to measure the speed of sound with echoes.

KEY TERMS

speed of sound

How fast sound travels through air:
about 343 m/s at 20 °C, slower in colder
air.

Mach number

Speed ÷ speed of sound. Mach 1 is the
speed of sound; Mach 2 is twice it.

shock wave

A thin region where air pressure, density and temperature jump suddenly, formed when air cannot move out of the way ahead of an object moving faster than sound.

sonic boom

The loud double crack heard on the ground when the shock waves from a supersonic aircraft pass by.

all-moving tail (stabilator)

A horizontal tail that pivots as a whole, used to keep control near and beyond the speed of sound.

CORE IDEAS

The story. During the 1940s, fighter pilots diving at high speed ran into a frightening problem: as they neared the speed of sound, their airplanes shook violently, the controls stopped working, and some could not pull out of their dives. Many engineers began to talk of a “sound barrier.” In 1945 the U.S. Army Air Forces and the NACA ordered a research airplane from the Bell Aircraft Company built to find out what happened at the speed of sound. The Bell X-1 was a small, bright orange rocket plane, carried aloft under a large four-engine airplane and dropped. On October 14, 1947, Captain Charles “Chuck” Yeager, a farm boy from West Virginia and a former wartime pilot, flew it to about 700 miles per hour, Mach 1.06, at about 43,000 feet over the California desert. He did it with two broken ribs from a horse-riding accident two nights earlier, using a sawed-off broom handle to close the cockpit door.

How they figured it out. The X-1 program moved step by step. Each flight went a little faster, with instruments recording the pressures on the wings and tail and the behavior of the controls. As the X-1 approached Mach 0.94, Yeager found that the elevator, the hinged back part of the tail, stopped working: the shock wave forming on the tail made it useless. The engineers had built the X-1 with a horizontal tail that could be tilted as a whole by an electric motor, and on the next flight Yeager used it to keep control. That “all-moving tail” solved the problem, and it became standard on supersonic airplanes. There was no barrier, only a region of new physics that engineers had to understand.

The physics. Sound is a pressure wave, and it travels at a speed that depends on the temperature of the air: roughly $v \approx 331 + 0.6 \times T$ m/s, where T is in $^{\circ}\text{C}$. At 20°C , $v \approx 331 + 12 = 343$ m/s. At 43,000 feet the air is about -55°C , so $v \approx 331 - 33 = 298$ m/s. The **Mach number** is speed $\div$ speed of sound: at 313 m/s (700 mph) in that cold air, $\text{Mach} = 313 \div 298 \approx 1.05$. Below Mach 1, pressure waves from an airplane travel ahead of it and warn the air to move aside smoothly. At Mach 1 and above, the airplane outruns its own pressure waves; they pile up into **shock waves**, where pressure jumps suddenly, which change the forces on the wings and tail.

The engineering. Supersonic airplanes are shaped for the new physics: thin, swept-back or triangular wings, sharp noses, slender bodies and all-moving tails. Engineers also learned to shape airliner wings so that the shock waves that form on them at high subsonic speeds are weak, letting airliners cruise efficiently at about Mach 0.85. Sonic booms are so loud that supersonic flight over land is restricted in many countries; NASA is now testing quieter shapes designed to turn the boom into a soft thump. The X-1 that Yeager flew hangs today in the Smithsonian's National Air and Space Museum in Washington.

PICTURE STUDY



The Bell X-1 in Flight, NASA photographer, About 1947 · Photograph · NASA Armstrong Flight Research Center

Image: [Wikimedia Commons](#), public domain

This is the X-1 that Chuck Yeager flew faster than sound. It carried its own rocket engine and fuel, and it was dropped from a larger airplane so it would not waste fuel climbing.

Look closely

- Look at the shape of the body. Why is it pointed at the front and smooth all over?
- Look at the wings. Are they thick or thin?
- Find the tail. Remember that the whole horizontal tail could tilt.
- Look for the rocket exhaust at the back.

Talk about it

1. Why was the X-1 dropped from another airplane instead of taking off from the ground?
2. Why did the X-1 need thin wings to fly near the speed of sound?
3. Why did the engineers test a little faster on each flight instead of trying for Mach 1 on the first flight?

Safety first. For echo tests, stay well away from roads and parking lots, and choose a wall such as a school building or a large barn on a quiet day with an adult. Do not use fireworks, starter pistols or anything that bangs; claps or two blocks of wood are enough. Protect your hearing: do not clap blocks near anyone's ear.

BUILD

Measuring the Speed of Sound

You will measure the speed of sound in two ways, compare your results with the formula $v \approx 331 + 0.6 \times T$, and work out how fast the X-1 had to go to pass Mach 1.

You will need

- Two blocks of wood to clap together (or your hands)
- A tape measure or measuring wheel (or count paces and measure your pace)
- A stopwatch, and a thermometer for the air temperature
- Optional: two smartphones with the free phyphox app (acoustic stopwatch)

Steps

1. **Echo method.** Find a large, flat wall with open ground in front of it. Stand at least 50 m away (farther is better) and measure the distance d exactly.
2. Clap the blocks once and listen for the echo. Then clap in a steady rhythm so that each clap falls exactly when you hear the echo of the one before. Have a partner time 20 claps.
3. Each clap interval is the time for sound to go to the wall and back ($2d$). Speed = $2d \times 20 \div \text{total time}$. Repeat three times and average.
4. **Two-phone method (optional).** Set up phyphox's acoustic stopwatch on two phones placed a measured distance apart (for example 20 m). A clap near the first phone starts both timers; a clap near the second phone stops them. Follow the app's instructions to calculate the speed.
5. Measure the air temperature. **Predict** the speed with $v \approx 331 + 0.6 \times T$. Compare your measured result and calculate the percent difference.
6. If you can, repeat on a much colder or warmer day. Did the speed change as predicted?
7. **Calculate the X-1's flight.** Find the speed of sound at -55°C . What speed in m/s and in mph ($1 \text{ m/s} \approx 2.24 \text{ mph}$) would the X-1 need to reach Mach 1?

8. **Improve.** Find the biggest source of error in your measurement (reaction time, distance, wind) and change one thing to reduce it. Repeat and compare.

Tips

- Timing many intervals and dividing reduces the error from reaction time.
- Wind blowing toward or away from the wall changes the result; a calm day is best.
- Very large distances make the echo faint. 60–100 m works well for clapping blocks.

Check your work

- ☐ I can measure the speed of sound and compare it with a calculated value.
- ☐ I can calculate a Mach number.
- ☐ I can explain what happened to airplanes near the speed of sound and how the all-moving tail helped.

ENGINEER'S NOTEBOOK

1. Draw the pressure waves around an airplane flying slower than sound, at the speed of sound and faster than sound.
2. Make a table of your trials, measured speeds, the predicted speed and the percent difference.
3. An airliner flies at 250 m/s where the air is -50°C . Calculate the speed of sound there and the airliner's Mach number.

From history. On the day of the record flight, people on the ground at Muroc Army Air Field heard the boom, and the instruments confirmed the X-1 had passed Mach 1. The flight was kept secret for months and officially announced in June 1948.

COMMON MISTAKES

- Forgetting that an echo travels to the wall and back (2d).
- Using the speed of sound at ground temperature for high-altitude flight.
- Thinking the sound barrier was a solid wall. It was a region of new aerodynamic behavior.

Make it a game • Mach Number Duel. Your parent names a temperature and a speed. Use speed of sound is about 331 plus 0.6 times temperature in Celsius to find it, then calculate the Mach number. Five rounds against the clock. Explain why airplanes had trouble near the speed of sound, and tell the story of the Bell X-1.

FLIGHT

In earlier years you learned the four forces of flight and how the Wright brothers solved the problem of control. This year you will measure lift yourself on a kitchen-scale balance in front of a box fan, use the lift equation, and see how the engineers of NACA tested dozens of wing shapes to build the first families of airfoils. You will tune a glider's center of gravity to make it stable, measure the thrust of a homemade jet, and find the speed of sound with an echo.

The stories run from Sir George Cayley and Alphonse Pénauud, who first understood how to make an aircraft fly steadily by itself, to Frank Whittle and Hans von Ohain, who each invented the jet engine without knowing of the other, and to Chuck Yeager, who flew the rocket-powered Bell X-1 faster than sound on October 14, 1947.

PREREQUISITES

- Knows the four forces of flight and Newton's third law (Grades 5–6)
- Can find a center of gravity by balancing
- Can use a formula with squares and square roots

MASTERY CHECKLIST

- ☐ I can explain lift correctly, using both the turning of the air and the pressure difference, and use the lift equation.
- ☐ I can measure lift against angle of attack and find the stall.
- ☐ I can explain how the center of gravity, the tail and dihedral make an aircraft stable.
- ☐ I can explain how a jet engine makes thrust and calculate thrust from mass flow and speed change.
- ☐ I can calculate a Mach number and measure the speed of sound.

OPTIONAL KITS FOR THIS UNIT

- **Estes model rockets:** Grades 6 and up, only with an adult, outdoors in an open field, following the National Association of Rocketry safety code. A model rocket shows thrust, stability (center of pressure behind the center of gravity) and the effects of drag.
- **Guillow's balsa gliders and rubber-powered models:** Ages 8 and up for simple gliders, older for the stick-and-tissue kits. Inexpensive balsa models for testing center of gravity, dihedral and trim in Lesson 7.2.

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 Airfoils and Wind-Tunnel Testing: From Langley to the NACA Airfoils

2 sessions of 50–60 minutes

7.2 Stability and Control: Cayley, Pénaud and the Tail

2 sessions of 50–60 minutes

7.3 The Jet Engine: Frank Whittle and Hans von Ohain

2 sessions of 50–60 minutes

7.4 Breaking the Sound Barrier: Chuck Yeager and the Bell X-1

2 sessions of 50–60 minutes

UNIT 7 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **10 pts**

Explain how a wing makes lift. Why is the “equal transit time” explanation wrong?

2. **10 pts**

Calculation: A wing of 20 m^2 flies at 40 m/s with $C_L = 0.6$ in air of density 1.2 kg/m^3 . Find the lift.

3. (8 pts)

What is a stall, and about what angle of attack does it happen at on most wings?

4. (8 pts)

What did the NACA engineers do with the Variable Density Tunnel that made their airfoil data so useful?

5. (10 pts)

Why must an airplane's center of gravity be ahead of its center of lift? What happens if it is too far back?

6. (8 pts)

How does dihedral help an airplane level its wings after a gust tips it?

7. (8 pts)

Name the four stages of a turbojet and what happens in each.

8. (10 pts)

Calculation: A jet engine takes in 80 kg of air per second at 150 m/s and expels it at 600 m/s. What is its thrust?

9. (10 pts)

Calculation: Find the speed of sound at -40°C and the Mach number of a jet flying at 280 m/s there.

10. (8 pts)

What problem did Chuck Yeager meet near Mach 0.94, and how did the X-1's design solve it?

11. (10 pts)

Written answer: Frank Whittle and Hans von Ohain both invented the jet engine. Explain what made it so hard to build a working one, and why turbofans are used on airliners today.

ANSWER KEY

1. The wing turns the passing air downward; by Newton's third law the air pushes the wing up. Turning the flow lowers the pressure on top and raises it below, and the pressure difference is the lift. The equal-transit idea is wrong because nothing forces the two flows to meet at the trailing edge; measurements show the air over the top arrives first.
2. $L = \frac{1}{2}\rho v^2 SC_L = 0.5 \times 1.2 \times 40^2 \times 20 \times 0.6 = 0.5 \times 1.2 \times 1,600 \times 20 \times 0.6 = 11,520 \text{ N}$.
3. A sudden loss of lift when the angle of attack is too large and the air separates from the top of the wing; about 15° .
4. They tested a family of related airfoils, changing one feature (thickness, camber, position of camber) at a time, in a tunnel pressurized so small models behaved like full-size wings, and published the results for designers to use.
5. So that a disturbance creates a moment that pushes the nose back (pitch stability), with the tail's lift helping. If the CG is too far back, a small nose-up disturbance grows until the airplane stalls; it is unstable.
6. The airplane slips sideways toward the lower wing, which then meets the air at a higher angle and makes more lift, rolling the airplane level.
7. Intake (air enters); compression (compressor squeezes it); combustion (fuel burns, raising temperature); exhaust (hot gas spins the turbine and rushes out the nozzle).
8. $F = \dot{m} \times (v_{\text{out}} - v_{\text{in}}) = 80 \times (600 - 150) = 80 \times 450 = 36,000 \text{ N}$.
9. $v \approx 331 + 0.6 \times (-40) = 331 - 24 = 307 \text{ m/s}$. $\text{Mach} = 280 \div 307 \approx 0.91$.
10. A shock wave on the tail made the elevator stop working, so he lost pitch control. The X-1's horizontal tail could be tilted as a whole (an all-moving tail), which kept control.
11. The turbine had to spin very fast in gas hotter than ordinary steel could stand, needing new alloys; the combustion had to be steady in a fast airstream; and the compressor had to be efficient enough for the turbine to drive it with energy left for thrust. Early engines overheated, ran away and shook apart. Turbofans move a large mass of air a little faster, which is more efficient and quieter than a turbojet's small, very fast jet.

PORTFOLIO PIECE: A TESTED, TUNED GLIDER

Design and build a glider (foam, card stock or balsa) that flies steadily and as far as possible from a measured launch height. Before testing, mark its center of lift and its center of gravity. Run a series of fair tests changing one thing at a time (CG position, dihedral, tail size), with at least three flights per setting, and measure the glide ratio for each. Write a one-page engineer's report with labeled drawings, your data tables and graphs, your best glide ratio, and an explanation of why your final design is stable.

LOOK FOR	WHAT IT MEANS
Design drawings	Side and front views with the CG, center of lift, tail and dihedral labeled and measured.
Fair tests	One variable changed at a time, at least three flights each, same launch height and method.
Data and calculation	Glide ratios calculated correctly and graphed against the variable tested.
Stability explanation	Explains pitch and roll stability using CG, tail and dihedral in the student's own words.
Improvement	Final design shows a measured improvement over the first, reported honestly.

UNIT 8

ROBOTICS

A robot senses the world, decides what to do and acts, over and over, many times a second. In this unit you will look at each part of that loop with the words and numbers robotics engineers use. You will count a robot arm's degrees of freedom and test end effectors, program a feedback controller and tune it, build a touch sensor and calculate how far ahead a self-driving vehicle must see, and measure the thrust of a drone motor and propeller.

The stories include the Canadarm that worked on the Space Shuttle for thirty years, Lawrence Sperry flying with his hands in the air above Paris in 1914, the little Sojourner rover finding its own way among the rocks of Mars, the robot cars of the DARPA Grand Challenge, and the first four-rotor flying machines of 1907 and 1922. The unit, and the year, ends with your capstone project and the family engineering fair.

PREREQUISITES

- Can write a program with loops and if-statements in Scratch, MakeCode or Arduino (Unit 4 and Grade 6)
- Knows sense–think–act (earlier grades)
- Can use $V = IR$, power and thrust (Units 4 and 7)

MASTERY CHECKLIST

- ☐ I can count the degrees of freedom of a robot arm and compare end-effector designs with data.
- ☐ I can explain feedback control and how the gain of a proportional controller changes its behavior.
- ☐ I can explain how lidar, radar, cameras and ultrasonic sensors measure distance, and calculate a stopping distance.
- ☐ I can explain how a quadcopter hovers, climbs, turns and moves, and calculate the thrust each motor must make.
- ☐ I can plan, build, test, improve and present a capstone engineering project.

OPTIONAL KITS FOR THIS UNIT

- **Makeblock mBot:** Ages 8 and up. A small wheeled robot with an ultrasonic distance sensor and line-follower sensors, programmed with free block coding; fits Lessons 8.2 and 8.3.
- **BBC micro:bit:** Ages 8 and up. Built-in accelerometer, compass and buttons, programmed in the free MakeCode editor; good for the feedback-control and sensor lessons.
- **Ryze Tello:** Ages 13 and up with an adult. A small indoor drone under 250 g that can be programmed with block coding; follow the FAA rules in Lesson 8.4.
- **CrunchLabs Build Box:** Ages 8 and up. Monthly engineering toys from Mark Rober, several with motors, gears and sensors; a fun source of capstone ideas.

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 Degrees of Freedom and End Effectors: The Canadarm 2 sessions of 50–60 minutes

8.2 Feedback Control: Sperry's Autopilot and a Coded Cruise Control

2 sessions of 50–60 minutes

8.3 Sensors and Autonomous Vehicles: From Sojourner to the DARPA Challenge

2 sessions of 50–60 minutes

8.4 How a Quadcopter Flies, and the Family Engineering Fair

2 sessions of 50–60 minutes, plus the fair

UNIT 8 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

What is a degree of freedom? How many does a robot need to place its tool at any position and in any orientation, and why?

2. **10 pts**

Calculation: A robot shoulder holds a 2.0 kg load 0.5 m away. What torque does the load require? What if the load is moved to 1.0 m?

3. **8 pts**

Describe the Canadarm's end effector and why it was a good design.

4. **8 pts**

What is the difference between open-loop and closed-loop control? Give one example of each.

5. **10 pts**

Calculation: A cruise control is set to 30 m/s. The car is going 26 m/s and $K_p = 0.5$. What is the error and the controller's output? What happens if K_p is made much larger?

6. **8 pts**

How did Lawrence Sperry's 1914 stabilizer keep his airplane level when his mechanic walked out on the wing?

7. **10 pts**

Calculation: An ultrasonic sensor hears an echo 0.006 s after sending a pulse (speed of sound 343 m/s). How far away is the object?

8. **10 pts**

Calculation: A self-driving car at 20 m/s has a reaction time of 0.1 s and brakes at 8 m/s^2 . Find its stopping distance.

9. **8 pts**

Why do autonomous vehicles use several kinds of sensors instead of one? Give one strength and one weakness of two different sensors.

10. **10 pts**

Explain how a quadcopter yaws (turns in place), and why its propellers spin in opposite directions.

11. 10 pts

Written answer: A friend wants to fly a new 300-gram drone at a park near a small airport. What rules must he follow, and what would you advise?

ANSWER KEY

1. One independent way a joint (or object) can move. Six: three for position (forward-back, left-right, up-down) and three for orientation (pitch, yaw, roll).
2. $\tau = 2.0 \times 9.8 \times 0.5 = 9.8 \text{ N}\cdot\text{m}$. At 1.0 m: 19.6 N·m (doubled).
3. A hollow cylinder with three wires that twisted closed like a snare around a grapple pin on each payload. It could catch the pin even if slightly off target and held it securely.
4. Open-loop does not measure the result (a toaster timer, a simple sprinkler timer); closed-loop measures and corrects (a thermostat, cruise control, an autopilot).
5. Error = $30 - 26 = 4 \text{ m/s}$; output = $0.5 \times 4 = 2$. A much larger K_p makes it react faster but overshoot and oscillate.
6. Gyroscopes kept their direction, so when the airplane tilted they sensed it; the movement worked valves that drove the ailerons and elevator to bring the airplane back to level.
7. $d = \text{speed} \times \text{time} \div 2 = 343 \times 0.006 \div 2 \approx 1.03 \text{ m}$.
8. $d = v \times t + v^2 \div 2a = 20 \times 0.1 + 400 \div 16 = 2 + 25 = 27 \text{ m}$.
9. Each has weaknesses that another covers (sensor fusion). Examples: camera sees color and signs but struggles in glare and dark; lidar measures distance precisely but is affected by heavy rain and snow; radar works in fog and measures speed but gives a blurry picture; ultrasonic is cheap but short range.
10. Two rotors spin clockwise and two counterclockwise so their twisting reactions cancel. To yaw, the controller speeds up one pair and slows the other, so the reactions no longer cancel and the frame turns, while total thrust stays the same.
11. Pass the free TRUST test; register the drone (it is over 250 g); fly no higher than 400 feet; keep it in sight; never fly over people or moving vehicles; do not fly near the airport without authorization; check the FAA's current rules. Advise choosing a different, open field away from the airport, people and power lines.

PORTFOLIO PIECE: CAPSTONE PROJECT AND FAMILY ENGINEERING FAIR

Choose a real problem at home, at church or in your community that a machine, structure or device could help solve, such as an automatic plant-watering system, a stronger shelf bracket, a feeder that keeps squirrels out, or a robot arm that can pick up dropped items. Write a design brief (the problem, who it serves, the requirements and a budget), sketch at least two ideas, choose one with reasons, and build a working prototype. Test it fairly at least three times, improve it, and test again. At the family engineering fair, present your capstone with its notebook pages and a short talk that includes one calculation, the results of your tests and what you would do next.

LOOK FOR	WHAT IT MEANS
Design brief and planning	Clear statement of the problem, the people it serves, measurable requirements and a budget; at least two ideas compared.
Working prototype	The prototype works as intended and is built safely and neatly.
Testing and improvement	At least three fair tests before and after one improvement, with data recorded and graphed.
Engineering reasoning	At least one correct calculation from this year (forces, energy, electricity, flow or control) used in the design.
Presentation	Clear, honest explanation at the fair, including what did not work and what the student would change.

8.1 DEGREES OF FREEDOM AND END EFFECTORS: THE CANADARM

OBJECTIVES

- Define degrees of freedom and count them for a robot arm and for your own arm.
- Explain the job of an end effector and compare different designs.
- Build a cardboard arm, test three end effectors and record their success rates.

Warm-up. Keep your shoulder still and touch your nose with your fingertip. Now keep your elbow straight too. What can you still reach? Count how many different ways your arm can bend or turn from shoulder to fingertip.

WATCH

Canadarm & End Effector with Dee

Kennedy Space Center Visitor Complex · 6:41

<https://www.youtube.com/watch?v=5r5xkUVJ96E>

WHEN TO WATCH

After the story paragraph.

BACKUP VIDEO

What is a 6-Axis Robot?

RealPars · 8:19

<https://www.youtube.com/watch?v=UxO0xqvVGcM>

After the physics paragraph: how six-axis factory robots move.

KEY TERMS

degree of freedom (DOF)

One independent way a joint can move, such as one rotation or one slide. A rigid object in space has six: three slides and three rotations.

joint

A connection between two links of a robot arm that lets them rotate (revolute joint) or slide (prismatic joint).

end effector

The tool at the end of a robot arm that does the work: a gripper, suction cup, welding torch, snare or hand.

workspace

All the points a robot arm can reach.

torque

The turning effect of a force about a joint: $\text{force} \times \text{distance}$ (N·m). A motor at the shoulder must supply enough torque to hold the arm and its load.

CORE IDEAS

The story. When NASA designed the Space Shuttle in the 1970s, it needed a way to lift satellites out of the cargo bay and catch them again in space. Canada offered to build the arm. Engineers at Spar Aerospace and Canada's National Research Council designed the Shuttle Remote Manipulator System, soon nicknamed the Canadarm. It was about 15 meters (50 feet) long, as thin as a person's thigh, made of light carbon-fiber tubes, and so slender that it could not lift even its own weight on Earth. In space, where everything floats, it could move satellites heavier than a loaded bus. It first flew on the Shuttle *Columbia* in November 1981 and went on to work on about 90 missions, helping to repair the Hubble Space Telescope and build the International Space Station, until the Shuttle retired in 2011.

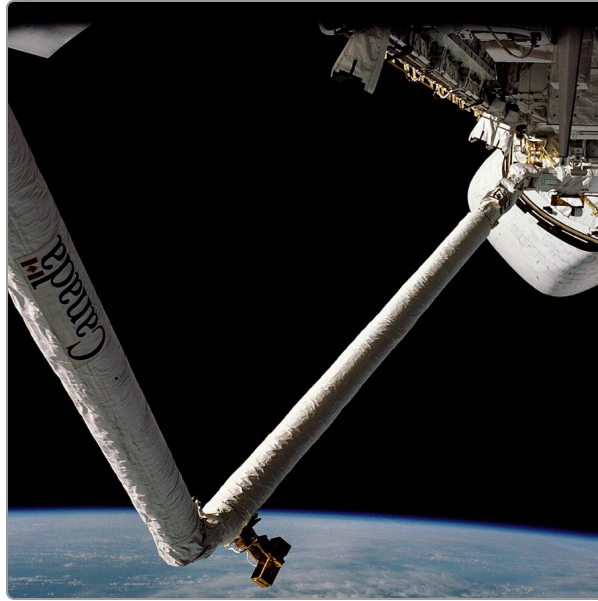
How they figured it out. The designers copied the human arm. The Canadarm has a shoulder that can swing side to side and up and down, an elbow that bends, and a wrist that can pitch, yaw and roll: six joints, giving six degrees of freedom, enough to put its end in any position and point it in any direction within reach. Because it could not be tested lifting itself on Earth, engineers tested it on a flat floor with air bearings, like a giant air-hockey table, and in computer simulations. The end effector was clever: instead of fingers, it had a hollow cylinder with three wires inside that twisted closed like a snare around a pin, called a grapple fixture, mounted on each payload. It could catch a pin even if the arm was a little off target, and it never let go accidentally.

The physics. Each joint adds one **degree of freedom**. A rigid object floating in space can move in six independent ways: forward-back, left-right, up-down, and rotate in pitch, yaw and roll. So a robot needs at least six DOF to place a tool anywhere in any

orientation; your arm, from shoulder to wrist, has seven. The joints near the base must be strongest, because they hold everything beyond them. The **torque** a joint must supply is $\text{force} \times \text{distance}$: to hold a 0.20 kg can 0.30 m from the shoulder, the shoulder needs $0.20 \times 9.8 \times 0.30 \approx 0.59 \text{ N}\cdot\text{m}$, plus whatever is needed to hold up the arm itself. Doubling the reach doubles the torque, which is why robot arms are built with heavy motors near the base and light links far out.

The engineering. Robot designers choose the fewest degrees of freedom that will do the job, because each joint adds cost, weight, error and things to break. A factory arm that only moves boxes from one belt to another may need four; a surgical robot or a space arm needs six or seven. The end effector is often the hardest part and is designed for each task: suction cups for flat boxes, soft fingers for fruit, magnets for steel sheets, welding torches, paint sprayers. Engineers measure success rate, speed and accuracy, and they design for safety, because a strong, fast arm can hurt a person; factory robots work behind fences or slow down and stop when sensors detect someone nearby.

PICTURE STUDY



The Canadarm's First Flight in Space, NASA astronaut photograph, November 1981 · Photograph · NASA, Space Shuttle mission STS-2

Image: [Wikimedia Commons](#), public domain

On the second Space Shuttle mission, astronauts tested the Canadarm in space for the first time. This photograph was taken through the windows at the back of the flight deck, where the operator stood.

Look closely

- Find the shoulder joint where the arm attaches to the Shuttle.
- Find the elbow and the wrist.
- Look at the end effector at the tip. What shape is it?
- Look at the Earth below. Where is the Shuttle in relation to it?

Talk about it

1. Why could this arm not lift its own weight on Earth but move huge satellites in space?
2. How many degrees of freedom do you think you can see in the arm's joints?
3. Why would the operator need cameras on the arm as well as the windows?

Safety first. An adult cuts cardboard with a craft knife. If you use syringes with water for hydraulics, work over a tray.

BUILD

A Cardboard Arm with Interchangeable End Effectors

You will build a cardboard robot arm with three degrees of freedom, worked by strings or syringe hydraulics, and then design and test three different end effectors on the same set of objects, recording the success rate of each.

You will need

- Corrugated cardboard, brass paper fasteners for joints, a paper plate or lazy Susan for the turning base
- String and straws as guides, or 4–6 plastic syringes with tubing and water for hydraulics
- Craft sticks, rubber bands, binder clips, tape, a few small magnets, a balloon or plastic bag, and pipe cleaners for end effectors
- Test objects: a ping-pong ball, a small wooden block, a paper clip, a crumpled paper ball, a bottle cap
- A stopwatch and engineer's notebook

Steps

1. **Plan.** Sketch an arm with a rotating base (DOF 1), a shoulder that tilts up and down (DOF 2) and an elbow (DOF 3). Mark the length of each link.
2. Build the base, upper arm and forearm from layered cardboard. Join them with paper fasteners. Make each joint move by pulling a string (with a rubber band to pull it back) or by pushing a syringe.
3. Draw the arm's workspace on a large sheet of paper: mark every spot the tip can reach on the table.
4. **Design three end effectors** that clip onto the forearm: for example, a two-finger pincer closed by a string, a scoop, and a pipe-cleaner snare or a magnet.
5. **Predict.** For each end effector, predict which objects it will pick up most reliably.
6. **Test.** Place each object in the same marked spot. Try to pick it up and drop it into a cup 15 cm away, 10 times with each end effector. Record successes and

the average time.

7. Make a table and bar graph of success rate for each end effector and object.

8. **Improve.** Take your best end effector and change one thing to raise its success rate on the hardest object. Test it 10 more times.

Tips

- Stiff, double-layered cardboard links bend less and make the arm more accurate.
- If the shoulder droops, the load is too far out or the string is too weak: a lesson in torque.
- Assign one person to run the arm and another to record, then switch.

Check your work

- ☐ I can count my arm's degrees of freedom and describe each.
- ☐ I can compare end effectors using success-rate data.
- ☐ I can explain why the shoulder joint must be the strongest.

ENGINEER'S NOTEBOOK

1. Draw your arm with each joint labeled with the motion it allows. Shade its workspace.
2. Make a table and bar graph of success rate by end effector and object.
3. A robot arm holds a 1.5 kg tool 0.8 m from its shoulder. What torque must the shoulder supply just for the tool? If the reach doubles, what is the new torque?

From history. Canada built a larger, smarter arm for the International Space Station, Canadarm2, which can move end over end along the station like an inchworm, and a robot “hand,” Dextre, for fine work. The Canadarm itself is displayed at the Canada Aviation and Space Museum in Ottawa.

COMMON MISTAKES

- Counting a joint twice, or counting the gripper opening as a degree of freedom of the arm's position.
- Changing the object's position between trials.
- Forgetting that the arm's own weight also needs torque.

Make it a game • Count the Joints. Hold your arm out and count the degrees of freedom at shoulder, elbow and wrist while your parent checks. Then your parent names a robot arm, such as the Canadarm, and you count its DOF. Pick an end effector for tasks they name: egg, bolt, paper. Defend each choice.

8.2 FEEDBACK CONTROL: SPERRY'S AUTOPILOT AND A CODED CRUISE CONTROL

OBJECTIVES

- Explain open-loop and closed-loop (feedback) control, with the terms setpoint, error and gain.
- Explain how a gyroscopic autopilot kept an airplane level.
- Program a proportional controller and test how the gain affects speed, overshoot and oscillation.

Warm-up. Balance a broom or a long ruler upright on your palm. Notice what your eyes and hand are doing. Now try with your eyes closed. Why is it so much harder? Write down the sensor, the decision and the action in this game.

WATCH

PID Control - A brief introduction

[Brian Douglas](#) · 7:44

<https://www.youtube.com/watch?v=UR0hOmjaHp0>

WHEN TO WATCH

After the physics paragraph. Pause on each part of the loop diagram and say it in your own words.

BACKUP VIDEO

The First Autopilots - How Lawrence Sperry Revolutionized Flight Control

[Planes, Trains & Automobiles](#) · 3:28

<https://www.youtube.com/watch?v=MU-Ta6UASUM>

After the story: more about Lawrence Sperry and the first autopilots.

KEY TERMS

open-loop control

Control that does not check the result, like a toaster that runs for a set time no matter how brown the toast is.

feedback (closed-loop) control

Control that measures the result and keeps adjusting to reach the goal.

setpoint

The value the system is trying to reach, such as 21 °C or 25 m/s.

error

Setpoint minus the measured value.

proportional control

A controller whose correction is the error multiplied by a gain: $\text{output} = K_p \times \text{error}$.

gyroscope

A spinning wheel, or today a tiny vibrating chip, that resists changes in its direction and senses rotation.

CORE IDEAS

The story. Elmer Sperry, an American inventor, built gyroscopic compasses and stabilizers for ships in the early 1900s. A spinning gyroscope keeps pointing the same way, so it can sense when the vehicle around it tips or turns. His son Lawrence, a young pilot, worked with him to build a gyroscopic stabilizer for airplanes. On June 18, 1914, at an aviation safety contest near Paris, Lawrence Sperry flew a Curtiss flying boat low past the crowd and the judges with both hands raised off the controls, while his mechanic, Emil Cachin, climbed out and walked along the wing. The extra weight on one side should have tipped the airplane, but the gyroscopes sensed the tilt and moved the controls to hold it level. Sperry won the first prize of 50,000 francs.

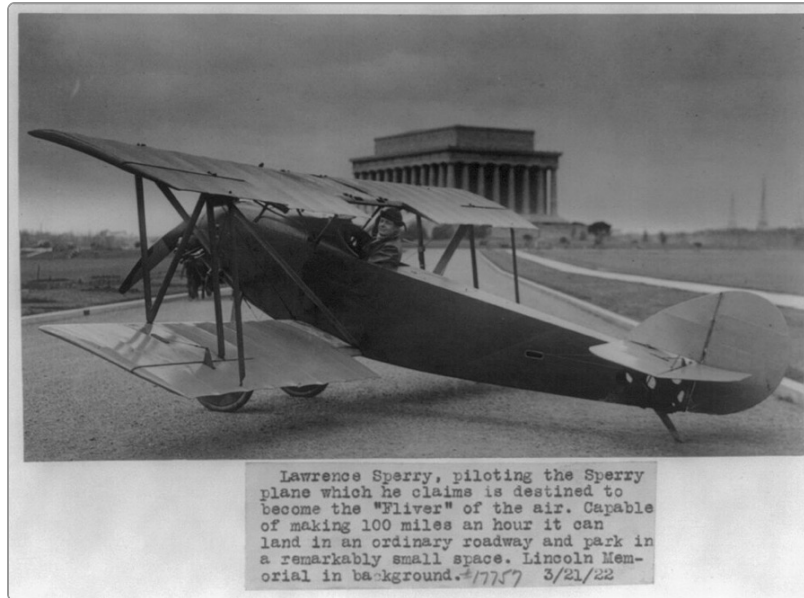
How they figured it out. The stabilizer used four gyroscopes. When the airplane rolled or pitched away from level, the gyroscopes stayed put, so the airplane moved relative to them. That movement opened air valves that drove the ailerons and elevator to push the airplane back toward level. The Sperrys had to tune the system so the correction was strong enough to fight a gust but not so strong that the airplane overshot and rocked back and forth. Later autopilots added a compass so the airplane could hold a heading, and by 1933 Wiley Post used a Sperry autopilot to fly around the world alone.

The physics. Every feedback controller follows the same loop: a **sensor** measures, the controller computes the **error** (setpoint – measurement), and an **actuator** acts to reduce it; then it measures again. In **proportional control**, $\text{correction} = K_p \times \text{error}$. Suppose a cruise control is set to 25 m/s and the car is going 20 m/s: the error is 5 m/s, and with $K_p = 0.4$, the controller adds $0.4 \times 5 = 2$ units of throttle. As the car speeds up, the error and the correction shrink. If K_p is too small, the car creeps

toward its target and may never quite reach it against wind and hills. If K_p is too large, it overshoots, then over-corrects, and oscillates. Engineers often add terms that respond to the error's history and its rate of change; with all three, this is called a PID controller.

The engineering. Feedback control is everywhere: thermostats, cruise control, the speed of a hard drive, the level of water in a toilet tank, a robot arm holding position, a drone holding still in the wind, and the insulin pumps that help people with diabetes. Engineers design controllers by modeling the system, simulating it, and then tuning the gains on the real machine, carefully, because a badly tuned controller can shake a machine apart. They also plan for sensor failure: an autopilot must notice when a sensor gives impossible readings and hand control back to the pilot.

PICTURE STUDY



Lawrence Sperry, National Photo Company, 1922 · Photograph · Library of Congress, Prints and Photographs Division

Image: [Wikimedia Commons](#), public domain

This 1922 photograph shows Lawrence Sperry in a small airplane of his own design, which he hoped would become an airplane for ordinary people. He landed it on the plaza near the Lincoln Memorial. Eight years earlier, at 21, he had won the 1914 safety prize with his gyroscopic stabilizer.

Look closely

- Look at the airplane. Where would a stabilizer have to move the controls?
- Find the control surfaces you can see: ailerons, elevator, rudder.
- Look at the size of the airplane compared with Sperry.
- Look for any instruments or equipment.

Talk about it

1. What would a gyroscope sense in this airplane, and what would it move?
2. Why is it dangerous for a stabilizer to over-correct?
3. What tasks today could a person safely hand to an autopilot, and which should a person still do?

Safety first. Screen time for this lesson should be used for programming and testing, not games. A parent sets up any accounts.

BUILD

Tuning a Cruise Control

You will program a simple car simulation in Scratch (or MakeCode) with a proportional cruise controller, then test different gains and measure how quickly the car reaches its target speed, how far it overshoots and whether it oscillates. This is how engineers tune controllers before trusting them with a real machine.

You will need

- A computer with free Scratch (scratch.mit.edu) or Microsoft MakeCode
- Engineer's notebook and graph paper
- Optional: a micro:bit, to repeat the idea with its built-in accelerometer as a tilt-balancing game

Steps

1. **Make variables:** speed, target, error, throttle, Kp. Set target to 25 and speed to 0 when the green flag is clicked.
2. **Write the loop** (repeat 300 times, with wait 0.05 seconds): set error to target – speed; set throttle to $K_p \times \text{error}$; if throttle is greater than 5, set it to 5 (the engine's limit); change speed by throttle $\times 0.1$; change speed by $-(\text{speed} \times 0.02)$ for drag; add speed to a list called log.
3. Show speed on the stage and make the car sprite move to an x-position that grows with speed, so you can see it.
4. **Predict.** What will happen with $K_p = 0.05, 0.3$ and 2? Sketch your predicted speed graphs.
5. **Test.** Run each gain. Export or copy the log, and from it record: the time to first reach 24 m/s, the highest speed (overshoot) and the final speed after the run.
6. Graph speed against time for all three gains on one set of axes.
7. **Add a hill.** Halfway through each run, add a constant -0.3 to speed every loop (the hill). Which gain holds the speed best? Does any gain leave a steady error?

8. **Improve.** Find the gain that reaches the target fastest with less than 1 m/s overshoot. Then try adding a small term that slowly adds up the error (integral control) and see if it removes the steady error on the hill.

Tips

- Change only K_p between runs.
- If the speed shoots off to huge numbers, check the sign of your error: it must be target – speed.
- Label your graphs with the gain used.

Check your work

- ☐ I can draw and label a feedback loop.
- ☐ I can explain how the gain changes the controller's behavior.
- ☐ I can explain how Sperry's gyroscopes kept an airplane level.

ENGINEER'S NOTEBOOK

1. Draw the feedback loop for the cruise control and for Sperry's stabilizer, with the sensor, controller, actuator and setpoint labeled.
2. Make a table of gain, time to reach the target, overshoot and final speed, and a graph of all three runs.
3. A thermostat's setpoint is 21 °C and the room is 17 °C. With $K_p = 0.5$ (in "heater units" per degree), what is the controller's output? What is it when the room reaches 20 °C?

From history. Elmer Sperry founded the Sperry Gyroscope Company, which made gyrocompasses for ships and instruments for airplanes for decades. Lawrence Sperry also invented an early turn indicator, one of the instruments that let pilots fly safely in clouds.

COMMON MISTAKES

- Thinking a bigger gain is always better.
- Measuring only the final speed and missing the overshoot.
- Confusing the setpoint with the measured value.

Make it a game • Error and Gain Game. Walk to a target mark with your eyes mostly closed while your parent calls out the error: "two steps too far." Adjust your step size by a fixed fraction of the error, which is proportional control. Compare gains, big and small. Explain setpoint, error and why Sperry's gyroscope autopilot used feedback.

8.3 SENSORS AND AUTONOMOUS VEHICLES: FROM SOJOURNER TO THE DARPA CHALLENGE

OBJECTIVES

- Explain how lidar, radar, ultrasonic sensors and cameras measure distance, and why vehicles combine them.
- Calculate a time-of-flight distance and a stopping distance.
- Build a touch sensor for a model rover and test how its speed affects how far it travels before stopping.

Warm-up. Close your eyes and have a partner guide you across the room by giving only one-word commands (“forward,” “stop,” “left”). Then try it with your partner only clapping when you are about to bump something. Which was safer? What “sensors” did you use?

WATCH

How Stanley Sees

Smithsonian National Air and Space Museum • 3:10

<https://www.youtube.com/watch?v=DEuWL9OawWk>

WHEN TO WATCH

After the story paragraph.

BACKUP VIDEO

How do self-driving cars “see”? - Sajan Saini

TED-Ed • 5:24

https://www.youtube.com/watch?v=PRg5RNU_JLk

After the physics paragraph: how self-driving cars combine sensors.

KEY TERMS

autonomous vehicle

A vehicle that senses its surroundings, plans a path and drives itself without a human at the controls.

time of flight

Measuring distance by timing a pulse of light, radio or sound to an object and back: $\text{distance} = \text{speed} \times \text{time} \div 2$.

lidar

A sensor that measures distance with pulses of laser light, often spinning to build a 3D map.

radar

A sensor that measures distance and speed with radio waves; works in rain and fog.

ultrasonic sensor

A sensor that measures short distances with pulses of high-pitched sound, as in a car's parking sensors.

sensor fusion

Combining several sensors so the strengths of one cover the weaknesses of another.

CORE IDEAS

The story. On July 4, 1997, NASA's Mars Pathfinder lander bounced down onto Mars inside a cluster of airbags, and two days later a small six-wheeled rover named Sojourner, about the size of a microwave oven, rolled down a ramp onto the surface. Radio signals took about ten minutes to travel between Earth and Mars, too long for drivers on Earth to steer it like a remote-control car. So engineers at the Jet Propulsion Laboratory gave Sojourner a little independence: drivers chose a target, and Sojourner found its own way there, shining laser stripes ahead and watching them with its cameras to spot rocks and drops it should avoid. On Earth, the U.S. defense research agency DARPA challenged teams in 2004 to build a car that could drive itself 142 miles across the Mojave Desert. No car finished; the best went about 7.4 miles. In October 2005 the challenge was held again, and five cars finished. The winner, Stanford University's "Stanley," a modified SUV, completed the 132-mile course in under seven hours.

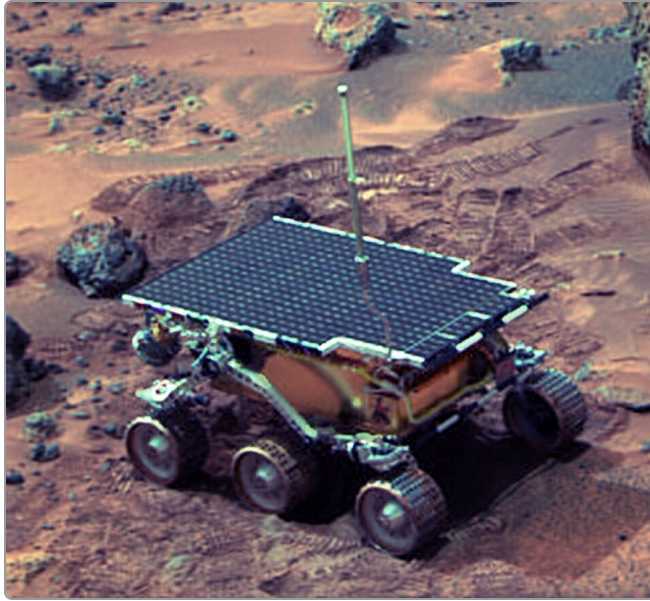
How they figured it out. The teams of 2004 learned that the hardest problem was not steering but seeing: telling a bush from a boulder, a shadow from a ditch, at speed. Stanley's team, led by Sebastian Thrun, fitted the car with five lidar units, a camera, radar and GPS, and wrote software that let the car learn from human driving which kinds of ground were safe. The lidars mapped the ground near the car precisely; the camera, trained by the lidar, recognized safe road much farther ahead, so the car could drive faster. Combining sensors, and letting each check the others, made the difference.

The physics. Many distance sensors use **time of flight**: send a pulse, time the echo, and calculate $\text{distance} = \text{speed} \times \text{time} \div 2$ (the pulse goes there and back). Light travels at 300,000,000 m/s, so a lidar pulse from an object 30 m away returns in 2×30

$\div 300,000,000 = 0.0000002$ s, 200 billionths of a second. Sound travels at about 343 m/s, so an ultrasonic echo from 1 m returns in about 0.0058 s. Every vehicle also needs a **stopping distance**: the distance traveled while reacting plus the distance while braking, $d = v \times t_{\text{react}} + v^2 \div (2a)$. At 25 m/s (about 56 mph), with a computer reaction time of 0.1 s and braking of 7 m/s^2 , $d = 2.5 + 625 \div 14 \approx 2.5 + 44.6 \approx 47$ m. The sensors must reliably see farther than that.

The engineering. Every sensor has weaknesses. Cameras see color and read signs but struggle in glare and darkness; lidar measures distance precisely but can be confused by heavy rain or snow; radar sees through fog and measures speed but gives a blurry picture; ultrasonic sensors are cheap but only work up close. Engineers combine them, build in backups, and test vehicles over millions of miles in simulation and on real roads. Robots in warehouses, farms, mines and on other planets already drive themselves in controlled settings. On busy public streets, engineers must prove a level of safety at least as good as a careful human driver, which is a very high bar.

PICTURE STUDY



Sojourner on Mars, NASA/JPL, 1997 · Photograph from the Mars Pathfinder lander · NASA Jet Propulsion Laboratory

Image: [Wikimedia Commons](#), public domain

The Mars Pathfinder lander's camera took this picture of Sojourner exploring the rocks near the landing site. Every move the rover made was planned on Earth and carried out by the rover itself, using its own sensors to avoid hazards.

Look closely

- Find Sojourner's six wheels. Why six instead of four?
- Find the flat solar panel on top.
- Look at the rocks and the ground. Which ones would be hazards for a small rover?
- Look for the tracks Sojourner left in the soil.

Talk about it

1. Why could engineers on Earth not simply steer Sojourner with a joystick?
2. What sensors would Sojourner need to avoid the rock in front of it?
3. How is driving on Mars like and unlike driving a car on a road?

Safety first. Use only batteries for the sensor circuit. Test the rover on the floor, away from stairs, and keep the ramp low.

BUILD

A Touch-Sensor Bumper and a Stopping-Distance Test

You will build a bumper switch from foil and cardboard that lights an LED or sounds a buzzer the instant your model rover touches an obstacle. Then you will roll the rover down a ramp at different speeds and measure how far it would travel after the sensor triggers, to see why faster vehicles need sensors that see farther ahead.

You will need

- A toy car or a simple cardboard rover on wheels
- Aluminum foil, cardboard, a small piece of sponge as a spring, tape
- A 2-AA battery holder, an LED with a 100 Ω resistor or a small buzzer, wires and alligator clips
- A ramp (a board on books), a tape measure, a smartphone with slow-motion video, and a soft obstacle (a sofa cushion or a box with a pillow taped to it)

Steps

1. **Build the switch.** Tape a strip of foil to the front of the rover. Tape a second foil strip to a cardboard bumper that sits 1 cm in front of it, held apart by a sponge. When the bumper is pushed, the foils touch.
2. Wire the battery, LED (with resistor) or buzzer, and the two foils in series. Press the bumper: the light should turn on. That is your sensor.
3. Place the obstacle 30 cm beyond the bottom of the ramp. Mark release heights of 5, 10 and 15 cm.
4. **Predict.** Calculate the speed at the bottom for each height with $v = \sqrt{2gh}$ (from Unit 1). Predict which run will press the bumper hardest and farthest.
5. **Test.** Film each run in slow motion from the side with a ruler in view. Find the frame where the light turns on and measure how far the rover traveled after that frame before stopping (the cushion absorbs it). Three runs per height.

6. Calculate the speed for each run from the video (distance over a few frames $\div$ time). Graph distance traveled after triggering against speed.
7. Calculate how far ahead a sensor would have to detect the obstacle for the rover to stop before touching it, if it took 0.2 s to react and could brake at 2 m/s^2 .
8. **Improve.** Redesign the sensor so it detects the obstacle before contact: a longer “whisker” bumper. Test whether it triggers early enough to stop the rover (you can stop it by hand when the light comes on, timing your own reaction).

Tips

- A light sponge keeps the foils apart until a real touch; too stiff and the sensor needs a big push.
- Count frames: most slow-motion video is 120 or 240 frames per second.
- If the light flickers, the foils are making poor contact; add more foil.

Check your work

- ☐ I can explain how my bumper sensor works as a switch.
- ☐ I can calculate a time-of-flight distance and a stopping distance.
- ☐ I can explain why faster vehicles need longer-range sensors and why vehicles combine several sensors.

ENGINEER'S NOTEBOOK

1. Draw a self-driving car seen from above and mark where you would put lidar, radar, cameras and ultrasonic sensors, with the range of each drawn as a shaded area.
2. Make a table and graph of speed and distance after triggering.
3. An ultrasonic sensor hears an echo 0.012 s after sending its pulse. How far away is the object? A lidar pulse returns after 0.0000004 s. How far away is that object?

From history. Sojourner was designed to last a week but worked for almost three months, driving about 100 meters in total and studying the rocks around the lander. Every Mars rover since has been more autonomous; NASA's Perseverance can plan its own path over hundreds of meters a day.

COMMON MISTAKES

- Forgetting to divide by 2 in time-of-flight distances.

- Thinking braking distance grows in proportion to speed. It grows with the square of the speed.
- Trusting a single sensor for every condition.

Make it a game · Stopping Distance Bet. Roll a small toy toward a wall and mark where a bumper triggers a stop. Predict the stopping distance at a higher speed. Calculate a lidar time-of-flight distance, such as a light pulse that returns in 20 nanoseconds. Explain why vehicles combine lidar, radar, ultrasound and cameras. Closest prediction wins.

Scripture. “If I take the wings of the morning, and dwell in the uttermost parts of the sea; Even there shall thy hand lead me, and thy right hand shall hold me.” (Psalm 139:9-10, KJV)

Engineers work hard to guide machines where no person can follow. The psalmist knew that no place, however far, is beyond the guiding hand of God.

8.4 HOW A QUADCOPTER FLIES, AND THE FAMILY ENGINEERING FAIR

OBJECTIVES

- Explain how a quadcopter hovers, climbs, turns (yaws) and moves, and why its propellers spin in opposite directions.
- Calculate the thrust each motor needs and the thrust-to-weight ratio.
- Measure the thrust of a hobby motor and propeller at different voltages, and present the capstone at the family engineering fair.

Warm-up. Drop a maple seed (or a paper helicopter) and watch it spin down. Then hold a spinning top or fidget spinner in your hand and try to tip it. What do you feel? A quadcopter uses both lift from spinning blades and the feeling you just noticed.

WATCH

How a Quadcopter Works - Flight Mechanics, Components, & Sensors (2).

EngineersEscape · 12:58

<https://www.youtube.com/watch?v=u-LfLW9Kgis>

WHEN TO WATCH

After the physics paragraph.

BACKUP VIDEO

HOW DO DRONES FLY?

The Travelling Scientist (Jesse Crowe) · 3:20

<https://www.youtube.com/watch?v=6Bc2nuOuRjM>

Optional: a shorter, simpler explanation.

KEY TERMS

quadcopter

A flying machine lifted and steered by four rotors, usually at the corners of an X-shaped frame.

thrust-to-weight ratio

Total maximum thrust ÷ weight. It must be greater than 1 to climb; about 2 is common for good control.

counter-rotation

Two rotors spinning one way and two the other, so their twisting effects on the frame (torques) cancel.

inertial measurement unit (IMU)

A chip with gyroscopes and accelerometers that senses rotation and tilt, used by the flight controller.

flight controller

The small computer that reads the IMU many times a second and adjusts each motor's speed to keep the drone stable.

CORE IDEAS

The story. The first machine to lift a person with spinning rotors was a quadcopter. In 1907 the French brothers Louis and Jacques Breguet, with Professor Charles Richet, built the Gyroplane No. 1, with four large rotors on long arms. It rose about half a meter off the ground with a pilot aboard, but men had to steady it because it could not be controlled. In 1922 the engineer George de Bothezat built a much larger four-rotor helicopter for the U.S. Army Air Service at McCook Field in Dayton, Ohio. In December 1922 it lifted off with a pilot, hovered for up to nearly two minutes, and made over a hundred flights, carrying up to four people, but it was hard to fly, slow and complicated, and the Army canceled the project in 1924. Single-rotor helicopters, with a tail rotor, won out for the next eighty years.

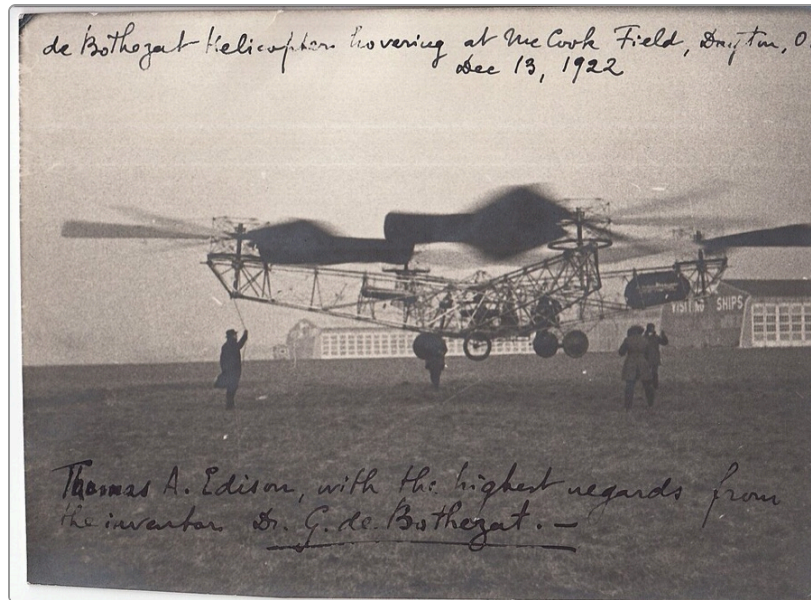
How they figured it out. The early four-rotor machines failed because a person could not adjust four rotors fast enough to keep the craft balanced. The answer came from electronics: by the late 2000s, tiny MEMS gyroscopes and accelerometers (the same sensors in phones), light lithium batteries, powerful brushless motors and cheap microcontrollers made it possible for a computer to measure the drone's tilt hundreds of times a second and adjust each motor's speed. The pilot, or the drone's own program, simply tells the flight controller what to do, and the feedback controller, like the one you built in Lesson 8.2, handles the balancing. Once that problem was solved, quadcopters became the most common drones in the world.

The physics. To **hover**, the four rotors together push down on the air with a force equal to the drone's weight; the air pushes back up (Newton's third law). A 0.80 kg drone weighs $0.80 \times 9.8 = 7.8$ N, so each rotor must make about 1.96 N, about 200 grams of thrust. For good control, each motor should be able to make about twice that, 400 g, a thrust-to-weight ratio of 2. To **climb**, all four speed up. To move

forward, the back two speed up so the drone tilts forward and part of its thrust pushes it ahead. Two rotors spin clockwise and two counterclockwise, so their twisting reactions on the frame cancel. To **yaw** (turn in place), the drone speeds up one pair and slows the other, so the twisting no longer cancels and the frame turns.

The engineering. Drone engineers balance weight, thrust and battery life: a bigger battery flies longer but weighs more, which needs more thrust, which drains the battery faster. Drones now inspect bridges, power lines, wind turbines and crops, map construction sites, help search-and-rescue teams and film from the air. With that usefulness comes responsibility. In the United States, recreational drone pilots must follow FAA rules: pass the free online Recreational UAS Safety Test (TRUST), register any drone of 250 grams or more, fly no higher than 400 feet, keep the drone within sight, and never fly over people, over moving vehicles, or near airports, emergency scenes or power lines. Check the FAA's website for the current rules before flying.

PICTURE STUDY



The de Bothezat Helicopter Hovering at McCook Field, U.S. Army Air Service photographer, December 13, 1922 · Photograph · McCook Field, Dayton, Ohio

Image: [Wikimedia Commons](#), public domain

Nearly a century before quadcopter drones filled the skies, the U.S. Army tested this four-rotor helicopter at McCook Field in Dayton, the same city where the Wright brothers had built their airplanes. De Bothezat signed this print for Thomas Edison.

Look closely

- Count the rotors and the blades on each rotor.
- Find the frame of tubes and wires holding the rotors apart. Why is it shaped like a cross?
- Find the pilot's seat and the engine in the middle.
- Look at the height of the machine above the ground.

Talk about it

1. How is this machine like a modern quadcopter, and how is it different?
2. Why would it have been so hard for a pilot to keep it balanced?
3. What modern inventions finally made four-rotor flight easy to control?

Safety first. Wear safety glasses. Mount the motor and propeller firmly so they cannot move, keep fingers, hair and loose clothing well away from the propeller, and disconnect the battery before touching it. Use only AA batteries. If you fly a real drone, an adult must be present and you must follow the FAA rules in the lesson. Never fly near people, roads, airports or power lines.

BUILD

A Propeller Thrust Test, and the Capstone Fair

First you will measure the thrust of a small hobby motor and propeller on a kitchen scale at three different voltages, measure the electrical power with a multimeter, and calculate how big a drone the motor could lift. Then you will finish your capstone project and present it, with your best builds from the year, at the family engineering fair.

You will need

- A small 1.5–3 V hobby motor with a light plastic propeller
- A battery holder for 1, 2 and 3 AA cells (or swap cells in a 3-cell holder with a wire jumper), alligator clips
- A stand: a short dowel or block taped firmly to a cup weighted with clay, with the motor taped on top so the propeller blows air upward
- A kitchen scale, a multimeter, safety glasses

Steps

1. Set the stand on the scale and press tare. The propeller blows air up, so its thrust pushes the motor down and the scale reading rises. (Check the direction: if the reading drops, reverse the battery wires.)
2. **Predict.** How will thrust change from 1 AA (1.5 V) to 2 AA (3 V) to 3 AA (4.5 V, briefly only)? Will doubling the voltage double the thrust?
3. **Test.** Connect 1 AA. Wait 3 seconds and record the thrust in grams. Measure the voltage across the motor and the current (meter in series). Disconnect. Repeat with 2 AA, then 3 AA for no more than 5 seconds. Three trials each.
4. Calculate electrical power ($P = V \times I$) and thrust per watt (grams $\div$ watts) for each voltage.
5. Graph thrust against power.
6. **Design calculation.** If a drone used four of these motors at their best setting with a thrust-to-weight ratio of 2, what is the most the whole drone could weigh? Is that realistic with batteries?

7. **Capstone and fair.** Finish your capstone (see the portfolio below). For the fair, set out your capstone and your best build from each unit, each with its notebook pages. Prepare a two-minute explanation of each that includes one calculation.
8. **Improve.** After the fair, write down the best question a visitor asked and how you would change your capstone in response.

Tips

- Small hobby motors heat up at higher voltages; keep runs short and let the motor cool.
- Shield the scale with a cardboard box so the propeller's wash does not push on it.
- Practice your fair explanations out loud to a family member first.

Check your work

- ☐ I can explain how a quadcopter hovers, climbs, moves and yaws.
- ☐ I can measure thrust and calculate thrust per watt and thrust-to-weight ratio.
- ☐ I can explain my capstone clearly, including one calculation.

ENGINEER'S NOTEBOOK

1. Draw a quadcopter from above with the spin direction of each rotor. Draw four small diagrams showing which motors speed up to climb, move forward, roll right and yaw left.
2. Make a table and graph of voltage, current, power and thrust.
3. A drone weighs 1.2 kg. What total thrust is needed to hover? What maximum thrust per motor would give a thrust-to-weight ratio of 2? Give answers in newtons and grams.

From history. Igor Sikorsky's VS-300 of 1939, with one main rotor and a small tail rotor, became the pattern for most helicopters. Sikorsky, a devout Christian who wrote books about his faith, lived to see his helicopters used to rescue many thousands of people.

COMMON MISTAKES

- Making all four propellers spin the same way, which makes the frame spin.
- Running a small motor at too high a voltage for too long.

- Forgetting to check the current FAA rules before flying a drone outdoors.

Make it a game · Opposite Spinners. Stand with a parent and spin your arms like a quadcopter pair: one clockwise, one counterclockwise. Show what happens if all four rotors spin the same way, then explain counter-rotation. Calculate thrust-to-weight for a 400 gram drone with 150 gram-force of thrust per motor. Name the IMU and flight controller.

UNIT 8

ROBOTICS

A robot senses the world, decides what to do and acts, over and over, many times a second. In this unit you will look at each part of that loop with the words and numbers robotics engineers use. You will count a robot arm's degrees of freedom and test end effectors, program a feedback controller and tune it, build a touch sensor and calculate how far ahead a self-driving vehicle must see, and measure the thrust of a drone motor and propeller.

The stories include the Canadarm that worked on the Space Shuttle for thirty years, Lawrence Sperry flying with his hands in the air above Paris in 1914, the little Sojourner rover finding its own way among the rocks of Mars, the robot cars of the DARPA Grand Challenge, and the first four-rotor flying machines of 1907 and 1922. The unit, and the year, ends with your capstone project and the family engineering fair.

PREREQUISITES

- Can write a program with loops and if-statements in Scratch, MakeCode or Arduino (Unit 4 and Grade 6)
- Knows sense–think–act (earlier grades)
- Can use $V = IR$, power and thrust (Units 4 and 7)

MASTERY CHECKLIST

- ☐ I can count the degrees of freedom of a robot arm and compare end-effector designs with data.
- ☐ I can explain feedback control and how the gain of a proportional controller changes its behavior.
- ☐ I can explain how lidar, radar, cameras and ultrasonic sensors measure distance, and calculate a stopping distance.
- ☐ I can explain how a quadcopter hovers, climbs, turns and moves, and calculate the thrust each motor must make.
- ☐ I can plan, build, test, improve and present a capstone engineering project.

OPTIONAL KITS FOR THIS UNIT

- **Makeblock mBot:** Ages 8 and up. A small wheeled robot with an ultrasonic distance sensor and line-follower sensors, programmed with free block coding; fits Lessons 8.2 and 8.3.
- **BBC micro:bit:** Ages 8 and up. Built-in accelerometer, compass and buttons, programmed in the free MakeCode editor; good for the feedback-control and sensor lessons.
- **Ryze Tello:** Ages 13 and up with an adult. A small indoor drone under 250 g that can be programmed with block coding; follow the FAA rules in Lesson 8.4.
- **CrunchLabs Build Box:** Ages 8 and up. Monthly engineering toys from Mark Rober, several with motors, gears and sensors; a fun source of capstone ideas.

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 Degrees of Freedom and End Effectors: The Canadarm 2 sessions of 50–60 minutes

8.2 Feedback Control: Sperry's Autopilot and a Coded Cruise Control

2 sessions of 50–60 minutes

8.3 Sensors and Autonomous Vehicles: From Sojourner to the DARPA Challenge

2 sessions of 50–60 minutes

8.4 How a Quadcopter Flies, and the Family Engineering Fair

2 sessions of 50–60 minutes, plus the fair

UNIT 8 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

What is a degree of freedom? How many does a robot need to place its tool at any position and in any orientation, and why?

2. 10 pts

Calculation: A robot shoulder holds a 2.0 kg load 0.5 m away. What torque does the load require? What if the load is moved to 1.0 m?

3. 8 pts

Describe the Canadarm's end effector and why it was a good design.

4. 8 pts

What is the difference between open-loop and closed-loop control? Give one example of each.

5. 10 pts

Calculation: A cruise control is set to 30 m/s. The car is going 26 m/s and $K_p = 0.5$. What is the error and the controller's output? What happens if K_p is made much larger?

6. 8 pts

How did Lawrence Sperry's 1914 stabilizer keep his airplane level when his mechanic walked out on the wing?

7. 10 pts

Calculation: An ultrasonic sensor hears an echo 0.006 s after sending a pulse (speed of sound 343 m/s). How far away is the object?

8. 10 pts

Calculation: A self-driving car at 20 m/s has a reaction time of 0.1 s and brakes at 8 m/s^2 . Find its stopping distance.

9. 8 pts

Why do autonomous vehicles use several kinds of sensors instead of one? Give one strength and one weakness of two different sensors.

10. 10 pts

Explain how a quadcopter yaws (turns in place), and why its propellers spin in opposite directions.

11. 10 pts

Written answer: A friend wants to fly a new 300-gram drone at a park near a small airport. What rules must he follow, and what would you advise?

ANSWER KEY

1. One independent way a joint (or object) can move. Six: three for position (forward-back, left-right, up-down) and three for orientation (pitch, yaw, roll).
2. $\tau = 2.0 \times 9.8 \times 0.5 = 9.8 \text{ N}\cdot\text{m}$. At 1.0 m: 19.6 N·m (doubled).
3. A hollow cylinder with three wires that twisted closed like a snare around a grapple pin on each payload. It could catch the pin even if slightly off target and held it securely.
4. Open-loop does not measure the result (a toaster timer, a simple sprinkler timer); closed-loop measures and corrects (a thermostat, cruise control, an autopilot).
5. Error = $30 - 26 = 4 \text{ m/s}$; output = $0.5 \times 4 = 2$. A much larger K_p makes it react faster but overshoot and oscillate.
6. Gyroscopes kept their direction, so when the airplane tilted they sensed it; the movement worked valves that drove the ailerons and elevator to bring the airplane back to level.
7. $d = \text{speed} \times \text{time} \div 2 = 343 \times 0.006 \div 2 \approx 1.03 \text{ m}$.
8. $d = v \times t + v^2 \div 2a = 20 \times 0.1 + 400 \div 16 = 2 + 25 = 27 \text{ m}$.
9. Each has weaknesses that another covers (sensor fusion). Examples: camera sees color and signs but struggles in glare and dark; lidar measures distance precisely but is affected by heavy rain and snow; radar works in fog and measures speed but gives a blurry picture; ultrasonic is cheap but short range.
10. Two rotors spin clockwise and two counterclockwise so their twisting reactions cancel. To yaw, the controller speeds up one pair and slows the other, so the reactions no longer cancel and the frame turns, while total thrust stays the same.
11. Pass the free TRUST test; register the drone (it is over 250 g); fly no higher than 400 feet; keep it in sight; never fly over people or moving vehicles; do not fly near the airport without authorization; check the FAA's current rules. Advise choosing a different, open field away from the airport, people and power lines.

PORTFOLIO PIECE: CAPSTONE PROJECT AND FAMILY ENGINEERING FAIR

Choose a real problem at home, at church or in your community that a machine, structure or device could help solve, such as an automatic plant-watering system, a stronger shelf bracket, a feeder that keeps squirrels out, or a robot arm that can pick up dropped items. Write a design brief (the problem, who it serves, the requirements and a budget), sketch at least two ideas, choose one with reasons, and build a working prototype. Test it fairly at least three times, improve it, and test again. At the family engineering fair, present your capstone with its notebook pages and a short talk that includes one calculation, the results of your tests and what you would do next.

LOOK FOR	WHAT IT MEANS
Design brief and planning	Clear statement of the problem, the people it serves, measurable requirements and a budget; at least two ideas compared.
Working prototype	The prototype works as intended and is built safely and neatly.
Testing and improvement	At least three fair tests before and after one improvement, with data recorded and graphed.
Engineering reasoning	At least one correct calculation from this year (forces, energy, electricity, flow or control) used in the design.
Presentation	Clear, honest explanation at the fair, including what did not work and what the student would change.

TOY LAB: THE ENGINEERING OF PLAY

Toys are some of the most carefully engineered objects in a home. They must work the first time and the thousandth time, survive being dropped and stepped on, cost little enough for families to buy, and above all be safe for children. In this optional bonus unit you will take four toys apart in your mind and on the workbench: the pinball machine with its solenoids and switches, the slot car with its motor and banked curves, the motion-sensing game controller with its tiny accelerometers and gyroscopes, and the plastic toy itself, which must be designed so it can be molded by the thousands.

Use the Toy Lab after the engineering fair, over the summer, or in any week that needs something fun. It reviews ideas from the whole year, electromagnets, friction, circular motion, sensors and manufacturing, and it ends with a portfolio project: designing a simple toy for manufacture and testing it for safety.

PREREQUISITES

- Has completed most of Units 1–8, especially electricity (Unit 4) and sensors (Unit 8)
- Can calculate with squares and square roots
- Can use a multimeter and a kitchen scale

MASTERY CHECKLIST

- ☐ I can explain how a solenoid works and how pinball machines use solenoids and switches.
- ☐ I can explain circular motion and use $v = \sqrt{\mu gr}$ and the banked-curve idea to explain why slot cars fly off curves.
- ☐ I can explain how a MEMS accelerometer and gyroscope sense motion and tilt.
- ☐ I can explain injection molding, draft angles and cost per part, and use the small-parts test for toy safety.
- ☐ I can design, test and improve a toy with safety and manufacturing in mind.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box:** Ages 8 and up. Monthly toy-engineering builds from Mark Rober, each with a video explaining the physics; an ideal companion to this unit.
- **KiwiCo crates:** Ages vary by line (Tinker 9–16, Eureka 14 and up). Many crates build working toys such as pinball games, arcade claws and motorized cars.
- **Snap Circuits:** Ages 8 and up. Includes motors, switches and electromagnets for no-solder toy circuits, useful for Lesson 9.1.

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 Pinball Machine: Solenoids, Switches and Scoring 2 sessions of 50–60 minutes

9.2 Slot Cars: Motors, Friction and the Banked Curve 2 sessions of 50–60 minutes

9.3 Game Controllers: Accelerometers and Gyroscopes 2 sessions of 50–60 minutes

9.4 Designing a Toy for Manufacture: Injection Molding and Toy Safety

2 sessions of 50–60 minutes

UNIT 9 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

How does a solenoid make a quick push or pull?

2. **10 pts**

Calculation: A solenoid has 300 turns and carries 1.5 A. What are its ampere-turns? How many turns would give the same strength at 0.5 A?

3. **8 pts**

How did electromechanical pinball machines keep score without computers?

4. **8 pts**

Why does a pinball flipper use a strong coil for the kick and a weaker holding coil?

5. **10 pts**

Calculation: A toy car takes a flat curve of radius 0.40 m with $\mu = 0.9$. What is the fastest speed it can go without sliding? ($g = 9.8 \text{ m/s}^2$)

6. **8 pts**

Explain how banking a curve lets a car go faster.

7. **8 pts**

An accelerometer lying still on a table reads 1 g. Why not zero?

8. **10 pts**

Calculation: A controller's accelerometer reads 0.71 g on its x-axis and 0.71 g on its z-axis. What is its tilt angle?

9. **8 pts**

Why do game controllers and phones combine accelerometers with gyroscopes?

10. **10 pts**

Calculation: A toy mold costs \$30,000. Each part needs \$0.06 of plastic and \$0.04 of machine time. Find the cost per part for 10,000 parts and for 300,000 parts.

11. **12 pts**

Written answer: Name three design rules for injection-molded parts and two safety tests for toys for young children, and explain why each matters.

ANSWER KEY

1. Current through the coil makes it an electromagnet, whose magnetic field pulls an iron plunger into its center.
2. $300 \times 1.5 = 450$ ampere-turns. $450 \div 0.5 = 900$ turns.
3. Targets closed switches that energized relays, which pulsed stepping units or turned score reels a notch at a time, adding points mechanically.
4. The strong coil gives a big quick impulse, but if left on it would overheat; the weak holding coil keeps the flipper up using little current.
5. $v = \sqrt{\mu g r} = \sqrt{(0.9 \times 9.8 \times 0.40)} = \sqrt{3.53} \approx 1.9$ m/s.
6. On a banked curve the track pushes perpendicular to its tilted surface, so part of that push points toward the center of the turn and supplies some of the centripetal force, so less friction is needed.
7. It cannot tell gravity from acceleration; the table pushes it up, and the sensor reads the 1 g of gravity, which is how it knows which way is down.
8. $\theta = \arctan(0.71 \div 0.71) = \arctan(1) = 45^\circ$.
9. Accelerometers find the direction of gravity but are fooled by shaking; gyroscopes measure quick turns well but drift over time. Together (sensor fusion) they give accurate, steady readings.
10. 10,000: $30,000 \div 10,000 + 0.10 = \$3.10$. 300,000: $30,000 \div 300,000 + 0.10 = \$0.20$.
11. Rules (any three): draft angles so parts release; even wall thickness so parts cool evenly without sinks or warping; rounded inside corners to prevent cracks; ribs instead of thick blocks; allowance for shrinkage. Safety (any two): the small-parts cylinder test (choking hazard for children under 3); drop, twist and pull tests so pieces cannot break off; sharp-edge and point tests; locked-in magnets and button batteries; chemical tests of paints and plastics. Each rule or test exists because poor design caused broken parts or injured children.

PORTFOLIO PIECE: A TOY DESIGNED FOR PLAY, SAFETY AND MANUFACTURE

Design a simple toy for a child of a particular age (for example a spinning top, a rolling toy, a marble game or a small puzzle). Make a labeled drawing showing how each part would be injection molded, with draft angles, wall thickness and parting lines marked. Build a prototype from cardboard, clay, plaster or wood. Test it with a fair test of how well it plays (for example spin time, roll distance or score), run the small-parts and drop tests, and calculate a cost per part for 10,000 and 100,000 toys. Write a one-page report and present it as if pitching it to a toy company.

LOOK FOR	WHAT IT MEANS
Design for manufacture	Drawing shows parts, parting lines, draft angles and even walls, with sensible dimensions.
Play test	A fair test of how well the toy works, repeated at least three times, with data recorded.
Safety tests	Small-parts and drop tests carried out correctly and the design changed if it failed.
Cost calculation	Cost per part calculated correctly for two quantities, with a sentence on what it means.
Presentation	Clear explanation of who the toy is for, how it works, why it is safe and what the student would improve.

9.1 THE PINBALL MACHINE: SOLENOIDS, SWITCHES AND SCORING

OBJECTIVES

- Explain how a solenoid turns electric current into a strong, quick push or pull.
- Describe how electromechanical pinball machines used switches, relays and solenoids to score and react.
- Build a solenoid and test how the number of turns and the battery voltage change its pull.

Warm-up. Tilt a cookie sheet or a board slightly and roll a marble down it. Put a ruler across the bottom as a flipper and try to bat the marble back up. How far up the slope can you send it? What would make it go higher?

WATCH

How a Pinball Machine works in Slow Motion - The Slow Mo Guys

The Slow Mo Guys • 13:54

<https://www.youtube.com/watch?v=Tmg5WOvPKpU>

WHEN TO WATCH

After the physics paragraph. Watch the flippers, bumpers and slingshots in slow motion and name the solenoid in each.

Note: The machines shown have commercial movie and comic themes; focus on the mechanisms. Stop at the end of the teaching.

KEY TERMS

solenoid

A coil of wire that becomes an electromagnet when current flows, pulling an iron plunger into its center.

plunger

The iron rod pulled into a solenoid; in pinball it kicks a flipper, bumper or kicker.

relay

A switch worked by an electromagnet, so one circuit can turn another on or off.

electromechanical (EM)

Machines that use switches, relays, motors and spinning score reels instead of computer chips to keep track of a game.

impulse

Force $\times$ time. A solenoid gives the ball a large force for a very short time.

CORE IDEAS

The story. Pinball grew out of bagatelle, an indoor game played in France in the 1700s in which players shot balls up a sloping board studded with pins. In 1871 Montague Redgrave patented an improved bagatelle with a spring plunger to shoot the ball, the same plunger pinball machines still have. In 1931 David Gottlieb's coin-operated *Baffle Ball* became a sensation, and within a few years designers added batteries and electricity: bumpers that kicked the ball away, lights, bells and scores counted automatically. The flipper, the part that lets the player keep the ball alive, did not appear until 1947, on Gottlieb's *Humpty Dumpty*, designed by Harry Mabs.

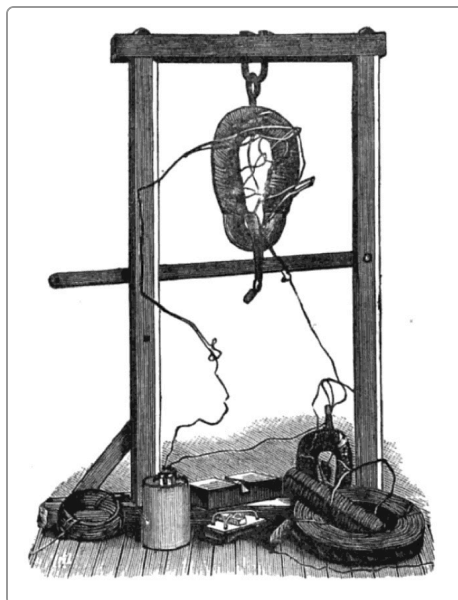
How they figured it out. Early electric machines had to do arithmetic without computers. Designers used chains of switches and relays: when the ball hit a target, it closed a switch, which energized a relay, which pulsed a stepping unit or turned a score reel one notch. To add 100 points, a relay might pulse the hundreds reel once; to add 1,000, it pulsed the thousands reel. Bumpers used a ring around the post that, when hit, closed a switch that fired a solenoid, pulling the ring down to kick the ball away. Engineers had to tune every spring and coil so that the machine felt lively but did not wear itself out, and they built in a "tilt" switch, a weighted pendulum inside a ring, that stopped the game if a player shook the machine too hard.

The physics. A **solenoid** is an electromagnet shaped as a coil. When current flows, the coil's magnetic field pulls an iron plunger into the middle. The strength of the field grows with the current and with the number of turns of wire, so engineers describe a solenoid by its **ampere-turns**: 0.5 A through 400 turns gives 200 ampere-turns, the same as 1 A through 200 turns. A pinball flipper is a lever worked by a solenoid: the plunger pulls a short arm, and the long flipper swings fast. The ball, a steel sphere of about 80 grams, rolls down a playfield tilted about 6.5°; its

acceleration down the slope is about $g \times \sin 6.5^\circ \times 5/7 \approx 0.79 \text{ m/s}^2$, since part of its energy goes into rolling. The flipper must give it a large **impulse**, a big force for a few thousandths of a second.

The engineering. A solenoid that stays powered gets hot, so pinball flippers use two windings: a strong coil for the quick kick and a weak holding coil once the flipper is up, switched by an end-of-stroke switch. Designers protect the coils with diodes, choose plunger springs, rubber rings and steel guides that survive millions of hits, and lay out the playfield so that skill, not luck, decides the score. Since the late 1970s, pinball machines have used computers instead of relays, but the solenoids and switches are the same. Solenoids are also the hidden workers in door locks, car starters, washing-machine valves and doorbells.

PICTURE STUDY



Joseph Henry's Great Electromagnet, Unknown engraver, About 1880 · Engraving · From a nineteenth-century account of Henry's experiments
Image: [Wikimedia Commons](#), public domain

In the late 1820s and 1830s the American scientist Joseph Henry discovered that many turns of insulated wire wound around iron made a far stronger electromagnet than a few turns. One of his magnets could lift more than a ton. Every pinball solenoid uses his discovery.

Look closely

- Find the iron core shaped like a horseshoe.
- Look at the wire wound around it. Why is it wrapped so thickly?
- Follow the wires down to the battery cell.
- Find the spare coils of wire on the floor.

Talk about it

1. Why did Henry insulate the wire, so that he could wind many turns close together?
2. How is this magnet like a solenoid, and how is it different?
3. Why would a pinball designer want a solenoid that is strong for a moment but not left on?

Safety first. Use only AA or D batteries. A solenoid is nearly a short circuit: connect it only for a second or two at a time, and disconnect it if the wire or battery gets warm. Wear safety glasses when the plunger is launched. Do not open any real pinball machine; they run on high voltage.

BUILD

Build and Test a Solenoid Kicker

You will wind a solenoid around a drinking straw, use it to pull a nail into the coil, and measure how hard it pulls. Then you will test how the number of turns and the number of batteries change its pull, and use it to kick a marble.

You will need

- A drinking straw, about 20 m of magnet wire (about 26 gauge), fine sandpaper, tape
- Iron nails that slide freely inside the straw (about 5–7 cm long)
- A D-cell holder for 1 or 2 cells, alligator clip leads, a push button or bare-wire switch
- A kitchen scale, a small cup of paper clips, a ruler, a marble
- A multimeter

Steps

1. Wind 100 turns of magnet wire neatly around the middle 4 cm of the straw. Tape it. Sand the ends of the wire.
2. **Measure pull.** Hang the nail half inside the straw from a thread tied to a cup on the kitchen scale (or rest the coil on the scale with the nail fixed above it). Press the button for one second and read the change on the scale. Convert to newtons.
3. **Predict.** If you add 100 more turns on top (200 total), will the pull double? What if you use 2 cells instead of 1?
4. **Test turns.** Measure the pull with 100, 200 and 300 turns, using 1 cell. Measure the current each time with the multimeter. Three trials each.
5. **Test voltage.** With 300 turns, compare 1 cell and 2 cells.
6. Calculate ampere-turns (current $\times$ turns) for each test and graph pull against ampere-turns.
7. **Kicker.** Lay the coil flat with the nail half inside and a marble touching the nail's tip. Press the button: the nail jumps in and the back of it can kick a second marble behind it. Measure how far the marble rolls on a flat table.

8. **Improve.** Change one thing to make a stronger kick (a tighter winding, a shorter nail, a smoother straw) and test it. Then make a cardboard flipper on a pin that the solenoid pulls.

Tips

- Keep each test to one second; the coil heats quickly.
- Wind the turns tightly and evenly. Loose turns weaken the field.
- More turns of the same wire also add resistance, so the current may drop; that is why ampere-turns, not just turns, matter.

Check your work

- ☐ I can explain how a solenoid pulls a plunger.
- ☐ I can show how turns and current changed my solenoid's pull.
- ☐ I can explain how a pinball flipper uses a solenoid and a lever.

ENGINEER'S NOTEBOOK

1. Draw a pinball playfield from above, labeling the plunger, flippers, bumpers, slingshots and drain, and mark which parts use solenoids.
2. Make a table and graph of turns, current, ampere-turns and pull.
3. A solenoid has 500 turns and draws 0.8 A. What are its ampere-turns? How much current would a 250-turn coil need to match it?

From history. Joseph Henry, who made the first powerful electromagnets, became the first Secretary of the Smithsonian Institution in 1846. He was a devout Presbyterian who saw no conflict between careful science and faith in God.

COMMON MISTAKES

- Leaving the solenoid connected until the battery and wire get hot.
- Forgetting to sand the enamel off the wire ends.
- Thinking more turns always means more pull without checking the current.

Make it a game · Solenoid Kicker Quiz. Your parent plays an old pinball machine and you play the repair person. Explain what a solenoid does when current flows, what the plunger does and how a relay and switch score a point. Then diagnose three breakdowns your parent describes, such as a weak kick or a stuck switch. Fix each in words.

Scripture. “And the streets of the city shall be full of boys and girls playing in the streets thereof.” (Zechariah 8:5, KJV)

The prophet pictured children at play as a sign of a peaceful, blessed city. Making good, safe toys is a small way of serving that joy.

9.2 SLOT CARS: MOTORS, FRICTION AND THE BANKED CURVE

OBJECTIVES

- Explain how a slot car gets its power and is guided along the track.
- Use $F = mv^2 \div r$ and $v = \sqrt{(\mu gr)}$ to explain why cars fly off curves, and explain how banking helps.
- Test the fastest speed a toy car can take a flat curve and a banked curve.

Warm-up. Put a coin on a lazy Susan, a turntable or a plate on the table near the edge, and slowly spin it faster. When does the coin slide off? Try it again with the coin nearer the center. What changes?

WATCH

How does a Scalextric car actually work?

DRIVETRIBE • 5:27

<https://www.youtube.com/watch?v=ZSNnhbndKqY>

WHEN TO WATCH

After the story paragraph.

BACKUP VIDEO

banked curves and circular motion explained

PhysicsHigh • 5:35

<https://www.youtube.com/watch?v=SylXc6W4C6g>

After the physics paragraph: banked curves explained with diagrams.

KEY TERMS

slot car

A small electric race car guided by a blade in a slot in the track, picking up power from metal rails beside the slot.

centripetal force

The inward force needed to keep an object moving in a circle: $F = mv^2 \div r$.

coefficient of friction (μ)

A number describing how grippy two surfaces are: the greatest sideways friction force $\div$ the force pressing them together.

banked curve

A curve whose surface tilts inward, so part of the track's push points toward the center of the turn.

magnetic traction

Magnets under a slot car that pull it toward the steel rails, pressing it down harder so it can corner faster.

CORE IDEAS

The story. Toy trains ran on electric rails from the 1890s, and soon toy makers tried electric race cars. In 1912 Lionel sold electric race cars that ran on a rail track. But the slot car as we know it took off in Britain in the late 1950s, when Fred Francis, a toy maker, introduced Scalextric in 1957: small model cars that ran in a slot cut into a plastic track, each controlled by its own hand throttle. By the early 1960s, slot-car racing had become a craze in Britain and America, with commercial raceways and clubs, and it still has a devoted following of builders and racers today.

How they figured it out. Designers had to solve several problems at once. The car needed power without wires trailing behind it, so they put two metal strips beside a slot and gave the car a pivoting guide blade with springy copper braids that brushed the strips. Each driver's throttle was a variable resistor that set the voltage to that lane's motor. The cars had to be light, low and grippy: designers learned that soft rubber tires, a low center of gravity, and later magnets pulling the car down toward the steel rails let cars go faster through curves without "deslotting." Track makers added banked turns and borders to give racers more speed and safety.

The physics. Anything moving in a circle needs an inward, **centripetal** force: $F = mv^2 \div r$. On a flat curve, only friction from the tires (and the guide blade) can provide it. The greatest friction is $\mu \times \text{weight} = \mu mg$, so the car slides out when $mv^2 \div r > \mu mg$, or when its speed is more than $v = \sqrt{(\mu gr)}$; notice that the mass cancels. For a curve of radius 0.30 m and $\mu = 0.8$, $v = \sqrt{(0.8 \times 9.8 \times 0.30)} = \sqrt{2.35} \approx 1.5$ m/s. Double the speed and the car needs four times the inward force. On a **banked curve**, the track pushes perpendicular to its tilted surface, so part of that push points toward the center and helps hold the car in the turn, even without friction. Magnetic traction increases the

downward force, and so the friction, which is why magnet cars can corner at speeds that seem impossible.

The engineering. The same physics designs real roads, racetracks and railways. Highway engineers bank (superelevate) curves and post safe speeds based on the radius; race tracks such as Daytona are banked steeply for high speeds; railways tilt the outer rail on curves. Slot-car makers balance speed against fun and durability: too much magnet and the racing is dull; too little and cars fly off and break. Toy safety matters too: small parts such as guide braids and tires must be fastened so young children cannot swallow them, and the power supply must be a safe, low-voltage transformer approved for toys.

PICTURE STUDY



Motor Racing at Brooklands, Agence Rol, 1924 · Photograph · Bibliothèque nationale de France

Image: [Wikimedia Commons](#), public domain

Brooklands, opened in England in 1907, was the world's first purpose-built motor-racing track, with long, steeply banked curves of concrete. The banking let cars take the turns far faster than on a flat road.

Look closely

- Find the banking. How steep is it compared with a normal road?
- Look at where the cars are on the banking. Are faster cars higher or lower?
- Look at the surface. Is it smooth?
- Look for spectators and safety barriers.

Talk about it

1. Why does banking let cars go faster through a curve?
2. Why would the fastest cars run higher up the banking?
3. What would happen to a car on this banking if it went too slowly?

Safety first. Keep ramps and tracks on the floor. Wear safety glasses if cars might fly off at speed. Keep small toy parts away from children under 3.

BUILD

Flat and Banked Curve Speed Test

You will roll a small toy car (or a marble) down a ramp onto a curved track and find the highest release height, and so the highest speed, at which it can stay in the curve. Then you will bank the curve and test again, changing only the banking.

You will need

- A small die-cast toy car, or a marble
- A ramp (a board on books) and a smooth floor or a large sheet of poster board
- Card stock strips and tape to make a curved track with a low guide wall, about 30 cm radius
- A protractor, a tape measure, a smartphone for slow-motion video
- Calculator

Steps

1. Build a quarter-circle curve of radius 30 cm at the bottom of the ramp, with a guide wall only 5 mm high on the outside (just enough to show when the car rides up over it).
2. Mark release heights on the ramp every 2 cm.
3. **Measure friction.** Tilt a piece of the track surface slowly with the car on it, wheels locked with tape, and record the angle θ at which it starts to slide. $\mu \approx \tan \theta$. (For rolling cars, the sideways grip is what matters; test it by sliding the car sideways.)
4. **Predict.** Calculate the highest speed the car should take the curve: $v = \sqrt{(\mu gr)}$. Then calculate the release height needed for that speed: $h = v^2 \div 2g$ (from Unit 1).
5. **Test.** Release the car from increasing heights until it rides over the outer wall. Record the highest height it stays in. Measure its speed entering the curve with slow-motion video. Three trials each.

6. **Bank it.** Prop up the outer edge of the curve with folded card to make a 10° banking, then 20° . Repeat the test at each banking.
7. Make a table and graph of banking angle against highest safe release height and speed.
8. **Improve.** Add weight to the car (tape on coins), changing nothing else. Did the safe speed change? Explain using the fact that mass cancels in $v = \sqrt{\mu gr}$.

Tips

- Release the car the same way every time; a push adds speed.
- Slow-motion video makes it easy to see exactly when the car rides over the wall.
- Keep the same car and the same track surface for all tests.

Check your work

- ☐ I can calculate the highest speed a car can take a flat curve.
- ☐ I can explain how banking lets a car go faster around a curve.
- ☐ I can explain why the car's mass did not change the safe speed much.

ENGINEER'S NOTEBOOK

1. Draw a car on a flat curve and on a banked curve, seen from behind, with arrows for weight, the track's push and friction.
2. Make a table and graph of banking angle and safe speed.
3. A slot car takes a curve of radius 0.25 m with $\mu = 1.2$. What is its fastest safe speed? If magnets doubled the downward force (so friction doubled), what would the new safe speed be?

From history. Serious slot-car racers still build and tune their own cars by hand, choosing motors, gears, tires and magnets and testing one change at a time on the track: an engineer's habits in miniature.

COMMON MISTAKES

- Thinking a heavier car can always corner faster; mass cancels unless something else changes.
- Forgetting that the force needed grows with the square of the speed.
- Changing the release method between trials.

Make it a game • Curve Speed Challenge. Use a coin on a tilted tray or a toy car on a curved track. Predict the top speed on a flat curve using v equals the square root of μ times g times r , and then on a banked curve. Test each. Explain centripetal force and why banking helps. Closest estimate wins.

9.3 GAME CONTROLLERS: ACCELEROMETERS AND GYROSCOPES

OBJECTIVES

- Explain how a MEMS accelerometer senses acceleration and tilt.
- Explain how a gyroscope senses rotation, from Foucault's spinning wheel to vibrating chips.
- Measure tilt and motion with a phone's sensors and compare them with a protractor and a stopwatch.

Warm-up. Hold a phone flat and turn on its screen rotation; tilt it on its side and watch the screen turn. Then put it flat on the table: does it know which way is up? Write down how you think it can tell.

WATCH

How a Smartphone Knows Up from Down (accelerometer)

[engineerguy](#) · 4:24

<https://www.youtube.com/watch?v=KZVgKu6v808>

WHEN TO WATCH

After the physics paragraph. Watch for the moving comb and the fixed comb.

BACKUP VIDEO

How the Wii Remote Works

[VonTower](#) · 3:31

<https://www.youtube.com/watch?v=ETAKfSkec6A>

After the story: how the Wii Remote's camera and accelerometer track your movements.

KEY TERMS

accelerometer

A sensor that measures acceleration, including the steady pull of gravity, in one, two or three directions.

MEMS

Micro-electro-mechanical systems: tiny moving machines, thinner than a hair, carved into silicon chips.

proof mass

The small mass inside an accelerometer, held by springs, that lags behind when the sensor accelerates.

gyroscope

A device that senses rotation. Old ones were spinning wheels; MEMS gyroscopes use vibrating structures.

g

A unit of acceleration equal to the pull of gravity, about 9.8 m/s^2 . An accelerometer lying still reads 1 g upward.

CORE IDEAS

The story. In 1852 the French physicist Léon Foucault built a heavy brass wheel in a set of rings, spun it very fast, and showed that its axis kept pointing in the same direction in space while the Earth turned beneath it. He named it the gyroscope, from Greek words meaning “to see the turning.” For a century, gyroscopes were heavy spinning wheels, used to steer ships and airplanes. In the 1990s engineers learned to carve tiny moving parts into silicon chips. Accelerometers made this way were first used to trigger car airbags, and then they spread into phones and game controllers. In 2006 Nintendo’s Wii Remote put a three-direction MEMS accelerometer, made by Analog Devices, into millions of homes, and in 2009 an add-on added a MEMS gyroscope as well.

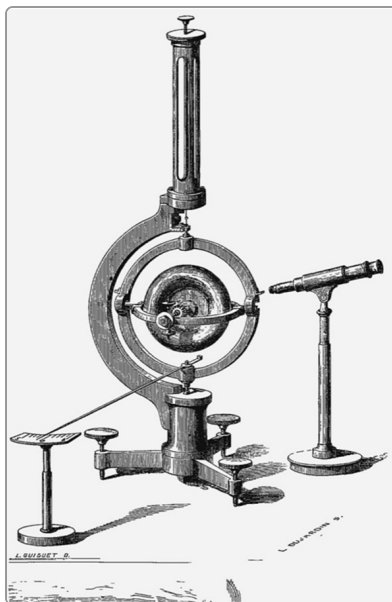
How they figured it out. The challenge was to sense motion with something tiny, cheap and tough enough to survive being dropped. The answer was a proof mass shaped like a comb, hung on springs of silicon thinner than a hair, with its teeth between the teeth of a fixed comb. When the chip accelerates, the mass lags behind and the gaps between the teeth change. Each pair of teeth is a tiny capacitor, so the change in the gaps changes the capacitance, which the chip measures, the same idea as the capacitors in Lesson 4.1. Making these parts meant borrowing the methods used to make computer chips: light, chemicals and etching to shape silicon by the millions.

The physics. An accelerometer cannot tell the difference between gravity and acceleration (Einstein noticed this too). Lying still on a table, it reads 1 g upward, which is how a phone knows which way is down. Tilt it, and the 1 g is shared

between its axes: if it reads a along its x-axis and b along its z-axis, the tilt angle is $\theta = \arctan(a \div b)$. Tilted 30° , it reads about 0.50 g on x and 0.87 g on z, and $\arctan(0.50 \div 0.87) \approx 30^\circ$. A **MEMS gyroscope** contains a structure that vibrates back and forth; when the chip rotates, the vibrating part is pushed sideways (the Coriolis effect), and that sideways motion measures the rate of turning in degrees per second.

The engineering. Accelerometers are good at finding down but are fooled by shaking; gyroscopes are good at quick turns but slowly drift. So engineers combine them, with software that trusts the gyroscope for fast changes and the accelerometer for the long-term direction of gravity: sensor fusion again, as in Lesson 8.3. The same chips steady camera images, count steps in fitness trackers, keep drones level, detect falls for elderly people and help phones navigate in tunnels. A game controller must also be durable: the case is molded to survive drops, the battery cover is screwed shut, and wrist straps keep it from flying out of a hand.

PICTURE STUDY



Foucault's Gyroscope, From Camille Flammarion, *Astronomie populaire*, 1894 (gyroscope built 1852) ·

Engraving · Published in Paris

Image: [Wikimedia Commons](#), public domain

Foucault built this gyroscope to show the Earth's rotation. Every tilt-sensing toy, phone and drone today carries the idea of this heavy brass instrument, shrunk onto a chip.

Look closely

- Find the heavy wheel in the center. What made it spin?
- Find the rings (gimbals) that let the wheel's axis point any way it likes.
- Look for the small microscope or pointer used to watch for slow movement.
- Look at the stand. Why is it so solid?

Talk about it

1. Why does a fast-spinning wheel keep pointing the same way?
2. How is a vibrating MEMS gyroscope like Foucault's spinning wheel, and how is it different?
3. What jobs could a gyroscope do on a ship or an airplane?

Safety first. Use a phone only with a parent's permission, in a protective case. Do not throw or drop the phone to test it; swing it gently on a short string over a soft bed or sofa only if a parent agrees. Never open a controller or phone: they contain lithium batteries.

BUILD

Measuring Tilt and Motion with Phone Sensors

You will use the free phyphox app (or a BBC micro:bit) to read a real MEMS accelerometer and gyroscope. You will check its tilt readings against a protractor, use it to measure a pendulum, and test how shaking fools the accelerometer.

You will need

- A smartphone with the free phyphox app (with a parent's permission), or a BBC micro:bit and the free MakeCode editor
- A protractor, a book or board to tilt, tape
- A string about 1 m long, a stopwatch
- Graph paper and a calculator with an arctan ($\tan^{-1}$) button

Steps

1. Open phyphox's "Acceleration with g" experiment. Lay the phone flat and read the x, y and z values. Which axis reads about 9.8 m/s^2 ?
2. **Predict.** If you tilt the phone 30° along its long side, what will the readings on the two axes be? (Use $9.8 \times \sin 30^\circ$ and $9.8 \times \cos 30^\circ$.)
3. **Test tilt.** Tape the phone to a book and tilt the book to 0° , 15° , 30° , 45° and 60° , checking with the protractor. Record the readings and calculate the angle with $\arctan(a \div b)$. Compare with the protractor.
4. Graph the calculated angle against the protractor angle. Draw the line where they would be equal.
5. **Gyroscope.** Open the gyroscope experiment. Turn the phone slowly through a quarter turn on the table in about 2 seconds. What rate does it read? Calculate $90^\circ \div 2 \text{ s}$ and compare.
6. **Pendulum.** With a parent's permission and over a bed or sofa, hang the phone in a bag on a 1 m string (or use a micro:bit) and let it swing gently. Use the acceleration graph to measure the period, and compare with timing ten swings with a stopwatch and with $T = 2\pi\sqrt{L \div g}$.

7. **Fooling the sensor.** Hold the phone at 30° and shake it gently back and forth. What happens to the calculated angle? Explain why game controllers combine accelerometers with gyroscopes.
8. **Improve.** Average the tilt readings over 3 seconds instead of one instant. Does the shaking error shrink?

Tips

- phyphox lets you export data or take screenshots of graphs for your notebook.
- Keep the phone in its case and the swing small and gentle.
- A micro:bit shows acceleration in milli-g ($1,000 = 1 \text{ g}$).

Check your work

- ☐ I can explain how a MEMS accelerometer senses tilt.
- ☐ I can calculate a tilt angle from two accelerometer readings.
- ☐ I can explain why controllers use both accelerometers and gyroscopes.

ENGINEER'S NOTEBOOK

1. Draw a MEMS accelerometer's comb structure, labeling the proof mass, springs, fixed comb and gaps, and show how the gaps change when it accelerates.
2. Make a table and graph of protractor angle against calculated angle.
3. An accelerometer reads 0.34 g on its x-axis and 0.94 g on its z-axis. What is the tilt angle?

From history. Before MEMS chips, a gyroscope good enough for an airliner's navigation system cost many thousands of dollars and weighed several kilograms. Today a combined accelerometer and gyroscope chip costs about a dollar and weighs less than a paper clip.

COMMON MISTAKES

- Thinking an accelerometer at rest reads zero. It reads 1 g , from gravity.
- Using arcsin or arccos with the wrong axis; check your answer with a protractor.
- Shaking the phone hard or dropping it to "test" it.

Make it a game • Proof Mass Mime. Hold a spoon dangling from a string to represent a proof mass. Tilt and accelerate your hand while your parent watches the spoon and says what the accelerometer reading would be. Then spin on the spot to show a gyroscope sensing rotation. Explain MEMS and Foucault's spinning wheel. Fewest mistakes wins.

9.4 DESIGNING A TOY FOR MANUFACTURE: INJECTION MOLDING AND TOY SAFETY

OBJECTIVES

- Explain how injection molding makes plastic parts and why parts need draft angles and even walls.
- Calculate the cost per part from mold cost, quantity and material cost.
- Test a toy with a homemade small-parts cylinder and a drop test, and cast parts in a simple mold.

Warm-up. Find three plastic toys or household objects (a bottle cap, a building brick, a toy car). Look closely for tiny round marks, thin lines along the edges and slightly sloping sides. Sketch what you find. What do you think made each mark?

WATCH

Plastic Injection Molding

[engineerguy](#) · 9:37

<https://www.youtube.com/watch?v=RMjtmsr3CqA>

WHEN TO WATCH

After the story paragraph.

Note: A toy blaster appears briefly among examples of molded parts; the video is about the manufacturing process.

BACKUP VIDEO

Injection Molding - Draft Angle (Why and How to Design)

[Protolabs](#) · 5:04

<https://www.youtube.com/watch?v=-2viyxUrQ2k>

Before the build: why molded parts need draft angles.

KEY TERMS

injection molding

A process that melts plastic pellets, forces the hot plastic into a steel mold under high pressure, cools it and pushes out the finished part.

wall thickness

The thickness of a molded part's walls. Even walls cool evenly; thick spots shrink, sink and warp.

parting line

The thin line on a part where the two halves of the mold met.

draft angle

A slight slope (often 1–2°) on the sides of a molded part so it slides out of the mold without scraping or sticking.

ejector pin

A pin that pushes the cooled part out of the mold, leaving a small round mark.

small-parts test

A U.S. safety test: any toy part for a child under 3 that fits entirely in a cylinder 1¼ inches (3.17 cm) wide and up to 2¼ inches (5.71 cm) deep is a choking hazard.

CORE IDEAS

The story. In the 1860s billiard balls were made of ivory, which was scarce and costly, and a company offered a large prize for a substitute. A young printer in Albany, New York, named John Wesley Hyatt, working with his brother Isaiah, developed celluloid, one of the first plastics, and in 1872 the brothers patented a machine that forced heated celluloid into a mold with a plunger, the ancestor of every injection-molding machine. In 1946 the American inventor James Watson Hendry built the first machine that used a turning screw to melt and push the plastic, which mixed it evenly and made the process far faster and more reliable. Today most plastic toys, from building bricks to toy cars, are injection molded.

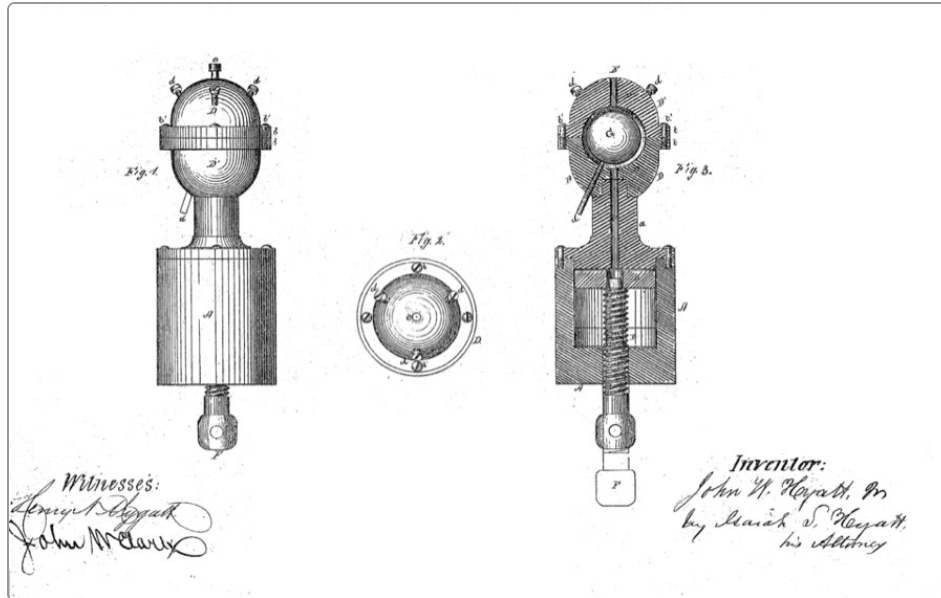
How they figured it out. Engineers learned the rules of molding by making parts that failed. Parts with perfectly straight sides stuck in the mold and were scratched or broken when pushed out, so designers added draft angles. Thick spots cooled slowly and shrank, leaving sinks and dents, so designers kept walls even and used ribs instead of solid blocks for strength. Sharp inside corners cracked, so they added small rounds. Plastic shrinks as it cools, often 0.5–2%, so mold makers cut every

mold slightly larger than the finished part. Each rule saves cost: a part that molds well can be made every few seconds, all day, for years.

The physics. Plastic pellets melt at about 200–300 °C, depending on the plastic. A screw pushes the melt into the mold at high pressure, often hundreds of atmospheres, to fill every corner before it cools. The cooling time grows roughly with the **square** of the wall thickness: a wall twice as thick takes about four times as long to cool, so thin, even walls make parts faster and cheaper. **Cost per part** = mold cost ÷ number of parts + material + machine time. Suppose a mold costs \$20,000 and makes 100,000 parts, with \$0.05 of plastic and \$0.03 of machine time each. Cost per part = $20,000 \div 100,000 + 0.05 + 0.03 = \$0.20 + \$0.08 = \$0.28$. Make only 1,000 parts and the same mold makes each one cost \$20.08.

The engineering. Toy engineers must design for safety as carefully as for cost. In the United States, toys must meet the federal toy safety standard: parts for children under 3 must not fit in the small-parts cylinder; toys are dropped, twisted, pulled and soaked to see if small parts break off; edges and points are tested for sharpness; small, powerful magnets and button batteries, which are very dangerous if swallowed, must be locked inside; and paints and plastics are tested for harmful chemicals. Every rule exists because children were once hurt. Good toy design is a way of loving the smallest neighbors, who cannot protect themselves.

PICTURE STUDY



Hyatt's Patent for Molding Celluloid, John Wesley Hyatt, 1871 · Patent drawing · United States Patent Office (patent no. 114,945)

Image: [Wikimedia Commons](#), public domain

This sheet of John Wesley Hyatt's 1871 patent shows the press he used to force heated material into a round mold to make billiard balls. A cutaway view shows the screw that pushes the material into the mold, the heart of every injection-molding machine since.

Look closely

- Find the round mold at the top. Where do the two halves meet (the parting line)?
- Find the screw in the cutaway view (Fig. 3). Which way does it push?
- Find the bolts that clamp the mold shut. Why must they be strong?
- Compare the outside view with the cutaway view.

Talk about it

1. Why must the mold be clamped tightly while the material is forced in?
2. How is Hyatt's screw like the screw in a modern injection-molding machine?
3. Where would you expect a mark, like a parting line, on the finished ball?

Safety first. An adult mixes plaster or handles hot water. Do not melt plastic or crayons on the stove. Keep cast parts and small test pieces away from children under 3. Never cut open a toy with a battery, magnet or wall plug.

BUILD

Draft Angles, Cost and Safety Tests

You will cast small parts in two kinds of molds, one with straight walls and one with a draft angle, and count how many come out cleanly. You will make a small-parts test cylinder and test real toys with it, run a drop test on a toy part you design, and calculate the cost per part for a toy you might sell.

You will need

- Modeling clay or a silicone ice-cube tray, card stock and tape to make simple molds
- Plaster of Paris (an adult mixes it) or gelatin dessert mix with hot water (adult) for casting
- A ruler, protractor, scissors
- A toilet-paper tube or card stock rolled into a cylinder 3.17 cm across and 5.71 cm deep, taped to a card base (the small-parts tester)
- Several small toys and toy parts to test (from a family toy box)
- A tape measure for the drop test and a calculator

Steps

1. **Make two molds.** Press a straight-sided block (for example a stack of coins wrapped in plastic wrap) into clay to make a pocket with vertical walls. Make a second pocket of the same size with sides sloping outward at about 5–10° (a tapered plug made of folded card).
2. **Predict.** Which mold will release its parts more cleanly? Why?
3. **Cast.** An adult mixes plaster (or gelatin). Fill both molds. When set, try to remove each part without damaging it. Record clean releases, chipped parts and stuck parts. Make five parts from each mold.
4. Calculate the percentage of good parts from each mold.
5. **Small-parts test.** Build the cylinder to the exact size. Test toys and parts from the toy box: drop each in without forcing. Any part that fits entirely inside would be a choking hazard for a child under 3. Record which toys pass and fail.

6. **Drop test.** Design a small toy part (for example a cardboard-and-clay figure or a plaster wheel). Drop it five times from 1.4 m onto a hard floor (the height used in toy testing for small children). Does any piece break off that would fail the small-parts test?
7. **Cost.** For a toy part, estimate a mold cost of \$15,000, plastic of \$0.04 and machine time of \$0.02 per part. Calculate the cost per part for 1,000, 10,000 and 100,000 parts and graph it.
8. **Improve.** Redesign your toy part to pass both tests (bigger, rounder, with no pieces that can snap off) and test it again.

Tips

- A light coat of cooking oil in the molds helps release, but use the same amount in both so the draft angle is the only variable.
- Measure the small-parts cylinder carefully; a few millimeters matter.
- Keep a list of every failure: real toy engineers do the same.

Check your work

- ☐ I can explain why molded parts need draft angles and even walls.
- ☐ I can calculate a cost per part and explain why large quantities make parts cheaper.
- ☐ I can use the small-parts test and a drop test to judge whether a toy is safe for young children.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of a two-part mold with the plastic inside, labeling the parting line, draft angle, wall thickness and ejector pin.
2. Make a table of mold type and good-part percentage, and a table of toys tested in the small-parts cylinder.
3. Graph cost per part against number of parts for the \$15,000 mold. Write two sentences explaining what the graph tells a toy company.

From history. Hyatt went on to hold more than 200 patents, including a roller bearing and a water filter. Celluloid was later replaced by safer, less flammable plastics, but his idea of forcing heated plastic into a mold is still how billions of toy parts are made each year.

COMMON MISTAKES

- Changing two things at once in the mold test (for example the oil and the draft).
- Forcing a part into the small-parts cylinder; it must fit without pushing.
- Forgetting that the mold cost is shared by all the parts.

Make it a game • Mold Cost Math. Your parent gives a mold cost of 5000 dollars in pretend money, a material cost of 0.20 per part and a quantity of 10000. Calculate the cost per part. Do it for three quantities. Explain draft angles, even walls and ejector pins. Cheapest correct design plan wins the round.

TOY LAB: THE ENGINEERING OF PLAY

Toys are some of the most carefully engineered objects in a home. They must work the first time and the thousandth time, survive being dropped and stepped on, cost little enough for families to buy, and above all be safe for children. In this optional bonus unit you will take four toys apart in your mind and on the workbench: the pinball machine with its solenoids and switches, the slot car with its motor and banked curves, the motion-sensing game controller with its tiny accelerometers and gyroscopes, and the plastic toy itself, which must be designed so it can be molded by the thousands.

Use the Toy Lab after the engineering fair, over the summer, or in any week that needs something fun. It reviews ideas from the whole year, electromagnets, friction, circular motion, sensors and manufacturing, and it ends with a portfolio project: designing a simple toy for manufacture and testing it for safety.

PREREQUISITES

- Has completed most of Units 1–8, especially electricity (Unit 4) and sensors (Unit 8)
- Can calculate with squares and square roots
- Can use a multimeter and a kitchen scale

MASTERY CHECKLIST

- ☐ I can explain how a solenoid works and how pinball machines use solenoids and switches.
- ☐ I can explain circular motion and use $v = \sqrt{\mu gr}$ and the banked-curve idea to explain why slot cars fly off curves.
- ☐ I can explain how a MEMS accelerometer and gyroscope sense motion and tilt.
- ☐ I can explain injection molding, draft angles and cost per part, and use the small-parts test for toy safety.
- ☐ I can design, test and improve a toy with safety and manufacturing in mind.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box:** Ages 8 and up. Monthly toy-engineering builds from Mark Rober, each with a video explaining the physics; an ideal companion to this unit.
- **KiwiCo crates:** Ages vary by line (Tinker 9–16, Eureka 14 and up). Many crates build working toys such as pinball games, arcade claws and motorized cars.
- **Snap Circuits:** Ages 8 and up. Includes motors, switches and electromagnets for no-solder toy circuits, useful for Lesson 9.1.

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 Pinball Machine: Solenoids, Switches and Scoring 2 sessions of 50–60 minutes

9.2 Slot Cars: Motors, Friction and the Banked Curve 2 sessions of 50–60 minutes

9.3 Game Controllers: Accelerometers and Gyroscopes 2 sessions of 50–60 minutes

9.4 Designing a Toy for Manufacture: Injection Molding and Toy Safety

2 sessions of 50–60 minutes

UNIT 9 REVIEW

Answer each question. For calculations, write the formula, put in the numbers with units, and give the answer with its unit. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

How does a solenoid make a quick push or pull?

2. **10 pts**

Calculation: A solenoid has 300 turns and carries 1.5 A. What are its ampere-turns? How many turns would give the same strength at 0.5 A?

3. **8 pts**

How did electromechanical pinball machines keep score without computers?

4. **8 pts**

Why does a pinball flipper use a strong coil for the kick and a weaker holding coil?

5. **10 pts**

Calculation: A toy car takes a flat curve of radius 0.40 m with $\mu = 0.9$. What is the fastest speed it can go without sliding? ($g = 9.8 \text{ m/s}^2$)

6. **8 pts**

Explain how banking a curve lets a car go faster.

7. **8 pts**

An accelerometer lying still on a table reads 1 g. Why not zero?

8. **10 pts**

Calculation: A controller's accelerometer reads 0.71 g on its x-axis and 0.71 g on its z-axis. What is its tilt angle?

9. **8 pts**

Why do game controllers and phones combine accelerometers with gyroscopes?

10. **10 pts**

Calculation: A toy mold costs \$30,000. Each part needs \$0.06 of plastic and \$0.04 of machine time. Find the cost per part for 10,000 parts and for 300,000 parts.

11. **12 pts**

Written answer: Name three design rules for injection-molded parts and two safety tests for toys for young children, and explain why each matters.

ANSWER KEY

1. Current through the coil makes it an electromagnet, whose magnetic field pulls an iron plunger into its center.
2. $300 \times 1.5 = 450$ ampere-turns. $450 \div 0.5 = 900$ turns.
3. Targets closed switches that energized relays, which pulsed stepping units or turned score reels a notch at a time, adding points mechanically.
4. The strong coil gives a big quick impulse, but if left on it would overheat; the weak holding coil keeps the flipper up using little current.
5. $v = \sqrt{\mu g r} = \sqrt{(0.9 \times 9.8 \times 0.40)} = \sqrt{3.53} \approx 1.9$ m/s.
6. On a banked curve the track pushes perpendicular to its tilted surface, so part of that push points toward the center of the turn and supplies some of the centripetal force, so less friction is needed.
7. It cannot tell gravity from acceleration; the table pushes it up, and the sensor reads the 1 g of gravity, which is how it knows which way is down.
8. $\theta = \arctan(0.71 \div 0.71) = \arctan(1) = 45^\circ$.
9. Accelerometers find the direction of gravity but are fooled by shaking; gyroscopes measure quick turns well but drift over time. Together (sensor fusion) they give accurate, steady readings.
10. 10,000: $30,000 \div 10,000 + 0.10 = \$3.10$. 300,000: $30,000 \div 300,000 + 0.10 = \$0.20$.
11. Rules (any three): draft angles so parts release; even wall thickness so parts cool evenly without sinks or warping; rounded inside corners to prevent cracks; ribs instead of thick blocks; allowance for shrinkage. Safety (any two): the small-parts cylinder test (choking hazard for children under 3); drop, twist and pull tests so pieces cannot break off; sharp-edge and point tests; locked-in magnets and button batteries; chemical tests of paints and plastics. Each rule or test exists because poor design caused broken parts or injured children.

PORTFOLIO PIECE: A TOY DESIGNED FOR PLAY, SAFETY AND MANUFACTURE

Design a simple toy for a child of a particular age (for example a spinning top, a rolling toy, a marble game or a small puzzle). Make a labeled drawing showing how each part would be injection molded, with draft angles, wall thickness and parting lines marked. Build a prototype from cardboard, clay, plaster or wood. Test it with a fair test of how well it plays (for example spin time, roll distance or score), run the small-parts and drop tests, and calculate a cost per part for 10,000 and 100,000 toys. Write a one-page report and present it as if pitching it to a toy company.

LOOK FOR	WHAT IT MEANS
Design for manufacture	Drawing shows parts, parting lines, draft angles and even walls, with sensible dimensions.
Play test	A fair test of how well the toy works, repeated at least three times, with data recorded.
Safety tests	Small-parts and drop tests carried out correctly and the design changed if it failed.
Cost calculation	Cost per part calculated correctly for two quantities, with a sentence on what it means.
Presentation	Clear explanation of who the toy is for, how it works, why it is safe and what the student would improve.