

GRADE 8 ENGINEERING & PHYSICS

First edition

8 units

32 lessons + Toy Lab

A video for every lesson

FIRST EDITION

COURSE GUIDE

This is the last and deepest of the School Launch K-8 engineering courses, and it is written as a bridge to high-school physics and engineering. It follows the same eight strands as every year: motion, bridges, architecture, electronics, public utilities, ships, flight and space, and a capstone. But now every idea comes with its equation, worked with numbers and units: $v = \Delta x \div \Delta t$, $p = mv$, $F = mv^2 \div r$, $mgh = \frac{1}{2}mv^2$, $\sigma = F \div A$, $P = I^2R$, $P = \rho gh$, $Q = Av$, $F = \dot{m}v_e$, $L = \frac{1}{2}\rho v^2 SC_L$, and more. Students learn the vocabulary engineers really use, such as load factors, critical paths, Froude numbers, cavitation and feedback control, and they meet the careers behind the work: the civil engineer and the PE license, the lineworker and the water operator, the naval architect, the project manager.

Every lesson follows the same path. **The story** is a real moment from history: Muybridge's galloping horse, the Ashtabula and Silver Bridge failures, Shannon's relay circuits, the 1965 and 2003 blackouts, Froude's towing tank, the *Trieste* at the bottom of the sea, MacCready's *Gossamer Albatross*, Sikorsky's helicopter, the Saturn V. Then **how they figured it out**: what failed, what they measured and what they changed. Then **the physics**, with a worked example, and **the engineering**: how the idea becomes a safe, affordable, maintainable thing. Last, the student repeats the discovery in a build with a prediction, a fair test, a data table and graph, a comparison of measurement with theory, and an improvement round.

God made an orderly world that can be measured and understood, and He made people in His image to be makers. Engineering is a vocation of service: a bridge that stays up, water that is clean, a light that comes on, a walkway that holds. This year ends with that calling, an ethics case that every engineer studies, a capstone project for a real person, and a family engineering fair. The old Latin saying *Fabricando fit faber*, "by making, one becomes a maker," is the method of the whole course. An optional ninth unit, the Toy Lab, explores the physics of gyroscopes, Slinkies, RC

airplanes and toy invention for families who want a bonus unit after the fair or over the summer.

Videos come from trusted teaching sources chosen lesson by lesson: Practical Engineering, The Efficient Engineer, engineerguy (Bill Hammack), Jared Owen, Flipping Physics, Veritasium, the American Society of Civil Engineers, the Royal Institution, The Henry Ford, NFPA, state transportation departments and others. Every video was checked in preview for content and accuracy. Several grade 8 videos are longer (up to about 20 minutes) and more technical than in earlier years; the lesson's "when" note says which part matters most. Some videos open with a short sponsor message, and a few on disasters (the 2003 blackout, the Hyatt Regency collapse) show news photographs; watch those together. Stop when the teaching ends.

Start with Lesson 1.1 →

WHO IT IS FOR

Written for students in grade 8 (about ages 13–14) who are comfortable with pre-algebra and beginning algebra: solving for an unknown, ratios, square roots, exponents and scientific notation. Right-triangle ratios are introduced where needed. A parent or teacher acts as lab partner and safety officer and handles sharp tools, hot glue and launches. No kits are required: every build uses household, craft-store or inexpensive electronics-store materials, and the one microcontroller lesson can be done in a free online simulator. Optional kits are listed in each unit.

HOW TO USE THIS COURSE

1. **The weekly rhythm.** The year has 32 lessons, one a week. Session 1 (about 60 minutes) is the warm-up, video, teaching and picture study. Session 2 (about 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.** Students at this age should read the core ideas themselves, then tell them back or discuss them with a parent. Work every worked example in the physics paragraph on paper before moving on; the unit reviews use the same kinds of problems.
3. **Equations with units.** Insist on the habit engineers use: write the formula, substitute the numbers with their units, and box the answer with its unit. Most

errors at this level are unit errors.

4. **Picture study.** Each lesson has one historic photograph, engineering drawing, patent or painting. Look at it quietly for two minutes, put it away, tell back what you saw, then work through the “look for” items and questions, which point to the physics and engineering.
5. **The engineer’s notebook.** Use a graph-paper composition book for the whole year. For every build: a dated prediction, a labeled sketch, a data table with units, a graph, a comparison of measured and predicted values with percent difference, and “what I would change.” Honest records matter more than perfect results: “a just weight is his delight” (Proverbs 11:1).
6. **Fair tests and improvement.** Every build changes one variable at a time, repeats trials and ends with an improvement round. A design that fails, is analyzed and then improved has taught more than one that worked the first time.
7. **Optional kits.** Some units list kits such as a Raspberry Pi Pico, Pitsco balsa supplies, Estes model rockets (adult required) or a small drone. Every lesson can be completed without them.
8. **Unit review and portfolio.** Each unit ends with a 100-point review with two or three worked calculations and short written answers, and a portfolio build that pulls the unit together, such as a calculated roller coaster, a load-tested truss with a method-of-joints analysis, a wind-tested tower, a sensing microcontroller project, a town utility plan, a tank-tested hull or a mission-designed glider.
9. **Safety.** Read the safety box before each build. Electricity comes only from batteries and USB-powered boards, never the outlets in the wall. Lithium batteries are never opened, punctured or charged if damaged. Water rockets and any model rockets are flown outdoors with an adult. Drones follow FAA rules. Wear safety glasses for anything that spins, snaps, flies or is under tension.
10. **The capstone and the family engineering fair.** Unit 8 is a four-week capstone: ethics, a project plan with a schedule and budget, a design project for a real client, and a family engineering fair in the last week, where the student presents the capstone and the best build from each unit.
11. **The Toy Lab (optional).** Unit 9 is a bonus unit on the physics of toys: the gyroscope and precession, the Slinky drop and waves, RC airplanes and toy drones, and inventing, testing and pitching a toy. Do it after the fair, over the summer, or any week that needs something fun.

SCOPE AND SEQUENCE

UNIT 1 • WEEKS 1–4

Physics of Motion

Motion graphs from Galileo's ramps and Muybridge's horse; momentum, impulse and crumple zones; circular motion from Ferris's wheel to the banked curve; and energy conservation in roller-coaster design.

- 1.1 Motion Graphs: Galileo's Ramps and Muybridge's Horse
- 1.2 Momentum, Collisions and Crumple Zones
- 1.3 Circular Motion: Ferris's Wheel and the Banked Curve
- 1.4 Energy Conservation and Roller-Coaster Design

UNIT 3 • WEEKS 9–12

Architecture

Architectural styles from the classical orders to Gothic to modern, and the structure behind each; CAD and 3D modeling in Tinkercad; building codes and fire safety after the Chicago fires; and the Burj Khalifa and wind engineering.

- 3.1 Styles and Structure: From the Classical Orders to Gothic to Modern
- 3.2 From Drafting Board to CAD: Modeling a Building in Tinkercad
- 3.3 Building Codes and Fire Safety: Lessons from Chicago
- 3.4 The Burj Khalifa: Confusing the Wind

UNIT 2 • WEEKS 5–8

Bridges

Load paths, reactions and design codes after the Ashtabula collapse; steel versus concrete, reinforced and prestressed; a balsa bridge efficiency competition with the method of joints; and the civil engineer, bridge inspection and the PE license.

- 2.1 Load Paths and Design Codes: From Ashtabula to the Rulebook
- 2.2 Steel versus Concrete: Eads, Magnel and the Reinforced Beam
- 2.3 A Balsa Bridge Efficiency Competition: Whipple and the Method of Joints
- 2.4 Careers: The Civil Engineer, Bridge Inspection and the PE License

UNIT 4 • WEEKS 13–16

Electronics

Binary and logic gates from Boole and Shannon; the transistor and the integrated circuit from Bell Labs onward; programming a Raspberry Pi Pico; and sensors and data logging from the flight recorder to the phone.

- 4.1 Binary and Logic Gates: Boole, Shannon and the Relay
- 4.2 From the Transistor to the Integrated Circuit: Bell Labs and Beyond
- 4.3 Raspberry Pi Projects: Programming a Microcontroller
- 4.4 Sensors and Data Logging: From the Black Box to Your Phone

UNIT 5 • WEEKS 17–20

Utilities

Grid reliability and the great blackouts of 1965 and 2003; water systems, head, pressure and pipe flow from the Croton Aqueduct; the internet's fiber, packets and data centers; and infrastructure careers: lineworker, water operator and engineer.

- 5.1 Grid Reliability and the Great Blackouts
- 5.2 Water Systems: Head, Pressure and Pipe Flow
- 5.3 The Internet: Fiber, Packets and Data Centers
- 5.4 Infrastructure Careers: Lineworker, Water Operator and Engineer

UNIT 7 • WEEKS 25–28

Flight and Space

Aircraft design trade-offs and wing loading from the *Gossamer Albatross* to the 747; Sikorsky and the helicopter; rocketry and orbits with Apollo and the Saturn V; and drones, feedback control and FAA rules.

- 7.1 Aircraft Design Trade-offs: Wing Loading from the Gossamer Albatross to the 747
- 7.2 Helicopters: Sikorsky and the Rotating Wing
- 7.3 Rocketry and Orbits: Apollo and the Saturn V
- 7.4 Drones and FAA Rules: Four Rotors and a Feedback Loop

UNIT 6 • WEEKS 21–24

Ships

Drag, hull speed and the bulbous bow in Froude's towing tank; propellers and cavitation with Parsons's *Turbinia*; submarines and deep-sea pressure with the *Trieste*; and modern shipbuilding from the Liberty ships to the block method.

- 6.1 Drag, Hull Speed and the Bulbous Bow: Froude's Towing Tank
- 6.2 Propellers and Cavitation: Parsons and the Turbinia
- 6.3 Submarines and Pressure: The Trieste Reaches the Deepest Sea
- 6.4 Modern Shipbuilding: Liberty Ships, Brittle Steel and the Block Method

UNIT 8 • WEEKS 29–32

Capstone: The Engineer's Calling

Engineering ethics and vocation through the Hyatt Regency walkway collapse; project management, schedules and budgets at Hoover Dam; a capstone design project for a real client; and the family engineering fair and presentation.

- 8.1 Engineering Ethics and Vocation: The Hyatt Regency Walkways
- 8.2 Project Management: Counting the Cost at Hoover Dam
- 8.3 A Capstone Design Project: From Problem to Prototype
- 8.4 The Engineering Fair and Presentation: Faraday's Christmas Lectures

UNIT 9 • WEEKS 33–36

Toy Lab: The Physics of Play

Optional bonus unit, the Toy Lab: the gyroscope and precession in depth; the Slinky drop and waves in slow motion; RC airplanes and toy drones; and inventing, prototyping, safety-testing and pitching a toy.

9.1 The Gyroscope and Precession

9.2 The Slinky Drop: Waves in Slow Motion

9.3 RC Airplanes and Toy Drones: Flying from the Ground

9.4 Capstone Toy: Invent, Prototype, Test and Pitch

WEEKLY PACING CALENDAR

WEEK	PLAN
1	• Session 1: Lesson 1.1 Motion Graphs: Galileo’s Ramps and Muybridge’s Horse: 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 Momentum, Collisions and Crumple Zones: warm-up, video, teaching and picture study • Session 2: Lesson 1.2 build project and engineer’s notebook
3	• Session 1: Lesson 1.3 Circular Motion: Ferris’s Wheel and the Banked Curve: warm-up, video, teaching and picture study • Session 2: Lesson 1.3 build project and engineer’s notebook
4	• Session 1: Lesson 1.4 Energy Conservation and Roller-Coaster Design: 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 Load Paths and Design Codes: From Ashtabula to the Rulebook: warm-up, video, teaching and picture study

WEEK	PLAN
	Session 2: Lesson 2.1 build project and engineer's notebook
6	- Session 1: Lesson 2.2 Steel versus Concrete: Eads, Magnel and the Reinforced Beam: warm-up, video, teaching and picture study - Session 2: Lesson 2.2 build project and engineer's notebook
7	- Session 1: Lesson 2.3 A Balsa Bridge Efficiency Competition: Whipple and the Method of Joints: warm-up, video, teaching and picture study - Session 2: Lesson 2.3 build project and engineer's notebook
8	- Session 1: Lesson 2.4 Careers: The Civil Engineer, Bridge Inspection and the PE License: 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
9	- Session 1: Lesson 3.1 Styles and Structure: From the Classical Orders to Gothic to Modern: warm-up, video, teaching and picture study - Session 2: Lesson 3.1 build project and engineer's notebook
10	- Session 1: Lesson 3.2 From Drafting Board to CAD: Modeling a Building in Tinkercad: warm-up, video, teaching and picture study - Session 2: Lesson 3.2 build project and engineer's notebook
11	- Session 1: Lesson 3.3 Building Codes and Fire Safety: Lessons from Chicago: warm-up, video, teaching and picture study - Session 2: Lesson 3.3 build project and engineer's notebook
12	- Session 1: Lesson 3.4 The Burj Khalifa: Confusing the Wind: 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 Binary and Logic Gates: Boole, Shannon and the Relay: warm-up, video, teaching and picture study - Session 2: Lesson 4.1 build project and engineer's notebook

WEEK	PLAN
14	• Session 1: Lesson 4.2 From the Transistor to the Integrated Circuit: Bell Labs and Beyond: warm-up, video, teaching and picture study • Session 2: Lesson 4.2 build project and engineer's notebook
15	• Session 1: Lesson 4.3 Raspberry Pi Projects: Programming a Microcontroller: warm-up, video, teaching and picture study • Session 2: Lesson 4.3 build project and engineer's notebook
16	• Session 1: Lesson 4.4 Sensors and Data Logging: From the Black Box to Your Phone: 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 Grid Reliability and the Great Blackouts: warm-up, video, teaching and picture study • Session 2: Lesson 5.1 build project and engineer's notebook
18	• Session 1: Lesson 5.2 Water Systems: Head, Pressure and Pipe Flow: warm-up, video, teaching and picture study • Session 2: Lesson 5.2 build project and engineer's notebook
19	• Session 1: Lesson 5.3 The Internet: Fiber, Packets and Data Centers: warm-up, video, teaching and picture study • Session 2: Lesson 5.3 build project and engineer's notebook
20	• Session 1: Lesson 5.4 Infrastructure Careers: Lineworker, Water Operator and Engineer: 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 Drag, Hull Speed and the Bulbous Bow: Froude's Towing Tank: warm-up, video, teaching and picture study • Session 2: Lesson 6.1 build project and engineer's notebook
22	• Session 1: Lesson 6.2 Propellers and Cavitation: Parsons and the Turbinia: warm-up, video, teaching and picture study • Session 2: Lesson 6.2 build project and engineer's notebook

WEEK	PLAN
23	• Session 1: Lesson 6.3 Submarines and Pressure: The Trieste Reaches the Deepest Sea: warm-up, video, teaching and picture study • Session 2: Lesson 6.3 build project and engineer's notebook
24	• Session 1: Lesson 6.4 Modern Shipbuilding: Liberty Ships, Brittle Steel and the Block Method: 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 Aircraft Design Trade-offs: Wing Loading from the Gossamer Albatross to the 747: warm-up, video, teaching and picture study • Session 2: Lesson 7.1 build project and engineer's notebook
26	• Session 1: Lesson 7.2 Helicopters: Sikorsky and the Rotating Wing: warm-up, video, teaching and picture study • Session 2: Lesson 7.2 build project and engineer's notebook
27	• Session 1: Lesson 7.3 Rocketry and Orbits: Apollo and the Saturn V: warm-up, video, teaching and picture study • Session 2: Lesson 7.3 build project and engineer's notebook
28	• Session 1: Lesson 7.4 Drones and FAA Rules: Four Rotors and a Feedback Loop: 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 Engineering Ethics and Vocation: The Hyatt Regency Walkways: warm-up, video, teaching and picture study • Session 2: Lesson 8.1 build project and engineer's notebook
30	• Session 1: Lesson 8.2 Project Management: Counting the Cost at Hoover Dam: warm-up, video, teaching and picture study • Session 2: Lesson 8.2 build project and engineer's notebook
31	• Session 1: Lesson 8.3 A Capstone Design Project: From Problem to Prototype: warm-up, video, teaching and picture study • Session 2: Lesson 8.3 build project and engineer's notebook

WEEK	PLAN
32	• Session 1: Lesson 8.4 The Engineering Fair and Presentation: Faraday’s Christmas Lectures: 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 Gyroscope and Precession: 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 The Slinky Drop: Waves in Slow Motion: warm-up, video, teaching and picture study • Session 2: Lesson 9.2 build project and engineer’s notebook
35	• Session 1: Lesson 9.3 RC Airplanes and Toy Drones: Flying from the Ground: warm-up, video, teaching and picture study • Session 2: Lesson 9.3 build project and engineer’s notebook
36	• Session 1: Lesson 9.4 Capstone Toy: Invent, Prototype, Test and Pitch: 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 scientific calculator

For predictions, data tables, graphs, calculations with units and “what I would change.”

Ruler, tape measure, protractor, kitchen scale (grams) and a smartphone with slow-motion video and a stopwatch

Measuring is the heart of every build; slow-motion video replaces many lab timers.

Free software: Tinkercad, CircuitVerse, the Thonny editor or the Wokwi simulator, the phyphox app and the FAA B4UFLY app

For Units 3, 4 and 7. A parent sets up any accounts.

Cardboard, card stock, foam board or foam trays, tape, white glue and wood glue

The main building materials all year.

Craft sticks, balsa or basswood sticks (about 3 mm square), straws, string, rubber bands and paper clips

For trusses, columns, gliders, rotors and the hanger model.

Pennies, washers, small bags of sand or rice, paper cups and a small bucket

Standard loads for load tests.

Marbles or steel balls, foam pipe insulation and a vinyl rain gutter with end caps

For the ramp, roller coaster and towing-tank builds.

Plaster of Paris and a dust mask

For the reinforced-beam build in Unit 2. An adult mixes it.

AA and 9 V batteries with holders, alligator clip leads, a breadboard, LEDs, resistors, NPN transistors, a photoresistor and a digital multimeter

For Units 4 and 5. Batteries only; never the outlets in the wall.

Two small DC hobby motors with propellers and tubing to couple them

For the motor-generator grid model, the thrust stands and the torque test.

Large plastic syringes (no needles), plastic bottles, a laser pointer of 5 mW or less, food coloring and plastic spoons

For the cavitation, Boyle's law, light-guide, dilution and brittleness builds.

2-liter soda bottles, a stopper and ball-inflation needle, and a bicycle pump with a gauge

For the water rocket in Unit 7, flown outdoors with an adult.

A box fan

The wind tunnel for tower tests.

Safety glasses

For anything that spins, snaps, flies, launches or is under tension.

Optional: a Raspberry Pi Pico, Pitsco balsa supplies, an Estes rocket starter set (adult required), a sub-250 g drone such as the Ryze Tello, or a bicycle front wheel for the Toy Lab

Never required. See the kits listed in each unit.

GRADING

Grades come from the builds, the engineer's notebook, the unit reviews and the portfolio builds. At this level the calculations matter: an answer earns full credit when the formula, the numbers with units and the boxed answer with its unit are all shown. 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 the capstone	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, measure carefully, calculate with units, compare honestly with theory and try an improvement?
- A notebook page earns full marks when it has a date, a labeled sketch, a data table with units, a graph where appropriate, a percent-difference comparison and a sentence about what to change.
- In the unit reviews, give partial credit for correct setup and units even if the arithmetic slips; engineers check arithmetic, but a wrong formula or missing unit is the more serious error.
- Keep each unit's portfolio pages and photographs in one folder. With the capstone report, they make a strong record of the year for a high-school transcript or portfolio.
- The optional Toy Lab (Unit 9) may be graded the same way or kept as enrichment.

A NOTE TO PARENTS

You do not need to be an engineer to teach this course, but this year you may want to be the student's lab partner rather than the teacher. Read the story together, let the student work the worked example, and then ask the two questions good engineering teachers ask most: "What do you predict, and why?" and "How do you know?" Check that every calculation has units. If the student is ready for algebra, this course will reinforce it constantly; if algebra is still new, work the first example in each lesson together.

Expect failures, and welcome them. Plaster beams will crack early, gliders will stall, and the motor-generator will refuse to turn. The course is built to show that failure carefully studied is how engineers learn: Froude tested models, MacCready rebuilt the *Condor* hundreds of times, and the F-1 engine was disturbed on purpose until it was stable. Praise careful measurement and honest records more than winning results. *Fabricando fit faber*: by making, one becomes a maker.

Several lessons tell of disasters: the Ashtabula and Silver Bridge collapses, the Chicago fires, the great blackouts, the Liberty ships and the Hyatt Regency walkways. At this age the numbers are given plainly, but the focus is always on what engineers learned, what they changed, and the responsibility that engineers carry for the people who trust their work. The capstone unit asks students to consider engineering as a vocation, a way of serving God and neighbor with skill and honesty, and many students find that this is the lesson they remember longest.

UNIT 1

PHYSICS OF MOTION

Everything an engineer builds either moves or must stand still while other things push on it. This year begins with motion itself, measured with numbers and units the way a high-school physics class measures it. You will read and draw motion graphs, as Galileo did with his rolling balls and Eadweard Muybridge did with his row of cameras. You will calculate momentum and impulse and see why the safest cars are built to crumple. You will swing objects in circles and learn the force that keeps a Ferris wheel car or a highway truck on its curved path.

The unit ends with energy: how a roller coaster trades height for speed and speed for height, why the first looping coasters hurt their riders, and how engineers reshaped the loop. Every lesson uses real equations ($v = \Delta x \div \Delta t$, $p = mv$, $F = mv^2 \div r$, $KE = \frac{1}{2}mv^2$) worked out with real numbers, and every build ends with a data table, a graph and an honest comparison between what the math predicted and what the measurement showed.

PREREQUISITES

- Comfortable with decimals, ratios, square roots and simple algebra (solving for one unknown)
- Knows Newton's three laws in words and can use $F = ma$
- Can draw a line graph with labeled axes and units
- Keeps a dated engineer's notebook with predictions and data tables

MASTERY CHECKLIST

- ☐ I can read and draw position–time and velocity–time graphs and find velocity from a slope and distance from an area.
- ☐ I can calculate momentum and impulse and explain with numbers why a crumple zone, an air bag or a helmet lowers the force of a collision.
- ☐ I can calculate centripetal acceleration and force ($a = v^2 \div r$, $F = mv^2 \div r$) and explain why roads and railways are banked on curves.
- ☐ I can use conservation of energy ($mgh = \frac{1}{2}mv^2$) to predict the speed of a roller coaster and explain why real loops are not circles.
- ☐ I can run a fair test, graph my data and compare measured results with calculated predictions, giving honest reasons for the difference.

OPTIONAL KITS FOR THIS UNIT

- **K'NEX roller coaster building sets**: Ages 9 and up. Larger K'NEX coaster sets have a motorized chain lift and long, adjustable track, which makes it easy to measure drop heights and test loops for Lessons 1.3–1.4 and the portfolio project.
- **Thames & Kosmos physics and engineering kits**: Ages 8 and up for most sets. Their physics and roller coaster engineering kits add ramps, carts and track pieces that fit Lessons 1.1 and 1.4.

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

1.1 Motion Graphs: Galileo's Ramps and Muybridge's Horse

2 sessions of 60 minutes

1.2 Momentum, Collisions and Crumple Zones

2 sessions of 60 minutes

1.3 Circular Motion: Ferris's Wheel and the Banked Curve

2 sessions of 60 minutes

1.4 Energy Conservation and Roller-Coaster Design

2 sessions of 60 minutes

UNIT 1 REVIEW

Answer each question. For calculations, write the formula, substitute the numbers with units, and box your answer. Use $g = 9.8 \text{ m/s}^2$. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

On a position–time graph, what does the slope tell you? On a velocity–time graph, what do the slope and the area under the line tell you?

2. **10 pts**

Calculation. A train starts from rest and reaches 18 m/s in 12 s with steady acceleration. Find its acceleration and the distance it travels in that time.

3. **8 pts**

Galileo found that a ball rolling from rest covers 1 unit of distance in the first second. How far has it gone in total after 3 seconds? What equipment did he use to measure the time?

4. **10 pts**

Calculation. A 1,200 kg car moving at 20 m/s stops in a crash. Find its momentum before the crash, and the average force on it if it stops in 0.08 s. What would the force be if a crumple zone stretched the stop to 0.16 s?

5. **8 pts**

Explain in two or three sentences why the safest car has soft ends and a stiff middle.

6. **8 pts**

A 2 kg cart moving at 3 m/s hits a stopped 1 kg cart, and they stick together. How fast do they move afterward?

7. **8 pts**

You whirl a ball on a string in a circle and the string breaks. Describe the ball's path and explain why.

8. **10 pts**

Calculation. A 1,500 kg car drives around a curve of radius 60 m at 15 m/s. Find its centripetal acceleration and the friction force needed. What happens to the needed force if the speed doubles?

9. **10 pts**

Why do highway and railway engineers bank curves? Give one reason highway banking is kept to only a few degrees.

10. **10 pts**

A roller-coaster car starts from rest at the top of a 45 m hill. Ignoring friction, how fast is it moving at the bottom? Does the mass of the car matter?

11. **10 pts**

Why did the early circular loops at Coney Island hurt riders, and how does a clothoid loop fix the problem?

ANSWER KEY

1. Position–time slope = velocity. Velocity–time slope = acceleration; area under the velocity–time line = displacement (distance traveled).
2. $a = \Delta v \div \Delta t = 18 \text{ m/s} \div 12 \text{ s} = 1.5 \text{ m/s}^2$. Distance = area of triangle = $\frac{1}{2} \times 12 \text{ s} \times 18 \text{ m/s} = 108 \text{ m}$. (Or $d = \frac{1}{2}at^2 = \frac{1}{2} \times 1.5 \times 144 = 108 \text{ m}$.)
3. Distance grows with the square of time, so $3^2 = 9$ units. He used a water clock, weighing the water that flowed out during each roll.
4. $p = mv = 1,200 \times 20 = 24,000 \text{ kg}\cdot\text{m/s}$. $F = \Delta p \div \Delta t = 24,000 \div 0.08 = 300,000 \text{ N}$. With 0.16 s: $24,000 \div 0.16 = 150,000 \text{ N}$, half as much.
5. The soft ends (crumple zones) crush to stretch out the stopping time, which lowers the force on the passengers ($F\Delta t = \Delta p$). The stiff safety cell keeps its shape so the people inside are not crushed and have room to be slowed by belts and air bags.
6. Momentum before = $2 \times 3 = 6 \text{ kg}\cdot\text{m/s}$. After: $(2 + 1) \times v = 6$, so $v = 2 \text{ m/s}$.
7. It flies off in a straight line tangent to the circle (in the direction it was moving at that instant), not straight outward. With no inward force, Newton's first law says it keeps moving in a straight line.
8. $a = v^2 \div r = 225 \div 60 = 3.75 \text{ m/s}^2$. $F = ma = 1,500 \times 3.75 = 5,625 \text{ N}$. If the speed doubles, the force becomes four times as large (22,500 N).
9. Tilting the road inward lets part of the road's push (normal force) point toward the center of the curve, so less friction is needed. Banking is limited because slow or stopped cars on icy roads could slide down toward the inside of the curve.
10. $v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 45} = \sqrt{882} \approx 29.7 \text{ m/s}$. The mass does not matter, because it cancels in $mgh = \frac{1}{2}mv^2$.
11. To get over the top of a circle, the car had to enter the bottom very fast, and at the bottom of a small circle that made a very large acceleration ($v^2 \div r$), pressing riders with several g's. A clothoid loop is wide (large radius) at the bottom where the car is fast and tight at the top where it is slow, keeping g-forces lower and more even.

PORTFOLIO PIECE: A CALCULATED ROLLER COASTER

Design and build a marble roller coaster from foam pipe insulation, card stock or a K'NEX set that includes a drop, a loop, a hill and a banked curve, and finishes with the marble stopping safely in a catch bin. Before building, draw a side view with every height labeled and predict the marble's speed at three points using energy conservation and your measured efficiency. After building, measure the speeds with slow-motion video, compare predictions with measurements in a table, and write a one-page engineer's report explaining the differences and what you changed to make the coaster run reliably ten times in a row.

LOOK FOR	WHAT IT MEANS
Design drawing and predictions	Scaled side view with heights in centimeters; predicted speeds calculated with $mgh = \frac{1}{2}mv^2$ and a stated efficiency.
Working coaster	Includes a drop, loop, hill and banked curve; the marble completes the course at least 8 times out of 10.
Measurement and data	Speeds measured at three points with three trials each; table compares predicted and measured values with percent difference.
Physics explanation	Report uses energy conservation, centripetal acceleration and friction correctly to explain the results.
Improvement	At least one specific change made after testing, with before-and-after data.

1.1 MOTION GRAPHS: GALILEO'S RAMPS AND MUYBRIDGE'S HORSE

OBJECTIVES

- Read and draw position–time and velocity–time graphs, and explain what slope and area mean on each.
- Calculate average velocity and acceleration with units ($v = \Delta x \div \Delta t$, $a = \Delta v \div \Delta t$).
- Measure a marble rolling down a ramp, graph its motion and test Galileo's discovery that distance grows with the square of time.

Warm-up. Walk across the room three ways while someone times you: slowly and steadily, quickly and steadily, and starting slow and speeding up. For each walk, sketch in your notebook what a graph of “distance from the wall” against “time” would look like. Which walk gives a straight line? Which gives a curve? Keep these sketches; you will check them at the end of the lesson.

WATCH

Understanding and Walking Position as a function of Time Graphs

Flipping Physics · 12:39

<https://www.youtube.com/watch?v=Mjnu5ePzXDM>

WHEN TO WATCH

After the physics paragraph. Pause before each walk is shown and predict how the person will move.

BACKUP VIDEO

Galileo's Measure Of Gravity Explained By Jim Al-Khalili | The Amazing World Of Gravity

Spark · 5:01

<https://www.youtube.com/watch?v=ZBr8Q2ROX9s>

With the story paragraph: a physicist rebuilds Galileo's ramp and water clock.

KEY TERMS

position

Where an object is, measured from a chosen reference point, with a direction (for example, 3 meters east of the door).

acceleration

How fast velocity changes: $a = \Delta v \div \Delta t$, measured in meters per second per second (m/s^2).

area under the curve

On a velocity–time graph, the area between the line and the time axis equals the displacement (how far the object moved).

velocity

How fast position changes, with direction: $v = \Delta x \div \Delta t$, measured in meters per second (m/s). Speed is the size of velocity without the direction.

slope

Rise over run on a graph. The slope of a position–time graph is velocity; the slope of a velocity–time graph is acceleration.

uniform acceleration

Motion in which velocity changes by the same amount every second, like a ball rolling down a straight ramp.

CORE IDEAS

The story. Two stories show the same idea three centuries apart. In the early 1600s, Galileo Galilei wanted to know how falling objects speed up, but a dropped ball falls too fast to time with any clock he had. So he “diluted” gravity: he rolled bronze balls down a long, smooth, gently sloping groove in a wooden beam. In 1878, in California, Leland Stanford hired the photographer Eadweard Muybridge to settle a question about galloping horses: are all four hooves ever off the ground at once? On June 19, 1878, Muybridge lined up twelve cameras beside a track, each fired by a thread as the mare Sallie Gardner ran past. The photographs, taken a fraction of a second apart, showed all four hooves in the air. More important for us, they turned motion into a series of measured positions at measured times.

How they figured it out. Galileo timed the rolling balls with a water clock: water ran from a large container through a thin pipe into a cup while the ball rolled, and he weighed the water collected to measure the time. He found that the distances covered in equal times grew as 1, 3, 5, 7, and so on, so the total distance grew as 1, 4, 9, 16: distance is proportional to the *square* of the time. He changed the slope of the

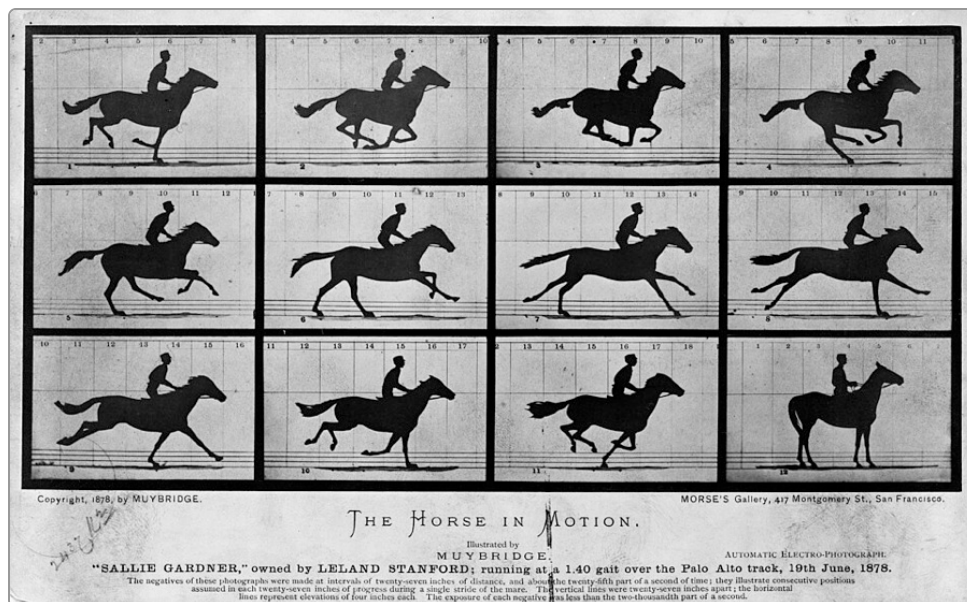
ramp and found the same pattern, only faster or slower. He published the results in 1638 in *Two New Sciences*. Muybridge's method of measuring position against time with a row of cameras was the ancestor of every slow-motion video used in engineering labs today.

The physics. A **position–time graph** shows where something is at each moment. Its slope is velocity: a steep line is fast, a flat line is stopped, and a curve that gets steeper means the object is speeding up. A **velocity–time graph** shows how fast it is going. Its slope is acceleration, and the area under it is the distance traveled. Worked example: a car starts from rest and reaches 24 m/s in 8.0 s. Its acceleration is $a = \Delta v \div \Delta t = (24 \text{ m/s} - 0) \div 8.0 \text{ s} = 3.0 \text{ m/s}^2$. The velocity–time graph is a straight line from 0 to 24 m/s, so the area under it is a triangle: $\frac{1}{2} \times 8.0 \text{ s} \times 24 \text{ m/s} = 96 \text{ m}$. For uniform acceleration from rest, $d = \frac{1}{2}at^2$, which is Galileo's square law: after 1 s the car has gone 1.5 m, after 2 s, 6 m, after 4 s, 24 m.

The engineering. Engineers draw motion graphs before they build anything that moves. An elevator designer limits not only acceleration but also *jerk* (how quickly acceleration changes) so riders are not jolted. A railway engineer plans how far a train needs to stop: a train braking at 1.0 m/s^2 from 30 m/s takes 30 s and covers $\frac{1}{2} \times 30 \text{ s} \times 30 \text{ m/s} = 450 \text{ m}$, so signals must be placed farther apart than that. Highway engineers use the same graphs to set yellow-light times and the sight distance needed before a curve. Every one of these numbers comes from the slope and the area of a simple graph.

Try it. When you graph your own ramp data, plot distance against time and then distance against time squared. If Galileo was right, the second graph will be a straight line through zero, and its slope will be $\frac{1}{2}a$.

PICTURE STUDY



The Horse in Motion, Eadweard Muybridge, 1878 · Photographs mounted on a printed card · Library of Congress

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

Muybridge's sequence turned a few seconds of motion into twelve measurements. Engineers still study motion this way, frame by frame, with high-speed cameras.

Look closely

- Find the numbered lines on the background. What do you think they were for?
- Follow the horse's nose from frame to frame. Does it move the same distance each time?
- Find the frame where all four hooves are off the ground.
- Look at the rider. Does his body move up and down as much as the horse's legs do?

Talk about it

1. If the frames were taken at equal time intervals, how could you use the background lines to find the horse's speed?
2. What would a position–time graph of the horse look like if it ran at a steady speed? What if it were speeding up?

3. Why was a row of cameras a better tool than a human eye for this question?

Safety first. Keep marbles off the floor when you finish; they are easy to slip on. Keep them away from small children, who could choke on them.

BUILD

Galileo's Ramp with a Phone Camera

You will repeat Galileo's experiment with a marble, a long ramp and a phone camera instead of a water clock. You will graph the marble's position against time, test the square law, find the acceleration, and then run a fair test to see how the ramp's angle changes it.

You will need

- A ramp at least 1.5 meters long: a straight board, a length of vinyl rain gutter, a curtain rod channel, or two meter sticks taped side by side with a gap for the marble
- A large marble or steel ball
- Books or blocks to raise one end; a tape measure and masking tape
- A phone that records slow-motion video (or a stopwatch and a partner)
- Graph paper or a free spreadsheet (Google Sheets or LibreOffice Calc)

Steps

1. Raise one end of the ramp 10 cm. Put tape marks every 25 cm from the start line (25, 50, 75, 100, 125, 150 cm). Measure the ramp length and height and write them down.
2. **Predict.** If the marble takes 1 time unit to reach 25 cm, how long will it take to reach 100 cm? Write your prediction using Galileo's square law.
3. Release the marble from rest at the start line (let go; do not push) and film it from the side in slow motion with the tape marks in view. Repeat three times.
4. Step through the video and record the time the marble passes each mark. Most phones show the time in the video editor; or count frames and divide by the frame rate (for example, 240 frames per second). Average your three trials in a table: distance (m), time (s), time² (s²).
5. Graph distance against time. Then graph distance against time squared. Draw the best straight line through the second graph and find its slope. Acceleration $a = 2 \times \text{slope}$.

6. **Fair test.** Change only the ramp height: try 5 cm, 10 cm and 20 cm, keeping the same marble, release point and ramp. Find the acceleration for each.
7. Compare with theory. For a rolling solid ball on a ramp, $a \approx (5/7) \times 9.8 \text{ m/s}^2 \times (\text{height} \div \text{length})$. Calculate this for each ramp and put it next to your measured value. Find the percent difference.
8. **Improve.** Find the biggest source of error (release, timing, a bumpy ramp) and change one thing to reduce it. Run the 10 cm test again and see whether your result moved closer to the prediction.

Tips

- Use a ruler as a starting gate: hold the marble behind it and lift the ruler straight up so you do not push the marble.
- Film from far enough back that the camera sees the whole ramp without turning; turning the camera makes the marks hard to read.
- Rolling balls accelerate more slowly than sliding objects because some energy goes into spinning. That is why the 5/7 appears.

Check your work

- ☐ I can find velocity from the slope of a position–time graph and distance from the area under a velocity–time graph.
- ☐ My distance-versus-time-squared graph is close to a straight line, and I calculated the acceleration from its slope.
- ☐ I compared my measured acceleration with the calculated one and explained the difference honestly.

ENGINEER'S NOTEBOOK

1. Redraw your three warm-up sketches. Under each, write whether it was correct and what you would change now.
2. Data table and two graphs from the ramp test, with axes labeled in units and the line of best fit drawn.
3. Draw a velocity–time graph for a car that speeds up for 5 s, cruises for 10 s and brakes for 5 s. Shade the area and calculate the total distance if the cruising speed is 20 m/s.
4. Write three sentences: what Galileo measured, what he could not measure, and how a phone camera changes the experiment.

From history. Muybridge went on to photograph people and animals walking, running and jumping, using up to 24 cameras, and he built a projector called the zoopraxiscope to show his sequences as moving pictures, a forerunner of the motion picture. Galileo's inclined-plane apparatus inspired many later copies, and a large one is displayed at the Museo Galileo in Florence.

COMMON MISTAKES

- Reading a position–time graph as a picture of the path. A line going up means moving away from the reference point, not climbing a hill.
- Confusing velocity and acceleration. An object can have a large velocity and zero acceleration (cruising), or zero velocity and a large acceleration (a ball at the very top of its toss).
- Forgetting units or using centimeters and meters in the same calculation. Convert everything to meters and seconds first.

Make it a game · Walk the Graph. Draw empty position–time axes. Your parent secretly walks across the room: steady, speeding up, or stopping halfway. Sketch the graph you saw and say what its slope means. Then swap: you walk, your parent sketches. Score a point for each correct graph and one more for explaining slope as velocity. First to six points wins.

Scripture. “The works of the LORD are great, sought out of all them that have pleasure therein.” (Psalm 111:2, KJV)

Galileo and Muybridge took delight in looking closely at ordinary motion. Careful measurement is one way of seeking out the works of the Lord.

1.2 MOMENTUM, COLLISIONS AND CRUMPLE ZONES

OBJECTIVES

- Calculate momentum ($p = mv$) and impulse ($J = F\Delta t = \Delta p$) with units.
- Use the impulse equation to explain why stretching out the time of a collision lowers the force.
- Design, test and improve a crumple zone for a cart that protects an egg “passenger.”

Warm-up. Toss a raw egg (inside a zip-top bag) gently to a partner, who catches it two ways: first with stiff hands that stop it suddenly, then with soft hands that move back with the egg. (If you would rather not risk an egg, use a water balloon outdoors.) Which catch felt gentler? Write one sentence predicting why, before you read the lesson.

WATCH

Demonstrating How Helmets Affect Impulse and Impact Force

Flipping Physics · 4:20

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

WHEN TO WATCH

After the physics paragraph. Watch the force–time graphs: the areas stay nearly the same, but the peak force drops.

BACKUP VIDEO

The Physics of Car Crashes

minutephysics · 3:09

<https://www.youtube.com/watch?v=v9ML4GA47Rg>

Before the engineering paragraph: where a moving car’s energy goes when it stops.

KEY TERMS

momentum

Mass times velocity, $p = mv$, measured in kilogram-meters per second ($\text{kg}\cdot\text{m/s}$). A heavy or fast object has a lot of momentum.

impulse

Force times the time it acts, $J = F\Delta t$, measured in newton-seconds ($\text{N}\cdot\text{s}$). The impulse on an object equals its change in momentum.

conservation of momentum

In a collision with no outside force, the total momentum before equals the total momentum after.

crumple zone

The front and rear parts of a car designed to crush in a controlled way during a crash, stretching out the stopping time.

safety cell

The stiff passenger compartment of a car, designed not to crush so that the people inside have room to survive.

CORE IDEAS

The story. In the early days of the automobile, most people thought a safe car was a stiff car: the heavier and more rigid, the better. Béla Barényi, a Hungarian-born engineer working for Daimler-Benz in Germany, saw the problem differently. If the car stops instantly, so do the people inside it. In 1951 he applied for a patent on a car body with a rigid passenger compartment and soft front and rear sections that would crush in a crash. The patent was granted in 1952, and the first production car built on his idea was the Mercedes-Benz “Fintail” sedan of 1959. That same year, Nils Bohlin, an engineer at Volvo in Sweden, introduced the three-point seat belt, and Volvo allowed other carmakers to use the design freely.

How they figured it out. Barényi and the engineers who followed him crashed real cars into barriers and filmed them, measured how far each part crushed and how quickly, and studied how the passengers moved. They learned that the goal is not to keep the car undamaged but to keep the passengers’ deceleration as low as possible. A wrecked hood is a crumple zone doing its job. Crash testing became a science, with instrumented test dummies, high-speed cameras and accelerometers recording thousands of measurements each second.

The physics. Momentum is mass times velocity: $p = mv$. A 1,500 kg car moving at 15 m/s (about 34 miles per hour) has $p = 1,500 \text{ kg} \times 15 \text{ m/s} = 22,500 \text{ kg}\cdot\text{m/s}$. To stop, it must lose all of that momentum, and the only way to change momentum is with an impulse: $F\Delta t = \Delta p$. The change in momentum is fixed, so the force depends on the time. If the car stops in 0.05 s, the average force is $22,500 \div 0.05 = 450,000 \text{ N}$. If a crumple zone stretches the stop to 0.15 s, the force falls to 150,000 N, one-third as much. The same is true for the passenger: a 60 kg person at 15 m/s has 900 kg·m/s of

momentum. A seat belt and air bag that stop her over 0.15 s apply about 6,000 N; hitting a hard dashboard in 0.01 s would mean 90,000 N.

The engineering. A modern car is designed in zones: soft, crushable ends made of carefully shaped steel rails that fold like an accordion, and a hard safety cell around the people, made of high-strength steel. Seat belts stretch slightly, air bags vent gas as they are struck, and helmets have crushable foam liners, all to make Δt longer. Momentum is also conserved between colliding objects: when a 1,500 kg car moving at 15 m/s strikes a stopped 1,500 kg car and they move off together, the pair moves at 7.5 m/s, because the total momentum (22,500 kg·m/s) must be the same before and after. Accident investigators use this law, with skid marks and crush measurements, to work out how fast vehicles were moving.

Today. Government and industry crash-test programs rate new cars with stars, and engineers now run thousands of computer crash simulations before a single real car is built. Then they crash real cars anyway, because a model is only trusted after a test confirms it.

PICTURE STUDY



A Frontal Crash Test, National Highway Traffic Safety Administration, 2006 · Photograph · U.S. Department of Transportation

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

Government engineers crash new vehicles into a rigid barrier at a set speed and measure the forces on instrumented dummies inside. This photograph shows a crash test a moment after impact.

Look closely

- Find the parts of the vehicle that crushed. Where do they stop?
- Look at the doors and the roof line. Did the passenger compartment change shape?
- Find the air bags. When in the crash must they finish opening to be useful?
- Look for markings or targets painted on the vehicle. What might the high-speed cameras use them for?

Talk about it

1. Why is it good engineering for the front of this truck to be badly damaged?
2. If the crushed length is 0.6 m and the truck was going 15 m/s, about how long did the stop take? (Hint: the average speed while stopping is half the starting speed.)

3. Why do engineers still crash real vehicles when they can simulate crashes on computers?

Safety first. Wear safety glasses during crash tests. Keep the raw egg sealed in a zip-top bag, and wash hands after handling raw eggs. Let carts run into a wall or a box, never toward people or pets.

BUILD

The Egg-Passenger Crash Test

You will roll a small cart down a ramp into a wall with a raw egg (in a bag) as its passenger. Then you will design crumple zones for the front of the cart, measure how far each one crushes, calculate the average stopping force, and improve your best design.

You will need

- A small cart: a toy car or truck big enough to carry an egg, or a cardboard box on four bottle-cap wheels with straw axles
- A ramp (a board or stiff cardboard) and books to raise it
- Raw eggs in zip-top bags, and modeling clay or tape to hold the egg in place
- Crumple-zone materials: paper strips, index cards, paper cups, drinking straws, small boxes
- A heavy box or wall to crash into, a ruler, a kitchen scale and safety glasses

Steps

1. Weigh the cart with its egg (in kilograms). Set the ramp so the cart's release point is 30 cm above the floor, and mark it. Calculate the speed at the bottom (ignoring friction): $v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 0.30} \approx 2.4 \text{ m/s}$. Record the cart's momentum, $p = mv$.
2. **Control test.** Run the cart with no crumple zone into the box. Did the egg survive? Note any crack.
3. **Design.** Sketch three different crumple zones that stick out no more than 8 cm in front of the cart and weigh no more than 10 g. Predict which will work best and why.
4. **Fair test.** Test each design from the same height, crashing into the same box. After each crash, measure how far the crumple zone crushed (the stopping distance d) and record whether the egg survived.
5. Calculate for each design: stopping time $\Delta t \approx 2d \div v$, and average force $F = p \div \Delta t$. Make a table: design, crush distance (m), stop time (s), force (N), egg

result.

6. Raise the release point to 60 cm and test your best design. Calculate the new speed. How did the force change?
7. **Improve.** Change one feature of your best design to make the crush longer and more even (for example, accordion folds or a cone shape) and retest at 60 cm.
8. Graph average force against crush distance for all your tests. Describe the pattern in one sentence.

Tips

- A crumple zone that is too stiff acts like no crumple zone; one that is too weak crushes completely and then the cart hits hard anyway. Engineers call that “bottoming out.”
- Film each crash in slow motion to see exactly when the crushing starts and stops.
- Use the same egg position every time; an egg that slides forward in the cart is like a passenger with no seat belt.

Check your work

- ☐ I can calculate momentum and the average force of a collision from the stopping time.
- ☐ I can explain why a longer stopping distance lowers the force, using $F\Delta t = \Delta p$.
- ☐ My table and graph show how my crumple-zone designs compared, and I improved my best one.

ENGINEER'S NOTEBOOK

1. Labeled cutaway sketch of a car showing the front crumple zone, the safety cell and the rear crumple zone.
2. Your crash-test data table and the force-versus-crush-distance graph.
3. Solve: a 0.06 kg egg falls and hits the floor at 4 m/s. Find the force if it stops in 0.002 s on tile and in 0.05 s on a folded towel.
4. Write a short paragraph to a younger student explaining why “soft hands” catch an egg without breaking it.

From history. Before crumple zones, a few physicians and engineers had studied survival in falls and crashes. Hugh DeHaven, who survived a 1917 training-plane crash, spent decades studying how the time and distance of a stop decide whether a person is hurt, and his work helped inspire seat belts and padded instrument panels. Barényi held more than 2,500 patents in his lifetime.

COMMON MISTAKES

- Thinking a crumple zone reduces the momentum that must be lost. It does not; it spreads the same change in momentum over a longer time.
- Mixing up momentum and kinetic energy. Momentum (mv) is conserved in every collision; kinetic energy ($\frac{1}{2}mv^2$) usually is not, because some turns into heat, sound and bent metal.
- Forgetting that velocity has a direction. A ball that bounces back has a larger change in momentum than one that stops dead.

Make it a game · Crash-Test Teacher. You have one minute to teach your parent why a crumple zone lowers force, using impulse, $J = F\Delta t = \Delta p$, and the job of the safety cell. Then your parent teaches it back and sneaks in one false fact. Catch it for a point. Finish by solving one momentum problem, $p = mv$, from memory with units.

Scripture. “A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished.” (Proverbs 22:3, KJV)

Safety engineering is prudence put into steel: engineers foresee the crash that may come and design so that people are protected when it does.

1.3 CIRCULAR MOTION: FERRIS'S WHEEL AND THE BANKED CURVE

OBJECTIVES

- Explain why an object moving in a circle at steady speed is accelerating toward the center.
- Calculate centripetal acceleration and force ($a = v^2 \div r$, $F = mv^2 \div r$) and speed from the period ($v = 2\pi r \div T$).
- Measure the force needed to keep a mass moving in a circle and compare it with the formula.

Warm-up. Put a coin on a paper plate and spin the plate slowly on a table, then faster. Then tie a soft ball in a sock and whirl it in a horizontal circle (outdoors, away from people). Let go of the sock at different points. Sketch the path the sock takes after you let go. Does it fly straight outward from the center, or along a line tangent to the circle?

WATCH

Centripetal Force Introduction and Demonstration

Flipping Physics · 5:25

<https://www.youtube.com/watch?v=jtg8q5rrZoU>

WHEN TO WATCH

After the physics paragraph. Before the turntable demonstration, predict which force keeps the object moving in a circle.

KEY TERMS

centripetal acceleration

The acceleration of any object moving in a circle, pointing toward the center:
 $a = v^2 \div r$.

centripetal force

The net force toward the center that keeps an object on a curved path: $F = mv^2 \div r$. It is not a new kind of force; it is supplied by tension, friction, gravity or a push from a track.

period

The time for one complete trip around the circle, T , in seconds. Speed $v = 2\pi r \div T$.

banked curve

A road or track tilted inward on a curve, so the push of the road surface helps turn the vehicle.

superelevation

The engineers' name for the amount a road or railway is banked on a curve; on railways it is also called cant.

CORE IDEAS

The story. For the World's Columbian Exposition in Chicago in 1893, the organizers wanted something to answer the Eiffel Tower, which had amazed visitors in Paris four years earlier. A young bridge engineer from Pittsburgh, George Washington Gale Ferris Jr., proposed a giant steel wheel that people could ride. Many thought it would collapse. Ferris's wheel was 250 feet across, with 36 cars that each held up to 60 riders, turning on an axle that weighed about 46 tons, then the largest single steel forging ever made. It opened in June 1893 and carried well over a million passengers that summer without a serious accident.

How they figured it out. Ferris's firm inspected steel and designed bridges, so he designed the wheel like a bridge: a light rim held in place by thin steel rods in tension, like the spokes of a bicycle wheel, rather than heavy beams in bending. His engineers calculated the loads from the cars, the riders, the wheel's own weight and the Chicago wind, and the wheel was built in only a few months. A wheel turning that slowly puts only small extra forces on the riders, but the same circular-motion physics becomes very large when speeds rise, as railway and highway engineers soon learned.

The physics. An object moving in a circle at constant speed is still accelerating, because its *direction* keeps changing. The acceleration points toward the center and equals $a = v^2 \div r$. By Newton's second law, something must supply a net inward force $F = mv^2 \div r$. On your whirled sock it was the tension in your arm; for a car on a curve it is friction between tires and road; for the Moon it is gravity. When the inward force is removed, the object goes straight along the tangent, which is why your sock flew off sideways, not outward. Worked example: a 1,200 kg car takes a curve of radius 50 m at 20 m/s (about 45 mph). $a = (20 \text{ m/s})^2 \div 50 \text{ m} = 8.0 \text{ m/s}^2$, and $F = 1,200 \text{ kg} \times 8.0 \text{ m/s}^2$

= 9,600 N of sideways friction. Double the speed and the force is four times as large, because v is squared.

The engineering. Tire friction is limited, and on wet or icy roads it is much smaller. So highway and railway engineers **bank** curves, tilting the surface inward so that part of the road's push points toward the center of the curve. A curve can be banked so that, at its design speed, a car would get around it with no sideways friction at all: $\tan \theta = v^2 \div (gr)$. For the curve above at 20 m/s, $\tan \theta = 400 \div (9.8 \times 50) \approx 0.82$, an angle of about 39° , which is far too steep for a highway. Real highways are banked only a few degrees (often limited to about $6\text{--}8^\circ$, partly because cars must not slide inward on ice), so engineers also choose large curve radii and post lower speed limits on sharp curves. Railways tilt their outer rail up by a few inches for the same reason.

Try it. In your build, a hanging weight will supply the centripetal force. If $F = mv^2 \div r$ is true, you can predict exactly how fast the stopper must whirl to hold the weight still.

PICTURE STUDY



The Ferris Wheel, Chicago, C. D. Arnold, 1893 · Photograph · Official Views of the World's Columbian Exposition, Chicago

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

Ferris built his wheel like a bridge turned on its side. Look at how much of it is thin rods and how little is heavy steel.

Look closely

- Find the axle and the two towers that hold it. Which parts are in compression?
- Find the thin spoke rods. Are they pushing or pulling on the rim?
- Find the passenger cars. How are they hung so that riders stay upright as the wheel turns?
- Compare the size of a car with the people or buildings near the base.

Talk about it

1. Why did Ferris use thin rods in tension instead of thick beams for the spokes?
2. The wheel was about 250 feet (76 m) across. If it took 10 minutes to make one turn, how fast did a car move? (Use $v = 2\pi r \div T$.) Was the centripetal acceleration large or small?
3. What loads besides the riders would the engineers have had to plan for?

Safety first. Wear safety glasses for the whirling test and do it outdoors or in a clear room, away from people, lamps and windows. Check the string and knots before every run.

BUILD

The Whirling-Stopper Force Test

You will whirl a small mass in a horizontal circle on a string that passes through a tube, with hanging washers on the other end supplying the force. By measuring the radius and the period, you can calculate the centripetal force and compare it with the weight of the washers.

You will need

- An empty ballpoint-pen tube or a smooth plastic tube about 15 cm long (smooth both ends with tape)
- About 1.5 m of strong, smooth string or fishing line
- A rubber stopper, a large cork with a screw eye, or a lump of modeling clay wrapped in tape (about 15–30 g)
- Metal washers and a paper clip to hang them
- A kitchen scale, a tape measure, a small binder clip or clothespin as a marker, a stopwatch and safety glasses

Steps

1. Weigh the stopper (m) and the washers. Tie the stopper to one end of the string, pass the string through the tube, and hang the washers on the other end with the paper clip.
2. Measure 0.50 m of string from the stopper to the top of the tube and clip the marker on the string just below the tube. When the marker stays just below the tube, the radius is 0.50 m.
3. Hold the tube upright and whirl the stopper in a horizontal circle over your head, adjusting the speed until the marker stays steady. Have a partner time 20 turns. Divide by 20 to get the period T. Do three trials.
4. Calculate $v = 2\pi r \div T$ and the centripetal force $F = mv^2 \div r$. Compare with the weight of the washers, $W = (\text{mass in kg}) \times 9.8 \text{ N/kg}$.
5. **Fair test.** Keep the washers the same and change the radius to 0.30 m and 0.70 m. Predict first: should the period get longer or shorter? Then test.

6. Make a table: radius (m), period (s), speed (m/s), calculated force (N), washer weight (N), percent difference.
7. Change the number of washers (double them) at $r = 0.50$ m. Predict the new period using $F = 4\pi^2 mr \div T^2$, then test.
8. **Improve.** Your calculated force will probably come out larger than the washer weight. Find the reasons (the string is not perfectly horizontal; friction in the tube) and try one change to reduce the error.

Tips

- Whirl with small wrist movements so the tube stays still; moving your hand in a circle changes the radius.
- Count “zero” at the start of the timing, not “one.”
- The string slopes down a little toward the stopper, so part of the tension holds the stopper up. That is one honest reason your numbers will not match exactly.

Check your work

- ☐ I can explain why an object moving in a circle at steady speed is accelerating.
- ☐ I calculated centripetal force from my measurements and compared it with the weight of the washers.
- ☐ I can explain why curves on highways and railways are banked.

ENGINEER'S NOTEBOOK

1. Top-view sketch of the whirling stopper with arrows for velocity (tangent) and acceleration (toward the center).
2. Your data table, and a graph of force against $v^2 \div r$ for all your trials. Is it a straight line? What should its slope be?
3. Cross-section sketch of a banked highway curve with the car, the road's push (normal force) and gravity drawn as arrows.
4. Solve: a train car of 40,000 kg goes around a curve of radius 800 m at 25 m/s. Find the centripetal force.

From history. Ferris's wheel was moved twice after the fair, first to a Chicago neighborhood and then to the 1904 World's Fair in St. Louis. It was taken down in 1906. Ferris died young, in 1896, but every observation wheel in the world, from county fairs to the London Eye, carries his name.

COMMON MISTAKES

- Believing in an outward “centrifugal force” that throws things out. In the ground's frame of reference there is no outward force; the object simply tries to keep going straight while something pulls it inward.
- Forgetting to square the speed. Going twice as fast around a curve needs four times the force.
- Using diameter instead of radius in $a = v^2 \div r$.

Make it a game • Merry-Go-Round Estimate. Estimation duel. Pick a circular ride: a Ferris wheel, a bike on a curve, a toy on a string. Each of you writes a guess for the centripetal acceleration, then calculates $a = v^2 \div r$. Closest guess wins the round. The loser explains in one sentence why steady speed in a circle is still acceleration. Play five rounds.

1.4 ENERGY CONSERVATION AND ROLLER-COASTER DESIGN

OBJECTIVES

- Calculate gravitational potential energy ($PE = mgh$) and kinetic energy ($KE = \frac{1}{2}mv^2$) and use energy conservation to find speed ($v = \sqrt{2gh}$).
- Explain why a looping coaster needs a minimum starting height and why engineers replaced circular loops with clothoid (teardrop) loops.
- Build a foam-track marble coaster, find the minimum height for a loop, and measure how much energy is lost to friction.

Warm-up. Hold a ball at shoulder height and drop it onto a hard floor. Measure how high it bounces. Then try to explain where the “missing” height went. Can a ball ever bounce higher than where you dropped it, if nobody throws it? Write your answer and your reason.

WATCH

How Roller Coasters Actually Work

Jared Owen · 15:49

<https://www.youtube.com/watch?v=irkAtqm-eCs>

WHEN TO WATCH

After the story, before the physics. Notice the history of the loop and the wheels that hold the cars on the track.

Note: Contains a short sponsor message for an online learning site; you can skip it.

BACKUP VIDEO

The Real Physics of Roller Coaster Loops

Art of Engineering · 18:02

<https://www.youtube.com/watch?v=4q2W5SJc5j4>

For strong math students after the physics paragraph: the full calculation of g-forces in circular and clothoid loops.

KEY TERMS

potential energy

Stored energy of position. Near the earth's surface, gravitational $PE = mgh$, measured in joules (J).

kinetic energy

Energy of motion, $KE = \frac{1}{2}mv^2$, measured in joules (J).

conservation of energy

Energy is never created or destroyed; it only changes form. In a coaster, PE becomes KE and back again, with some always turning into heat and sound through friction.

g-force

An acceleration expressed as a multiple of g (9.8 m/s^2). Riders feel g-forces as being pressed into or lifted out of their seats.

clothoid loop

A loop whose curve gets tighter toward the top, like an upside-down teardrop. It keeps the g-forces on riders lower than a circular loop of the same height.

CORE IDEAS

The story. In June 1884, LaMarcus Adna Thompson opened his Switchback Railway at Coney Island in New York. Riders climbed a tower, sat in a car that rolled down a gentle wooden track at about 6 miles per hour to a second tower, and then were rolled back on a parallel track. It cost a nickel and was a great success. Others soon wanted thrills, and in 1895 the Flip Flap Railway at Coney Island sent riders around a *circular* loop. It was famous for a rough ride; many riders complained of sore necks. In 1901 Edwin Prescott built the Loop-the-Loop, also at Coney Island, with an oval loop shaped more like a teardrop. It was gentler, but it carried only a few riders at a time and soon closed. Looping coasters disappeared for decades.

How they figured it out. The problem with the circular loop was speed and radius. To get a car over the top of a loop, it needs enough speed there, so it must enter the bottom much faster, and at the bottom of a small circle a fast car makes a very large acceleration. Riders were being pressed into their seats with several times their own weight in a fraction of a second. Engineers in the 1970s, led by the German engineer Werner Stengel, used the clothoid curve, already used for highway and railway

transitions, whose radius changes smoothly. A clothoid loop is wide at the bottom, where the car is fastest, and tight at the top, where it is slowest, so the g-forces stay nearly even. Modern looping coasters are designed this way, with computer models checking the forces at every point.

The physics. At the top of the lift hill a coaster has potential energy $PE = mgh$. As it falls, PE turns into kinetic energy $KE = \frac{1}{2}mv^2$. With no friction, $mgh = \frac{1}{2}mv^2$, so $v = \sqrt{2gh}$; the mass cancels, so a full train and an empty train reach the same speed. Worked example: a 40 m drop gives $v = \sqrt{(2 \times 9.8 \text{ m/s}^2 \times 40 \text{ m})} = \sqrt{784} \approx 28 \text{ m/s}$, about 63 mph. Now the loop: at the top, gravity alone must be enough to curve the car's path, so $v^2 \geq gr$. With energy conservation, a car sliding without friction must start at least 2.5 times the loop's radius above the bottom ($h = 2.5r$). At the bottom of a circular loop of radius 10 m, a car entering at 20 m/s has $a = v^2 \div r = 400 \div 10 = 40 \text{ m/s}^2$, about 4 g, and riders feel that plus 1 g of gravity, about 5 g. That is far too much to put on riders' necks suddenly.

The engineering. Real coasters lose energy to friction in the wheels, to air drag and to sound, so each hill must be lower than the one before, and designers measure exactly how much energy a train loses per meter of track. Modern steel coasters run on polyurethane wheels: road wheels on top, side-friction wheels, and up-stop wheels underneath so the train cannot lift off the track. Safety engineers set limits on how many g's riders may feel and for how long, design brakes that need no electricity (magnetic brakes and spring-applied friction brakes), and inspect the track and trains every day before opening. Roller-coaster design is a real career that combines mechanical engineering, structural engineering and careful attention to the human body.

Try it. In your build you will find the lowest release height that gets a marble around a loop, then compare it with the 2.5r rule. A rolling marble also stores energy in its spin, which will be one honest reason your number comes out higher.

PICTURE STUDY



Loop the Loop, Coney Island, Unknown photographer, about 1901–1905 · Photograph · Coney Island, Brooklyn, New York

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

Edwin Prescott's Loop-the-Loop was one of the first coasters to take riders upside down. Its loop was taller than it was wide, an early step toward the modern clothoid shape.

Look closely

- Find the loop. Is it a perfect circle? Where is it tightest?
- Find the lift hill or starting tower. How much higher is it than the top of the loop?
- Look at the framework holding up the track. Which parts look like they are in compression?
- Find the spectators. Why might watching have been more popular than riding?

Talk about it

1. Why does a car need to start well above the top of the loop, not just level with it?
2. Why is a loop that is tight at the top and wide at the bottom gentler on riders than a circle?

3. What would you want to measure before letting anyone ride a coaster like this?

Safety first. Keep marbles away from small children. If you mount the track on furniture or a wall, use painter's tape so nothing is damaged, and do not stand on chairs without an adult holding them.

BUILD

A Foam-Track Coaster with a Loop

You will build a marble roller coaster from foam pipe insulation, find the lowest release height that carries the marble around a loop, and measure the marble's speed to find how much of its energy survives the trip.

You will need

- Two or three lengths of foam pipe insulation (about 1.8 m each), cut lengthwise in half by an adult to make open channels
- Masking or painter's tape, a tape measure and a marker
- Marbles (a glass marble and a steel ball if you have one)
- A kitchen scale, a phone that films slow-motion video, a cardboard box for a catch bin
- Chairs, a bookshelf or a wall for supports

Steps

1. Tape one channel into a vertical loop with a diameter of about 30 cm and tape it firmly to a support so it holds its shape. Measure the loop's radius r .
2. Attach a long, straight drop section leading into the loop and an exit section leading into a catch box. Mark heights on the drop every 5 cm, measured straight up from the bottom of the loop.
3. **Predict.** Using $h = 2.5r$, calculate the lowest release height for a sliding object. Write a second prediction for your rolling marble: higher or lower, and why?
4. Release the marble from rest at different heights, starting low and moving up 5 cm at a time. Run three trials at each height and record whether it completes the loop. Find the lowest height that works every time.
5. **Speed test.** Put two tape marks 10 cm apart on the flat section just before the loop. Film the marble from a release height of 60 cm and find the time between marks. Calculate $v = 0.10 \text{ m} \div t$.
6. Calculate the energy: PE at the start = mgh , KE at the marks = $\frac{1}{2}mv^2$. Energy efficiency = $KE \div PE \times 100\%$. (For a rolling solid ball, about 2/7 of the energy goes into spinning; you may note this.)

7. **Fair test.** Change only the loop shape: squeeze it into a taller, teardrop (clothoid-like) loop with the same height. Find the new minimum release height and compare.
8. **Improve.** Add a hill after the loop. Use your efficiency number to predict the tallest hill the marble can climb, then build it and test your prediction.

Tips

- Tape the loop at many points; a loop that sags or wobbles steals energy.
- Smooth joints matter. Overlap channels so the marble rolls from the upper piece down onto the lower one, never into an edge.
- A steel ball and a glass marble of different masses should reach the same speed from the same height. Test it.

Check your work

- ☐ I can use $mgh = \frac{1}{2}mv^2$ to calculate the speed of a coaster at the bottom of a drop.
- ☐ I found the minimum release height for my loop and compared it with the $2.5r$ rule.
- ☐ I measured my coaster's energy efficiency and used it to make a prediction that I then tested.

ENGINEER'S NOTEBOOK

1. Labeled side view of your coaster with heights marked, and an energy bar chart (PE, KE, lost energy) at the start, at the bottom of the loop and at the top of the loop.
2. Data tables for the minimum-height test and the speed test, with your efficiency calculation.
3. Sketch a circular loop and a clothoid loop of the same height side by side. Mark where each is tightest and explain which is gentler on riders.
4. Solve: a coaster car falls 55 m. Find its speed at the bottom if 10% of the energy is lost to friction.

From history. LaMarcus Thompson built dozens of “scenic railways” across the United States and Europe and is often called the father of the American gravity ride. In the early 1900s, coaster designers such as John A. Miller patented the up-stop wheels and safety ratchets (the clicking “chain dogs” on lift hills) that keep trains on the track and stop them from rolling backward, and versions of those ideas are still used today.

COMMON MISTAKES

- Thinking heavier coaster trains go faster down a hill. Without friction, speed depends only on height, because the mass cancels.
- Believing the car only needs to start as high as the top of the loop. It must still be moving fast enough at the top to stay on the curve.
- Forgetting to square the speed in $KE = \frac{1}{2}mv^2$, or forgetting the $\frac{1}{2}$.

Make it a game • Will It Make the Loop?. Draw a coaster hill and a loop on paper. Your parent names a starting height. In twenty seconds, say whether a car can finish the loop, then find its bottom speed with $v = \sqrt{2gh}$. Wrong answers cost a point. Switch roles and set a harder hill. Bonus point for naming why a teardrop loop is gentler on riders.

UNIT 1

PHYSICS OF MOTION

Everything an engineer builds either moves or must stand still while other things push on it. This year begins with motion itself, measured with numbers and units the way a high-school physics class measures it. You will read and draw motion graphs, as Galileo did with his rolling balls and Eadweard Muybridge did with his row of cameras. You will calculate momentum and impulse and see why the safest cars are built to crumple. You will swing objects in circles and learn the force that keeps a Ferris wheel car or a highway truck on its curved path.

The unit ends with energy: how a roller coaster trades height for speed and speed for height, why the first looping coasters hurt their riders, and how engineers reshaped the loop. Every lesson uses real equations ($v = \Delta x \div \Delta t$, $p = mv$, $F = mv^2 \div r$, $KE = \frac{1}{2}mv^2$) worked out with real numbers, and every build ends with a data table, a graph and an honest comparison between what the math predicted and what the measurement showed.

PREREQUISITES

- Comfortable with decimals, ratios, square roots and simple algebra (solving for one unknown)
- Knows Newton's three laws in words and can use $F = ma$
- Can draw a line graph with labeled axes and units
- Keeps a dated engineer's notebook with predictions and data tables

MASTERY CHECKLIST

- ☐ I can read and draw position–time and velocity–time graphs and find velocity from a slope and distance from an area.
- ☐ I can calculate momentum and impulse and explain with numbers why a crumple zone, an air bag or a helmet lowers the force of a collision.
- ☐ I can calculate centripetal acceleration and force ($a = v^2 \div r$, $F = mv^2 \div r$) and explain why roads and railways are banked on curves.
- ☐ I can use conservation of energy ($mgh = \frac{1}{2}mv^2$) to predict the speed of a roller coaster and explain why real loops are not circles.
- ☐ I can run a fair test, graph my data and compare measured results with calculated predictions, giving honest reasons for the difference.

OPTIONAL KITS FOR THIS UNIT

- **K'NEX roller coaster building sets**: Ages 9 and up. Larger K'NEX coaster sets have a motorized chain lift and long, adjustable track, which makes it easy to measure drop heights and test loops for Lessons 1.3–1.4 and the portfolio project.
- **Thames & Kosmos physics and engineering kits**: Ages 8 and up for most sets. Their physics and roller coaster engineering kits add ramps, carts and track pieces that fit Lessons 1.1 and 1.4.

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

1.1 Motion Graphs: Galileo's Ramps and Muybridge's Horse

2 sessions of 60 minutes

1.2 Momentum, Collisions and Crumple Zones

2 sessions of 60 minutes

1.3 Circular Motion: Ferris's Wheel and the Banked Curve

2 sessions of 60 minutes

1.4 Energy Conservation and Roller-Coaster Design

2 sessions of 60 minutes

UNIT 1 REVIEW

Answer each question. For calculations, write the formula, substitute the numbers with units, and box your answer. Use $g = 9.8 \text{ m/s}^2$. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

On a position–time graph, what does the slope tell you? On a velocity–time graph, what do the slope and the area under the line tell you?

2. **10 pts**

Calculation. A train starts from rest and reaches 18 m/s in 12 s with steady acceleration. Find its acceleration and the distance it travels in that time.

3. **8 pts**

Galileo found that a ball rolling from rest covers 1 unit of distance in the first second. How far has it gone in total after 3 seconds? What equipment did he use to measure the time?

4. **10 pts**

Calculation. A 1,200 kg car moving at 20 m/s stops in a crash. Find its momentum before the crash, and the average force on it if it stops in 0.08 s. What would the force be if a crumple zone stretched the stop to 0.16 s?

5. **8 pts**

Explain in two or three sentences why the safest car has soft ends and a stiff middle.

6. **8 pts**

A 2 kg cart moving at 3 m/s hits a stopped 1 kg cart, and they stick together. How fast do they move afterward?

7. **8 pts**

You whirl a ball on a string in a circle and the string breaks. Describe the ball's path and explain why.

8. **10 pts**

Calculation. A 1,500 kg car drives around a curve of radius 60 m at 15 m/s. Find its centripetal acceleration and the friction force needed. What happens to the needed force if the speed doubles?

9. **10 pts**

Why do highway and railway engineers bank curves? Give one reason highway banking is kept to only a few degrees.

10. **10 pts**

A roller-coaster car starts from rest at the top of a 45 m hill. Ignoring friction, how fast is it moving at the bottom? Does the mass of the car matter?

11. **10 pts**

Why did the early circular loops at Coney Island hurt riders, and how does a clothoid loop fix the problem?

ANSWER KEY

1. Position–time slope = velocity. Velocity–time slope = acceleration; area under the velocity–time line = displacement (distance traveled).
2. $a = \Delta v \div \Delta t = 18 \text{ m/s} \div 12 \text{ s} = 1.5 \text{ m/s}^2$. Distance = area of triangle = $\frac{1}{2} \times 12 \text{ s} \times 18 \text{ m/s} = 108 \text{ m}$. (Or $d = \frac{1}{2}at^2 = \frac{1}{2} \times 1.5 \times 144 = 108 \text{ m}$.)
3. Distance grows with the square of time, so $3^2 = 9$ units. He used a water clock, weighing the water that flowed out during each roll.
4. $p = mv = 1,200 \times 20 = 24,000 \text{ kg}\cdot\text{m/s}$. $F = \Delta p \div \Delta t = 24,000 \div 0.08 = 300,000 \text{ N}$. With 0.16 s: $24,000 \div 0.16 = 150,000 \text{ N}$, half as much.
5. The soft ends (crumple zones) crush to stretch out the stopping time, which lowers the force on the passengers ($F\Delta t = \Delta p$). The stiff safety cell keeps its shape so the people inside are not crushed and have room to be slowed by belts and air bags.
6. Momentum before = $2 \times 3 = 6 \text{ kg}\cdot\text{m/s}$. After: $(2 + 1) \times v = 6$, so $v = 2 \text{ m/s}$.
7. It flies off in a straight line tangent to the circle (in the direction it was moving at that instant), not straight outward. With no inward force, Newton's first law says it keeps moving in a straight line.
8. $a = v^2 \div r = 225 \div 60 = 3.75 \text{ m/s}^2$. $F = ma = 1,500 \times 3.75 = 5,625 \text{ N}$. If the speed doubles, the force becomes four times as large (22,500 N).
9. Tilting the road inward lets part of the road's push (normal force) point toward the center of the curve, so less friction is needed. Banking is limited because slow or stopped cars on icy roads could slide down toward the inside of the curve.
10. $v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 45} = \sqrt{882} \approx 29.7 \text{ m/s}$. The mass does not matter, because it cancels in $mgh = \frac{1}{2}mv^2$.
11. To get over the top of a circle, the car had to enter the bottom very fast, and at the bottom of a small circle that made a very large acceleration ($v^2 \div r$), pressing riders with several g's. A clothoid loop is wide (large radius) at the bottom where the car is fast and tight at the top where it is slow, keeping g-forces lower and more even.

PORTFOLIO PIECE: A CALCULATED ROLLER COASTER

Design and build a marble roller coaster from foam pipe insulation, card stock or a K'NEX set that includes a drop, a loop, a hill and a banked curve, and finishes with the marble stopping safely in a catch bin. Before building, draw a side view with every height labeled and predict the marble's speed at three points using energy conservation and your measured efficiency. After building, measure the speeds with slow-motion video, compare predictions with measurements in a table, and write a one-page engineer's report explaining the differences and what you changed to make the coaster run reliably ten times in a row.

LOOK FOR	WHAT IT MEANS
Design drawing and predictions	Scaled side view with heights in centimeters; predicted speeds calculated with $mgh = \frac{1}{2}mv^2$ and a stated efficiency.
Working coaster	Includes a drop, loop, hill and banked curve; the marble completes the course at least 8 times out of 10.
Measurement and data	Speeds measured at three points with three trials each; table compares predicted and measured values with percent difference.
Physics explanation	Report uses energy conservation, centripetal acceleration and friction correctly to explain the results.
Improvement	At least one specific change made after testing, with before-and-after data.

UNIT 2

BRIDGES

In earlier years you learned the shapes of bridges and the forces inside them. This year you will learn to think about a bridge the way a licensed civil engineer does. You will trace the load path of every pound from the deck to the ground, calculate support reactions and bending moments, and learn why engineers design to written codes with load factors instead of trusting their own judgment alone. You will learn why the codes exist: the iron bridge at Ashtabula, Ohio, that fell under a train in 1876, and the Silver Bridge over the Ohio River that fell in 1967.

You will compare the two great bridge materials, steel and concrete, by casting and breaking your own reinforced beams, and then you will design, build, weigh and load-test a balsa truss bridge in an efficiency competition, analyzing its members by the method of joints first worked out by Squire Whipple. The unit ends with the people: what a civil engineer does all day, how the Professional Engineer license works, and why the public trusts the engineer's seal on a drawing.

PREREQUISITES

- Can solve one-step and two-step equations and use ratios
- Knows compression, tension, shear and buckling, and why triangles make trusses rigid
- Can use sine, cosine or similar triangles to split a slanted force into horizontal and vertical parts (taught briefly in Lesson 2.3)
- Has finished Unit 1 and can draw a force arrow diagram

MASTERY CHECKLIST

- ☐ I can trace a load path from the deck of a bridge to the foundations and calculate the support reactions of a simple beam.
- ☐ I can explain what load factors and design codes are and apply a load factor to a dead and live load.
- ☐ I can compare steel and concrete by strength, stiffness, weight, cost and durability, and explain why concrete is reinforced and prestressed.
- ☐ I can find the force in each member of a simple truss by the method of joints and calculate a bridge's structural efficiency.
- ☐ I can describe the path to a Professional Engineer license and the duty an engineer owes to the public.

OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits and supplies**: Ages 11 and up with an adult. Pitsco sells precut balsa and basswood, gusset plates, plans and bridge testers, a good fit for the balsa efficiency competition in Lesson 2.3 and the portfolio bridge.
- **K'NEX bridge building sets**: Ages vary by set. Useful for quickly building and comparing truss patterns before you cut balsa in Lesson 2.3.

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

2.1 Load Paths and Design Codes: From Ashtabula to the Rulebook

2 sessions of 60 minutes

2.2 Steel versus Concrete: Eads, Magnel and the Reinforced Beam

2 sessions of 60 minutes

2.3 A Balsa Bridge Efficiency Competition: Whipple and the Method of Joints

2 sessions of 60 minutes

2.4 Careers: The Civil Engineer, Bridge Inspection and the PE License

2 sessions of 60 minutes

UNIT 2 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

List the load path of a truss bridge from a car on the deck to the soil.

2. 10 pts

Calculation. A beam 8.0 m long rests on supports A and B. A 20 kN load sits 2.0 m from A. Find both reactions and the largest bending moment.

3. 8 pts

A girder carries 200 kN of dead load and 120 kN of live load. Using load factors of 1.25 and 1.75, what load is it designed for? Why does live load get the larger factor?

4. 8 pts

What did engineers learn from the Ashtabula bridge collapse of 1876, and what did they do about it?

5. 10 pts

Calculation. A steel rod has a cross-sectional area of 400 mm² and carries a tension of 100 kN. Find the stress in MPa. If the steel yields at 414 MPa, what is the ratio of yield stress to working stress?

6. **8 pts**

Why is the steel in a reinforced-concrete beam placed near the bottom? How does prestressing improve on this?

7. **8 pts**

Give two advantages of steel and two advantages of concrete for bridges.

8. **10 pts**

Calculation. A triangular truss spans 6.0 m with its peak 2.0 m above the middle, so each sloping member is about 3.6 m long. A 12 kN load hangs at the peak. Find the force in each sloping member and in the bottom chord, and say whether each is in tension or compression.

9. **8 pts**

Bridge A has a mass of 40 g and holds 18 kg. Bridge B has a mass of 25 g and holds 14 kg. Which is more efficient? Show the numbers.

10. **8 pts**

What is fatigue, and why did a small crack bring down the whole Silver Bridge?

11. **6 pts**

List the four main steps to becoming a licensed Professional Engineer.

12. **8 pts**

Write a short paragraph explaining what an engineer's seal on a drawing means and why the public relies on it.

ANSWER KEY

1. Deck → stringers/floor beams → trusses (or girders) → bearings → piers and abutments → foundations → soil or rock.
2. ΣM about A: $R_B \times 8.0 = 20 \times 2.0$, $R_B = 5.0$ kN. $R_A = 20 - 5.0 = 15$ kN. Largest moment under the load: $M = 15 \text{ kN} \times 2.0 \text{ m} = 30 \text{ kN}\cdot\text{m}$.
3. $1.25 \times 200 + 1.75 \times 120 = 250 + 210 = 460$ kN. Live load (traffic) is much less predictable than the structure's own weight, so it needs a larger margin.
4. That bridges needed written specifications and independent checking by experienced engineers rather than untried details and guesswork. They wrote standard specifications and loadings (such as Cooper's train loading) and began requiring inspections.
5. $\sigma = F \div A = 100,000 \text{ N} \div 400 \text{ mm}^2 = 250 \text{ N/mm}^2 = 250 \text{ MPa}$. Ratio = $414 \div 250 \approx 1.66$.
6. When a beam bends under load, the bottom is in tension, and concrete is weak in tension, so steel is placed there to carry it. Prestressing squeezes the concrete with stretched tendons before loading, so the bottom stays in compression and does not crack.
7. Steel: high strength-to-weight ratio for long spans; ductile; fast to erect; strong in tension. Concrete: inexpensive; moldable; fire and weather resistant; low maintenance; strong in compression. (Any two each.)
8. Each reaction = 6.0 kN. At a support: $F \times (2.0 \div 3.6) = 6.0$, so $F \approx 10.8$ kN compression. Bottom chord = $10.8 \times (3.0 \div 3.6) = 9.0$ kN tension.
9. A: $18,000 \div 40 = 450$. B: $14,000 \div 25 = 560$. Bridge B is more efficient even though it held less.
10. Fatigue is damage that grows from many repeated loads below the material's strength, usually starting as a small crack at a stress concentration. The Silver Bridge's eyebars had only two bars per link and no other load path (no redundancy), so when one eybar cracked through, the chain failed and the bridge collapsed.
11. An accredited engineering degree; pass the FE exam; about four years of experience under a PE; pass the PE exam (then keep up continuing education).
12. Answers should explain that the seal is the licensed engineer's legal and professional statement that the design meets codes and is safe; the public cannot check the calculations themselves, so they trust the engineer's competence and honesty, and the engineer is accountable for that trust.

PORTFOLIO PIECE: A DESIGNED, ANALYZED AND LOAD-TESTED TRUSS BRIDGE

Design and build a balsa or basswood truss bridge to the Lesson 2.3 competition rules (or a K'NEX or craft-stick bridge scaled up with rules of your own). Before building, prepare a design package like a real engineer: a full-size drawing, a method-of-joints analysis of the main members for a 100 N center load, and a materials list with the predicted mass. After testing, write a two-page engineer's report with the measured mass, failure load, efficiency, a description and photograph of the failure, a comparison of the failure with your analysis, and a recommendation for the next design. Sign and date it as the responsible engineer.

LOOK FOR	WHAT IT MEANS
Design package	Neat full-size drawing with dimensions; member forces calculated and labeled T or C; predicted mass.
Construction	Two matching side trusses, square joints with gussets, top and bottom bracing; meets the span, width and mass rules.
Test and data	Weighed before testing; load applied slowly at center; failure load and efficiency calculated correctly; test filmed or photographed.
Failure analysis	Report identifies the first failure and explains it using tension, compression, buckling or joint strength, compared with the calculations.
Professional report	Clear, honest writing with units, tables and a specific recommendation; signed and dated.

2.1 LOAD PATHS AND DESIGN CODES: FROM ASHTABULA TO THE RULEBOOK

OBJECTIVES

- Trace the load path through a bridge and explain redundancy.
- Calculate the support reactions and the largest bending moment of a simple beam with a point load.
- Explain what a design code is and apply load factors ($1.25 \times \text{dead} + 1.75 \times \text{live}$) to find a factored load.

Warm-up. Stand a ruler across two stacks of books and set a heavy coin near one end. Which stack of books do you think is carrying more of the coin's weight? Move the coin to the middle, then to the other end. Write a rule in your own words for how the load is shared. You will test your rule with kitchen scales in the build.

WATCH

Understanding Stresses in Beams

The Efficient Engineer · 14:48

<https://www.youtube.com/watch?v=f08Y39UiC-o>

WHEN TO WATCH

After the physics paragraph. Watch the first nine minutes closely (bending moment, compression on top, tension on the bottom, and why I-beams work); the shear-stress section at the end is optional.

KEY TERMS

load path

The route a load travels through a structure from where it is applied to the ground: deck → beams or stringers → girders or trusses → bearings → piers and abutments → foundations → soil or rock.

reaction

The force a support pushes back with. For a structure at rest, the reactions balance all the loads (the sum of forces is zero).

bending moment

The turning effect of forces that bends a beam, force $\times$ distance, measured in newton-meters (N·m) or kilonewton-meters (kN·m).

dead load and live load

Dead load is the permanent weight of the structure itself; live load is the moving or changing weight on it, such as trains, trucks and people.

load factor

A number greater than 1 that a design code multiplies loads by, so the structure is designed for loads larger than expected.

redundancy

Having more than one load path, so that if one member fails the load can find another way to the ground.

CORE IDEAS

The story. On the snowy night of December 29, 1876, a passenger train crossing the iron bridge over the Ashtabula River in Ohio fell when the bridge gave way beneath it. More than 90 people died. The bridge was an iron Howe truss, about 150 feet long, designed eleven years earlier by the railroad's own officials. It had passed a load test when new, but it had been built from untried iron details, and no independent engineer had checked the design. The country was shocked. Engineers asked hard questions: who should design a bridge, by what rules, and who should check it?

How they figured it out. Investigators from the Ohio legislature and from the American Society of Civil Engineers studied the wreck. They found that the iron members were held at the joints by cast-iron angle blocks and that some members could slip; the design relied on parts working together exactly as planned, with little reserve if one part was weak. Their lesson was that bridges needed *written specifications* worked out by experienced engineers and applied to every bridge. Over the next two decades engineers wrote them. In 1894, Theodore Cooper published a standard set of train loads, a row of locomotive axle weights to be used in every railroad bridge design. A form of his loading, called Cooper E80, is still used for railroad bridges in North America today. Highway bridges got their own national specification in 1931.

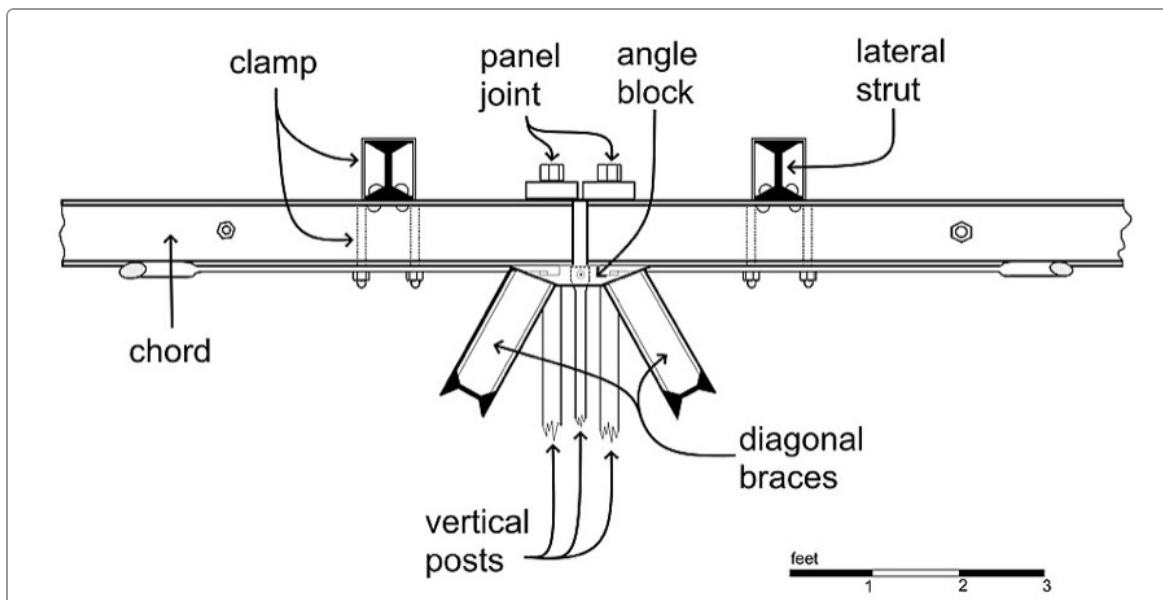
The physics. A bridge at rest obeys two rules: the forces balance ($\Sigma F = 0$) and the turning effects balance ($\Sigma M = 0$). Take a simple beam 6.0 m long resting on two supports, A and B, with a 12 kN load placed 2.0 m from A. Taking moments about A: $R_B \times 6.0 \text{ m} = 12 \text{ kN} \times 2.0 \text{ m}$, so $R_B = 4.0 \text{ kN}$. Then $R_A = 12 - 4.0 = 8.0 \text{ kN}$. The support

nearer the load carries more, as your warm-up rule probably said. The largest bending moment is under the load: $M = R_A \times 2.0 \text{ m} = 16 \text{ kN}\cdot\text{m}$. The beam must be strong and stiff enough to resist that moment, with compression on top and tension on the bottom.

The engineering. Today's highway bridges in the United States are designed by the AASHTO *LRFD Bridge Design Specifications* (Load and Resistance Factor Design). Loads are multiplied by load factors, because they could be heavier than expected, and the calculated strength is multiplied by a resistance factor less than 1, because materials and workmanship could be weaker than expected. In the most common case, dead load is multiplied by 1.25 and vehicle live load by 1.75 (live loads vary more, so they get the bigger factor). If a girder carries 100 kN of dead load and 80 kN of live load, it is designed for $1.25 \times 100 + 1.75 \times 80 = 265 \text{ kN}$. A good engineer also designs for **redundancy**, so that the failure of one member does not bring down the whole bridge. A member whose failure would collapse the bridge is called *fracture critical* and is inspected especially closely.

Today. Codes are not a substitute for thinking; they are the written memory of every lesson engineers have learned, often at great cost. Each new edition adds what was learned from new research and from failures.

PICTURE STUDY



Joint Details of the Ashtabula Bridge, Diagram after Charles MacDonald's 1877 study, 1877 (redrawn) · Engineering diagram · Published with MacDonald's paper on the failure, American Society of Civil Engineers

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

After the collapse, the engineer Charles MacDonald studied the wreck and published drawings of how the iron members met at each joint. This diagram, based on his work, shows one joint. Drawings like this are how engineers pass on what failure teaches.

Look closely

- Find the angle block where the diagonal braces meet the chord. What held the braces in place there?
- Find the vertical posts. Were they in tension or compression in a Howe truss?
- Find the clamps and the lateral strut. What job did they do?
- Use the scale bar. About how long is the part of the chord shown?

Talk about it

1. If a diagonal brace slipped off its angle block, what would happen to the load it was carrying?
2. Why is it important that engineers publish drawings and reports of failures instead of keeping them quiet?

3. How would a written specification have helped the people who built this bridge?

BUILD

Measuring Support Reactions with Kitchen Scales

You will rest a beam on two kitchen scales, place a load at different points, and measure how the load divides between the supports. Then you will check your measurements against the equations of statics, $\Sigma F = 0$ and $\Sigma M = 0$.

You will need

- Two kitchen scales of the same height (or one scale and a block of equal height, moving the scale between tests)
- A stiff board or a yardstick about 60–100 cm long
- A load of known mass: a full water bottle, a can or a bag of rice (weigh it first)
- A tape measure, a marker and masking tape

Steps

1. Weigh the board alone. Set it across the two scales with its ends just over the scale centers, and measure the span L between the centers of the scales. Zero (tare) both scales with the board on them, so they read only the added load.
2. Mark the board every 10 cm from support A. Weigh your load (in grams) and convert to newtons: $F = (\text{grams} \div 1,000) \times 9.8$.
3. **Predict.** For the load at each mark, calculate $R_B = F \times a \div L$ and $R_A = F - R_B$, where a is the distance from A. Write the predictions in a table.
4. Place the load at each mark in turn and record both scale readings. Convert to newtons.
5. Check: does $R_A + R_B$ equal the load every time? Calculate the percent difference between predicted and measured reactions.
6. Graph R_A and R_B against the load's position on one set of axes. Where do the lines cross?
7. **Two loads.** Add a second known load at another point. Predict both reactions using $\Sigma M = 0$ about A, then measure.
8. **Improve and extend.** Remove the tare and include the board's own weight as a dead load acting at its middle. Calculate a factored design load for the

board using $1.25 \times \text{dead} + 1.75 \times \text{live}$.

Tips

- Make sure the board rests on the center of each scale platform, not on its edge, and that nothing else touches the board.
- Digital scales sometimes drift. Lift the load and check that both scales return to zero between readings.
- Measure every distance from the same point (the center of support A).

Check your work

- ☐ I can calculate support reactions using $\Sigma F = 0$ and $\Sigma M = 0$, and my measurements agreed with my predictions within a few percent.
- ☐ I can trace the load path of a real bridge from deck to foundation.
- ☐ I can apply load factors to dead and live loads and explain why they are different.

ENGINEER'S NOTEBOOK

1. Choose a bridge you have crossed. Sketch it and draw arrows showing its load path from a car on the deck to the soil, naming each part.
2. Your prediction-versus-measurement table and the reactions graph.
3. Draw a free-body diagram of the 6.0 m beam from the lesson with the 12 kN load and both reactions. Then move the load to the middle and calculate the new reactions and largest bending moment ($M = PL \div 4$).
4. Write a paragraph: Why do engineers follow a written code even when they are confident in their own judgment?

From history. Theodore Cooper, whose loading is still used, was also the consulting engineer on the Quebec Bridge, which collapsed during construction in 1907. That disaster led to further reforms in how large bridges are checked.

COMMON MISTAKES

- Assuming each support always carries half the load. That is true only when the load is centered.
- Forgetting that the structure's own weight is a load. For long bridges the dead load is often larger than the traffic.

- Mixing units in moment calculations (newtons with centimeters, kilonewtons with meters). Choose one set of units and stay with it.

Make it a game • Two Truths, One Beam. Describe a simple beam bridge with a point load and make three claims about it: two true, one tall tale, covering load path, support reactions and redundancy. Your parent guesses the tale. Then work out the reactions and largest bending moment for a load you invent. Swap roles and keep score over five rounds.

Scripture. “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding. Who hath laid the measures thereof, if thou knowest? or who hath stretched the line upon it?” (Job 38:4-5, KJV)

God laid the foundations of the earth with perfect measure. Human builders must measure humbly and carefully, and written codes are one way engineers admit they need checking.

2.2 STEEL VERSUS CONCRETE: EADS, MAGNEL AND THE REINFORCED BEAM

OBJECTIVES

- Calculate stress ($\sigma = F \div A$) and compare the strength and stiffness of steel and concrete in tension and compression.
- Explain why concrete is reinforced with steel, why the steel goes near the bottom of a beam, and how prestressing works.
- Cast and break plaster beams to test where reinforcement does the most good.

Warm-up. Hold a piece of chalk at both ends and bend it until it snaps. Look at the broken ends. Did it break on the side being stretched or the side being squeezed? Now try to crush a piece of chalk by pressing its ends together between two books. Which is easier: breaking chalk by pulling (bending) or by squeezing? Chalk, like concrete and stone, is far stronger in compression than in tension.

WATCH

Why Concrete Needs Reinforcement

Practical Engineering · 8:11

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

WHEN TO WATCH

Before the build. Notice where the beams crack first and how the rebar changes the way they fail.

BACKUP VIDEO

Understanding Material Strength, Ductility and Toughness

The Efficient Engineer · 7:19

<https://www.youtube.com/watch?v=WSRqJdT2COE>

After the physics paragraph, for the stress–strain curve and the difference between ductile steel and brittle concrete.

KEY TERMS

stress

Force divided by the area it acts on, $\sigma = F \div A$, measured in pascals (Pa) or megapascals (MPa). 1 MPa = 1 newton per square millimeter.

modulus of elasticity

Stiffness: stress $\div$ strain while a material springs back. Steel's is about 200,000 MPa; ordinary concrete's is about 25,000–30,000 MPa.

reinforced concrete

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

strain

How much a material stretches or squeezes compared with its length: change in length $\div$ original length. It has no units.

ductile and brittle

A ductile material (steel) stretches and bends a great deal before breaking, giving warning; a brittle material (plain concrete, glass) breaks suddenly.

prestressed concrete

Concrete squeezed by tightly stretched steel tendons before it carries any load, so that it stays in compression even when the load tries to bend it.

CORE IDEAS

The story. Two bridges mark the arrival of the two great modern bridge materials. In 1874 James Buchanan Eads opened his bridge over the Mississippi River at St. Louis, the first major bridge in the world built with steel members. Steel was then new and expensive, and Eads had to write his own testing rules and reject batch after batch of steel that did not meet them. Seventy-six years later, in 1950, Philadelphia completed the Walnut Lane Bridge, the first major prestressed-concrete bridge in the United States, designed with the help of the Belgian engineer Gustave Magnel. Its girders were cast concrete squeezed by stretched steel wires.

How they figured it out. Both men had to persuade doubters with tests. Eads built testing machines and pulled and crushed samples of his steel, publishing the results. In Philadelphia, city engineers were unsure of the unfamiliar prestressed design, so a full-size test girder was built and loaded far beyond its design load before the bridge was approved; it carried far more than its design load before it finally failed. Testing to failure is how engineers learn what a design will really do.

The physics. Stress is force per area: $\sigma = F \div A$. Ordinary concrete can carry roughly 30 MPa in compression but only about 3 MPa in tension, about one-tenth as much. Common reinforcing steel yields at about 414 MPa (60,000 psi), in tension or compression. Worked example: a steel bar 20 mm across has an area $A = \pi \times (10 \text{ mm})^2 \approx 314 \text{ mm}^2$, so it can carry about $414 \text{ N/mm}^2 \times 314 \text{ mm}^2 \approx 130,000 \text{ N}$, the weight of about 13 metric tons. A concrete column of the same area could carry only about 9,400 N in compression and much less in tension. When a beam bends, its bottom is in tension, so plain concrete cracks there first. Steel bars placed near the bottom carry that tension. The two materials work together partly because they expand by almost the same amount when heated (about 0.00001 of their length per degree Celsius), so temperature changes do not tear them apart.

The engineering. Engineers compare materials by more than strength. Steel is strong, ductile and fast to erect, and its strength-to-weight ratio makes it best for very long spans; but it rusts unless painted or galvanized, and it must be protected from fire. Concrete is cheap, can be cast into almost any shape, resists fire and weather, and needs little maintenance; but it is heavy, brittle and weak in tension, and it shrinks and slowly creeps under load. Reinforced concrete puts steel where the tension is. **Prestressed** concrete goes further: stretched steel tendons squeeze the concrete before any load arrives, so when traffic bends the beam, the bottom only becomes less compressed instead of going into tension, and it does not crack. Most highway overpasses built today are prestressed concrete girders; most very long spans are steel.

Today. Many bridges use both: steel girders with a concrete deck connected by steel studs so they act as one composite beam, each material doing what it does best.

PICTURE STUDY



The Walnut Lane Bridge, Philadelphia, Historic American Engineering Record, photograph made for the HAER survey · Photograph · Library of Congress

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

The Walnut Lane Bridge was the first major prestressed-concrete bridge in the United States. Engineers from all over the country came to watch it being built and tested.

Look closely

- Find the girders spanning between the piers. How deep are they compared with the length of the span?
- Find the piers and abutments. Trace the load path from the road to the ground.
- Look at the surface of the concrete. Can you see any signs of cracking or weathering?
- Compare the shape of the girders with the Eads Bridge arches or a steel truss. What looks different?

Talk about it

1. Why would a plain concrete girder this long crack at the bottom, and how does prestressing stop it?
2. Why might an engineer choose concrete instead of steel for a bridge over a road and a creek?

3. What would you want to inspect on this bridge after seventy years of service?

Safety first. Plaster of Paris gets warm as it sets. Mix it with an adult, wear a dust mask when pouring the dry powder, never pour it down a drain, and never put a hand or any body part inside setting plaster. Wear safety glasses when breaking the beams.

BUILD

Cast and Break Reinforced Plaster Beams

You will cast small beams of plaster of Paris (a stand-in for concrete), some plain and some with wire reinforcement placed in different positions. After they harden, you will load them to failure and find out where the reinforcement helps most. Cast the beams at the end of Session 1 and test them in Session 2.

You will need

- Plaster of Paris (craft store) and water; a disposable mixing bowl and spoon; a dust mask
- Molds: six cardboard troughs about 20 cm long, 3 cm wide and 3 cm deep, lined with plastic wrap (or cut-down milk cartons)
- Reinforcement: straightened large paper clips or thin steel wire, all the same length (about 18 cm)
- Two equal stacks of books for supports, a strong paper cup or small bucket hung on a string loop, sand or pennies, and a kitchen scale
- Safety glasses and a ruler

Steps

1. Label six molds: two “plain,” two “bottom steel,” two “top steel.” Bend a small hook at each end of the wires so they grip the plaster, like the hooks on real rebar.
2. With an adult, mix the plaster to the package directions and fill each mold halfway. For “bottom steel” beams, first pour a 0.5 cm layer, lay the wire on it, then fill. For “top steel,” fill most of the way and lay the wire 0.5 cm below the top surface. Tap the molds to remove bubbles and smooth the tops.
3. Let the beams cure at least 24 hours (longer is better). Unmold them and weigh each one.
4. **Predict.** Rank the three kinds of beams from strongest to weakest when loaded from the top, and explain your ranking using tension and compression.
5. Rest a beam across two book stacks 15 cm apart, with the side marked “top” facing up. Hang the cup from the middle on a string loop and add sand

slowly until the beam breaks. Weigh the cup and sand. Watch closely: where does the first crack appear?

6. Test all six beams the same way. Record: beam type, mass, failure load (g and N), where the first crack began, and how it broke (suddenly, or bending first).
7. Calculate each beam's strength-to-weight ratio (failure load $\div$ beam mass) and average each pair.
8. **Improve.** Using what you learned, cast one more beam you think will beat the best one using the same amount of wire (for example, two wires near the bottom, or a bent-up wire like the stirrups and bent bars in real beams). Test it.

Tips

- Add the sand slowly and steadily; a sudden drop of sand adds an impact load, not a slow one.
- The reinforced beams may crack and still hold. Keep adding load and record both the first-crack load and the final failure load.
- Mark “top” on every beam before you unmold it so you test each one the right way up.

Check your work

- ☐ I can calculate stress and compare steel and concrete in tension and compression.
- ☐ My test showed where reinforcement helps most, and I can explain why using the forces in a bending beam.
- ☐ I can explain how prestressing keeps concrete from cracking.

ENGINEER'S NOTEBOOK

1. Cross-section sketches of a plain beam, a reinforced beam and a prestressed beam, with arrows showing compression and tension under load.
2. Your beam data table, a bar graph of average failure loads, and a sketch of how each type cracked.
3. Make a comparison chart of steel and concrete: strength in tension, strength in compression, stiffness, weight, cost, fire, rust, ease of shaping.
4. Solve: a steel cable has an area of 500 mm^2 and carries 150 kN. Find the stress in MPa. Is it below 414 MPa?

From history. Reinforced concrete began in France in the mid-1800s: the gardener Joseph Monier patented iron-reinforced concrete flower tubs in 1867 and later bridges and beams, and the builder François Hennebique developed a complete reinforced-concrete building system in the 1890s. The French engineer Eugène Freyssinet developed practical prestressed concrete in the late 1920s and 1930s, and Magnel brought it to wide use.

COMMON MISTAKES

- Thinking the steel in reinforced concrete is there to make the concrete stronger in compression. Its main job is to carry tension.
- Putting reinforcement in the middle of a beam's depth, where bending stress is nearly zero.
- Treating strength and stiffness as the same thing. A material can be strong but bendy, or stiff but brittle.

Make it a game • Steel or Concrete?. Memory match with homemade cards. Write properties on one set, such as strong in tension, strong in compression, ductile, brittle, and materials on the other: steel, concrete, reinforced, prestressed. Turn all cards face down and flip pairs from memory. Each match must be justified aloud with one reason. Beat your own pair count on the second game.

2.3 A BALSA BRIDGE EFFICIENCY COMPETITION: WHIPPLE AND THE METHOD OF JOINTS

OBJECTIVES

- Use the method of joints to find the forces in the members of a simple truss and label each as tension or compression.
- Calculate structural efficiency (load held ÷ bridge mass) and use it to compare designs.
- Design, build, weigh and load-test a balsa truss bridge to rules, and analyze its failure.

Warm-up. Lay two pencils on the table in a V shape, touching at the point, and press down on the point with one finger while holding the far ends still. Which way do the pencils want to slide? Now tie a string between the two far ends and press again. What does the string do? Sketch the forces with arrows.

WATCH

Understanding and Analysing Trusses

The Efficient Engineer · 17:40

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

WHEN TO WATCH

After the physics paragraph. Pause after the method-of-joints example and redo it yourself before watching the method of sections.

BACKUP VIDEO

Balsa Wood Bridge Tips and Tricks

Lyles School of Civil and Construction Engineering · 5:30

<https://www.youtube.com/watch?v=zbOlZC94YUQ>

Before you build: university civil-engineering students show how to lay out, glue and brace a balsa truss.

KEY TERMS

member

One straight piece of a truss, joined to others only at its ends.

method of joints

A way to find member forces by applying $\Sigma F_x = 0$ and $\Sigma F_y = 0$ at one joint at a time.

structural efficiency

Load carried at failure divided by the structure's own mass. Engineers try to carry the most load with the least material.

joint (node)

A point where members meet. In truss analysis, joints are treated as pins that cannot carry bending.

chord

The top or bottom line of members in a truss. In a simply supported truss, the top chord is in compression and the bottom chord is in tension.

gusset

A flat plate glued or bolted over a joint to connect the members and spread the force.

CORE IDEAS

The story. In the early 1800s American bridge builders made trusses mostly by experience and rule of thumb. Some worked; some failed. Squire Whipple, a self-taught engineer and instrument maker from New York, patented an iron bowstring truss in 1841 for the bridges over the Erie Canal. In 1847 he published *A Work on Bridge Building*, the first book to show how to calculate the force in every member of a truss. A few years later Herman Haupt published his own study. For the first time, a builder could size each member for the force it would actually carry instead of guessing.

How they figured it out. Whipple's key idea was to treat each joint as a point where forces must balance. If the joint is not moving, all the forces on it, the loads and the pushes and pulls of the members, must add up to zero in every direction. Starting at a support, where the reaction is known, he could solve for the two unknown member forces there, then move to the next joint, and so on across the whole truss. Engineers still learn truss analysis exactly this way in their first statics course.

The physics. Try it on a simple triangular truss: a bottom chord 4.0 m long between two supports, and two sloping members meeting at a peak 1.5 m above the middle.

Each sloping member is 2.5 m long (a 1.5–2.0–2.5 right triangle). A 10 kN load hangs at the peak, so each support pushes up 5.0 kN. At the left support joint, only the sloping member can balance the 5.0 kN reaction vertically: $F \times (1.5 \div 2.5) = 5.0$ kN, so $F = 8.3$ kN, and it pushes on the joint, so it is in **compression**. Its horizontal part is $8.3 \times (2.0 \div 2.5) = 6.7$ kN, which must be balanced by the bottom chord pulling the other way: the bottom chord carries 6.7 kN in **tension**. Notice that the sloping members carry more force than the load that each support feels. A flatter truss would make those forces larger still.

The engineering. Once you know the force in each member, you choose its size. Tension members can be thin; their strength depends only on area. Compression members must be thick enough not to buckle, which depends on their length and shape, so long compression members need bracing or a larger cross section. Joints must be stronger than the members, or the bridge will come apart at a joint long before any member reaches its strength. Engineers judge a design by its **efficiency**: a balsa bridge with a mass of 25 g that holds 25 kg has an efficiency of $25,000 \text{ g} \div 25 \text{ g} = 1,000$. Student bridge competitions around the world use exactly this measure.

Try it. Before you glue anything, analyze your own truss with the method of joints. You will know which members to make double (the top chord) and which can be single (most diagonals in tension).

PICTURE STUDY



Whipple Bowstring Truss Bridge, Historic American Engineering Record, survey photograph of an 1867 bridge · Photograph · Library of Congress
Image: [Wikimedia Commons](#), public domain

This iron bridge near Albany, New York, follows Squire Whipple's bowstring design. The arched top and straight bottom work together like a bow and its string.

Look closely

- Find the curved top chord (the bow). Is it in tension or compression?
- Find the straight bottom chord (the string). What force does it carry?
- Find the thin diagonal rods. Why can they be so thin?
- Look at the joints. How are the members connected?

Talk about it

1. If you pressed down on the middle of this bridge, which members would push and which would pull?
2. Why did Whipple use cast iron for some members and wrought iron for others? (Hint: cast iron is strong in compression but brittle in tension.)
3. How did being able to calculate member forces save iron and money?

Safety first. An adult should do any cutting with a craft knife, using a metal ruler and a cutting mat. Wear safety glasses during load testing; balsa can snap and fly. Keep feet clear of the loading bucket.

BUILD

The Balsa Bridge Efficiency Competition

You will design, analyze, build and test a balsa truss bridge to a set of competition rules. The winner is not the bridge that holds the most, but the one with the highest efficiency: the most load per gram of bridge.

You will need

- Balsa or basswood sticks about 3 mm × 3 mm (craft store), about 10 sticks 90 cm long
- Wood glue (or a medium cyanoacrylate glue handled by an adult), wax paper, pins and a cardboard building board
- A craft knife (adult), a miter box or sanding block, and a metal ruler
- A kitchen scale that reads to 0.1 g or 1 g
- Test rig: two tables or stacks of books 30 cm apart, a 2 cm × 2 cm wooden loading block, a string or S-hook, and a bucket with sand

Steps

1. **Rules.** Span: 30 cm clear between supports. Maximum mass: 30 g. Width: at least 5 cm. Load applied at the center of the deck through the loading block hung below the bridge. Write the rules at the top of your notebook page.
2. Draw a full-size side view of your truss on paper. Use the method of joints for a 100 N center load to find the force in at least four members, and label each T (tension) or C (compression).
3. Make compression members shorter, doubled or braced; keep tension members single. Plan gussets at every joint.
4. Tape wax paper over the drawing, pin the sticks on top and build two identical side trusses. Join them with cross members and diagonal bracing on top and bottom so the bridge cannot twist.
5. Let the glue dry fully (24 hours). Weigh the bridge and record its mass.
6. **Test.** Hang the bucket from the loading block and add sand slowly and evenly until the bridge fails. Weigh the bucket and sand. Film the test in slow motion.

7. Calculate efficiency = load held (g) ÷ bridge mass (g). Watch the video and find the first member or joint to fail. Was it in tension or compression? Did your calculations predict it?
8. **Improve.** Build a second bridge that strengthens the first failure point without adding much mass (or removes mass where nothing failed). Test and compare efficiencies. If friends or siblings are building too, hold a competition and rank by efficiency.

Tips

- Most balsa bridges fail at a joint or by a top-chord member buckling sideways. Gussets and lateral bracing fix both.
- Choose sticks of even density; weigh several and use the heavier ones for compression members.
- Square, tight-fitting joints matter more than extra glue. Excess glue adds mass but little strength.

Check your work

- ☐ I can use the method of joints to find member forces and say which are in tension and which in compression.
- ☐ I calculated my bridge's efficiency and found where and why it failed.
- ☐ I improved my design based on the failure, and I can show the data.

ENGINEER'S NOTEBOOK

1. Full-size truss drawing with member forces labeled T or C and your method-of-joints calculations.
2. Test record: mass, failure load, efficiency, a sketch of the failure, and a still frame from your video if you can print one.
3. Solve: in the lesson's triangle truss, what are the member forces if the peak is only 0.5 m high? (The sloping members are then about 2.06 m long.) What does this tell you about shallow trusses?
4. Engineer's conclusion: three sentences on what you would change in a third bridge and why.

From history. Whipple's bowstring trusses were built in large numbers along the Erie Canal, and a few survive. He also designed a long-span trapezoidal truss, often called the Whipple truss, that many railroads used. Today, college students compete each year in the Student Steel Bridge Competition, building scale steel bridges that are judged on weight, stiffness, cost and speed of construction.

COMMON MISTAKES

- Building the truss well but forgetting the cross bracing, so the two sides lean over and the bridge twists apart at low load.
- Forgetting the sign convention: a member that pulls on its joint is in tension; one that pushes is in compression.
- Adding load quickly or dropping sand in, which hits the bridge with an impact load and gives an unfair result.

Make it a game • Truss Detective. Draw a simple triangle truss with one load on top. Your parent covers one member's label, and you must work out the force by the method of joints and call it tension or compression. Then each of you invents a bridge with a mass and a load, and you compare structural efficiency, load held ÷ mass. Highest score wins.

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

An efficiency competition depends on honest weighing of both the bridge and the load. Record what really happened, not what you hoped would happen.

2.4 CAREERS: THE CIVIL ENGINEER, BRIDGE INSPECTION AND THE PE LICENSE

OBJECTIVES

- Describe the main branches of civil engineering and what civil engineers do.
- Explain the path to a Professional Engineer (PE) license and what an engineer's seal means.
- Explain how fatigue and corrosion damage bridges and why bridges are inspected on a schedule, and carry out a safe visual inspection of a local bridge.

Warm-up. List every structure or system you used today that a civil engineer helped design: start with the road outside, the water from the tap and the building you are in. Try to reach at least ten. Then guess: who checks that each of them is still safe?

WATCH

Day in the Life of a Bridge Inspector

Virginia Department of Transportation (VDOT) · 5:06

<https://www.youtube.com/watch?v=b5HkZw-Fpjk>

WHEN TO WATCH

After the physics paragraph. Write down every tool the inspectors use and every kind of damage they look for.

Note: From a state transportation department. A short, recent video with few views, but it shows real inspectors at work.

BACKUP VIDEO

The benefits of a P.E. license

NCEES Media · 2:11

<https://www.youtube.com/watch?v=3kfOuVuuO5g>

With the engineering paragraph: the national licensing council explains the PE license.

KEY TERMS

civil engineering

The branch of engineering that designs, builds and maintains public works: bridges, roads, buildings, dams, water and sewer systems, railways and airports.

fatigue

Damage that grows from many repeated loads, each smaller than the material's strength, often starting as a tiny crack.

fracture-critical member

A steel member in tension whose failure would cause the bridge to collapse because there is no other load path.

Professional Engineer (PE)

An engineer licensed by a state after an accredited degree, the FE exam, about four years of supervised experience and the PE exam. Only a PE may seal engineering plans for public works.

corrosion

The slow chemical destruction of a metal, such as steel rusting, which reduces its area and strength.

condition rating

A number from 0 (failed) to 9 (excellent) that U.S. inspectors give the deck, superstructure and substructure of a bridge.

CORE IDEAS

The story. Two moments shaped how engineers are held responsible today. In 1907, Wyoming became the first state to require engineers and surveyors to be licensed. Its state engineer, Clarence Johnston, was frustrated that people with no training were drawing the maps and plans used to divide the state's precious water, and many were wrong. He wrote the law. Sixty years later, on December 15, 1967, the Silver Bridge across the Ohio River between Point Pleasant, West Virginia, and Ohio collapsed at rush hour, and 46 people died. Investigators found that one steel eyebar in its suspension chain had cracked through at a tiny flaw that had grown for years where no one could see it.

How they figured it out. The Silver Bridge used chains of eyebars, long steel bars with a hole at each end, linked by pins, with only two bars per link. When one cracked, the other could not carry the load alone, and the whole bridge fell within about a minute. Investigators pieced together the wreckage and found a small crack, made worse by corrosion and repeated loading, at the edge of one eyebar's hole. The

bridge had no redundancy, and the crack was hidden. In response, Congress created the National Bridge Inspection Standards in 1971. Since then, nearly every public highway bridge in the United States must be inspected by qualified inspectors, usually at least once every 24 months, with fracture-critical members examined at arm's length.

The physics. Steel can fail at stresses well below its strength if a load is repeated millions of times. This is **fatigue**. Each passing truck opens a tiny crack a little wider. Cracks start where stress is concentrated, such as the edge of a hole, a sharp notch or a rough weld, because the force must crowd around the flaw. The stress at the edge of a small round hole in a plate in tension is about three times the average stress. Corrosion makes it worse by eating away area (raising $\sigma = F \div A$) and roughening the surface. That is why inspectors look closely at holes, welds, pins and anywhere water collects.

The engineering. Civil engineering has several branches: **structural** (bridges and buildings), **geotechnical** (soil, foundations and slopes), **transportation** (roads, traffic and railways), **water resources** (dams, pipes and flood control), **environmental** (water and wastewater treatment) and **construction** (planning and managing the building). The usual path to a license is a four-year engineering degree from an accredited program; the Fundamentals of Engineering (FE) exam, often taken in the last year of college; about four years of work under a licensed engineer; and the Principles and Practice of Engineering (PE) exam. A PE's seal and signature on a drawing is a legal and moral promise that the design is safe. The National Society of Professional Engineers' code begins by saying engineers shall "hold paramount the safety, health, and welfare of the public."

Today. Bridge inspectors now use drones, rope access, ultrasonic testing that finds hidden cracks, and sensors that record strain and movement around the clock. But the heart of inspection is still a trained person looking closely, measuring carefully and writing an honest report.

PICTURE STUDY



The Silver Bridge, Unknown photographer, 1928 · Photograph · Point Pleasant, West Virginia

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

The Silver Bridge opened in 1928 and was admired for its aluminum-painted steel. Look at the chains that hold up the deck: they are made of eyebars, not spun wire.

Look closely

- Find the main chains running over the towers. How are they different from the wire cables of the Brooklyn Bridge?
- Find the vertical hangers that connect the chains to the deck. Trace the load path from the deck to the anchorages.
- Find the towers. Are they in tension or compression?
- Look for any place where a single part carries the whole load.

Talk about it

1. A wire cable has thousands of wires. Each link of this chain had only two eyebars. Why does that matter if one part cracks?
2. Where on an eyebar would you expect a fatigue crack to start, and why?
3. What would you want an inspector to do on this bridge every two years?

Safety first. Inspect only from public sidewalks, paths and parks, with an adult. Never climb on or under a bridge, walk on railroad tracks or trestles, stand in traffic, or go near deep or fast water. Use a phone camera zoom instead of getting closer.

BUILD

A Bridge Inspection Report

You will act as a bridge inspector for a small bridge near you, a pedestrian bridge, a road bridge over a creek or a culvert, working only from safe public places. You will record what you see, give condition ratings, and write a professional report. If you can, you will also interview an engineer.

You will need

- A clipboard and inspection form (made in your notebook)
- A phone or camera with zoom, binoculars if you have them
- A tape measure (for anything you can safely reach from the sidewalk, such as railing height or sidewalk width)
- A printed or sketched map of the location

Steps

1. Choose a bridge with an adult and plan where you can safely stand. Look up its name, the road it carries and what it crosses. If you can, look it up in the public National Bridge Inventory data or on your state transportation department's map to find its year built and type.
2. Sketch the bridge's side view and label its type (beam, truss, arch, culvert), its material and its main parts: deck, superstructure, substructure (piers, abutments), bearings and railings.
3. Trace and draw the load path from the deck to the ground.
4. Inspect by looking and photographing. Record: cracks or spalling in concrete (pieces broken off), exposed or rusty rebar, rust or peeling paint on steel, missing bolts, damaged railings, plants growing from joints, water stains, erosion of the bank near the abutments (called scour), and potholes on the deck.
5. Give simplified condition ratings for the deck, superstructure and substructure using a 0–9 scale: 9 excellent, 7 good, 5 fair (minor section loss or cracking), 4 poor (advanced deterioration), 2 critical, 0 failed. Give a reason and a photograph for each rating.

6. Write a one-page report: location, date, weather, bridge description, findings, ratings, and recommendations (for example, “clean the drains,” “repaint the girder ends,” “have an engineer check the scour at the east abutment”).
7. **Interview.** With a parent’s help, ask a civil engineer, a surveyor or a public-works employee (in person, by phone or by email) three questions: What do you do in a typical week? What school subjects matter most? What part of your work protects the public?
8. **Improve.** Revisit your bridge on a different day or after rain. Add anything you missed and note whether water drains well.

Tips

- Write only what you can see. Say “rust staining on the lower flange of the east girder” rather than “the bridge is falling apart.” Honest, specific records are what make an inspection useful.
- Take a wide photograph first to show where each close-up was taken.
- Most damage starts where water collects: at the ends of girders under deck joints, at drains and on bearing seats.

Check your work

- ☐ I can name the branches of civil engineering and describe the path to a PE license.
- ☐ I can explain fatigue and why cracks start at holes and welds.
- ☐ I wrote a clear, honest inspection report with ratings, photographs and recommendations.

ENGINEER’S NOTEBOOK

1. Your labeled bridge sketch with the load path, and your completed inspection form.
2. Draw an eyebar chain link of two bars and a pin. Mark where a fatigue crack would start and explain what happens when one bar fails.
3. Make a flow chart of the path to a PE license, with approximate ages and years at each step.
4. Write a paragraph: what does it mean for an engineer to “hold paramount” the safety of the public? Give one example of a choice an engineer might face.

From history. Engineers in Canada, after the Quebec Bridge collapses of 1907 and 1916, began a ceremony in which new engineers receive an iron ring worn on the little finger of the working hand, as a reminder of their duty. In the United States, a similar Order of the Engineer was begun in 1970, and many engineering graduates take its obligation and receive a steel ring.

COMMON MISTAKES

- Thinking a bridge that looks rusty is about to fall, or that one that looks clean is fine. Inspectors look for specific damage in specific places and measure it.
- Thinking a crack must be large to be dangerous. A small crack in a fracture-critical member, in the wrong place, can be the most serious finding of all.
- Believing an engineering license is only a test. It also requires years of supervised experience, continuing education and a duty to the public that can be taken away for misconduct.

Make it a game · Inspector's Rounds. Walk through your house or yard as a bridge inspector. In sixty seconds, find and name five things that could show fatigue, corrosion or a missing backup, and give each a condition rating. Your parent challenges one rating. Then explain in your own words what a PE seal means. Try to beat your count tomorrow.

Scripture. “For unto whomsoever much is given, of him shall be much required: and to whom men have committed much, of him they will ask the more.” (Luke 12:48, KJV)

The public commits its safety to engineers who seal a design. That trust is a gift that carries a heavy responsibility.

UNIT 2

BRIDGES

In earlier years you learned the shapes of bridges and the forces inside them. This year you will learn to think about a bridge the way a licensed civil engineer does. You will trace the load path of every pound from the deck to the ground, calculate support reactions and bending moments, and learn why engineers design to written codes with load factors instead of trusting their own judgment alone. You will learn why the codes exist: the iron bridge at Ashtabula, Ohio, that fell under a train in 1876, and the Silver Bridge over the Ohio River that fell in 1967.

You will compare the two great bridge materials, steel and concrete, by casting and breaking your own reinforced beams, and then you will design, build, weigh and load-test a balsa truss bridge in an efficiency competition, analyzing its members by the method of joints first worked out by Squire Whipple. The unit ends with the people: what a civil engineer does all day, how the Professional Engineer license works, and why the public trusts the engineer's seal on a drawing.

PREREQUISITES

- Can solve one-step and two-step equations and use ratios
- Knows compression, tension, shear and buckling, and why triangles make trusses rigid
- Can use sine, cosine or similar triangles to split a slanted force into horizontal and vertical parts (taught briefly in Lesson 2.3)
- Has finished Unit 1 and can draw a force arrow diagram

MASTERY CHECKLIST

- ☐ I can trace a load path from the deck of a bridge to the foundations and calculate the support reactions of a simple beam.
- ☐ I can explain what load factors and design codes are and apply a load factor to a dead and live load.
- ☐ I can compare steel and concrete by strength, stiffness, weight, cost and durability, and explain why concrete is reinforced and prestressed.
- ☐ I can find the force in each member of a simple truss by the method of joints and calculate a bridge's structural efficiency.
- ☐ I can describe the path to a Professional Engineer license and the duty an engineer owes to the public.

OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits and supplies**: Ages 11 and up with an adult. Pitsco sells precut balsa and basswood, gusset plates, plans and bridge testers, a good fit for the balsa efficiency competition in Lesson 2.3 and the portfolio bridge.
- **K'NEX bridge building sets**: Ages vary by set. Useful for quickly building and comparing truss patterns before you cut balsa in Lesson 2.3.

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

2.1 Load Paths and Design Codes: From Ashtabula to the Rulebook

2 sessions of 60 minutes

2.2 Steel versus Concrete: Eads, Magnel and the Reinforced Beam

2 sessions of 60 minutes

2.3 A Balsa Bridge Efficiency Competition: Whipple and the Method of Joints

2 sessions of 60 minutes

2.4 Careers: The Civil Engineer, Bridge Inspection and the PE License

2 sessions of 60 minutes

UNIT 2 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

List the load path of a truss bridge from a car on the deck to the soil.

2. **10 pts**

Calculation. A beam 8.0 m long rests on supports A and B. A 20 kN load sits 2.0 m from A. Find both reactions and the largest bending moment.

3. **8 pts**

A girder carries 200 kN of dead load and 120 kN of live load. Using load factors of 1.25 and 1.75, what load is it designed for? Why does live load get the larger factor?

4. **8 pts**

What did engineers learn from the Ashtabula bridge collapse of 1876, and what did they do about it?

5. **10 pts**

Calculation. A steel rod has a cross-sectional area of 400 mm^2 and carries a tension of 100 kN. Find the stress in MPa. If the steel yields at 414 MPa, what is the ratio of yield stress to working stress?

6. **8 pts**

Why is the steel in a reinforced-concrete beam placed near the bottom? How does prestressing improve on this?

7. **8 pts**

Give two advantages of steel and two advantages of concrete for bridges.

8. **10 pts**

Calculation. A triangular truss spans 6.0 m with its peak 2.0 m above the middle, so each sloping member is about 3.6 m long. A 12 kN load hangs at the peak. Find the force in each sloping member and in the bottom chord, and say whether each is in tension or compression.

9. **8 pts**

Bridge A has a mass of 40 g and holds 18 kg. Bridge B has a mass of 25 g and holds 14 kg. Which is more efficient? Show the numbers.

10. **8 pts**

What is fatigue, and why did a small crack bring down the whole Silver Bridge?

11. **6 pts**

List the four main steps to becoming a licensed Professional Engineer.

12. **8 pts**

Write a short paragraph explaining what an engineer's seal on a drawing means and why the public relies on it.

ANSWER KEY

1. Deck → stringers/floor beams → trusses (or girders) → bearings → piers and abutments → foundations → soil or rock.
2. ΣM about A: $R_B \times 8.0 = 20 \times 2.0$, $R_B = 5.0$ kN. $R_A = 20 - 5.0 = 15$ kN. Largest moment under the load: $M = 15 \text{ kN} \times 2.0 \text{ m} = 30 \text{ kN}\cdot\text{m}$.
3. $1.25 \times 200 + 1.75 \times 120 = 250 + 210 = 460$ kN. Live load (traffic) is much less predictable than the structure's own weight, so it needs a larger margin.
4. That bridges needed written specifications and independent checking by experienced engineers rather than untried details and guesswork. They wrote standard specifications and loadings (such as Cooper's train loading) and began requiring inspections.
5. $\sigma = F \div A = 100,000 \text{ N} \div 400 \text{ mm}^2 = 250 \text{ N/mm}^2 = 250 \text{ MPa}$. Ratio = $414 \div 250 \approx 1.66$.
6. When a beam bends under load, the bottom is in tension, and concrete is weak in tension, so steel is placed there to carry it. Prestressing squeezes the concrete with stretched tendons before loading, so the bottom stays in compression and does not crack.
7. Steel: high strength-to-weight ratio for long spans; ductile; fast to erect; strong in tension. Concrete: inexpensive; moldable; fire and weather resistant; low maintenance; strong in compression. (Any two each.)
8. Each reaction = 6.0 kN. At a support: $F \times (2.0 \div 3.6) = 6.0$, so $F \approx 10.8$ kN compression. Bottom chord = $10.8 \times (3.0 \div 3.6) = 9.0$ kN tension.
9. A: $18,000 \div 40 = 450$. B: $14,000 \div 25 = 560$. Bridge B is more efficient even though it held less.
10. Fatigue is damage that grows from many repeated loads below the material's strength, usually starting as a small crack at a stress concentration. The Silver Bridge's eyebars had only two bars per link and no other load path (no redundancy), so when one eybar cracked through, the chain failed and the bridge collapsed.
11. An accredited engineering degree; pass the FE exam; about four years of experience under a PE; pass the PE exam (then keep up continuing education).
12. Answers should explain that the seal is the licensed engineer's legal and professional statement that the design meets codes and is safe; the public cannot check the calculations themselves, so they trust the engineer's competence and honesty, and the engineer is accountable for that trust.

PORTFOLIO PIECE: A DESIGNED, ANALYZED AND LOAD-TESTED TRUSS BRIDGE

Design and build a balsa or basswood truss bridge to the Lesson 2.3 competition rules (or a K'NEX or craft-stick bridge scaled up with rules of your own). Before building, prepare a design package like a real engineer: a full-size drawing, a method-of-joints analysis of the main members for a 100 N center load, and a materials list with the predicted mass. After testing, write a two-page engineer's report with the measured mass, failure load, efficiency, a description and photograph of the failure, a comparison of the failure with your analysis, and a recommendation for the next design. Sign and date it as the responsible engineer.

LOOK FOR	WHAT IT MEANS
Design package	Neat full-size drawing with dimensions; member forces calculated and labeled T or C; predicted mass.
Construction	Two matching side trusses, square joints with gussets, top and bottom bracing; meets the span, width and mass rules.
Test and data	Weighed before testing; load applied slowly at center; failure load and efficiency calculated correctly; test filmed or photographed.
Failure analysis	Report identifies the first failure and explains it using tension, compression, buckling or joint strength, compared with the calculations.
Professional report	Clear, honest writing with units, tables and a specific recommendation; signed and dated.

UNIT 3

ARCHITECTURE

Architecture is where engineering meets beauty. The Roman writer Vitruvius said a good building must have firmness, usefulness and delight, and in this unit you will see that every great style of building grew out of a structural idea. Greek temples are stone beams on stone columns; Gothic cathedrals are pointed arches pushed sideways against flying buttresses; modern towers are steel and concrete frames hung with glass. You will test columns of different proportions, learn to draw and model buildings with free computer-aided design (CAD) software, and see how architects turn a computer model into plans, elevations and sections.

Then you will study what keeps people safe inside a building. Fires in Chicago in 1871 and 1903 taught hard lessons that are now written into building codes: fire-resistant materials, protected steel, sprinklers, and exit doors that open outward with panic bars. The unit ends at the top of the world's tallest building, the Burj Khalifa in Dubai, where engineers used a three-winged shape and wind-tunnel testing to "confuse the wind."

PREREQUISITES

- Knows stress ($\sigma = F \div A$), compression, tension and buckling (Unit 2)
- Can measure in metric units and use a scale such as 1:50
- Can use a computer or tablet with a web browser and a free account made by a parent (for Tinkercad)
- Knows wind and earthquake loads in simple terms (Grade 5 or earlier)

MASTERY CHECKLIST

- ☐ I can identify the Doric, Ionic and Corinthian orders, Gothic features and the steel frame, and explain the structural idea behind each style.
- ☐ I can explain how slenderness affects buckling, using the rule that doubling a column's length cuts its buckling load to about one-quarter.
- ☐ I can build a building model in Tinkercad to scale and produce a plan and elevation from it.
- ☐ I can explain how building codes protect people from fire: fire-resistant construction, sprinklers, and exits, and calculate required exit width.
- ☐ I can explain how the Burj Khalifa's shape, core and wind-tunnel testing let it stand 828 meters tall.

OPTIONAL KITS FOR THIS UNIT

- **KEVA planks:** All ages. Identical maple planks for building columns, arches, domes and towers with no glue; good for trying classical and Gothic forms in Lesson 3.1 and wind tests in Lesson 3.4.
- **Tinkercad ([free online CAD from Autodesk](#)):** Free; a parent creates the account for students under 13. Used in Lesson 3.2 and the portfolio. Not a kit, but the one tool this unit leans on.

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 Styles and Structure: From the Classical Orders to Gothic to Modern

2 sessions of 60 minutes

3.2 From Drafting Board to CAD: Modeling a Building in Tinkercad

2 sessions of 60 minutes

3.3 Building Codes and Fire Safety: Lessons from Chicago

2 sessions of 60 minutes

3.4 The Burj Khalifa: Confusing the Wind

2 sessions of 60 minutes

UNIT 3 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Name the three Greek orders and describe the capital of each.

2. 8 pts

Explain why Greek temples have closely spaced columns while Gothic cathedrals have huge windows.

3. 10 pts

Calculation. A column 4 m tall can carry 120 kN before buckling. Using the $1 \div L^2$ rule, estimate the buckling load of the same column at 2 m and at 8 m tall.

4. 8 pts

What is the difference between a plan, an elevation and a section?

5. 8 pts

At a scale of 1:50, a wall measures 9.0 cm on a plan. How long is the real wall?
What would a room 6.0 cm $\times$ 5.0 cm on the plan measure in square meters?

6. 8 pts

What was important about Ivan Sutherland's Sketchpad, and what is a "clash" in a building information model?

7. 8 pts

What did Chicago and other cities change after the Iroquois Theater fire of 1903?

8. **10 pts**

Calculation. A school gym holds 600 people. Using 0.2 inch of exit width per person, how much total exit width is required? If each exit door is 36 inches wide, how many doors are needed?

9. **8 pts**

Why must structural steel be fireproofed, and name two ways it is done.

10. **10 pts**

Calculation. Find the wind pressure on a tower in a 30 m/s wind ($\rho = 1.2 \text{ kg/m}^3$). What would it be at 60 m/s?

11. **6 pts**

What is vortex shedding, and why is it dangerous for tall, slender structures?

12. **8 pts**

Describe two features of the Burj Khalifa that help it resist wind.

ANSWER KEY

1. Doric: plain cushion-shaped capital; Ionic: scroll-shaped volutes; Corinthian: rows of acanthus leaves (with small scrolls).
2. Greek temples use stone lintels, which bend and crack on the bottom (tension) if the span is long, so columns must be close. Gothic builders used pointed arches and ribbed vaults to gather the loads onto piers and flying buttresses to resist the sideways thrust, so the walls between did not carry load and could be windows.
3. At 2 m (half the length): $4 \times 120 = 480$ kN. At 8 m (double the length): $120 \div 4 = 30$ kN.
4. A plan is seen from above (cut horizontally, showing walls, doors, windows); an elevation is one outside face seen straight on; a section is a vertical slice through the building showing floors, walls and roof inside.
5. $9.0 \times 50 = 450$ cm = 4.5 m. The room is $3.0 \text{ m} \times 2.5 \text{ m} = 7.5 \text{ m}^2$.
6. Sketchpad (1963) was the first interactive computer drawing program, with a light pen, copies of shapes and rules (constraints) between parts, the beginning of CAD. A clash is when two parts in the model occupy the same space, such as a duct passing through a beam, found by the computer before construction.
7. They required enough exits for the crowd, exit doors that open outward, unlocked and clearly marked exits with lighted signs, and panic bars on exit doors (along with other theater rules such as fire curtains).
8. $600 \times 0.2 = 120$ inches. $120 \div 36 = 3.33$, so 4 doors (always round up), placed far apart.
9. Steel loses about half its strength at around 550–600 °C, temperatures reached in building fires, so an unprotected frame could collapse. It is insulated with sprayed fireproofing, gypsum board, concrete encasement or clay tile (any two).
10. $q = \frac{1}{2} \times 1.2 \times 30^2 = 540$ Pa. At 60 m/s: $\frac{1}{2} \times 1.2 \times 3,600 = 2,160$ Pa, four times as much.
11. Swirling eddies peel off alternately from each side of an object in the wind, pushing it from side to side. If the rhythm matches the structure's natural frequency, resonance can make the swaying grow.
12. Any two: the Y-shaped, three-winged plan buttressing a central core (like a tripod); setbacks at different heights that spiral up, changing the shape with height so vortices cannot organize ("confusing the wind"); orientation and

shaping refined by many wind-tunnel tests; the tapering form reducing area high up.

PORTFOLIO PIECE: A DESIGNED AND WIND-TESTED TOWER

Design a tower at least 60 cm tall for a real purpose (an office, a bell tower, a lookout) in Tinkercad, with a clear structural idea from this unit (a classical colonnade at its base, a buttressed core, setbacks, or a frame and curtain wall). Produce a dimensioned plan and elevation from the CAD model, then build it from card stock, craft sticks or KEVA planks. Test it in the box-fan wind tunnel, record sway at two fan speeds, improve it once, and include an egress plan for its ground floor with exits sized by the 0.2-inch rule for a stated number of occupants. Present the drawings, data and photographs in a short design report.

LOOK FOR	WHAT IT MEANS
CAD design and drawings	Accurate Tinkercad model with exact dimensions; printed plan and elevation with dimensions and scale.
Structural idea	Clearly uses and explains one structural system from the unit (orders, arch, buttressed core, frame).
Wind test and data	Sway measured at two speeds with three trials each; results tabled and graphed; vibration noted.
Life safety	Ground-floor egress plan with occupant number, required exit width calculated, and at least two separated exits.
Improvement and report	One change made and retested with before-and-after data; clear, honest report.

3.1 STYLES AND STRUCTURE: FROM THE CLASSICAL ORDERS TO GOTHIC TO MODERN

OBJECTIVES

- Identify the Doric, Ionic and Corinthian orders and the main features of Gothic and modern architecture.
- Explain how each style follows its structural system: post and lintel, arch and vault, and the steel or concrete frame.
- Test how a column's slenderness ratio ($\text{height} \div \text{diameter}$) affects the load it can hold before buckling.

Warm-up. Look at three buildings: one in a photograph of a Greek temple, one of a cathedral, and one modern office tower (or walk outside and find real ones). For each, ask: what holds up the roof? Where are the walls thick and where are they thin? Where are the windows largest? Write one sentence for each building.

WATCH

The classical orders

Smarthistory • 11:07

<https://www.youtube.com/watch?v=nrRJkzXl4a4>

WHEN TO WATCH

After the story. Sketch one capital from each order as you watch.

BACKUP VIDEO

Building a Cathedral without Science or Mathematics: The Engineering Method Explained

engineerguy • 11:54

https://www.youtube.com/watch?v=_ivqWN4L3zU

With the Gothic part of the physics paragraph: a chemical engineer shows how medieval master builders laid out arches with rope and rules of proportion.

KEY TERMS

post and lintel

A structural system of upright columns (posts) carrying horizontal beams (lintels). The lintel bends, so its bottom is in tension.

entablature

The horizontal band carried by classical columns: architrave (the stone beam), frieze and cornice.

slenderness ratio

A column's height divided by its thickness. The higher the ratio, the more easily the column buckles.

classical orders

The Greek and Roman systems of column and beam with set proportions: Doric (plain capital, stout column), Ionic (scroll-shaped volutes), Corinthian (acanthus leaves, slenderest).

pointed arch and ribbed vault

Gothic inventions that direct the weight of a stone ceiling down to a few points, where it can be carried by piers and buttresses.

curtain wall

A thin outer wall, often glass, hung on a building's frame. It keeps out weather but carries no load from the floors above.

CORE IDEAS

The story. Between 447 and 432 BC, the architects Ictinus and Callicrates built the Parthenon in Athens of white marble, with Doric columns about 10 meters tall. About 1,600 years later, in the 1140s, Abbot Suger rebuilt the choir of the abbey church of Saint-Denis near Paris with pointed arches, ribbed vaults and walls of stained glass, the beginning of the Gothic style. And in 1891 in St. Louis, the architect Louis Sullivan finished the Wainwright Building, a ten-story office block on a steel frame, and soon wrote that “form ever follows function.” Three buildings, three eras, three structural ideas.

How they figured it out. Greek builders worked by proportion and experience. Stone is very strong in compression but weak in tension, so a stone lintel can span only a short distance before its bottom cracks; that is why Greek temples have closely spaced columns. The Romans carried more with the round arch, which keeps all its stones in compression. Gothic builders went further: the pointed arch pushes less

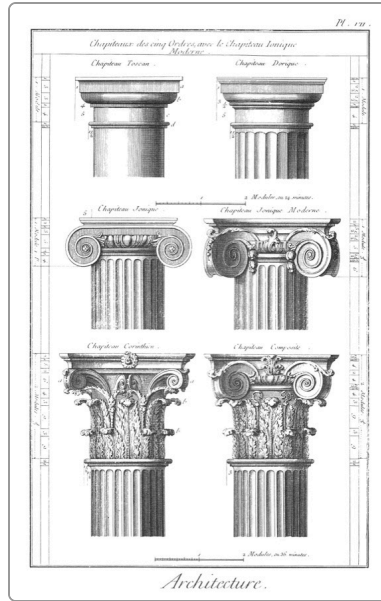
sideways than a round one and can be made any height, and the ribbed vault gathers the ceiling's weight onto a few piers. The leftover sideways push was caught by flying buttresses outside the building, so the walls between could become windows. The master builders found these rules by building, watching cracks, and building again, passing their geometry from master to apprentice. Steel and reinforced concrete finally freed the wall from carrying anything at all.

The physics. Columns usually fail by **buckling** before the material crushes, and buckling depends strongly on slenderness. For a column of a given material and cross section, the buckling load is proportional to $1 \div L^2$: double the height and the load it can carry before buckling drops to about one-quarter; triple it and the load drops to one-ninth. A thicker column resists buckling much better, because the resistance grows with the fourth power of the diameter for a solid round column. The orders show this: Doric columns are about 5 to 6 diameters tall (the Parthenon's are about 5.5), Ionic about 9, and Corinthian about 10. The more slender orders were used for lighter roofs or where elegance mattered more than carrying heavy stone.

The engineering. Each style is an answer to a structural problem. **Post and lintel:** short spans, closely spaced columns, heavy beams. **Arch and vault:** longer spans, all in compression, but with sideways thrust that must be resisted by thick walls or buttresses. **Frame:** a framework of columns and beams that carries everything, so the outside can be a light curtain wall of glass. Good architects and engineers today still borrow from all three, and classical proportions are still used because people find them restful and dignified. Firmness, usefulness and delight are meant to go together.

Try it. In your build, columns rolled from the same sheet of paper will have different slenderness ratios. If the $1 \div L^2$ rule is right, your shortest columns will carry far more than your tallest.

PICTURE STUDY



The Classical Orders, Plate from Diderot and d'Alembert's *Encyclopédie*, 18th century · Engraving ·
Encyclopédie, Paris

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

Plates like this taught builders across Europe the exact proportions of each order. The columns are drawn side by side so you can compare them.

Look closely

- Find the Doric column. How many of its own diameters tall is it? Compare it with the Corinthian.
- Find the capitals. Which has scrolls (volutes) and which has leaves?
- Find the entablature over each column. Which part is the stone beam that spans between columns?
- Look at the bases. Which order has no base at all in its Greek form?

Talk about it

1. Which of these columns would you use to hold up a heavy stone roof, and why?
2. Why must columns be closely spaced when the beams on top are stone?
3. These proportions were found by experience long before anyone calculated buckling. Why might experience have led to the same answer as physics?

Safety first. Stack books gently on the columns and keep fingers out from under the stack; when a column buckles, the books drop. Wear safety glasses if you test KEVA plank or wooden columns.

BUILD

Paper Columns: The Slenderness Test

You will roll columns from identical sheets of paper with different heights and diameters, load each with books until it buckles, and find how the buckling load depends on slenderness. Then you will see whether the classical proportions make sense.

You will need

- A ream of identical printer paper (all columns use one sheet each, so mass stays the same)
- Clear tape, scissors and a ruler
- Several hardcover books of similar size, a kitchen scale (or a bathroom scale for heavy loads)
- A stiff square of cardboard to place between the column and the books

Steps

1. Weigh the books one at a time and label each with its mass.
2. Roll three columns from full sheets the long way, each 28 cm tall, with diameters of 2 cm, 4 cm and 6 cm (overlap and tape the seam the full length). Calculate the slenderness ratio $\text{height} \div \text{diameter}$ for each.
3. **Predict.** Rank them by load, and predict how much more the 6 cm column will hold than the 2 cm one.
4. Stand a column on a hard floor, set the cardboard square on top, and add books one at a time, gently and centered, until it buckles. Record the last mass held. Test two of each size and average.
5. **Fair test: height.** Now keep the diameter at 4 cm and cut columns to 28 cm, 14 cm and 7 cm (cut each from a full rolled column so the wall thickness is the same). Test two of each.
6. Make a table: height (cm), diameter (cm), slenderness ratio, buckling load (kg and N). Graph buckling load against $1 \div \text{height}^2$ for the height test. Is it close to a straight line?

7. Roll a “Doric” column (ratio about 5.5) and a “Corinthian” column (ratio about 10) of equal height from one sheet each. Test both and compare.
8. **Improve.** Using one sheet of paper only, design the strongest 20 cm column you can (try folding flutes, a square tube, or a tube inside a tube). Test it and explain why it worked.

Tips

- Square, flat column ends matter. Trim them neatly; a crooked end makes the column fail early.
- Place books exactly in the center; an off-center load bends the column sooner.
- Short, fat columns may crush instead of buckle. Note which way each column failed.

Check your work

- ☐ I can identify the three classical orders and say what structural system Greek, Gothic and modern buildings use.
- ☐ My data show how slenderness affects buckling, and I can state the $1 \div L^2$ rule.
- ☐ I can explain why Gothic walls could be filled with glass.

ENGINEER'S NOTEBOOK

1. Sketch a Doric, Ionic and Corinthian capital from the picture study, with the proportions noted.
2. Draw cross sections of a Greek temple (post and lintel), a Gothic cathedral (vault and flying buttress) and an office tower (frame and curtain wall). Draw arrows for the load path in each.
3. Your column data table and graph.
4. Solve: a column 3 m tall can carry 80 kN before buckling. About how much could the same column carry if it were 6 m tall? 1.5 m tall?

From history. The only complete architecture book to survive from ancient times is Vitruvius's *Ten Books on Architecture*, written in the first century BC. Renaissance architects such as Palladio and Vignola measured Roman ruins and published the orders with exact proportions, and their books were used by builders for centuries, including by Thomas Jefferson when he designed Monticello and the University of Virginia.

COMMON MISTAKES

- Thinking the style of a building is only decoration. In the great styles, the look comes largely from the structure.
- Assuming a column fails by being crushed. Slender columns almost always fail by buckling first.
- Confusing the orders by their shafts. Look at the capital: plain cushion (Doric), scrolls (Ionic), leaves (Corinthian).

Make it a game • Name That Style. Mystery-object game. Your parent describes a building clue by clue: a flat beam on columns, a pointed arch, a glass wall hung on steel. You guess the style, name its structural system and give the order if it is classical. Fewer clues used earns more points. Swap roles, then draw the three column orders from memory.

Scripture. “Through wisdom is an house builded; and by understanding it is established: And by knowledge shall the chambers be filled with all precious and pleasant riches.” (Proverbs 24:3-4, KJV)

Wisdom, understanding and knowledge build a house that stands and is a pleasure to live in: firmness, usefulness and delight.

3.2 FROM DRAFTING BOARD TO CAD: MODELING A BUILDING IN TINKERCAD

OBJECTIVES

- Explain the three standard architectural views (plan, elevation, section) and how a scale such as 1:50 works.
- Tell how computer-aided design began with Ivan Sutherland's Sketchpad and how architects and engineers use CAD and building information modeling today.
- Build a small building in Tinkercad to exact dimensions, produce a plan and elevation from it, and check the accuracy of a cardboard model built from the CAD.

Warm-up. Put a cereal box or a mug on the table. Draw exactly what you see from straight above, then from straight in front, then from the side, as if you could see only one face at a time with no perspective. These are the three views engineers have used for centuries. Which view shows the height? Which shows the width and depth?

WATCH

Make a Tinkercad House Step by Step for Absolute Beginners

HL ModTech • 13:59

<https://www.youtube.com/watch?v=cbl6GC96Lm4>

WHEN TO WATCH

During Session 2, at the computer. Pause and follow each step in your own Tinkercad window.

BACKUP VIDEO

TinkerCAD - Tutorial for Beginners in 9 MINUTES! [COMPLETE]

Skills Factory • 9:46

https://www.youtube.com/watch?v=gOs6Mdj7y_4

Before Session 2, for a quick tour of every Tinkercad tool: shapes, holes, grouping, align and the ruler.

KEY TERMS

plan

A drawing of a building seen from directly above, usually cut through about a meter above the floor to show walls, doors and windows.

section

A drawing of a building sliced vertically, showing floors, walls, roof and foundations inside.

CAD

Computer-aided design: software for drawing and modeling objects precisely in two or three dimensions.

elevation

A drawing of one outside face of a building seen straight on, with no perspective.

scale

The ratio between a drawing or model and the real thing. At 1:50, 1 cm on the drawing is 50 cm (0.5 m) in the building.

BIM

Building information modeling: a 3D computer model of a building that also stores information about every part, such as materials, cost and schedule.

CORE IDEAS

The story. For centuries, buildings and machines were designed on paper with pencils, T-squares, triangles and compasses at drafting boards. In 1963 a graduate student at the Massachusetts Institute of Technology, Ivan Sutherland, wrote a program called Sketchpad for an experimental computer called the TX-2. Using a light pen on the screen, he could draw lines and circles, copy shapes, zoom in and out, and tell the computer that two lines must stay parallel or that a shape must keep a certain size. When one part changed, the computer fixed the rest. It was the first interactive computer drawing program, and Sutherland later received the Turing Award, the highest prize in computer science.

How they figured it out. Sutherland realized a drawing could be more than marks on paper: it could be a set of *objects with rules*. A bolt drawn once could be copied a hundred times, and changing the master would change every copy. That idea, together with cheaper computers, grew into the CAD programs engineers use today. AutoCAD appeared for personal computers in 1982. By the 2000s, architects and engineers were building complete 3D models with building information modeling,

in which every wall, beam and pipe knows its size, material and cost. Free tools such as Tinkercad, released in 2011, put 3D modeling in a web browser.

The physics. Drawings rest on simple geometry. An **orthographic (straight-on) projection** looks at an object straight on from each side, so every length on the drawing is true to scale. To read a scale: at 1:50, a wall that measures 8.0 cm on the plan is $8.0 \times 50 = 400 \text{ cm} = 4.0 \text{ m}$ long. Areas scale with the square: a 1:50 plan room of $10 \text{ cm} \times 8 \text{ cm}$ is $5 \text{ m} \times 4 \text{ m} = 20 \text{ m}^2$ in real life, and the area on paper is 2,500 times smaller. Volumes scale with the cube, which is why a model made of cardboard is so much lighter than the building it represents.

The engineering. In a modern firm, the architect, structural engineer, mechanical engineer and electrical engineer each build part of the same 3D model. The computer can then find **clashes**, such as a duct running straight through a steel beam, before anything is built, when fixing it costs only a few clicks. The model produces the plans, elevations and sections automatically, counts materials, and can even be used to run computer tests of structure, energy use and daylight. Yet engineers still sketch by hand to think, and they check that the computer's answers make sense. A drawing is a set of instructions that strangers will build from, so it must be clear, dimensioned and correct.

Try it. In Tinkercad you will use exact dimensions, not guesses. Turn on the ruler tool and type in sizes; that is the difference between sketching a house and designing one.

PICTURE STUDY



Independence Hall, South Front, Historic American Buildings Survey, survey photograph · Large-format survey photograph · Library of Congress
Image: [Wikimedia Commons](#), public domain

The Historic American Buildings Survey has recorded thousands of American buildings since 1933 with measured drawings and large-format photographs like this one. A photograph shows perspective; an architect's elevation of the same face would show every line true to scale.

Look closely

- Find the tower. Do its sides look parallel, or do they seem to lean together toward the top? That is perspective.
- Count the windows on each floor of the main block. Look for symmetry about the tower.
- Find classical details: the arched window, the pediment shapes and the cornice under the roof.
- Find the stages of the tower. How many separate levels can you count?

Talk about it

1. How would an elevation drawing of this face differ from this photograph?
2. What would a plan of this building show that neither a photograph nor an elevation can?

3. If an elevation of this building were drawn at 1:100 and the building were 40 m long, how long would it be on the paper?

Safety first. A parent should set up the Tinkercad account (it is free; students under 13 need a parent or teacher account). An adult handles the craft knife for the cardboard model, using a metal ruler and a cutting mat.

BUILD

Design a Small Building in CAD, Then Build It

You will design a small building, such as a garden shed, a reading pavilion or a chapel, in Tinkercad using real dimensions. Then you will make a plan and elevation from your model and build a 1:50 cardboard model from your own drawings, measuring how accurately you built it.

You will need

- A computer or tablet with Tinkercad (free, tinkercad.com) and a parent-created account
- Graph paper, a sharp pencil, a metric ruler and an architect's scale if you have one
- Card stock or thin cardboard (cereal boxes), white glue, a craft knife (adult) and a cutting mat
- Optional: a 3D printer at a library or makerspace

Steps

1. **Program.** Write what your building is for, who will use it and how big it must be. Choose real dimensions in meters (for example, a pavilion 4.0 m × 3.0 m with walls 2.5 m high and a gable roof). Hand-sketch it in your notebook first.
2. In Tinkercad, set the grid to millimeters and decide that 1 mm = 50 mm (so a 4.0 m wall is drawn 80 mm long). Build the floor slab, four walls, door and window openings (using Hole shapes) and a roof, typing exact dimensions with the ruler tool.
3. Add one structural idea from this unit: columns in one of the classical proportions, an arch, or a frame with a glass wall.
4. Use the view cube to look straight down (plan) and straight at each face (elevations). Screenshot each view, print it, and add dimensions by hand in meters.
5. **Build.** Cut the walls, floor and roof from card stock at 1:50 using only your printed drawings, then glue them together.

6. **Check accuracy.** Measure eight dimensions of your cardboard model (lengths, heights, door and window sizes). Compare each with the CAD value and calculate the percent error. Make a table.
7. Find the largest error and its cause (a dull knife, a misread dimension, glue thickness).
8. **Improve.** Fix the cause and rebuild the worst part. Then change one thing in the CAD model that the physical model taught you (for example, the roof overhang or the door height) and update your drawings.

Tips

- Group shapes in Tinkercad only when a part is finished; ungroup if you need to change it.
- Name and save versions (“pavilion v1,” “pavilion v2”) so you can go back.
- Real doors are about 2.0–2.1 m tall and 0.9 m wide. Check your sizes against your own home with a tape measure.

Check your work

- ☐ I can read and draw a plan and an elevation and use a 1:50 scale.
- ☐ I built an accurate CAD model with exact dimensions and turned it into drawings.
- ☐ I measured my physical model’s accuracy and improved the worst part.

ENGINEER’S NOTEBOOK

1. Your hand sketch, the printed plan and elevation with dimensions in meters, and a photograph of the cardboard model.
2. Accuracy table: dimension, CAD value, model value, percent error.
3. Solve: a room is 6.5 m × 4.0 m. Draw it at 1:50. What are the drawing dimensions in centimeters? What is the real area?
4. Write a paragraph comparing Sketchpad in 1963 with Tinkercad today. What idea do they share?

From history. Ivan Sutherland's older brother, Bert Sutherland, also became a computer pioneer. Ivan Sutherland went on to build one of the first head-mounted displays, an early ancestor of today's virtual-reality headsets, in 1968. The Historic American Buildings Survey, which made the drawing in the picture study, began in 1933 to give work to unemployed architects and has recorded more than 40,000 historic places.

COMMON MISTAKES

- Drawing perspective views when an elevation is asked for. In an elevation, parallel lines stay parallel and nothing shrinks with distance.
- Mixing scales between the plan and elevation, or forgetting to write the scale on the drawing.
- Building the model by eye instead of from the drawings. The point of a drawing is that someone else could build it exactly.

Make it a game • Plan, Elevation, Section. Choose a small object, like a shoebox with a door. In two minutes, draw its plan, elevation and section at a scale you state, such as 1:50. Your parent checks one measurement. Then your parent draws a mystery object and you must say which view you are looking at and the real size. Three rounds, pretend points.

3.3 BUILDING CODES AND FIRE SAFETY: LESSONS FROM CHICAGO

OBJECTIVES

- Explain how the Great Chicago Fire of 1871 and the Iroquois Theater fire of 1903 led to fire-resistant construction, sprinklers and safer exits.
- Explain heat transfer (conduction, convection, radiation), why steel must be fireproofed, and how a sprinkler head works.
- Calculate required exit width for a room, and test how well different coverings insulate a metal “column” from heat.

Warm-up. Walk through your home and find every way out of each bedroom. Count the steps from your bed to the nearest outside door. Which way does that door swing? Is there a smoke alarm in or near each sleeping room? Write down what you find. (You will use it for your family’s fire-escape plan in the build.)

WATCH

Lessons from History The Chicago Fire of 1871

NFPA Kids • 7:10

https://www.youtube.com/watch?v=tl-_AtGkvT4

WHEN TO WATCH

After the story paragraph. List each lesson Chicago learned about building.

BACKUP VIDEO

How fire sprinkler systems work (3D Animation)

ScienceWorld • 4:09

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

With the engineering paragraph: how a glass-bulb sprinkler head opens, and the different kinds of sprinkler systems.

KEY TERMS

building code

A set of minimum rules, adopted as law, for how buildings must be designed and built to protect health and safety.

conduction, convection, radiation

The three ways heat moves: through a solid by contact, by moving hot air or liquid, and by invisible infrared light.

panic bar

A push bar across an exit door that unlatches when pressed, so a crowd pushing against the door opens it instead of trapping itself.

fire-resistance rating

How long, in hours, a wall, floor or column can hold its load and stop fire passing through it in a standard fire test.

means of egress

The continuous path from any point in a building to the outside: exit access, the exit itself (stairs, exit doors) and the exit discharge.

automatic sprinkler

A water outlet on a pipe that is held shut by a heat-sensitive glass bulb or metal link and opens by itself when the air near it gets hot enough.

CORE IDEAS

The story. On the night of October 8, 1871, a fire started in a barn on Chicago's west side. Driven by a strong wind after a long dry summer, it jumped the Chicago River and burned for more than a day. When rain helped put it out, more than 17,000 buildings were gone, about 100,000 people were homeless, and about 300 had died. Most of the city was built of wood, with wooden sidewalks and roofs. Thirty-two years later, on December 30, 1903, fire broke out on the stage of the new Iroquois Theater in Chicago during a crowded holiday afternoon show. The theater had been advertised as "absolutely fireproof," but more than 600 people died, most of them unable to get out: some exits were locked or hidden behind curtains, and some doors opened inward against the crowd.

How they figured it out. After 1871, Chicago banned new wooden buildings downtown and required brick, stone and iron. Engineers soon learned that iron and steel, though they do not burn, lose strength in a fire, so they began wrapping columns and beams in clay tile and later concrete. William Le Baron Jenney's Home Insurance Building of 1885, often called the first skyscraper, had a metal frame

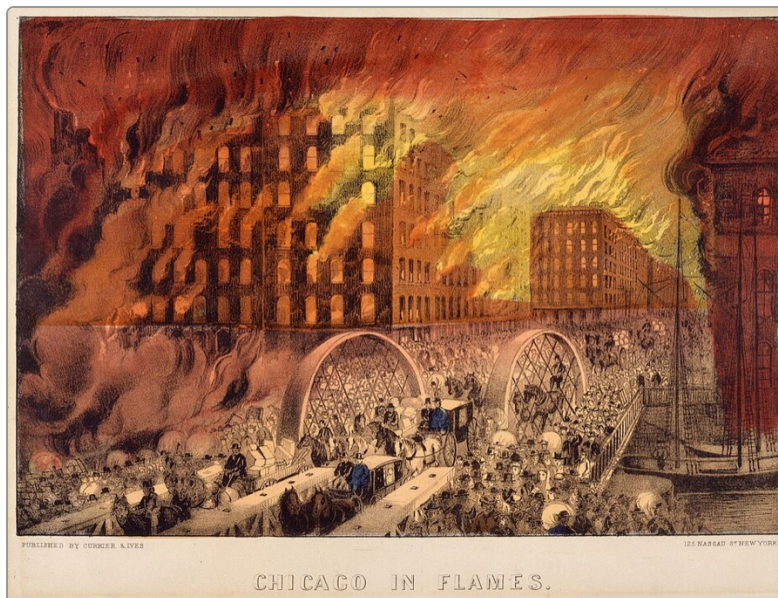
protected this way. After the Iroquois fire, investigators showed that the building had not failed; its exits had. Cities rewrote their codes to require exit doors that open outward, lighted exit signs, and enough exits for the crowd. Carl Prinzler, a salesman who had been scheduled to attend that show, worked with engineers to develop the panic bar, first sold in 1908.

The physics. Fire needs fuel, oxygen and heat (the fire triangle); remove any one and it goes out. Heat moves by **conduction** (through solids, like a hot pan handle), **convection** (rising hot gases, which carry smoke up stairways), and **radiation** (infrared light that can ignite things across a room). Structural steel keeps only about half its strength at around 550–600 °C, temperatures easily reached in a building fire, so it must be insulated with sprayed fireproofing, gypsum board or concrete. A sprinkler head is plugged by a small glass bulb filled with liquid. When the air around it heats up (a common red bulb is rated at 68 °C, or 155 °F), the liquid expands, the bulb bursts and water sprays out. Only the heads near the fire open, not every sprinkler in the building.

The engineering. Modern building codes, such as the International Building Code used in most of the United States, work in layers: keep fires from starting, keep them small (sprinklers and fire-resistant materials), keep the structure standing (fire-resistance ratings), and get people out (alarms and exits). Exits are calculated, not guessed. The code generally requires about 0.2 inch of exit width for each occupant (stairways need more). For a church hall with 300 people: $300 \times 0.2 \text{ in} = 60 \text{ inches}$ of exit width, and the code would also require at least two separate exits, placed far apart, so one fire cannot block both. Fire protection engineering is a specialized career, and the National Fire Protection Association, founded in 1896 to write the first sprinkler standard, still writes many of the codes.

Today. Thanks to codes, sprinklers and smoke alarms, the risk of dying in a building fire in the United States is far lower than it was a century ago. Your family's part is simple: working smoke alarms, a plan with two ways out of each room, and a meeting place outside.

PICTURE STUDY



Chicago in Flames, Currier & Ives, 1871 · Hand-colored lithograph · Published in New York

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

Currier & Ives printed this view within weeks of the fire for a public eager to see what had happened. Look at it as a fire engineer would: what was burning, and how did the fire spread?

Look closely

- Find the river. Why might people have expected it to stop the fire?
- Look at the direction the smoke is blowing. How did the wind help the fire spread?
- Find buildings that are close together. What happens to radiant heat between buildings that touch?
- Look for anything that is not burning. What might it be made of?

Talk about it

1. Which of the three kinds of heat transfer do you think spread the fire from block to block?
2. What three rules would you have written for rebuilding Chicago?
3. Why is a city built of brick and stone still not completely safe from fire?

Safety first. Use only hot tap water for the insulation test, never boiling water or a flame, and have an adult nearby. Never test smoke alarms with fire or smoke; use the test button. Agree on the family fire plan with your parents.

BUILD

Fireproofing Test and a Family Egress Plan

You will model fireproofing on a steel column by wrapping small metal cans in different coverings and standing them in hot water, measuring how fast the inside warms. Then you will act as a fire-protection engineer for your own home: measure exit paths, check alarms, and draw a family fire-escape plan.

You will need

- Four identical small steel food cans (labels removed, edges taped), each filled with the same amount of room-temperature water
- Coverings: none, aluminum foil, three layers of corrugated cardboard, and a thick layer of cotton batting or felt, each held with tape
- A kitchen thermometer (or one per can), a large pan or plastic tub, hot tap water, a stopwatch
- A tape measure, graph paper and colored pencils for the floor plan

Steps

1. **Predict.** Rank the coverings from best to worst insulator and explain your ranking using conduction, convection and radiation.
2. Wrap three cans, leaving the tops open, and leave one bare. Record each can's starting water temperature.
3. Fill the tub with hot tap water to a set depth (the same for every can) and record its temperature. Stand all four cans in it at once.
4. Record each can's inside water temperature every minute for 12 minutes. Keep the thermometer at the same depth each time.
5. Graph temperature against time for all four cans on one graph. Find the time each can took to rise 10 °C. That time is like a fire-resistance rating.
6. **Improve.** Design a covering of no more than 1 cm thickness that beats your best one (try combining a shiny outer layer with a cardboard or felt inner layer). Test it against the original winner.
7. **Egress plan.** Draw a floor plan of your home to scale. Mark every bedroom's two ways out, the smoke alarms, and the outside meeting place. Measure the

travel distance from each bed to the nearest exit door.

8. With your family, hold a practice drill from one bedroom and time it. Write a one-paragraph report with recommendations (for example, a new smoke alarm, a clear path, or an escape ladder for an upstairs room).

Tips

- Stir the hot water gently before each reading so the temperature is even.
- Keep the tops of all cans the same (open or covered) so you change only the side covering.
- Shiny foil reflects radiant heat well but conducts heat quickly when it touches something hot. That is a good lesson about choosing materials for the right kind of heat transfer.

Check your work

- ☐ I can explain why steel must be fireproofed and how a sprinkler head opens.
- ☐ My graph shows which covering slowed heat transfer the most, and I improved on it.
- ☐ I made a scaled family egress plan with two ways out of each sleeping room and a meeting place.

ENGINEER'S NOTEBOOK

1. Your temperature-versus-time graph with each covering labeled and its “rating” (time to rise 10 °C).
2. Your home egress plan with travel distances, alarms and the meeting place.
3. Draw a cross section of a sprinkler head and label the bulb, the plug, the frame and the deflector. Explain in two sentences how it opens.
4. Solve: a hall holds 450 people. Using 0.2 inch per person, how many inches of exit width are needed? If each door is 36 inches wide, how many doors? Why must there be at least two?

From history. Henry Parmelee patented one of the first practical automatic sprinklers in 1874 to protect his piano factory, and Frederick Grinnell improved the design in the 1880s and 1890s. Insurance companies soon offered lower rates to buildings with sprinklers, which did as much as any law to spread them. The first fire escape and building rules in America go back to colonial cities such as Boston and New Amsterdam, which banned wooden chimneys.

COMMON MISTAKES

- Thinking steel buildings cannot be harmed by fire because steel does not burn. Steel loses strength when hot and must be protected.
- Believing that all the sprinklers in a building go off at once, as in films. Each head opens on its own when it gets hot.
- Thinking “fireproof” means nothing can go wrong. The Iroquois Theater was called fireproof; its exits, not its walls, decided the outcome.

Make it a game · Escape Plan Race. Beat the clock. Draw your home's floor plan from memory in two minutes and mark two exits from every bedroom. Then your parent calls out a blocked exit and you trace the other route with a finger while saying aloud what means of egress means. Finish by explaining conduction, convection and radiation with one household example each.

3.4 THE BURJ KHALIFA: CONFUSING THE WIND

OBJECTIVES

- Explain the structural system of the Burj Khalifa: the buttressed core, the Y-shaped plan, and the spiraling setbacks.
- Calculate wind pressure ($q = \frac{1}{2}\rho v^2$) and the frequency of vortex shedding, and explain why it matters for tall buildings.
- Test tower shapes in a box-fan wind tunnel and measure how shape affects sway.

Warm-up. Hold a ruler or a flat strip of card stock upright in front of a fan, first with its flat face to the wind and then edge-on. Then try a round pencil. Which one shakes back and forth, and which one only bends? Write your observations; you will see the same effect on a skyscraper scale.

WATCH

Burj Khalifa - How To Build Higher

Real Engineering • 7:38

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

WHEN TO WATCH

After the physics paragraph. Watch for the vortex shedding animation and the tuned mass damper in Taipei 101.

Note: Begins with a brief sponsor message.

BACKUP VIDEO

How the world's tallest skyscraper was built - Alex Gendler

TED-Ed • 6:07

<https://www.youtube.com/watch?v=el1K-xlLtwo>

With the story paragraph: an animated history of how tall buildings developed and how the Burj Khalifa's structure works.

KEY TERMS

buttressed core

The Burj Khalifa's structural system: a central hexagonal concrete core braced on three sides by the walls of the building's three wings, like a tripod.

vortex shedding

The pattern of swirling eddies that peel off alternately from each side of an object in a wind, pushing it from side to side.

high-performance concrete

Concrete with special mixes and additives that make it much stronger and easier to pump than ordinary concrete.

setback

A place where a tall building steps in, so the floors above are smaller than those below.

wind tunnel test

Testing a scale model of a building in a controlled wind to measure pressures and sway before it is built.

CORE IDEAS

The story. Construction of the Burj Khalifa began in 2004 in Dubai, in the United Arab Emirates, and it opened on January 4, 2010. At 828 meters (2,717 feet), it is the tallest building in the world. The architect was Adrian Smith and the structural engineer was Bill Baker, both of the Chicago firm Skidmore, Owings & Merrill. The plan was inspired partly by a desert flower with three petals and partly by an older dream: in 1956 Frank Lloyd Wright had drawn a mile-high tower for Chicago that was never built.

How they figured it out. For a building this tall, wind, not weight, is the biggest problem. Baker's team gave the tower a Y-shaped plan: three wings around a central hexagonal core, each wing bracing the others like the legs of a tripod. They made each wing step back at a different height, so that the shape of the building changes as it rises in a spiral. Then they tested scale models in a wind tunnel again and again, adjusting the setbacks and the orientation of the tower. Because the cross section changes with height, the swirling vortices of wind cannot organize into a steady

rhythm along the building's height. Engineers say the building was designed to “confuse the wind.”

The physics. Wind pressure grows with the square of wind speed: $q = \frac{1}{2}\rho v^2$, where air density $\rho \approx 1.2 \text{ kg/m}^3$. At 40 m/s (about 90 mph), $q = \frac{1}{2} \times 1.2 \times 40^2 = 960 \text{ Pa}$, nearly a hundred kilograms of push on every square meter of wall. Winds are also faster high above the ground. As wind flows around a building, vortices peel off alternately from each side at a frequency $f \approx 0.2 \times v \div D$, where D is the building's width. For a section 40 m wide in a 20 m/s wind, $f \approx 0.2 \times 20 \div 40 = 0.1 \text{ Hz}$, one push every 10 seconds. If that matches the building's own natural swaying period, the pushes add up by **resonance**, the same physics that destroyed the Tacoma Narrows Bridge. Changing the width with height spreads the vortex frequencies apart so they cannot all match at once.

The engineering. The tower's core and wing walls are reinforced concrete, with a steel spire on top. Concrete had to be pumped more than 600 meters straight up, a world record at the time; just to lift it took a pressure of about $\rho gh = 2,400 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 600 \text{ m} \approx 14 \text{ MPa}$, plus friction in the pipe. Workers often poured at night, and ice was added to the mix to keep it from setting too fast in the desert heat. The tower stands on a reinforced-concrete raft about 3.7 meters thick, carried by 192 bored concrete piles, each 1.5 meters across and about 43 meters deep, which grip the ground by friction. Elevators, water pumps, cooling and window cleaning all had to be specially designed for the height.

Today. Even taller towers are being planned. Every one of them will be shaped in the wind tunnel first.

PICTURE STUDY



The Burj Khalifa Rising, Unknown photographer (released into the public domain), mid-2000s, during construction · Photograph · Dubai, United Arab Emirates

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

This photograph shows the tower early in its construction. You can see the concrete core and the start of the three wings, with tower cranes riding on top of the structure.

Look closely

- Find the cranes on top. How do they rise as the building grows?
- Find the central core and the wings beginning to spread from it. Can you see the Y shape starting?
- Look at the floors. Which parts are finished concrete and which are still formwork?
- Look at the building site around it. How would trucks bring concrete and steel to the pumps?

Talk about it

1. Why is the concrete core built ahead of the rest of each floor?
2. Why is a three-winged plan more stable than a single thin slab of the same floor area?
3. What would you need to pump water or concrete to the top of this tower?

Safety first. Keep fingers and paper away from the fan blades; put the fan's grille between you and the blades at all times, and run it on a low or medium setting.

BUILD

Wind-Tunnel Test of Tower Shapes

You will build four card-stock towers of the same height and nearly the same amount of material, square, round, Y-shaped and tapered with setbacks, and test each one in front of a box fan, measuring how far its top sways and whether it shakes.

You will need

- Card stock (about 10 sheets), tape and glue
- A heavy cardboard or wood base for each tower, or modeling clay to anchor them
- A box fan, a ruler or tape measure taped upright beside the tower as a sway gauge
- A drinking straw taped to each tower top as a pointer, and a phone for slow-motion video

Steps

1. Build four towers, each 50 cm tall, each from the same number of card-stock sheets: (1) square tube 6 cm wide, (2) round tube of the same perimeter, (3) Y shape: three wings 6 cm long around a small triangular core, (4) Y or square tower with three setbacks that step inward at different heights on each wing. Weigh each tower.
2. Anchor each tower firmly to its base. Tape a straw pointer to the top and set the upright ruler behind it so you can read the top's position.
3. Place the fan 1 m away on its lowest setting, aimed at the tower's middle. Record the steady sway of the top (how far it moves from its still position) and whether it vibrates from side to side.
4. **Fair test.** Test every tower at the same distance and fan speeds (low, medium), and test the square tower both flat-face and corner-first to the wind. Record three readings each.
5. Film each test in slow motion and count side-to-side shakes per second, if any.

6. Make a table: tower shape, mass, sway at low (mm), sway at medium (mm), side-to-side vibration (yes/no, how many per second).
7. Calculate the wind pressure ratio between fan speeds if you can measure the air speed (a free anemometer phone app, or time a tissue scrap over a known distance), using $q = \frac{1}{2}\rho v^2$.
8. **Improve.** Change your worst tower in one way (add setbacks, round its corners, add a slot through it, or turn it) and retest. Explain the result.

Tips

- A box fan's wind is uneven; mark the floor so every tower stands in exactly the same spot.
- Card-stock towers can be damaged by repeated tests; inspect the base joint before each run.
- Rounded or chamfered corners often reduce side-to-side shaking. The Burj Khalifa's designers used setbacks for the same purpose.

Check your work

- ☐ I can explain how the Burj Khalifa's buttressed core and Y-plan resist wind.
- ☐ I can calculate wind pressure and vortex shedding frequency with units.
- ☐ My wind-tunnel data show which tower shape swayed and shook least, and I improved my worst tower.

ENGINEER'S NOTEBOOK

1. Plan sketch of the Burj Khalifa's Y shape with the core and three wings labeled, and a side sketch showing the spiraling setbacks.
2. Your wind-tunnel data table and a bar graph of sway for each tower.
3. Draw vortex shedding behind a round tower (top view), showing eddies leaving alternately from each side and the side-to-side push.
4. Solve: what is the wind pressure at 25 m/s? At 50 m/s? How many times larger is the second?

From history. Before the Burj Khalifa, the tallest building was Taipei 101 in Taiwan (508 m, finished in 2004), which hangs a 660-metric-ton steel ball near its top as a tuned mass damper to calm its swaying. Many tall towers now use dampers like it, or water tanks that slosh against the motion.

COMMON MISTAKES

- Thinking the biggest load on a supertall building is its own weight. For very tall, slender towers, wind usually controls the design.
- Believing wind only pushes a building downwind. Vortex shedding pushes it from side to side, across the wind.
- Forgetting that pressure goes with the square of speed: double the wind speed, four times the pressure.

Make it a game · Confuse the Wind. Cut paper into tower shapes: square, round, tapered and stepped. Each of you predicts which one would be hardest for the wind to organize into vortices. Then blow gently from the same distance and watch which sways least. Score a point for each correct prediction. Explain why setbacks and the Y-shaped plan of the Burj Khalifa help.

Scripture. “And they said, Go to, let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name, lest we be scattered abroad upon the face of the whole earth.” (Genesis 11:4, KJV)

The builders of Babel built to make a name for themselves. A Christian engineer can admire a great tower and still ask the deeper question: whom does this building serve?

UNIT 3

ARCHITECTURE

Architecture is where engineering meets beauty. The Roman writer Vitruvius said a good building must have firmness, usefulness and delight, and in this unit you will see that every great style of building grew out of a structural idea. Greek temples are stone beams on stone columns; Gothic cathedrals are pointed arches pushed sideways against flying buttresses; modern towers are steel and concrete frames hung with glass. You will test columns of different proportions, learn to draw and model buildings with free computer-aided design (CAD) software, and see how architects turn a computer model into plans, elevations and sections.

Then you will study what keeps people safe inside a building. Fires in Chicago in 1871 and 1903 taught hard lessons that are now written into building codes: fire-resistant materials, protected steel, sprinklers, and exit doors that open outward with panic bars. The unit ends at the top of the world's tallest building, the Burj Khalifa in Dubai, where engineers used a three-winged shape and wind-tunnel testing to "confuse the wind."

PREREQUISITES

- Knows stress ($\sigma = F \div A$), compression, tension and buckling (Unit 2)
- Can measure in metric units and use a scale such as 1:50
- Can use a computer or tablet with a web browser and a free account made by a parent (for Tinkercad)
- Knows wind and earthquake loads in simple terms (Grade 5 or earlier)

MASTERY CHECKLIST

- ☐ I can identify the Doric, Ionic and Corinthian orders, Gothic features and the steel frame, and explain the structural idea behind each style.
- ☐ I can explain how slenderness affects buckling, using the rule that doubling a column's length cuts its buckling load to about one-quarter.
- ☐ I can build a building model in Tinkercad to scale and produce a plan and elevation from it.
- ☐ I can explain how building codes protect people from fire: fire-resistant construction, sprinklers, and exits, and calculate required exit width.
- ☐ I can explain how the Burj Khalifa's shape, core and wind-tunnel testing let it stand 828 meters tall.

OPTIONAL KITS FOR THIS UNIT

- **KEVA planks:** All ages. Identical maple planks for building columns, arches, domes and towers with no glue; good for trying classical and Gothic forms in Lesson 3.1 and wind tests in Lesson 3.4.
- **Tinkercad ([free online CAD from Autodesk](#)):** Free; a parent creates the account for students under 13. Used in Lesson 3.2 and the portfolio. Not a kit, but the one tool this unit leans on.

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 Styles and Structure: From the Classical Orders to Gothic to Modern

2 sessions of 60 minutes

3.2 From Drafting Board to CAD: Modeling a Building in Tinkercad

2 sessions of 60 minutes

3.3 Building Codes and Fire Safety: Lessons from Chicago

2 sessions of 60 minutes

3.4 The Burj Khalifa: Confusing the Wind

2 sessions of 60 minutes

UNIT 3 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Name the three Greek orders and describe the capital of each.

2. 8 pts

Explain why Greek temples have closely spaced columns while Gothic cathedrals have huge windows.

3. 10 pts

Calculation. A column 4 m tall can carry 120 kN before buckling. Using the $1 \div L^2$ rule, estimate the buckling load of the same column at 2 m and at 8 m tall.

4. 8 pts

What is the difference between a plan, an elevation and a section?

5. 8 pts

At a scale of 1:50, a wall measures 9.0 cm on a plan. How long is the real wall?
What would a room 6.0 cm $\times$ 5.0 cm on the plan measure in square meters?

6. 8 pts

What was important about Ivan Sutherland's Sketchpad, and what is a "clash" in a building information model?

7. 8 pts

What did Chicago and other cities change after the Iroquois Theater fire of 1903?

8. **10 pts**

Calculation. A school gym holds 600 people. Using 0.2 inch of exit width per person, how much total exit width is required? If each exit door is 36 inches wide, how many doors are needed?

9. **8 pts**

Why must structural steel be fireproofed, and name two ways it is done.

10. **10 pts**

Calculation. Find the wind pressure on a tower in a 30 m/s wind ($\rho = 1.2 \text{ kg/m}^3$). What would it be at 60 m/s?

11. **6 pts**

What is vortex shedding, and why is it dangerous for tall, slender structures?

12. **8 pts**

Describe two features of the Burj Khalifa that help it resist wind.

ANSWER KEY

1. Doric: plain cushion-shaped capital; Ionic: scroll-shaped volutes; Corinthian: rows of acanthus leaves (with small scrolls).
2. Greek temples use stone lintels, which bend and crack on the bottom (tension) if the span is long, so columns must be close. Gothic builders used pointed arches and ribbed vaults to gather the loads onto piers and flying buttresses to resist the sideways thrust, so the walls between did not carry load and could be windows.
3. At 2 m (half the length): $4 \times 120 = 480$ kN. At 8 m (double the length): $120 \div 4 = 30$ kN.
4. A plan is seen from above (cut horizontally, showing walls, doors, windows); an elevation is one outside face seen straight on; a section is a vertical slice through the building showing floors, walls and roof inside.
5. $9.0 \times 50 = 450$ cm = 4.5 m. The room is $3.0 \text{ m} \times 2.5 \text{ m} = 7.5 \text{ m}^2$.
6. Sketchpad (1963) was the first interactive computer drawing program, with a light pen, copies of shapes and rules (constraints) between parts, the beginning of CAD. A clash is when two parts in the model occupy the same space, such as a duct passing through a beam, found by the computer before construction.
7. They required enough exits for the crowd, exit doors that open outward, unlocked and clearly marked exits with lighted signs, and panic bars on exit doors (along with other theater rules such as fire curtains).
8. $600 \times 0.2 = 120$ inches. $120 \div 36 = 3.33$, so 4 doors (always round up), placed far apart.
9. Steel loses about half its strength at around 550–600 °C, temperatures reached in building fires, so an unprotected frame could collapse. It is insulated with sprayed fireproofing, gypsum board, concrete encasement or clay tile (any two).
10. $q = \frac{1}{2} \times 1.2 \times 30^2 = 540$ Pa. At 60 m/s: $\frac{1}{2} \times 1.2 \times 3,600 = 2,160$ Pa, four times as much.
11. Swirling eddies peel off alternately from each side of an object in the wind, pushing it from side to side. If the rhythm matches the structure's natural frequency, resonance can make the swaying grow.
12. Any two: the Y-shaped, three-winged plan buttressing a central core (like a tripod); setbacks at different heights that spiral up, changing the shape with height so vortices cannot organize ("confusing the wind"); orientation and

shaping refined by many wind-tunnel tests; the tapering form reducing area high up.

PORTFOLIO PIECE: A DESIGNED AND WIND-TESTED TOWER

Design a tower at least 60 cm tall for a real purpose (an office, a bell tower, a lookout) in Tinkercad, with a clear structural idea from this unit (a classical colonnade at its base, a buttressed core, setbacks, or a frame and curtain wall). Produce a dimensioned plan and elevation from the CAD model, then build it from card stock, craft sticks or KEVA planks. Test it in the box-fan wind tunnel, record sway at two fan speeds, improve it once, and include an egress plan for its ground floor with exits sized by the 0.2-inch rule for a stated number of occupants. Present the drawings, data and photographs in a short design report.

LOOK FOR	WHAT IT MEANS
CAD design and drawings	Accurate Tinkercad model with exact dimensions; printed plan and elevation with dimensions and scale.
Structural idea	Clearly uses and explains one structural system from the unit (orders, arch, buttressed core, frame).
Wind test and data	Sway measured at two speeds with three trials each; results tabled and graphed; vibration noted.
Life safety	Ground-floor egress plan with occupant number, required exit width calculated, and at least two separated exits.
Improvement and report	One change made and retested with before-and-after data; clear, honest report.

ELECTRONICS

Every phone, car and microwave holds billions of tiny switches that turn on and off according to the rules of logic. In this unit you will follow those switches from the mathematics of George Boole and the relays of Claude Shannon, through the first transistor built at Bell Labs in 1947, to the integrated circuit and the computer chips of today. You will build logic gates from switches and LEDs, measure the current gain of a real transistor, and see why one invention changed the whole world.

Then you will program: first a Raspberry Pi Pico microcontroller (or a free online simulation of one) to blink, sense a button and time your reactions, and then your own phone, used as a laboratory full of sensors, to log real data the way a flight data recorder does. You will learn the words engineers use for this work: bits, bytes, truth tables, gain, analog-to-digital conversion, sampling rate and resolution.

PREREQUISITES

- Knows voltage, current and resistance and can use Ohm's law ($V = IR$)
- Has built series and parallel circuits with batteries, LEDs and resistors
- Can count in powers of 2 and use exponents
- Has used Scratch, MakeCode or another block-coding tool (helpful, not required)

MASTERY CHECKLIST

- ☐ I can convert between binary and decimal and explain why computers use two states.
- ☐ I can write truth tables for NOT, AND, OR, NAND and XOR and build AND, OR and XOR with switches.
- ☐ I can explain how a transistor works as a switch and an amplifier and calculate its current gain ($\beta = I_C \div I_B$).
- ☐ I can program a microcontroller to read an input and control an output, using loops and conditionals.
- ☐ I can explain sampling rate and ADC resolution, and log and graph sensor data from a real experiment.

OPTIONAL KITS FOR THIS UNIT

- **Raspberry Pi Pico:** Ages 12 and up with an adult. A small microcontroller board programmed in MicroPython over a USB cable, inexpensive and powered by the computer. Used in Lesson 4.3; the free Wokwi simulator (wokwi.com) can stand in for it.
- **Snap Circuits (Elenco):** Ages 8 and up. Larger sets include transistors, a photoresistor and integrated circuits that snap together with no soldering; a quick way to build the circuits in Lessons 4.1–4.2.
- **Arduino starter kits:** Ages 12 and up with an adult. The Arduino Uno and its starter kit add sensors, motors and a breadboard and are an excellent next step after Lesson 4.3 for students who want more.

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 Binary and Logic Gates: Boole, Shannon and the Relay 2 sessions of 60 minutes

4.2 From the Transistor to the Integrated Circuit: Bell Labs and Beyond

2 sessions of 60 minutes

4.3 Raspberry Pi Projects: Programming a Microcontroller 2 sessions of 60 minutes

4.4 Sensors and Data Logging: From the Black Box to Your Phone

2 sessions of 60 minutes

UNIT 4 REVIEW

Answer each question. For calculations, write the formula, substitute the numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Convert 1101 and 101010 from binary to decimal, and 19 from decimal to binary.

2. 8 pts

Write the truth table for XOR and for AND. Which two gates make a half adder, and what does each one give?

3. 8 pts

What did Claude Shannon show in 1937? How do switches in series and in parallel act as logic gates?

4. 8 pts

Give three reasons transistors replaced vacuum tubes.

5. 10 pts

Calculation. A transistor has a base current of 0.08 mA and a collector current of 12 mA. Find its current gain. With the same gain, what base current would give 20 mA?

6. 8 pts

What did Kilby and Noyce each contribute to the integrated circuit? What is Moore's law?

7. 10 pts

Calculation. A Pico pin outputs 3.3 V. A red LED drops 2.0 V. What resistor gives a current of 10 mA? Would a 100 Ω resistor be safe if the pin can supply 12 mA?

8. 8 pts

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

9. 8 pts

Write, in words or code, a reaction-time program that also catches a player who presses too soon.

10. 10 pts

Calculation. A 12-bit ADC measures 0 to 3.3 V. What is its resolution? If it logs 50 samples per second at 2 bytes each, how much memory is used in 10 minutes?

11. 8 pts

In the drop test, a ball falls 1.20 m in 0.50 s. What value of g does this give? Give one reason it might differ from 9.8 m/s².

12. **6 pts**

Why are flight recorders orange, and why have they helped make flying so safe?

ANSWER KEY

1. $1101 = 8 + 4 + 1 = 13$. $101010 = 32 + 8 + 2 = 42$. $19 = 16 + 2 + 1 = 10011$.
2. XOR: $00 \rightarrow 0$, $01 \rightarrow 1$, $10 \rightarrow 1$, $11 \rightarrow 0$. AND: $00 \rightarrow 0$, $01 \rightarrow 0$, $10 \rightarrow 0$, $11 \rightarrow 1$. A half adder uses XOR for the sum and AND for the carry.
3. That relay and switch circuits follow Boole's algebra, so logic and arithmetic can be built from switches. Two switches in series act as AND; two in parallel act as OR.
4. Any three: much smaller; use far less power and produce less heat; no filament to burn out, so more reliable and longer lasting; cheaper to make in large numbers; can be made smaller and combined on chips.
5. $\beta = I_C \div I_B = 12 \div 0.08 = 150$. $I_B = 20 \text{ mA} \div 150 \approx 0.13 \text{ mA}$.
6. Kilby (Texas Instruments, 1958) built the first working circuit on one piece of semiconductor; Noyce (Fairchild, 1959) developed a practical way to make a whole circuit in silicon with flat, printed connections. Moore's law is the observation that the number of transistors on a chip doubled about every two years.
7. $R = (3.3 - 2.0) \div 0.010 = 130 \Omega$. With 100Ω : $I = 1.3 \div 100 = 13 \text{ mA}$, more than 12 mA , so it is not safe; use 130Ω or larger (220Ω is a good choice).
8. Without it, the input pin is not connected to anything when the button is released, so it "floats" and can read random highs and lows. The pull-down holds it at 0 V until the button connects it to 3.3 V .
9. Wait a random time; during the wait, if the button is pressed, print "Too soon" and restart. Turn on the LED and record the start time. Loop until the button is pressed; record the end time. Print end – start in milliseconds. (Any correct logic accepted.)
10. Resolution = $3.3 \text{ V} \div 4,096 \approx 0.0008 \text{ V}$ (0.8 mV). Memory = $50 \times 2 \times 600 \text{ s} = 60,000$ bytes (about 60 kB).
11. $g = 2h \div t^2 = 2.4 \div 0.25 = 9.6 \text{ m/s}^2$. Reasons: timing error from the tap or sound triggers; measuring h inaccurately; air resistance (small).
12. Bright orange makes them easy to find in wreckage. Their data let investigators find exactly what went wrong, so aircraft, training and procedures can be changed to prevent the same accident again.

PORTFOLIO PIECE: A SENSING, LOGGING MICROCONTROLLER PROJECT

Design and build a working electronic device that senses something, makes a decision and acts, and logs data you analyze. Use a Raspberry Pi Pico (or the Wokwi simulator), a transistor circuit, or both. Examples: a night light that counts how many times it switched on; a reaction-time game that stores and averages scores; a door-opening counter; or a temperature logger that lights an LED when a room is too warm. Include a schematic, the commented program, a truth table or flow chart for its decisions, a data table and graph from at least one hour (or 30 trials) of use, and a one-page report on how you tested it and what you improved.

LOOK FOR	WHAT IT MEANS
Working device	Senses an input, makes a correct decision and drives an output reliably when shown working.
Schematic and program	Neat schematic with standard symbols and correct resistor values; program commented and readable.
Logic	Flow chart or truth table that matches what the device does, including one unusual case (such as a too-early press).
Data and analysis	Logged data presented in a table and graph with units; mean or trend described honestly.
Testing and improvement	Report describes tests, at least one problem found, and the change made to fix it.

4.1 BINARY AND LOGIC GATES: BOOLE, SHANNON AND THE RELAY

OBJECTIVES

- Count in binary and convert between binary and decimal numbers.
- Write truth tables for NOT, AND, OR, NAND and XOR and explain how a half adder adds two bits.
- Build AND, OR and XOR circuits from switches and LEDs and test them against their truth tables.

Warm-up. Hold up your ten fingers and count to 10. Now pretend each finger can only be up (1) or down (0), and each finger is worth twice the one to its right: 1, 2, 4, 8, 16... Show 5 ($4 + 1$) on one hand. What is the largest number you can show on one hand this way? On two hands? Write your answers before you read on.

WATCH

Understanding Logic Gates

Spanning Tree · 7:27

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

WHEN TO WATCH

After the physics paragraph. Pause before each gate's truth table appears and fill it in yourself.

KEY TERMS

bit

A binary digit, 0 or 1: the smallest piece of information. Eight bits make a byte, which can hold $2^8 = 256$ different values.

logic gate

A circuit that takes one or more on/off inputs and gives an on/off output by a fixed rule, such as AND, OR or NOT.

binary

The base-2 number system, using only 0 and 1. Each place is worth twice the place to its right: 1, 2, 4, 8, 16, 32...

truth table

A table listing every possible combination of inputs and the output a logic gate gives for each.

Boolean algebra

The mathematics of true and false (1 and 0), invented by George Boole, in which AND, OR and NOT are the basic operations.

relay

A switch worked by an electromagnet, so that one circuit can turn another on or off.

CORE IDEAS

The story. In 1854 George Boole, a largely self-taught mathematics professor in Cork, Ireland, published *An Investigation of the Laws of Thought*. He showed that logical statements (true or false, joined by AND, OR and NOT) could be written and worked like algebra. For eighty years it seemed like pure mathematics with little practical use. Then in 1937 a 21-year-old graduate student at MIT, Claude Shannon, wrote a master's thesis showing that circuits of switches and relays obey exactly Boole's algebra: two switches in series act as AND, two in parallel act as OR. Any rule of logic could be built from switches, and so could arithmetic.

How they figured it out. Shannon had worked on a large mechanical calculating machine at MIT and had studied Boole's logic in college. He noticed that the telephone company's relay circuits were designed by trial and error and were hard to check. By writing each circuit as a Boolean expression, he could simplify it on paper, find mistakes, and design new circuits to do arithmetic. Engineers soon built calculating machines from relays. The Harvard Mark I, finished in 1944 by Howard Aiken and IBM, was 51 feet long and clattered loudly as its relays and counter wheels switched. Later machines replaced relays with vacuum tubes and then transistors, but the logic stayed the same.

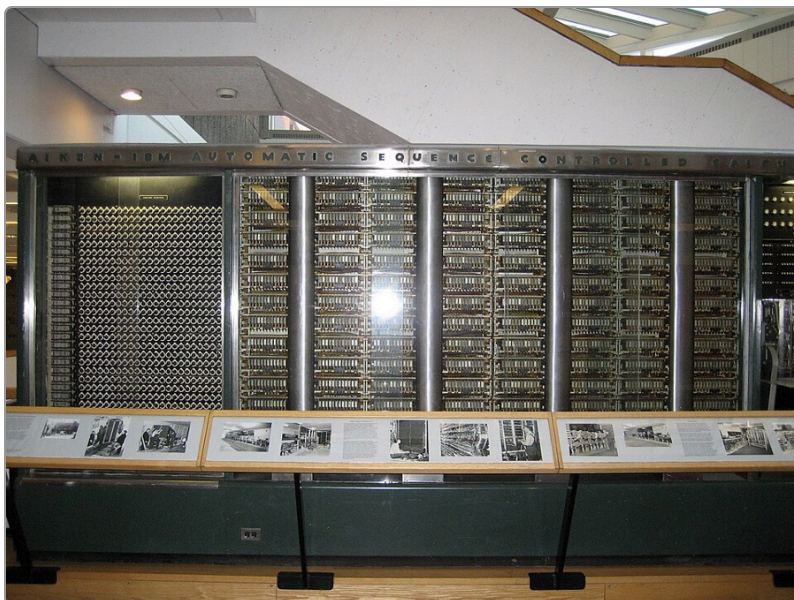
The physics. A computer uses two states because they are easy to tell apart reliably: a voltage near 0 V means 0, and a voltage near the supply (for example 3.3 V) means 1. Small amounts of noise cannot turn a 0 into a 1. Binary counting works like decimal, but each place is worth 2 times the last. The binary number $1011 = 8 + 0 + 2 + 1 = 11$. An 8-bit byte can hold 0 to 255. The gates follow simple rules: **NOT** flips the input; **AND** is 1 only if both inputs are 1; **OR** is 1 if either input is 1; **NAND** is NOT-AND; **XOR** (exclusive or) is 1 if the inputs are different. To add two bits, a **half adder** uses an XOR for the sum and an AND for the carry: $1 + 1 = \text{binary } 10$ (sum 0, carry 1).

The engineering. Engineers build everything from a few gate types; in fact, NAND alone can make every other gate. Chains of adders make a calculator, and millions of

gates arranged with memory make a processor. Real gates are now made of transistors only a few billionths of a meter across, and a modern processor has billions of them switching billions of times each second. Designers use logic simulators to test a design before it is turned into silicon, because one wrong gate in a billion can ruin a chip.

Try it. In your build, two switches and an LED will become a real AND gate. When you put switches in series, you are doing exactly what Shannon described in 1937.

PICTURE STUDY



The Harvard Mark I, Unknown photographer, built 1944; photographed on display at Harvard · Photograph · Harvard University

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

The Harvard Mark I was one of the first large automatic calculators. Part of it is now displayed at Harvard. Inside its cabinets are thousands of relays and counter wheels that did Boolean logic and arithmetic one clicking step at a time.

Look closely

- Find the rows of switches and dials behind the glass. What do you think they were set to?
- Find the name across the top of the cabinets. What does “automatic sequence controlled calculator” tell you about how it worked?
- Compare the machine’s length with the display panels in front. How big is it?
- Look for repeated sections. Why would engineers build a machine from many identical units?

Talk about it

1. The Mark I took about six seconds to multiply two numbers. Why would a relay computer be so slow compared with a transistor computer?
2. If each relay can be on or off, how many different patterns can 10 relays make?

3. What could go wrong with a machine that has hundreds of thousands of moving parts?

Safety first. Use only AA batteries in a holder. Always put a resistor (220–470 Ω) in series with an LED, and never connect a bare wire straight across the battery.

BUILD

Switch-and-LED Logic Gates

You will build NOT, AND, OR and XOR gates from homemade switches, LEDs and a battery pack, check each one against its truth table, and then build a half adder in a free online logic simulator.

You will need

- A 2-AA battery holder (3 V), red LEDs and 220 Ω resistors
- Alligator clip leads or hookup wire and a small breadboard
- Homemade switches: brass paper fasteners pushed through cardboard with paper clips that swing between them (make two single on/off switches and two two-way switches with a middle fastener and two contacts)
- A computer or tablet with the free CircuitVerse simulator (circuitverse.org)

Steps

1. Make a binary table from 0 to 15 with four columns (8, 4, 2, 1). Check five rows by converting back to decimal.
2. **AND.** Wire battery $\rightarrow$ switch A $\rightarrow$ switch B $\rightarrow$ resistor $\rightarrow$ LED $\rightarrow$ battery. Test all four input combinations (00, 01, 10, 11) and fill in the truth table. Does it match the AND rule?
3. **OR.** Put switches A and B side by side (in parallel) in place of the two series switches. Test and fill in the truth table.
4. **NOT.** Wire battery $\rightarrow$ resistor $\rightarrow$ LED, and connect one switch directly across the LED (from one leg to the other). When the switch closes, current takes the easy path around the LED. Record the truth table. (The resistor keeps the battery safe.)
5. **XOR.** Use the two two-way switches wired like the light switches at the top and bottom of a staircase: the LED is on only when the switches are in different positions. Draw your wiring and test all four combinations.

6. In CircuitVerse, build a half adder with one XOR gate and one AND gate. Test all four input pairs and write the sum and carry. Then join two half adders and an OR gate to make a full adder, and test that $1 + 1 + 1 = \text{binary } 11$.
7. **Fair test and improve.** Time how long it takes a partner to work out $1011 + 0110$ by hand in binary, then design (in CircuitVerse) a 4-bit adder from full adders and check the answer. Record any wiring mistakes you made and how you found them.

Tips

- LEDs work only one way round: the longer leg goes toward the positive side of the battery.
- If a gate misbehaves, test each switch alone first; homemade paper-clip switches often make poor contact.
- In CircuitVerse, label every input and output; engineers name every wire.

Check your work

- ☐ I can convert binary to decimal and decimal to binary.
- ☐ My AND, OR, NOT and XOR circuits matched their truth tables.
- ☐ I can explain how a half adder adds two bits, with a sum and a carry.

ENGINEER'S NOTEBOOK

1. Truth tables for NOT, AND, OR, NAND and XOR, with the gate symbol drawn beside each.
2. Wiring diagrams for your four switch gates, with arrows showing current flow when the LED is lit.
3. Convert to binary: 13, 37, 100, 255. Convert to decimal: 1010, 11001, 1111111.
4. Write a paragraph: How did an idea from 1854 become useful only after 1937?

From history. Claude Shannon went on, in 1948, to found information theory, which explains how much information can be sent over a noisy channel and is the basis of every modern phone and internet connection. He is sometimes called the father of the information age. He also loved building gadgets, including a mechanical mouse that could learn its way through a maze.

COMMON MISTAKES

- Reading binary from the wrong end. The rightmost bit is worth 1, the next 2, then 4, 8, and so on.

- Confusing OR with XOR. OR is 1 when both inputs are 1; XOR is 0 then.
- Leaving out the resistor with the LED. The LED and battery can be damaged without it.

Make it a game · Binary Body Count. Use ten fingers as ten binary digits. Your parent calls a number from 0 to 1023 and you show it in binary within five seconds, then say it in decimal. Next, act out a logic gate: two players raise a hand or not, and you call the output for AND, OR, NAND and XOR. Track your streak.

4.2 FROM THE TRANSISTOR TO THE INTEGRATED CIRCUIT: BELL LABS AND BEYOND

OBJECTIVES

- Tell the story of the point-contact transistor (1947) and the integrated circuit (1958–1959), and explain why they replaced vacuum tubes.
- Explain semiconductors, doping and how a bipolar transistor works as a switch and an amplifier.
- Build a transistor switch and a light-activated night light, and measure the transistor's current gain.

Warm-up. Look at any electronic gadget at home (do not open it) and guess how many transistors are inside. A phone has billions. Then think about the earliest electronic computer, ENIAC (1946), which used about 17,500 glass vacuum tubes, each about the size of a thumb and glowing hot. How big would a phone be if it used vacuum tubes? Write your guess and your reasoning.

WATCH

How the first transistor worked

[engineerguy](#) · 4:46

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

WHEN TO WATCH

After the story paragraph. Watch how a small current at one contact controls a larger one.

BACKUP VIDEO

Transistors Explained - How transistors work

[The Engineering Mindset](#) · 18:19

https://www.youtube.com/watch?v=J4oO7PT_nzQ

Before the build: NPN and PNP transistors, base, collector and emitter, current gain, and switch circuits like the one you will build.

KEY TERMS

semiconductor

A material such as silicon or germanium that conducts electricity better than an insulator but worse than a metal, and whose conduction can be controlled.

transistor

A semiconductor device in which a small current or voltage at one terminal controls a larger current through the other two. It can act as a switch or an amplifier.

current gain (β)

The ratio of collector current to base current, $\beta = I_C \div I_B$. Common small transistors have gains of about 100 or more.

doping

Adding tiny amounts of other elements to a semiconductor to give it extra electrons (n-type) or extra “holes” (p-type).

base, collector, emitter

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

integrated circuit (IC)

A complete circuit of many transistors, resistors and connections made together on one small chip of semiconductor.

CORE IDEAS

The story. By the 1940s, radios, telephone amplifiers and the first electronic computers depended on vacuum tubes: glass bulbs with hot glowing filaments. They were bulky, used a lot of power and often burned out. ENIAC, finished in 1946 to calculate mathematical tables for the U.S. Army, had about 17,500 tubes, weighed about 30 tons and used about 150 kilowatts. 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 gold contacts, very close together, onto a crystal of germanium and saw a weak signal come out amplified. On December 23 they showed their bosses that it could amplify speech. They called it a transistor. Bardeen, Brattain and Shockley shared the Nobel Prize in Physics in 1956.

How they figured it out. Their path was full of failed attempts. Shockley’s first designs, using an electric field to control current in a semiconductor, did not work.

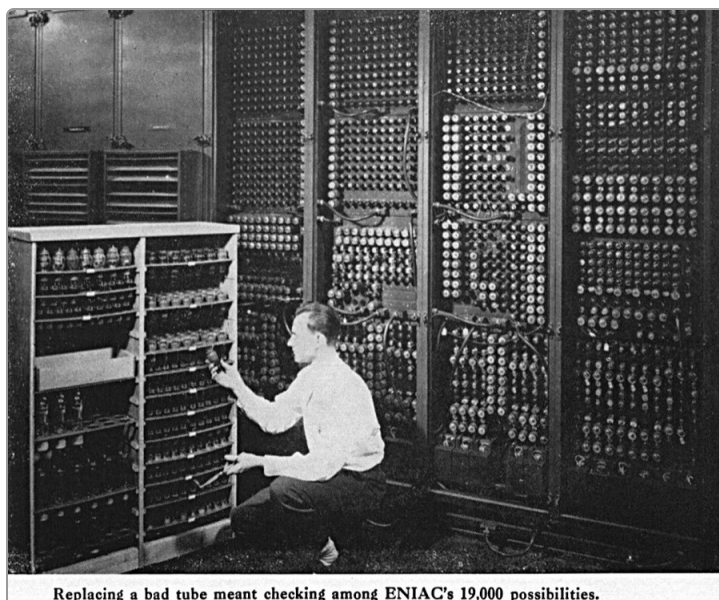
Bardeen worked out that electrons were being trapped at the surface of the crystal, and he and Brattain experimented with electrolytes, oxide layers and contacts to get around it, keeping careful notebook records of every try. The first transistor was fragile and hard to make. A month later Shockley worked out the theory of a sturdier junction transistor, built from layers of differently doped semiconductor. Then the next problem appeared: wiring thousands of separate transistors together by hand. In 1958 Jack Kilby at Texas Instruments built a working circuit on one piece of germanium, and in 1959 Robert Noyce at Fairchild Semiconductor patented a way to make a whole circuit of silicon with flat, printed connections. That was the integrated circuit.

The physics. Silicon atoms each share four outer electrons with their neighbors, so pure silicon conducts poorly. Adding a trace of phosphorus gives extra free electrons (**n-type**); adding boron leaves gaps called holes (**p-type**). An NPN transistor is a thin p-type layer (the base) between two n-type layers. With no base current, almost no current can cross from collector to emitter. A small current into the base lets a much larger collector current flow, about β times as large. Worked example: with a base current of 0.10 mA and $\beta = 150$, the collector current can be up to $150 \times 0.10 \text{ mA} = 15 \text{ mA}$, enough to light an LED brightly. As a **switch**, the transistor is either fully off or fully on; as an **amplifier**, a small changing base current makes a large copy of itself in the collector circuit.

The engineering. Transistors were smaller, cooler, cheaper and far more reliable than tubes, and they could be made smaller and smaller. In 1965 Gordon Moore, a founder of Fairchild and later Intel, noticed that the number of transistors on a chip was doubling about every year; he later revised it to about every two years. This trend, called Moore's law, held for about fifty years. Chips are made by photolithography: light shines through a pattern onto silicon wafers coated with light-sensitive chemicals, and the patterns are etched, doped and layered dozens of times in ultra-clean factories. A chip factory is among the most precise and expensive things people have ever built.

Today. A single modern processor chip holds tens of billions of transistors, each far smaller than a virus. More transistors have been made than any other manufactured object in history.

PICTURE STUDY



Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.

Changing a Tube in ENIAC, U.S. Army photograph, about 1946 · Photograph · U.S. Army

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

ENIAC's thousands of vacuum tubes did the same job transistors do today. This photograph shows why engineers wanted something better: tubes were large, hot, and had to be checked and replaced by hand.

Look closely

- Find the vacuum tube in the technician's hand. How big is it compared with his fingers?
- Count how many tubes you can see in one panel. Estimate how many panels would hold 17,500 tubes.
- Look for wires and plug boards. How was this computer programmed?
- Look at the size of the room the computer fills.

Talk about it

1. Each tube needed a heated filament. What problems would 17,500 hot filaments cause?
2. Why would a transistor, made of solid crystal with no filament, last so much longer?
3. How would replacing tubes with transistors change the size, power and cost of a computer?

Safety first. Use a 9 V battery or 3 AA batteries only. Check every transistor's pin order on its data sheet before connecting, and always use a resistor in series with the base and with the LED; without them the transistor or LED can overheat. Disconnect the battery when you change wiring.

BUILD

A Transistor Switch and Light-Activated Night Light

You will use an NPN transistor as a switch, measure its base and collector currents to find its current gain, and then turn it into a night light that switches on by itself when it gets dark.

You will need

- NPN transistors such as the 2N2222 or 2N3904 (inexpensive from electronics suppliers)
- A breadboard, jumper wires, a 9 V battery with snap connector (or a 3-AA holder)
- Resistors: 470 Ω (for the LED), 10 k Ω , 47 k Ω and 100 k Ω (for the base); a red LED; a photoresistor (light-dependent resistor)
- A digital multimeter that measures milliamps and microamps

Steps

1. Find the transistor's pins (emitter, base, collector) from its data sheet and draw the pin-out in your notebook.
2. **Switch circuit.** Connect: battery + $\rightarrow$ 470 Ω $\rightarrow$ LED $\rightarrow$ collector; emitter $\rightarrow$ battery $-$. Connect the base to battery + through a 47 k Ω resistor by touching a wire to it. The LED should light only while the base is connected.
3. **Measure gain.** Put the multimeter in series with the base resistor to measure I_B , then in series with the LED to measure I_C . Calculate $\beta = I_C \div I_B$.
4. **Fair test.** Change only the base resistor: 100 k Ω , 47 k Ω , 10 k Ω . For each, record I_B , I_C and LED brightness. When does the collector current stop increasing? That is when the transistor is fully on (saturated): it has become a switch.
5. **Night light.** Build a voltage divider: battery + $\rightarrow$ 10 k Ω $\rightarrow$ base point $\rightarrow$ photoresistor $\rightarrow$ battery $-$, and connect the base point to the transistor base through a 10 k Ω resistor. In light, the photoresistor's low resistance pulls the base voltage down and the LED is off; in darkness, its resistance rises and the

LED turns on. (If yours works backward, swap the photoresistor and the 10 k Ω resistor.)

6. Test it: measure the photoresistor's resistance in bright light, room light and darkness (cover it with your hand) and record whether the LED is on.
7. **Improve.** Change the 10 k Ω divider resistor to make the light turn on at the darkness you want (for example, at dusk but not in a dim room). Explain the change using the voltage-divider idea.

Tips

- Measure current with the meter in series (the current must flow through the meter); measure voltage with the meter in parallel.
- Move the meter's red lead to the milliamp jack for current and back to the volt jack afterward, or the meter's fuse may blow.
- Transistors vary. Your β might be anywhere from about 75 to 300.

Check your work

- ☐ I can tell the story of the transistor and the integrated circuit and explain why they replaced tubes.
- ☐ I measured my transistor's current gain and can explain switching and saturation.
- ☐ My night light turns on in the dark, and I can explain how the photoresistor and voltage divider control it.

ENGINEER'S NOTEBOOK

1. Schematic diagrams of your switch circuit and night light, using standard symbols for battery, resistor, LED, transistor and photoresistor.
2. Gain data table (base resistor, I_B , I_C , β) and a graph of I_C against I_B , marking where the transistor saturates.
3. Draw a cross section of an NPN transistor and label the n, p and n layers, the base, collector and emitter.
4. Solve: a transistor with $\beta = 120$ has a base current of 0.05 mA. What collector current can flow? If the LED needs 20 mA, is the base current large enough?

From history. The first transistor radios went on sale in 1954, and soon pocket radios spread around the world. In 1971 Intel released the 4004, the first commercial microprocessor, a whole computer processor on one chip with about 2,300 transistors. Jack Kilby received the Nobel Prize in Physics in 2000 for the integrated circuit; Robert Noyce had died in 1990, and the prize is not given after death.

COMMON MISTAKES

- Thinking the transistor makes electricity. It controls current from the battery; it does not create it.
- Connecting the base directly to the battery without a resistor, which lets too much base current flow and can destroy the transistor.
- Mixing up the pins. Pin order differs between transistor types and makers; always check the data sheet.

Make it a game • Transistor Tell-Back. Be the transistor's biographer. In ninety seconds, tell the 1947 story of the point-contact transistor and why it replaced vacuum tubes. Your parent holds up one finger each time you leave out a key idea: base, collector, emitter, doping, switch, amplifier. Swap and have your parent quiz you. Fewest missed ideas wins the round.

4.3 RASPBERRY PI PROJECTS: PROGRAMMING A MICROCONTROLLER

OBJECTIVES

- Explain what a microcontroller is and how its GPIO pins act as inputs and outputs.
- Write MicroPython programs that use variables, loops, conditionals and time.
- Build and test a reaction-time game on a Raspberry Pi Pico (or the Wokwi simulator) and analyze the data statistically.

Warm-up. Have a partner hold a ruler vertically with its zero mark between your open thumb and finger. Without warning, your partner drops it, and you catch it. Record where you caught it in centimeters. Do it five times. Using $d = \frac{1}{2}gt^2$, your reaction time is $t = \sqrt{(2d \div 9.8)}$ with d in meters. Calculate your average. Later, a microcontroller will measure it to the millisecond.

WATCH

Raspberry Pi Pico - A Beginners Guide

Tinkernut · 7:15

<https://www.youtube.com/watch?v=L03jT5slWnw>

WHEN TO WATCH

After the story. Notice the difference between a microcontroller and a full computer.

BACKUP VIDEO

Raspberry Pi Pico W LESSON 1: Write Your First Program for Absolute Beginners

Paul McWhorter · 29:11

https://www.youtube.com/watch?v=SL4_oU9t8Ss

During Session 2, at the computer: a patient, step-by-step setup of Thonny and your first MicroPython program.

KEY TERMS

microcontroller

A small computer on a single chip, with its own processor, memory and input/output pins, made to control one device or task.

MicroPython

A version of the Python programming language made to run on small microcontrollers.

loop and conditional

A loop repeats instructions (while, for); a conditional chooses what to do based on a test (if, else).

GPIO

General-purpose input/output: pins that a program can set high or low (output) or read as high or low (input).

pull-down resistor

A resistor that holds an input pin at 0 (low) when a button is not pressed, so it does not float and give random readings.

mean and standard deviation

The mean is the average of a set of measurements; the standard deviation tells how spread out they are.

CORE IDEAS

The story. In 2006, Eben Upton and colleagues at the University of Cambridge in England noticed that students applying to study computer science knew far less about programming than students had in the 1980s, when many families owned simple home computers that invited tinkering. Computers had become sealed, expensive boxes. They set out to build a computer cheap enough for every student to own and experiment with. After years of prototypes, the Raspberry Pi Foundation launched the first Raspberry Pi on February 29, 2012, a full computer on a board the size of a credit card for \$35. In January 2021 the foundation released the Raspberry Pi Pico, a tiny microcontroller board for about \$4, built around a chip they designed themselves.

How they figured it out. The challenge was cost. The team designed around a single inexpensive chip made for set-top TV boxes, put everything else on one small board, and left off the case, keyboard and screen so families could use what they already had. They expected to sell perhaps a thousand. Orders were so great that the first website crashed on launch day, and tens of millions of Raspberry Pi computers

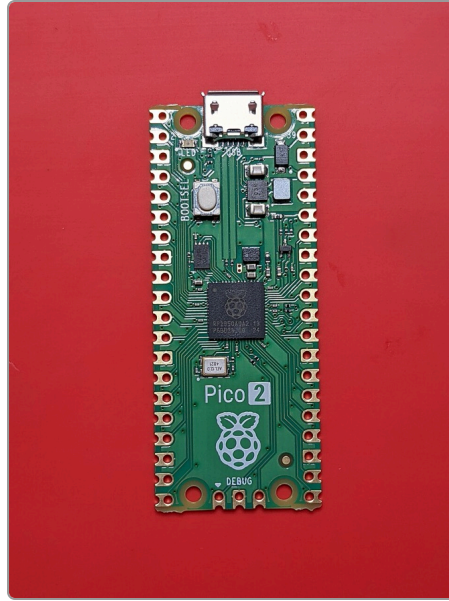
have now been sold, many used by engineers in factories and laboratories as well as by students.

The physics. A microcontroller's pins connect to tiny transistor switches inside the chip. As an **output**, a pin is switched to 3.3 V (high, 1) or 0 V (low, 0), which can light an LED through a resistor. As an **input**, the pin reads whether the voltage on it is high or low. A button connects the pin to 3.3 V when pressed; a **pull-down** resistor (built into the chip, switched on in code) holds it at 0 V when released. Each pin can only supply a small current, about 12 milliamps or less, so an LED needs a resistor: with a red LED dropping about 2.0 V, a 220 Ω resistor gives $I = (3.3 - 2.0) \text{ V} \div 220 \Omega \approx 6 \text{ mA}$, which is safe. The processor runs at over 100 million cycles a second, so it can time an event to well under a millisecond.

The engineering. Microcontrollers are hidden in almost every device: washing machines, thermostats, cars (a modern car has dozens), toys and medical devices. An embedded-systems engineer writes the program, chooses sensors and outputs, and makes sure the device behaves safely even when something goes wrong, such as a stuck button. A good program is tested with many trials, including unusual inputs, and its results are measured, not assumed.

Try it. Your reaction-time game must also handle a cheater: someone who presses the button before the light comes on. Designing for that is real engineering.

PICTURE STUDY



A Raspberry Pi Pico 2 Board, Unknown photographer (released as CC0), about 2024 · Photograph · Wikimedia Commons

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

Compare this tiny board with the room-sized ENIAC from the last lesson. The black chip in the middle holds a processor, memory and input/output circuits.

Look closely

- Find the main chip. What do you think is inside it?
- Find the USB connector. What two jobs does it do?
- Count the pin holes along the edges. Each can be an input or an output.
- Look for the small button and the tiny LED on the board.

Talk about it

1. This board costs a few dollars. What made it possible to put so much on such a small, cheap board?
2. Name three devices in your home that probably contain a microcontroller like this.
3. Why do you think the makers left the pins as plain holes instead of attaching parts?

Safety first. Power the Pico only from a computer's USB port or a USB power bank. Never connect a pin to more than 3.3 V, and always use a resistor with an LED. Unplug the USB cable before changing wires.

BUILD

A Reaction-Time Game with Data

You will program a Raspberry Pi Pico in MicroPython to blink an LED, read a button, and then run a reaction-time game: after a random wait the LED turns on, and the program measures how many milliseconds you take to press the button. You will collect data from your family and analyze it. If you do not have a Pico, use the free Wokwi simulator (wokwi.com), which runs the same code on a virtual Pico.

You will need

- A Raspberry Pi Pico with header pins, a USB cable, a breadboard, an LED, a 220 Ω resistor, a push button and jumper wires (or the free Wokwi simulator)
- A computer with the free Thonny editor (thonny.org) set to MicroPython
- Graph paper or a spreadsheet

Steps

1. Install MicroPython on the Pico by following the Raspberry Pi “Getting started” page, and open Thonny. (In Wokwi, start a new Pi Pico MicroPython project.)
2. **Blink.** Connect GP15 $\rightarrow$ 220 Ω $\rightarrow$ LED $\rightarrow$ GND. Write a loop that turns the LED on for 0.5 s and off for 0.5 s. Change the timing and watch the result.
3. **Button.** Connect one side of the button to 3.3 V and the other to GP14. In code, set GP14 as an input with the internal pull-down. Write: if the button is pressed, turn the LED on; else, off.
4. **Reaction game.** Write a program that waits a random time between 2 and 5 seconds (`random.uniform()`), turns the LED on, records `time.ticks_ms()`, waits for the button, then prints the difference in milliseconds. Add a check: if the button is already pressed before the LED lights, print “Too soon!”
5. Collect 10 trials each for at least three people. Record the results in a table.
6. For each person, calculate the mean and the range (largest – smallest). If you can, use a spreadsheet to find the standard deviation.

7. **Fair test.** Test one variable: dominant hand versus other hand, or LED versus a sound cue (add a small piezo buzzer), keeping everything else the same. Compare the means.
8. **Improve.** Compare your microcontroller times with your ruler-drop times from the warm-up. Which method is more precise, and why? Improve the program to show the average after 10 trials automatically.

Tips

- Indentation matters in Python. Lines inside a loop or an if must be indented the same amount.
- If your button reads randomly, check that the pull-down is turned on in your code.
- Save your program on the Pico as `main.py` if you want it to run by itself whenever the Pico is powered.

Check your work

- ☐ I can explain how GPIO pins work as inputs and outputs and why the LED needs a resistor.
- ☐ My program uses a loop, a conditional and time, and it catches a press that comes too soon.
- ☐ I collected reaction-time data, found means and ranges, and ran a fair test.

ENGINEER'S NOTEBOOK

1. Wiring diagram of the Pico with the LED, resistor and button, with pin numbers labeled.
2. Your final program, printed or copied neatly, with a comment explaining each part.
3. Data table and bar graph of mean reaction time for each person and each test condition.
4. Write a paragraph: What does a microcontroller do that a simple switch cannot?

From history. The first microcontrollers appeared in the early 1970s, including Texas Instruments' TMS1000, which ended up in calculators, toys and microwave ovens. Today billions of microcontrollers are made each year, far more than the processors in all the world's computers and phones put together.

COMMON MISTAKES

- Forgetting the pull-down resistor, so the input “floats” and the program sees phantom button presses.
- Using `time.sleep()` while waiting for the button, which makes the program blind to the press during the sleep.
- Drawing conclusions from one or two trials. Reaction times vary; collect many and average.

Make it a game · Human Microcontroller. Act out a program. Your parent plays a button on a GPIO pin; you are the microcontroller with a loop and a conditional. Say: if the button is pressed, turn the pretend LED on. Then write a five-line MicroPython program on paper that times a reaction. Swap roles and try to find each other's bug.

Scripture. “The hearing ear, and the seeing eye, the LORD hath made even both of them.” (Proverbs 20:12, KJV)

Your reaction game measures the time from your eye to your finger. No engineer has built a sensor or processor to match the eye, ear and brain the Lord made.

4.4 SENSORS AND DATA LOGGING: FROM THE BLACK BOX TO YOUR PHONE

OBJECTIVES

- Explain how sensors turn a physical quantity into a voltage and how an analog-to-digital converter turns that voltage into numbers.
- Calculate ADC resolution and choose a sensible sampling rate for an experiment.
- Use a phone's sensors with the free phyphox app to log real data, graph it and calculate a physical quantity from it.

Warm-up. Close your eyes and have someone push you gently forward in a desk chair with wheels (or ride as a passenger in a car pulling away from a stop). Can you feel the speed or only the change in speed? Your inner ear is an accelerometer. Write down what it can and cannot sense.

WATCH

Smartphone-Experiment: Free fall (en).

phyphox • 5:26

https://www.youtube.com/watch?v=zRGh9_a1J7s

WHEN TO WATCH

Before the build. This is the app you will use, from the university that made it.

BACKUP VIDEO

Black box: Inside a flight data recorder

engineerguy • 2:15

<https://www.youtube.com/watch?v=xLY5W7be5jU>

With the story paragraph: an engineer opens an old flight data recorder that scratched its data onto metal foil.

KEY TERMS

sensor

A device that responds to a physical quantity (temperature, light, acceleration, pressure) by changing a voltage, current or resistance.

analog-to-digital converter (ADC)

A circuit that measures a voltage and turns it into a whole number. A 12-bit ADC gives $2^{12} = 4,096$ possible values.

resolution

The smallest change a measuring system can detect. For an ADC: full-scale range $\div$ number of levels.

sampling rate

How many measurements are taken each second, in hertz (Hz). It must be at least twice as fast as the fastest change you want to see.

accelerometer

A sensor that measures acceleration. In phones it is a tiny MEMS device with a microscopic mass on springs.

data logger

An instrument that records measurements automatically over time for later study.

CORE IDEAS

The story. In 1953 and 1954, several of the world's first jet airliners, the de Havilland Comet, broke up in flight, and investigators had little evidence of what had happened in the last moments. David Warren, a young chemist at Australia's Aeronautical Research Laboratories, helped investigate. He thought of a small, protected recorder that would capture both the pilots' voices and the instrument readings, and in 1958 he and his colleagues built a prototype called the "Flight Memory Unit." At first, officials showed little interest. In the 1960s Australia became one of the first countries to require cockpit recorders, and today every airliner carries a flight data recorder and a cockpit voice recorder, painted bright orange so they can be found.

How they figured it out. Early American recorders scratched a few measurements, such as speed, height and heading, onto metal foil with styluses. Warren's design recorded on magnetic wire, which held both sound and data. Engineers had to solve the hardest parts: surviving huge impacts and fire (the recorder is armored with steel or titanium and insulated) and recording enough channels for long enough. Later recorders moved to magnetic tape and then to solid-state memory chips, which now record thousands of measurements many times a second for 25 hours or more. Investigators have used them to find causes of accidents and change aircraft and procedures, one reason air travel has become so safe.

The physics. A sensor changes some electrical property with the thing being measured: a thermistor's resistance falls as it warms; a photoresistor's falls in light; a phone's accelerometer measures the tiny movement of a microscopic mass on springs etched in silicon. A circuit turns that into a voltage, and an ADC converts the

voltage into a number. Worked example: a 12-bit ADC measuring 0 to 3.3 V has 4,096 levels, so its resolution is $3.3 \text{ V} \div 4,096 \approx 0.0008 \text{ V}$, or 0.8 mV. The **sampling rate** must be fast enough: to see a pendulum swinging once every 2 seconds, a few samples per second will do, but to capture a bouncing ball's impact, which lasts a few thousandths of a second, you need hundreds or thousands of samples per second.

The engineering. Data logging is how engineers know what really happened, rather than what they think happened. Bridges and dams carry strain gauges and tilt sensors that log around the clock; cars log data for their safety systems; weather stations log temperature and pressure. Engineers must choose the sensor, its range and resolution, the sampling rate, how much memory is needed (samples per second $\times$ bytes per sample $\times$ seconds), and how the data will be checked for errors. A phone is a remarkable data logger: it contains an accelerometer, gyroscope, magnetometer, barometer, light sensor and microphone.

Try it. In your build, you will use the phone's microphone as a precision timer to measure the acceleration of gravity, and its accelerometer to record an elevator or car ride.

PICTURE STUDY



NTSB Investigators with Flight Recorders, National Transportation Safety Board, about 2018 ·

Photograph · National Transportation Safety Board, United States

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

The National Transportation Safety Board recovers and reads flight recorders to learn what happened during an accident and how to prevent another. Here investigators handle two recorders at the scene.

Look closely

- Find the recorders. Why are they orange, not black?
- Look at their shapes. Which part do you think holds the memory?
- Look for any labels or writing on them.
- Compare the different recorders. What do you think changed between older and newer designs?

Talk about it

1. What must a recorder survive, and how would you design it to survive?
2. Why does recording thousands of measurements many times a second help investigators more than a few measurements once a second?
3. How do flight recorders make air travel safer for everyone, not only on the flight that had the accident?

Safety first. Never use a phone near water, while walking near traffic or stairs, or while driving; a parent drives and the student is the passenger. For the drop test, drop only a small ball or marble onto a carpet or towel, never the phone.

BUILD

Measure g and Record a Ride with Phone Sensors

You will use the free phyphox app (from RWTH Aachen University) as a data logger. First you will time a falling ball with the acoustic stopwatch and calculate the acceleration of gravity. Then you will record the acceleration of an elevator or car ride and work out the speed from the graph.

You will need

- A smartphone with the free phyphox app (phyphox.org)
- A small steel ball or marble, a ruler and tape measure, a stable support (a table edge) and a towel
- A metal spoon or ruler to tap
- Access to an elevator (an office building or store) or a car ride with a parent driving

Steps

1. **Acoustic stopwatch.** Open the “Acoustic Stopwatch” experiment. Set the threshold so a sharp tap starts the timer and the next sound stops it. Hold the ball at a measured height h above the floor (start with 1.00 m). Tap the ball off a ruler (the tap starts the timer) and the landing click stops it. Record t . Do five drops.
2. Calculate $g = 2h \div t^2$ for each drop and the average. Compare with 9.8 m/s^2 and find the percent difference.
3. **Fair test.** Repeat at heights of 0.50 m, 1.00 m and 1.50 m. Graph h against t^2 . The slope is $g \div 2$.
4. **Ride recording.** Open “Acceleration (without g).” Place the phone flat on the elevator floor (or flat on the car seat beside you with a parent driving). Start recording, ride from one floor to another (or from a stop sign to cruising speed), and stop.
5. Export or screenshot the graph. Find the speeding-up and slowing-down parts and estimate the peak acceleration in m/s^2 .

6. Estimate the top speed from the area under the acceleration–time graph (as a triangle or rectangle). Compare with what you know: elevators move a few meters per second; a car at 25 mph is about 11 m/s.
7. Record the sampling rate phyphox shows. Is it fast enough for these motions? Explain.
8. **Improve.** Find the largest source of error in the drop test (for example, the tap, room echoes, or measuring h) and change one thing to reduce it. Repeat at 1.00 m and compare.

Tips

- Do the acoustic test in a quiet room. Background noise can trigger the timer.
- Measure h from the bottom of the ball to the floor.
- Elevators accelerate gently for comfort, usually about 1 m/s^2 or less. Compare yours.

Check your work

- ☐ I can explain how a sensor and an ADC turn a physical quantity into numbers, and calculate ADC resolution.
- ☐ I measured g from my own data and compared it honestly with the accepted value.
- ☐ I recorded and interpreted an acceleration–time graph and estimated a speed from its area.

ENGINEER'S NOTEBOOK

1. Drop-test data table with your g calculations, and the graph of h against t^2 with its slope.
2. Printed or sketched acceleration–time graph of your ride, labeled with speeding up, constant speed and slowing down.
3. Block diagram of a data logger: sensor → amplifier → ADC → processor → memory → display, with a sentence for each block.
4. Solve: a 10-bit ADC measures 0 to 5.0 V. What is its resolution? How many bytes are needed to log 100 samples per second for one hour, if each sample takes 2 bytes?

From history. David Warren's father died in an airplane crash in 1934, when David was a boy, which he later said helped him understand why recorders mattered. He lived to see his invention in every airliner in the world, and in 2002 he was honored by the Australian government for his service to aviation safety.

COMMON MISTAKES

- Thinking an accelerometer measures speed. It measures changes in velocity; speed must be worked out from the area under the graph.
- Sampling too slowly and missing short events, or so fast that the memory fills with unneeded data.
- Trusting a single reading. Sensors have noise; repeat and average.

Make it a game · Sensor to Number. Pick a household quantity, like room warmth or brightness, and write how a sensor would turn it into a voltage. Then calculate the resolution of a 10-bit ADC with a 5 V range. Your parent names an experiment, such as a swinging door, and you pick a sensible sampling rate with a reason. Three rounds, with points for sound reasoning.

ELECTRONICS

Every phone, car and microwave holds billions of tiny switches that turn on and off according to the rules of logic. In this unit you will follow those switches from the mathematics of George Boole and the relays of Claude Shannon, through the first transistor built at Bell Labs in 1947, to the integrated circuit and the computer chips of today. You will build logic gates from switches and LEDs, measure the current gain of a real transistor, and see why one invention changed the whole world.

Then you will program: first a Raspberry Pi Pico microcontroller (or a free online simulation of one) to blink, sense a button and time your reactions, and then your own phone, used as a laboratory full of sensors, to log real data the way a flight data recorder does. You will learn the words engineers use for this work: bits, bytes, truth tables, gain, analog-to-digital conversion, sampling rate and resolution.

PREREQUISITES

- Knows voltage, current and resistance and can use Ohm's law ($V = IR$)
- Has built series and parallel circuits with batteries, LEDs and resistors
- Can count in powers of 2 and use exponents
- Has used Scratch, MakeCode or another block-coding tool (helpful, not required)

MASTERY CHECKLIST

- ☐ I can convert between binary and decimal and explain why computers use two states.
- ☐ I can write truth tables for NOT, AND, OR, NAND and XOR and build AND, OR and XOR with switches.
- ☐ I can explain how a transistor works as a switch and an amplifier and calculate its current gain ($\beta = I_C \div I_B$).
- ☐ I can program a microcontroller to read an input and control an output, using loops and conditionals.
- ☐ I can explain sampling rate and ADC resolution, and log and graph sensor data from a real experiment.

OPTIONAL KITS FOR THIS UNIT

- **Raspberry Pi Pico:** Ages 12 and up with an adult. A small microcontroller board programmed in MicroPython over a USB cable, inexpensive and powered by the computer. Used in Lesson 4.3; the free Wokwi simulator (wokwi.com) can stand in for it.
- **Snap Circuits (Elenco):** Ages 8 and up. Larger sets include transistors, a photoresistor and integrated circuits that snap together with no soldering; a quick way to build the circuits in Lessons 4.1–4.2.
- **Arduino starter kits:** Ages 12 and up with an adult. The Arduino Uno and its starter kit add sensors, motors and a breadboard and are an excellent next step after Lesson 4.3 for students who want more.

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 Binary and Logic Gates: Boole, Shannon and the Relay 2 sessions of 60 minutes

4.2 From the Transistor to the Integrated Circuit: Bell Labs and Beyond

2 sessions of 60 minutes

4.3 Raspberry Pi Projects: Programming a Microcontroller 2 sessions of 60 minutes

4.4 Sensors and Data Logging: From the Black Box to Your Phone

2 sessions of 60 minutes

UNIT 4 REVIEW

Answer each question. For calculations, write the formula, substitute the numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Convert 1101 and 101010 from binary to decimal, and 19 from decimal to binary.

2. 8 pts

Write the truth table for XOR and for AND. Which two gates make a half adder, and what does each one give?

3. 8 pts

What did Claude Shannon show in 1937? How do switches in series and in parallel act as logic gates?

4. 8 pts

Give three reasons transistors replaced vacuum tubes.

5. 10 pts

Calculation. A transistor has a base current of 0.08 mA and a collector current of 12 mA. Find its current gain. With the same gain, what base current would give 20 mA?

6. 8 pts

What did Kilby and Noyce each contribute to the integrated circuit? What is Moore's law?

7. 10 pts

Calculation. A Pico pin outputs 3.3 V. A red LED drops 2.0 V. What resistor gives a current of 10 mA? Would a 100 Ω resistor be safe if the pin can supply 12 mA?

8. 8 pts

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

9. 8 pts

Write, in words or code, a reaction-time program that also catches a player who presses too soon.

10. 10 pts

Calculation. A 12-bit ADC measures 0 to 3.3 V. What is its resolution? If it logs 50 samples per second at 2 bytes each, how much memory is used in 10 minutes?

11. 8 pts

In the drop test, a ball falls 1.20 m in 0.50 s. What value of g does this give? Give one reason it might differ from 9.8 m/s².

12. **6 pts**

Why are flight recorders orange, and why have they helped make flying so safe?

ANSWER KEY

1. $1101 = 8 + 4 + 1 = 13$. $101010 = 32 + 8 + 2 = 42$. $19 = 16 + 2 + 1 = 10011$.
2. XOR: $00 \rightarrow 0$, $01 \rightarrow 1$, $10 \rightarrow 1$, $11 \rightarrow 0$. AND: $00 \rightarrow 0$, $01 \rightarrow 0$, $10 \rightarrow 0$, $11 \rightarrow 1$. A half adder uses XOR for the sum and AND for the carry.
3. That relay and switch circuits follow Boole's algebra, so logic and arithmetic can be built from switches. Two switches in series act as AND; two in parallel act as OR.
4. Any three: much smaller; use far less power and produce less heat; no filament to burn out, so more reliable and longer lasting; cheaper to make in large numbers; can be made smaller and combined on chips.
5. $\beta = I_C \div I_B = 12 \div 0.08 = 150$. $I_B = 20 \text{ mA} \div 150 \approx 0.13 \text{ mA}$.
6. Kilby (Texas Instruments, 1958) built the first working circuit on one piece of semiconductor; Noyce (Fairchild, 1959) developed a practical way to make a whole circuit in silicon with flat, printed connections. Moore's law is the observation that the number of transistors on a chip doubled about every two years.
7. $R = (3.3 - 2.0) \div 0.010 = 130 \Omega$. With 100Ω : $I = 1.3 \div 100 = 13 \text{ mA}$, more than 12 mA , so it is not safe; use 130Ω or larger (220Ω is a good choice).
8. Without it, the input pin is not connected to anything when the button is released, so it "floats" and can read random highs and lows. The pull-down holds it at 0 V until the button connects it to 3.3 V .
9. Wait a random time; during the wait, if the button is pressed, print "Too soon" and restart. Turn on the LED and record the start time. Loop until the button is pressed; record the end time. Print end – start in milliseconds. (Any correct logic accepted.)
10. Resolution = $3.3 \text{ V} \div 4,096 \approx 0.0008 \text{ V}$ (0.8 mV). Memory = $50 \times 2 \times 600 \text{ s} = 60,000$ bytes (about 60 kB).
11. $g = 2h \div t^2 = 2.4 \div 0.25 = 9.6 \text{ m/s}^2$. Reasons: timing error from the tap or sound triggers; measuring h inaccurately; air resistance (small).
12. Bright orange makes them easy to find in wreckage. Their data let investigators find exactly what went wrong, so aircraft, training and procedures can be changed to prevent the same accident again.

PORTFOLIO PIECE: A SENSING, LOGGING MICROCONTROLLER PROJECT

Design and build a working electronic device that senses something, makes a decision and acts, and logs data you analyze. Use a Raspberry Pi Pico (or the Wokwi simulator), a transistor circuit, or both. Examples: a night light that counts how many times it switched on; a reaction-time game that stores and averages scores; a door-opening counter; or a temperature logger that lights an LED when a room is too warm. Include a schematic, the commented program, a truth table or flow chart for its decisions, a data table and graph from at least one hour (or 30 trials) of use, and a one-page report on how you tested it and what you improved.

LOOK FOR	WHAT IT MEANS
Working device	Senses an input, makes a correct decision and drives an output reliably when shown working.
Schematic and program	Neat schematic with standard symbols and correct resistor values; program commented and readable.
Logic	Flow chart or truth table that matches what the device does, including one unusual case (such as a too-early press).
Data and analysis	Logged data presented in a table and graph with units; mean or trend described honestly.
Testing and improvement	Report describes tests, at least one problem found, and the change made to fix it.

UNIT 5

UTILITIES

Public utilities are the engineering most people never think about until it stops working: the power grid, the water mains, the sewers and the network of cables that carries the internet. In this unit you will study them the way the engineers who run them do, with numbers. You will learn why the North American grid failed in the great blackouts of 1965 and 2003 and what engineers changed, why power lines run at hundreds of thousands of volts, how water pressure depends on height (head) and how friction in a pipe steals it, and how light trapped in a glass thread carries a video call across an ocean.

The unit ends with the people. Lineworkers, water and wastewater operators, and civil and electrical engineers keep these systems running every hour of every day, often in storms and at night. You will learn the story of the first chlorinated city water supply in America, practice the arithmetic every water operator uses, and think about which of these vocations might be yours. Running clean water and steady light to every house is one of the most practical ways people love their neighbors.

PREREQUISITES

- Knows Ohm's law ($V = IR$) and electric power ($P = VI$)
- Knows pressure as force $\div$ area and the units Pa and psi
- Can use exponents and scientific notation
- Has seen how a generator works (Faraday's law, earlier grades)

MASTERY CHECKLIST

- ☐ I can explain why supply and demand on the grid must balance every second, how grid frequency shows the balance, and how a cascading blackout happens.
- ☐ I can calculate power-line losses ($P = I^2R$) and explain why transmission uses high voltage.
- ☐ I can calculate water pressure from head ($P = \rho gh$; 1 ft of water $\approx$ 0.433 psi) and flow from $Q = Av$, and explain friction loss in pipes.
- ☐ I can explain total internal reflection and packet switching, and estimate the time for light to cross an ocean in a fiber.
- ☐ I can describe the work and training of a lineworker, a water operator and a utility engineer, and use the operator's "pounds formula."

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco)**: Ages 8 and up. Sets with a motor and hand-crank or fan generator let you see loads slowing a generator, a good companion to Lesson 5.1.
- **Thames & Kosmos science kits**: Ages vary by kit. Their water, hydraulics and renewable-energy kits add pumps, turbines and generators that fit Lessons 5.1–5.2.

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

5.1 Grid Reliability and the Great Blackouts

2 sessions of 60 minutes

5.2 Water Systems: Head, Pressure and Pipe Flow

2 sessions of 60 minutes

5.3 The Internet: Fiber, Packets and Data Centers

2 sessions of 60 minutes

5.4 Infrastructure Careers: Lineworker, Water Operator and Engineer

2 sessions of 60 minutes

UNIT 5 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Why must electricity generation equal demand at every moment, and what happens to the grid's frequency when demand suddenly rises?

2. **8 pts**

Name two causes of the 2003 blackout and two changes made afterward.

3. **10 pts**

Calculation. 200 MW is sent over a line with $5\ \Omega$ resistance. Find the current and the power lost at 500,000 V. How many times larger would the loss be at 50,000 V?

4. **8 pts**

What is a cascading failure, and what is the N-1 rule?

5. **10 pts**

Calculation. A water tower's surface is 45 m above a fire hydrant. Find the static pressure in kPa and in psi. ($1\ \text{psi} \approx 6.9\ \text{kPa}$.)

6. **8 pts**

A pipe has a cross-sectional area of $0.010\ \text{m}^2$, and water flows at $2.0\ \text{m/s}$. Find the flow rate in m^3/s and in liters per second.

7. **8 pts**

Give two ways engineers reduce friction (head) loss in a water main, and explain why a water tower helps a town.

8. **10 pts**

Calculation. Light travels from water ($n = 1.33$) toward air ($n = 1.00$). Find the critical angle. Then find how long light takes to travel 3,000 km in a fiber with $n = 1.47$ ($c = 300,000$ km/s).

9. **8 pts**

What was Charles Kao's key insight about glass fibers, and what are packets?

10. **10 pts**

Calculation. A plant treats 3.2 million gallons per day at a chlorine dose of 1.8 mg/L. How many pounds of chlorine are needed per day?

11. **6 pts**

Why is a bird on a power line safe, and what should you do if you find a downed line?

12. **6 pts**

Write a short paragraph: Which infrastructure career described in this unit interests you most, and how does it serve other people?

ANSWER KEY

1. The grid stores very little energy, so power must be made as it is used. When demand rises, energy is drawn from the spinning generators, which slow down slightly, so the frequency drops below 60 Hz until control systems add more power.
2. Causes (any two): lines sagging into overgrown trees; a failed alarm program so operators did not know; poor situational awareness and coordination. Changes (any two): mandatory, enforceable reliability standards; strict tree-trimming rules; better operator training and backup tools; better real-time monitoring.
3. $I = P \div V = 200,000,000 \div 500,000 = 400 \text{ A}$. $\text{Loss} = I^2R = 400^2 \times 5 = 800,000 \text{ W} = 0.8 \text{ MW}$. At 50,000 V the current is 10 times larger, so the loss is 100 times larger (80 MW).
4. A chain reaction in which one failure shifts load onto other parts, which overload and fail in turn. N-1 means the grid must keep working normally if any single major element (one line, generator or transformer) is lost.
5. $P = \rho gh = 1,000 \times 9.8 \times 45 = 441,000 \text{ Pa} = 441 \text{ kPa}$. $441 \div 6.9 \approx 64 \text{ psi}$. (Or $45 \text{ m} \approx 148 \text{ ft} \times 0.433 \approx 64 \text{ psi}$.)
6. $Q = Av = 0.010 \times 2.0 = 0.020 \text{ m}^3/\text{s} = 20 \text{ L/s}$.
7. Use a larger diameter pipe; use a shorter route; use smoother pipe; keep velocity lower (any two). A tower stores water high up, giving steady pressure from its height and a reserve for fires and peak demand, so pumps can run steadily.
8. $\sin \theta_c = 1.00 \div 1.33 = 0.752$, $\theta_c \approx 49^\circ$. $v = 300,000 \div 1.47 \approx 204,000 \text{ km/s}$; $t = 3,000 \div 204,000 \approx 0.015 \text{ s}$ (15 ms).
9. That losses came from impurities, not the glass itself, so very pure glass could carry light signals for kilometers. Packets are small numbered blocks of data with headers (source, destination, sequence), sent separately through the network and reassembled.
10. $\text{lb/day} = \text{MGD} \times \text{mg/L} \times 8.34 = 3.2 \times 1.8 \times 8.34 \approx 48 \text{ lb/day}$.
11. The bird touches only one wire, so its body is all at the same voltage and no current flows through it. Stay far away (at least 35 feet), do not touch anything near it, keep others away, and call 911 and the utility; if near one, shuffle away with small steps, feet together.
12. Answers vary; a good answer names the career, describes its work and training accurately, and explains a specific way it protects or serves the public.

PORTFOLIO PIECE: A TOWN UTILITY PLAN

Design the water and power systems for a small imaginary town of about 500 homes on a map you draw, with a hill, a river and a valley. Place a water source, treatment plant, pump and water tower, and calculate the static pressure at the highest and lowest homes. Choose a main pipe size and justify it with $Q = Av$ and friction. Lay out power from a substation with at least two supply paths (N-1), and calculate line loss for one feeder at two voltages. Add a fiber line to the town center. Then build one working piece (the siphon water system or the motor-generator model) and include its test data. Present it as an engineer's report with the map, calculations and photographs.

LOOK FOR	WHAT IT MEANS
Town map	Neat, labeled map with source, treatment, pump, tower, mains, substation, two power paths and fiber route; elevations marked.
Water calculations	Static pressures at high and low homes in psi and kPa; pipe flow sized with $Q = Av$; pressure zones or valves considered.
Power calculations	Line loss calculated at two voltages with $P = I^2R$; redundancy explained using the N-1 rule.
Working model and data	Siphon or motor-generator model built and tested with a data table and graph.
Report	Clear explanations with units, an honest comparison of model results with calculations, and one improvement.

5.1 GRID RELIABILITY AND THE GREAT BLACKOUTS

OBJECTIVES

- Explain why generation must match demand at every moment and how the grid's frequency (60 Hz) shows whether it does.
- Tell what caused the Northeast blackouts of 1965 and 2003 and what engineers changed afterward.
- Calculate transmission losses with $P = I^2R$ and show with a motor-generator model how added load slows a generator.

Warm-up. Count every device in your home that is plugged in or charging right now. Then imagine every home in your town turning on its air conditioner at 5 p.m. on a hot day. Where does the extra electricity come from, in that very second? Write your best guess. (Most people guess “a battery somewhere.” Read on.)

WATCH

What Really Happened During the 2003 Blackout?

Practical Engineering · 20:39

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

WHEN TO WATCH

After the story paragraph. Make a timeline in your notebook as you watch: each line that tripped, and why.

KEY TERMS

grid

The connected network of power plants, transmission lines, substations and distribution lines that delivers electricity over a large region.

frequency

How many times per second alternating current reverses: 60 hertz (Hz) in North America. It rises when generation exceeds demand and falls when demand exceeds generation.

protective relay

An automatic device that senses a fault or overload and opens a circuit breaker to protect equipment.

cascading failure

A chain reaction in which one failure shifts load onto other parts, which then overload and fail in turn.

N-1 criterion

The planning rule that the grid must keep working normally if any single major element (one line, one generator, one transformer) suddenly fails.

load shedding

Deliberately cutting power to some customers to keep the rest of the grid from collapsing.

CORE IDEAS

The story. At 5:16 p.m. on November 9, 1965, a protective relay at the Sir Adam Beck hydroelectric station near Niagara Falls, Ontario, opened a heavily loaded transmission line. Its setting had been chosen years earlier, when the line carried less power. The power on that line jumped onto the others, which also tripped, and within minutes the outage spread across Ontario, New York and much of New England. About 30 million people lost power, some for up to 13 hours. Thirty-eight years later, on the hot afternoon of August 14, 2003, transmission lines in Ohio sagged into trees that had not been trimmed, and an alarm program in a utility control room had silently stopped working, so operators did not know. In about an hour the failure cascaded across eight states and Ontario, and about 50 million people lost power.

How they figured it out. After 1965, utilities that had run their own systems separately learned that connected grids share their problems as well as their strengths. In 1968 they formed what became the North American Electric Reliability Corporation (NERC) to set common reliability rules, including planning so the grid can survive the loss of any one major element (the N-1 rule). After 2003, a joint U.S.–Canada task force pieced together the event second by second from recorded data. Its report found inadequate tree trimming, the failed alarm, poor situational awareness and weak coordination. The reliability standards that had been voluntary were made mandatory and enforceable in 2005, with specific rules for vegetation around power lines, operator training and backup tools in control rooms.

The physics. Electricity is not stored in the grid in large amounts; every watt used must be generated at that same moment. The big spinning generators all turn in step with one another, making alternating current that reverses 60 times a second (60 Hz). When demand rises, the extra energy is first drawn from the spinning mass of the generators, so they slow slightly and the frequency drops; control systems then open steam or water valves to add power. If frequency falls too far (around 59.3 Hz in

many areas), relays automatically shed load to save the system. Transmission lines lose power as heat: $P_{\text{loss}} = I^2 R$. Worked example: sending 100 MW at 345,000 V needs a current of about $I = P \div V \approx 290$ A. In a line with 10 Ω of resistance, loss = $(290)^2 \times 10 \approx 0.84$ MW. Sending the same power at 34,500 V needs 2,900 A, and the loss would be 100 times larger, about 84 MW. That is why transmission uses very high voltages. Heat also makes lines expand and sag: aluminum grows about 23 millionths of its length for each $^{\circ}\text{C}$, so a hot, heavily loaded 300 m span can droop tens of centimeters lower, toward the trees.

The engineering. Grid engineers design for reliability in layers: extra generating capacity held in reserve, multiple transmission paths (redundancy), relays coordinated so that only the faulted part is cut off, automatic load shedding as a last defense, and control rooms where operators watch the whole system in real time. They trim trees along thousands of miles of lines, test relay settings, and study every disturbance. Each energy source has engineering trade-offs: large spinning generators (hydro, coal, gas, nuclear) provide steady power and inertia; wind and solar have no fuel cost but vary with weather and connect through electronic inverters, so grid engineers add batteries, fast-responding plants and new controls to keep frequency steady. A reliable grid needs all of these to be planned together.

Try it. In your build, a motor driven by a battery will turn a second motor used as a generator. When you add LEDs to the generator, listen: the pitch drops as the machine slows. That is a frequency drop under load.

PICTURE STUDY



A Power-Plant Switchboard, Unknown photographer, about 1910 · Photograph · Possibly the Cedar Falls hydroelectric plant, Washington

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

Early power plants were controlled by operators standing at marble switchboards, reading meters and throwing switches by hand. Today's control rooms do the same job with computer screens, but the questions are the same: how much power, how much load, what frequency?

Look closely

- Find the round meters. What might they measure? (Think volts, amperes, power and frequency.)
- Find the large switch handles. What happens when an operator throws one?
- Why do you think the panels were made of marble?
- Look for labels. How would an operator know which switch controls which line?

Talk about it

1. If the frequency meter showed the generators slowing, what should the operator do?
2. What could go wrong if a switch were thrown by mistake, and how could the design prevent it?

3. How is a modern grid control room like this switchboard, and how is it different?

Safety first. Use only batteries for the model. Never go near power lines, substations, transformers or downed wires, and never fly kites or drones near lines. If you see a downed line, stay far away and call 911 and the utility.

BUILD

A Motor-Generator Model of the Grid

You will couple two small hobby motors shaft to shaft. One, powered by batteries, plays the turbine; the other is the generator. As you add LED and resistor loads to the generator, you will measure its output voltage and watch it slow down, a small model of what happens to the grid when demand rises.

You will need

- Two identical small DC hobby motors (1.5–6 V) and a short piece of snug plastic tubing (aquarium or fuel tubing) to join their shafts
- A 2-AA or 3-AA battery holder with a switch
- A digital multimeter, red LEDs and resistors (100 Ω , 220 Ω , 470 Ω), alligator clip leads
- Tape or a block of wood and rubber bands to hold the motors in line
- A phone with a free spectrum or tuner app (optional, to measure the hum pitch)

Steps

1. Mount the two motors facing each other and join their shafts with tubing so they turn together. Connect motor A (the “turbine”) to the battery pack.
2. Connect the multimeter (volts) across motor B (the “generator”). Run the set with no load and record the generator voltage. If you have a tuner app, record the pitch of the hum.
3. **Predict.** What will happen to the voltage and the speed as you add loads? Write it down.
4. **Fair test.** Add loads one at a time across the generator: a 470 Ω resistor, then 220 Ω , then 100 Ω , then the 100 Ω with an LED in parallel. Keep the same batteries. For each, record generator voltage and pitch. Calculate the generator’s output power $P = V^2 \div R$ for each resistor.
5. Graph generator voltage against output power. Describe the pattern.
6. **Grid response.** With the heaviest load connected, add one more battery to the turbine side (more “steam”). What happens to the voltage and pitch? That

is what a grid operator does when frequency falls.

7. **Cascade model.** On paper, draw a simple grid with three lines from a power plant to a city, each able to carry 100 MW, together carrying 240 MW. Show what happens when one line trips (each remaining line must carry 120 MW). Then decide what the operators should do in the first minute.
8. **Improve.** Add a small flywheel (a coin or washer glued to the shaft, or a plastic bottle cap with modeling clay) to the motor set and repeat the heavy-load test. Does the speed drop more slowly when load is suddenly added? This is what inertia does for the grid.

Tips

- Hobby motors get warm under load. Run each test for only 10–20 seconds.
- Make sure the shafts are lined up well; a bent coupling wastes energy and wobbles.
- If the generator voltage reads negative, swap the meter leads; the motor is simply turning the other way.

Check your work

- ☐ I can explain why generation must equal demand every second and how frequency shows the balance.
- ☐ I can calculate transmission losses and explain why high voltage is used.
- ☐ My data show the generator slowing and its voltage falling as load increased, and I tested the effect of more drive and of a flywheel.

ENGINEER'S NOTEBOOK

1. Timeline of the 2003 blackout from the video, with the cause of each step.
2. Your generator data table and graph, with a sentence explaining the shape.
3. Draw the path of electricity from a power plant to your home: generator, step-up transformer, transmission line, substation, distribution line, pole transformer, service drop, meter. Label the voltage at each step if you can.
4. Solve: 50 MW is sent over a line with $8\ \Omega$ resistance. Find the loss at 138,000 V and at 500,000 V.

From history. The 1965 blackout struck at evening rush hour, and New York City's subways stopped with hundreds of thousands of riders aboard; yet it was remembered for how calmly people helped one another. One lasting change after 2003 was the spread of phasor measurement units, sensors that time-stamp grid measurements using GPS clocks, so engineers can see the whole grid's behavior many times a second.

COMMON MISTAKES

- Thinking the grid stores electricity like a giant battery. Almost all electricity is used the instant it is made; storage is still small compared with the whole grid.
- Assuming one failure cannot cause a big blackout. A cascade spreads exactly because the grid is connected.
- Confusing voltage and power. High voltage lets the same power travel with less current, and so with far less heating loss.

Make it a game • Balance the Grid. Use buttons or beans as power. Your parent plays demand and adds or removes buttons from a pile marked demand. You must keep generation equal by adjusting a second pile within five seconds, or the frequency drifts and you lose a point. Play three minutes, then explain how a cascading failure grew in the 2003 blackout.

5.2 WATER SYSTEMS: HEAD, PRESSURE AND PIPE FLOW

OBJECTIVES

- Calculate water pressure from height (head) using $P = \rho gh$ and the rule 1 foot of water ≈ 0.433 psi.
- Calculate flow with $Q = Av$ and explain how pipe length, diameter and roughness cause friction (head) loss.
- Measure how head and tube length change the flow through a siphon, and how depth changes the speed of a water jet.

Warm-up. Fill a tall plastic bottle with water over a sink. Poke one small hole near the top and one near the bottom with a pushpin (an adult can help), then uncap. Which jet shoots farther? Why? Write your explanation using the word “depth.”

WATCH

Flow and Pressure in Pipes Explained

Practical Engineering · 12:42

<https://www.youtube.com/watch?v=ZQKpu-obzIU>

WHEN TO WATCH

After the physics paragraph. Watch the clear standpipes along the pipe and how the water level drops from one to the next.

Note: Includes a brief sponsor message at the start.

BACKUP VIDEO

How Water Towers Work

Practical Engineering · 10:59

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

With the engineering paragraph: why towns store water up high.

KEY TERMS

head

The height of a column of water, used by engineers as a measure of pressure. 10 m of head $\approx$ 98 kPa; 1 ft of head $\approx$ 0.433 psi.

flow rate

The volume of water passing a point each second: $Q = A \times v$, in m^3/s or liters per second (gallons per minute in the U.S.).

gravity-fed system

A water system in which water flows downhill from a higher source or tank to users without pumping.

hydrostatic pressure

The pressure in still water caused by the weight of the water above: $P = \rho gh$.

head loss

The pressure lost to friction as water flows through pipes, valves and fittings. It grows with pipe length and with the square of velocity, and falls sharply with larger diameter.

water hammer

A sudden pressure spike when flowing water is stopped quickly, such as by a fast-closing valve.

CORE IDEAS

The story. In the 1830s New York City was growing fast and drinking from polluted wells. After a cholera outbreak in 1832 and the Great Fire of 1835, which burned much of lower Manhattan because there was not enough water to fight it, the city decided to bring water from the Croton River in Westchester County, about 41 miles north. The chief engineer was John B. Jervis. The Croton Aqueduct opened in 1842, carrying water by gravity alone through a brick-lined tunnel to reservoirs in Manhattan. To cross the Harlem River, Jervis built the High Bridge, a stone-arched bridge finished in 1848 that carried the water in great iron pipes. It is the oldest standing bridge in New York City.

How they figured it out. Jervis had to keep the water flowing downhill all the way without letting it run too fast and scour the tunnel. He surveyed a route that fell only about 13 inches per mile, a slope of about 1 in 4,800, carefully following the land, tunneling through hills and building embankments across valleys. Engineers measured the flow and found how much friction slowed it. Where the aqueduct crossed the Harlem River, the water left the open channel and flowed through closed

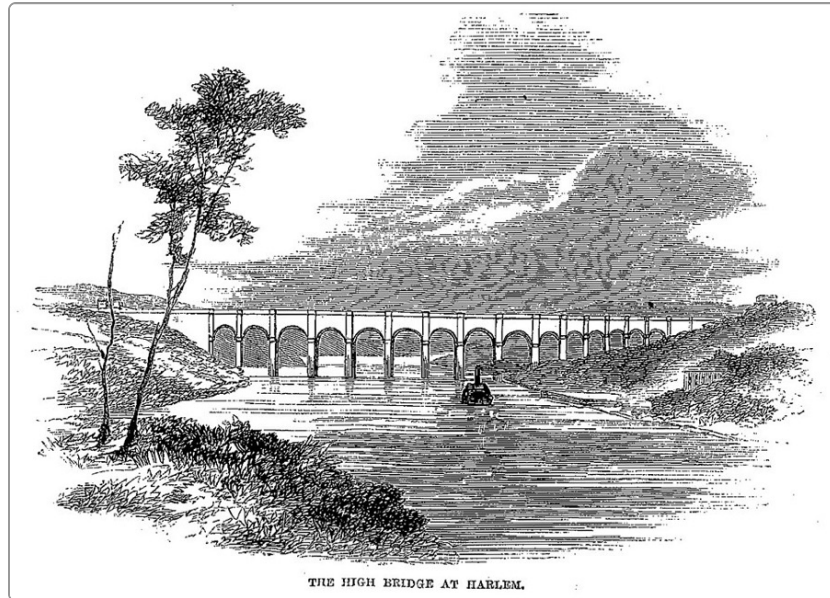
iron pipes under pressure, pushed across by the head of water upstream. The system delivered tens of millions of gallons a day, and it was soon enlarged because the city kept growing.

The physics. In still water, pressure grows with depth: $P = \rho gh$. Worked example: a water tower whose water surface is 40 m above a house's faucet gives $P = 1,000 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 40 \text{ m} = 392,000 \text{ Pa} \approx 392 \text{ kPa}$, about 57 psi (using $1 \text{ ft} \approx 0.433 \text{ psi}$: $131 \text{ ft} \times 0.433 \approx 57 \text{ psi}$). The shape and width of the tower do not matter, only the height. When water flows, friction against the pipe walls costs pressure. Flow rate is $Q = Av$: a 50 mm (2-inch) pipe has $A = \pi \times (0.025 \text{ m})^2 \approx 0.00196 \text{ m}^2$; at 1.5 m/s it carries $0.0029 \text{ m}^3/\text{s}$, about 2.9 liters per second. Friction loss grows with pipe length and roughly with v^2 , and it drops dramatically with diameter: doubling a pipe's diameter at the same flow cuts the friction loss by about 30 times. Engineers calculate it with formulas such as Hazen–Williams and Darcy–Weisbach.

The engineering. City water systems aim to keep pressure at taps roughly between 40 and 80 psi: enough to reach upper floors and fight fires, not so much that pipes and fixtures leak or burst. Water towers and hilltop tanks provide steady pressure and store water for fires and peak demand, letting pumps run steadily. Engineers size every main so friction loss stays reasonable, divide hilly towns into pressure zones, add pressure-reducing valves and booster pumps, and design hydrants for fire flows of 1,000 gallons per minute or more. They close valves slowly to avoid water hammer, which can split a pipe.

Try it. In your build, a bucket on a chair will be your water tower and aquarium tubing your water main. You will measure how the flow changes when you raise the bucket (more head) and when you lengthen the tube (more friction).

PICTURE STUDY



The High Bridge at Harlem, Unknown engraver, Harper's Magazine, 1860 · Wood engraving · Harper's New Monthly Magazine

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

The High Bridge carried the Croton Aqueduct's water across the Harlem River. It looks like a Roman aqueduct, but inside its walkway ran iron pipes under pressure.

Look closely

- Count the arches. Why are they all about the same height?
- Find the top of the bridge. Is it level or sloping? Why does that matter for water?
- Look at the river. How tall would a ship's mast have to be to pass under?
- Compare this bridge with the Pont du Gard or other Roman aqueducts you know.

Talk about it

1. Why did the water in this bridge flow through closed pipes instead of an open channel?
2. If the water surface at the reservoir upstream was 30 m higher than the bottom of a pipe here, what was the pressure in that pipe in kPa and psi?

3. Why do you think the city later replaced several arches with a single steel span?

Safety first. Do the water tests outdoors, in a bathtub or over a sink, with an adult present. Start a siphon by filling the tube with water (submerge it or use a squeeze bulb), never by mouth. Mop up spills so no one slips.

BUILD

Head, Friction and Flow: A Siphon Lab

You will make a small gravity-fed water system: a bucket “reservoir” raised on a chair feeding water through clear aquarium tubing. You will measure how flow rate depends on head and on tube length, and how jet distance depends on depth.

You will need

- A bucket and a sturdy chair or step stool
- Clear aquarium or vinyl tubing: two lengths of the same diameter (1 m and 3 m), and if you can, one of a larger diameter
- A measuring cup or a container and a kitchen scale (1 g of water = 1 mL), a stopwatch
- A tape measure, a tall plastic bottle, a pushpin and masking tape

Steps

1. **Jets.** Poke three holes in a line up the side of the tall bottle at 5, 15 and 25 cm below the top. Cover them with tape, fill the bottle to the top, and remove the tapes over a sink or outdoors. Measure how far each jet lands from the bottle on a flat surface (keep the water topped up). Calculate the pressure at each hole with $P = \rho gh$.
2. Set the full bucket on the chair. Fill the 1 m tube with water, cap one end with your thumb, put the other end in the bucket, and let the capped end down to a catch container on the floor. Release to start the siphon.
3. **Head test.** Measure the head: the height from the bucket’s water surface down to the tube outlet. Collect water for exactly 10 s and measure the volume. Do three trials. Repeat with the outlet raised so the head is about half as much.
4. **Friction test.** Keep the head the same and switch to the 3 m tube (coil the extra on the floor). Measure flow again. If you have a wider tube, test it at the same head.
5. Calculate Q in mL/s for each test and the water speed $v = Q \div A$ (measure the tube’s inside diameter).

6. Make a table: tube length, diameter, head (cm), flow (mL/s), speed (m/s). Graph flow against head for the 1 m tube.
7. **Predict and check.** Using your data, predict the flow for a head halfway between your two tests. Test it.
8. **Improve.** Design the “water main” that delivers the most water in 10 s using only your tubes and the bucket on the chair. Explain your choice using head and friction.

Tips

- Keep the bucket topped up so the head does not fall during the test, or measure the starting and ending water levels and use the average.
- Air bubbles in the tube reduce flow; tap the tube to clear them.
- Measure head from the water surface, not from the bucket rim.

Check your work

- ☐ I can calculate pressure from head in kPa and psi.
- ☐ My data show that more head increases flow and a longer tube decreases it, and I can explain why.
- ☐ I can explain how a water tower keeps pressure steady in a town.

ENGINEER'S NOTEBOOK

1. Side-view sketch of your siphon system with the head labeled, and your data table and graph.
2. Sketch of a town water system: source, treatment plant, pump, tower, mains and houses on a hill and in a valley. Mark where pressure is highest and lowest.
3. Solve: a house is 25 m below a tank's water surface. What is the static pressure in psi? If friction costs 8 psi when water flows, what pressure reaches the tap?
4. Explain in a paragraph why doubling a pipe's diameter helps flow so much.

From history. The Croton system was later expanded with the New Croton Aqueduct (1890) and then the Catskill and Delaware systems, which still bring New York City more than a billion gallons a day, mostly by gravity. The High Bridge was closed for decades but reopened to people on foot and bicycle in 2015.

COMMON MISTAKES

- Thinking a wider tank gives more pressure. Only the height of the water surface matters for pressure.
- Forgetting that flowing water loses pressure to friction, so pressure at a tap is lower when water is running than when it is still.
- Mixing units: keep meters with pascals, or feet with psi.

Make it a game • Pressure Pegs. Draw a water tower and a house below it on paper. Your parent names a height in feet. You must call out the pressure at the faucet using 0.433 psi per foot, within ten seconds. Then name three things that increase head loss in a pipe. Each right answer earns a peg, a button or bean, and ten pegs wins.

Scripture. “Therefore with joy shall ye draw water out of the wells of salvation.” (Isaiah 12:3, KJV)

Clean water flowing from a tap is a daily gift most people never think about. Isaiah uses drawing water as a picture of the joy of salvation.

5.3 THE INTERNET: FIBER, PACKETS AND DATA CENTERS

OBJECTIVES

- Explain total internal reflection and calculate a critical angle with Snell's law.
- Tell the history of optical fiber and packet switching, and explain how data travels as packets.
- Guide laser light in a stream of water, and estimate how long a signal takes to cross an ocean.

Warm-up. Look at a glass of water from the side and slightly from below, so you are looking up through the side wall at the water's surface. At some angle the surface looks like a silver mirror. Find that angle and sketch what you see. You have found total internal reflection, the physics of every fiber-optic cable.

WATCH

Fiber optic cables: How they work

[engineerguy](#) · 5:35

https://www.youtube.com/watch?v=0MwMkBET_5I

WHEN TO WATCH

After the physics paragraph. Notice how the transatlantic cable is built.

BACKUP VIDEO

The Internet: Packets, Routing & Reliability

[CodeAI](#) · 6:25

<https://www.youtube.com/watch?v=AYdF7b3nMto>

With the engineering paragraph. One of the inventors of the internet's protocols explains packets.

KEY TERMS

refraction

The bending of light as it passes from one material into another, because light travels at different speeds in them.

index of refraction (n)

How much a material slows light: $n = c \div v$. Air ≈ 1.00 , water ≈ 1.33 , glass fiber core ≈ 1.47 .

total internal reflection

When light inside a denser material strikes the boundary at more than the critical angle, all of it reflects back inside.

optical fiber

A hair-thin strand of very pure glass with a core and a cladding of slightly lower index, which traps light by total internal reflection.

packet

A small block of data with a header that says where it came from, where it is going and its place in the message.

data center

A building full of computer servers, network equipment, backup power and cooling, where websites and online services run.

CORE IDEAS

The story. In 1842 the Swiss physicist Daniel Colladon, giving a lecture in Geneva, shone a beam of sunlight into a jet of water pouring from a tank. The light followed the curving stream and made it glow. More than a century later, in 1966, Charles Kao and George Hockham, working in England, showed that a glass fiber could carry light signals over long distances if the glass were made pure enough. In 1970 Robert Maurer, Donald Keck and Peter Schultz at Corning Glass Works made the first fiber that met their target. Meanwhile, in the 1960s Paul Baran in the United States and Donald Davies in Britain each worked out a new way to send data: chop it into small blocks, which Davies called packets. On October 29, 1969, the first message passed over the ARPANET, the network that grew into the internet.

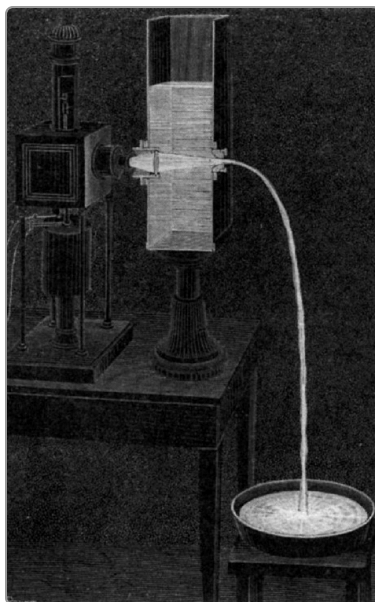
How they figured it out. Kao's insight was that the glass itself was not the problem; impurities were. Ordinary glass lost almost all of the light within a few meters. He measured losses carefully and calculated that if the loss could be cut to 20 decibels per kilometer (1% of the light left after a kilometer), fibers would be practical. Corning's team spent years melting ultrapure silica from vapor and drawing it into fibers, and reached about 17 dB/km in 1970; today fibers lose less than 0.2 dB/km. On the data side, the first ARPANET message was supposed to be "LOGIN," sent from UCLA to Stanford Research Institute; the system crashed after "LO." Engineers fixed it, and later Vint Cerf and Bob Kahn designed the TCP/IP rules that let different networks connect, adopted across the ARPANET on January 1, 1983. Kao received the Nobel Prize in Physics in 2009.

The physics. Light slows down in denser materials: its speed is $v = c \div n$. When it travels from a higher index to a lower one, it bends away from the perpendicular, following **Snell's law**: $n_1 \sin \theta_1 = n_2 \sin \theta_2$. Beyond the **critical angle**, $\sin \theta_c = n_2 \div n_1$, no light escapes. For water into air: $\sin \theta_c = 1.00 \div 1.33$, so $\theta_c \approx 49^\circ$. In a fiber with a core of 1.47 and a cladding of 1.45, $\theta_c \approx 81^\circ$, so light running nearly along the fiber bounces along it for kilometers. Worked example: in glass, light travels at about $c \div 1.47 \approx 204,000$ km/s. A cable from New York to London about 5,600 km long takes $5,600 \div 204,000 \approx 0.027$ s, about 27 milliseconds, one way.

The engineering. Data is sent as rapid flashes of laser light, billions per second, on many colors at once in each fiber. Undersea cables carry dozens of fibers inside steel wires and copper and plastic armor, with amplifiers every 50–100 km powered through the cable. The first transatlantic fiber cable, TAT-8, began service in 1988; today hundreds of cables cross the oceans and carry nearly all intercontinental internet traffic. A message is cut into packets, each routed separately through the network by routers that choose paths; if one link fails, packets go another way, and TCP asks for any lost packet to be sent again. Data centers house thousands of servers with backup generators and enormous cooling systems, because nearly every watt of electricity a computer uses becomes heat.

Try it. In your build you will repeat Colladon's 1842 experiment with a laser pointer and a stream of water, and then become a human network that sends a message as packets.

PICTURE STUDY



Colladon's Light Fountain, Engraving in *La Nature*, 1884 · Wood engraving · *La Nature* magazine, Paris

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

This engraving shows Daniel Colladon's experiment showing light guided inside a stream of water. It is the great-grandparent of the fiber-optic cables that carry the internet.

Look closely

- Find the source of light. Where does it enter the water?
- Follow the stream. Where does the light seem to escape?
- Find where the stream lands. Why would it glow there?
- Look for any lenses or mirrors used to aim the light.

Talk about it

1. Why does the light stay inside the curving stream instead of going straight?
2. What would happen if the stream bent too sharply?
3. How is this experiment like an optical fiber, and how is it different?

Safety first. Use only a low-power laser pointer (red or green, 5 mW or less) with an adult. Never look into the beam or point it at anyone, at pets, at shiny surfaces toward eyes, or at aircraft or vehicles. Do the water experiment over a sink or tub.

BUILD

Light in a Water Stream and a Packet Network

You will guide laser light inside a stream of water as Colladon did, measure the critical angle in a container of water, and then act out packet switching with your family to see how the internet copes with lost data.

You will need

- A clear plastic bottle, a nail or drill (adult) to make a 4–6 mm hole near the bottom, tape
- A low-power laser pointer, a dark room, a sink or tub
- A clear rectangular plastic container, a protractor and a little milk (a few drops make the beam visible)
- Index cards, a pencil, and three or more family members

Steps

1. **Light stream.** Have an adult make a hole near the bottom of the bottle. Cover it with tape and fill the bottle. In a dark room over a sink, aim the laser straight through the bottle from the opposite side so the beam hits the hole. Remove the tape. Record where the light goes and where the stream glows. Try different water levels (stream curves) and record whether the light stays in.
2. **Critical angle.** Fill the clear container with water and add a few drops of milk. Shine the laser up through the side wall toward the water surface from below at different angles. Measure (with the protractor against the container) the angle from the vertical at which the beam stops escaping into the air and reflects completely.
3. Compare your measured critical angle with the calculated value, 49° . Find the percent difference and give a reason for it.
4. **Packets.** Write a 20-word message. Split it into 5 packets on index cards, each with a header: from, to, packet number (1 of 5...). Give the packets to different family members, who carry them by different routes through the house to the receiver.
5. The receiver reassembles them by number. Time the whole delivery.

6. **Fair test.** Repeat with one “router” told to drop one packet secretly. The receiver must notice the missing number and request it again. Time it. Then try sending the whole message on one card by one route and compare the time and the risk.
7. **Improve.** Design a rule that makes your packet network faster or more reliable (for example, a checksum: the number of letters on each card written in the header). Test it.

Tips

- A green laser shows up more brightly in water, but red works well in a dark room.
- A smooth, steady stream guides light best; a sharp hole gives a smoother jet than a ragged one.
- Keep the bottle topped up so the stream does not shrink during your observations.

Check your work

- ☐ I can explain total internal reflection and calculate a critical angle.
- ☐ I guided light in a stream of water and measured the critical angle of water.
- ☐ I can explain how packets are numbered, routed separately and reassembled, and how lost packets are replaced.

ENGINEER’S NOTEBOOK

1. Ray diagram of light inside a fiber: core, cladding, critical angle, and a ray bouncing along it.
2. Your critical-angle measurements and comparison with Snell’s law.
3. Your packet-network results: times with and without a lost packet, and your improved rule.
4. Solve: light in a fiber travels 204,000 km/s. How long does a signal take to cross the Pacific (about 9,000 km)? Why might a video call feel delayed?

From history. Long before fiber, the first transatlantic telegraph cable was completed in 1858, with Lord Kelvin (a devout Christian physicist) as one of its scientific advisers; it failed after a few weeks. Kelvin’s improved instruments and cable designs helped the lasting 1866 cable succeed. Each generation of ocean cable, telegraph, telephone and fiber, has followed similar routes across the sea floor.

COMMON MISTAKES

- Thinking fiber optic signals travel at the speed of light in a vacuum. In glass they travel about two-thirds as fast.
- Believing the whole internet travels by satellite. Almost all long-distance data goes through undersea and underground fiber.
- Thinking a message travels as one piece along one wire. It travels as many packets, which may take different paths.

Make it a game · Light Stays In. Riddle round about optical fiber. Your parent gives clues: a thin glass strand, light bouncing inside, a signal chopped into labeled bundles. You answer: total internal reflection, packet, data center. Then calculate a critical angle with Snell's law for an index of your choice. Swap, and try to write the history of fiber in six words.

5.4 INFRASTRUCTURE CAREERS: LINEWORKER, WATER OPERATOR AND ENGINEER

OBJECTIVES

- Describe the work, training and safety practices of lineworkers, water and wastewater operators, and utility engineers.
- Explain the physics of electrical safety for lineworkers: potential difference, grounding, step potential and approach distances.
- Use the water operator's "pounds formula" and concentration in mg/L, and model dilution with a careful experiment.

Warm-up. Watch a bird sitting on a power line (from a distance, outside). It is touching a wire carrying thousands of volts. Why is it unharmed? Write your best explanation. What would happen if its wing touched a second wire or the pole at the same time?

WATCH

What does it take to be a water treatment plant operator?

Rural Community Assistance Partnership - RCAP · 3:05

<https://www.youtube.com/watch?v=S1wUOad-0ag>

WHEN TO WATCH

After the story paragraph. List the skills the operators say they need.

BACKUP VIDEO

What it Takes to Be a Lineman

NVEnergyTV · 2:50

<https://www.youtube.com/watch?v=NI9R7V7Or5I>

With the physics paragraph: utility pre-apprentices learning to climb poles safely.

KEY TERMS

lineworker

A skilled tradesperson who builds and repairs power lines, usually trained through a multi-year apprenticeship to become a journeyman.

water and wastewater operator

A state-certified professional who runs treatment plants, tests water, adjusts chemical doses and keeps equipment working around the clock.

mg/L

Milligrams per liter, the usual unit of concentration in water treatment. In dilute water, 1 mg/L is the same as 1 part per million (ppm).

chlorine dose and residual

The dose is how much chlorine is added; the residual is how much remains after it has reacted, still protecting the water in the pipes.

step potential

The voltage between a person's feet when current flows into the ground near a fallen line; it is why you should shuffle away with small steps, feet together.

SCADA

Supervisory control and data acquisition: the computer systems that let operators monitor and control pumps, valves, breakers and substations remotely.

CORE IDEAS

The story. In the early 1900s, typhoid fever, spread by contaminated water, took the lives of thousands of Americans every year. Jersey City, New Jersey, drew its water from the Boonton Reservoir, and the water company was in court over whether the water was safe. Dr. John L. Leal, a physician, and George Warren Fuller, a sanitary engineer, proposed something new: add a small, carefully measured dose of chlorine compound to destroy the germs. On September 26, 1908, the Boonton plant began continuously disinfecting the water supply of a large American city for the first time. Within a few years cities across the country followed, and typhoid deaths fell dramatically. Disinfection of drinking water is counted among the greatest public-health achievements of the twentieth century.

How they figured it out. Leal and Fuller had to show that a dose small enough to be harmless to people was large enough to destroy bacteria. Fuller designed the feed system to add a steady, measured amount of chlorinated lime to the flowing water, and laboratory workers tested samples daily, counting bacteria. The court eventually accepted their records. Their method set the pattern still followed: measure the flow, calculate the dose, test the result, and keep honest records every day. Meanwhile, as electric lines spread across the country, lineworkers learned their trade the hard way; early linework was among the most dangerous jobs in America, and today's strict safety rules, rubber protective equipment and apprenticeship training grew from those lessons.

The physics. Current flows only when there is a **potential difference** across a path. A bird on one wire is at the same voltage as the wire, so no current flows through it. A person touching a live wire and a grounded pole at once completes a path, and even a small current through the chest can stop the heart. Lineworkers therefore treat every line as live until it is tested and grounded: they open switches, test for voltage, and attach heavy grounding cables so that if the line were accidentally energized, the current would flow through the grounds, not through them. When a line falls, current spreads into the soil, and the voltage changes with distance from the wire, so a person's two feet can be at different voltages (**step potential**). That is why anyone near a downed line should shuffle away with feet together. Lineworkers also keep minimum approach distances that grow with voltage, and wear rubber gloves rated for the voltage they work near.

The engineering. Water operators use one equation every day, the **pounds formula**: chemical feed (lb/day) = flow (million gallons per day) $\times$ dose (mg/L) $\times$ 8.34 (the weight in pounds of one gallon of water). Worked example: a town treats 2.5 million gallons per day at a chlorine dose of 1.5 mg/L: $2.5 \times 1.5 \times 8.34 \approx 31$ lb of chlorine per day. Too little, and germs survive; too much, and the water tastes bad and wastes money. Operators earn state certificates by passing exams and gaining experience, from entry level to the highest grade. Lineworkers usually complete a three- to four-year apprenticeship to become journeymen. Utility engineers, mostly civil, electrical and mechanical, design the systems these workers run. Many of these jobs need no four-year degree; all of them need mathematics, care and courage.

Today. When a big storm knocks out power, utilities send lineworker crews hundreds of miles to help one another under mutual-assistance agreements. When you see their trucks, you are looking at neighbors serving neighbors.

PICTURE STUDY



A Lineman at the Top of a Pole, Unknown photographer, about 1916–1918 · Photograph · Alaska;
University of Washington Libraries

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

Long before bucket trucks, linemen climbed every pole with steel spurs strapped to their legs and a leather belt around the pole. This lineman is repairing a line in Alaska about a century ago.

Look closely

- Find his climbing spurs and belt. How do they hold him on the pole?
- Look at the top of the pole. What would the wires be fastened to?
- Find the car on the muddy road below. What does it tell you about the time and the place?
- Look at the landscape. What would make building and repairing lines here hard?

Talk about it

1. Why must wires be held on insulators instead of nailed straight to the pole?
2. What safety equipment do you think a lineworker today has that this man did not?
3. Why is a telegraph or telephone line much less dangerous to work on than a power line?

Safety first. Never touch, climb or go near power poles, transformers, substations or downed lines; a downed line can be live even if it is not sparking. Stay at least 35 feet away and call 911. Never open manholes or enter storm drains. Call 811 before anyone digs in your yard. In the build, do not drink or taste any of the solutions.

BUILD

Dose, Dilution and a Utility Career Interview

You will practice the concentration math of a water operator by making a careful series of dilutions with food coloring, using them as a color scale to estimate an unknown, and doing the pounds-formula calculations. Then you will research and, if possible, interview someone who works in a utility.

You will need

- Six identical clear glasses or jars, a measuring cup and measuring spoons (or a medicine syringe marked in mL)
- Liquid food coloring and water; a white sheet of paper for a background
- A kitchen scale
- Your notebook and a calculator

Steps

1. **Stock.** Assume one drop of food coloring is about 0.05 mL. Add 20 drops (1 mL) to 1,000 mL (1 L) of water. This is your stock: about 1 mL of dye per liter, or 1,000 parts per million (ppm) by volume.
2. **Serial dilution.** Put 100 mL of stock in glass 1. Mix 10 mL of stock with 90 mL of water in glass 2 (100 ppm). Mix 10 mL of glass 2 with 90 mL of water in glass 3 (10 ppm). Continue to 1 ppm and 0.1 ppm. Label each glass.
3. Set them in a row on white paper and photograph them. Which is the faintest color you can still see? That is the detection limit of your eye for this dye.
4. **Unknown.** Have someone secretly make an “unknown” from stock and water. Estimate its concentration by comparing it with your scale, then have them tell you the real value. Calculate your percent error.
5. **Operator math.** Solve: (a) 0.75 MGD at 2.0 mg/L; (b) 4.0 MGD at 1.2 mg/L; (c) How many mg/L dose is a feed of 50 lb/day into 3.0 MGD? Show units.
6. **Fair test.** Repeat your dilution scale with careless measuring (eyeballing amounts instead of measuring). Compare how well each scale lets you estimate the unknown. What does this teach about an operator’s care?

7. **Career research.** Choose one: lineworker, water or wastewater operator, utility civil engineer, or electrical engineer. Find out the training, certificates, typical hours and dangers. With a parent, contact your local utility or water department to ask whether someone would answer three questions by phone or email.
8. **Improve.** Write a one-page career profile with what you learned, including one thing that surprised you and one way the work serves the community.

Tips

- Rinse the measuring spoon or syringe between dilutions so you do not carry extra dye forward.
- Mix each glass completely before you take the next 10 mL out of it.
- Hold all glasses against the same white background in the same light when comparing colors.

Check your work

- ☐ I can explain why a bird on a wire is safe and why grounding and step potential matter for lineworkers.
- ☐ I can use the pounds formula with units and explain what mg/L means.
- ☐ I made a dilution scale, used it to estimate an unknown, and wrote a career profile.

ENGINEER'S NOTEBOOK

1. Photograph or colored sketch of your dilution series with concentrations labeled, and your unknown estimate.
2. Worked pounds-formula problems with units written at every step.
3. Draw a lineworker grounding a de-energized line, and show where current would go if the line were accidentally energized.
4. Your career profile.

From history. Jersey City's chlorination was challenged in court, and in 1910 the judge's decision effectively accepted that chlorination made the water safe, which encouraged other cities to adopt it. George Warren Fuller went on to design water and sewage works for many American cities, and the American Water Works Association still gives an award in his name.

COMMON MISTAKES

- Thinking a fallen power line is safe because it is not sparking or because the lights are out.
- Dropping units in water calculations. Writing $\text{MGD} \times \text{mg/L} \times 8.34 \text{ lb/gal}$ keeps the answer in pounds per day.
- Believing that infrastructure work is only for engineers with degrees. Skilled trades and certified operators run these systems every day.

Make it a game • Career Interview Role-Play. Your parent plays a lineworker, a water operator or a utility engineer, and you interview them with five questions you wrote from the lesson. Next, switch: you play the worker, and your parent asks about grounding, step potential or chlorine dose and residual. Score one point for every answer given correctly without notes.

Scripture. “But it shall not be so among you: but whosoever will be great among you, let him be your minister;” (Matthew 20:26, KJV)

“Minister” means servant. The operators, lineworkers and engineers who keep water and power flowing are servants of their whole community, and Jesus calls that kind of service greatness.

UNIT 5

UTILITIES

Public utilities are the engineering most people never think about until it stops working: the power grid, the water mains, the sewers and the network of cables that carries the internet. In this unit you will study them the way the engineers who run them do, with numbers. You will learn why the North American grid failed in the great blackouts of 1965 and 2003 and what engineers changed, why power lines run at hundreds of thousands of volts, how water pressure depends on height (head) and how friction in a pipe steals it, and how light trapped in a glass thread carries a video call across an ocean.

The unit ends with the people. Lineworkers, water and wastewater operators, and civil and electrical engineers keep these systems running every hour of every day, often in storms and at night. You will learn the story of the first chlorinated city water supply in America, practice the arithmetic every water operator uses, and think about which of these vocations might be yours. Running clean water and steady light to every house is one of the most practical ways people love their neighbors.

PREREQUISITES

- Knows Ohm's law ($V = IR$) and electric power ($P = VI$)
- Knows pressure as force $\div$ area and the units Pa and psi
- Can use exponents and scientific notation
- Has seen how a generator works (Faraday's law, earlier grades)

MASTERY CHECKLIST

- ☐ I can explain why supply and demand on the grid must balance every second, how grid frequency shows the balance, and how a cascading blackout happens.
- ☐ I can calculate power-line losses ($P = I^2R$) and explain why transmission uses high voltage.
- ☐ I can calculate water pressure from head ($P = \rho gh$; 1 ft of water $\approx$ 0.433 psi) and flow from $Q = Av$, and explain friction loss in pipes.
- ☐ I can explain total internal reflection and packet switching, and estimate the time for light to cross an ocean in a fiber.
- ☐ I can describe the work and training of a lineworker, a water operator and a utility engineer, and use the operator's "pounds formula."

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco)**: Ages 8 and up. Sets with a motor and hand-crank or fan generator let you see loads slowing a generator, a good companion to Lesson 5.1.
- **Thames & Kosmos science kits**: Ages vary by kit. Their water, hydraulics and renewable-energy kits add pumps, turbines and generators that fit Lessons 5.1–5.2.

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

5.1 Grid Reliability and the Great Blackouts

2 sessions of 60 minutes

5.2 Water Systems: Head, Pressure and Pipe Flow

2 sessions of 60 minutes

5.3 The Internet: Fiber, Packets and Data Centers

2 sessions of 60 minutes

5.4 Infrastructure Careers: Lineworker, Water Operator and Engineer

2 sessions of 60 minutes

UNIT 5 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Why must electricity generation equal demand at every moment, and what happens to the grid's frequency when demand suddenly rises?

2. **8 pts**

Name two causes of the 2003 blackout and two changes made afterward.

3. **10 pts**

Calculation. 200 MW is sent over a line with $5\ \Omega$ resistance. Find the current and the power lost at 500,000 V. How many times larger would the loss be at 50,000 V?

4. **8 pts**

What is a cascading failure, and what is the N-1 rule?

5. **10 pts**

Calculation. A water tower's surface is 45 m above a fire hydrant. Find the static pressure in kPa and in psi. ($1\ \text{psi} \approx 6.9\ \text{kPa}$.)

6. **8 pts**

A pipe has a cross-sectional area of $0.010\ \text{m}^2$, and water flows at $2.0\ \text{m/s}$. Find the flow rate in m^3/s and in liters per second.

7. **8 pts**

Give two ways engineers reduce friction (head) loss in a water main, and explain why a water tower helps a town.

8. **10 pts**

Calculation. Light travels from water ($n = 1.33$) toward air ($n = 1.00$). Find the critical angle. Then find how long light takes to travel 3,000 km in a fiber with $n = 1.47$ ($c = 300,000$ km/s).

9. **8 pts**

What was Charles Kao's key insight about glass fibers, and what are packets?

10. **10 pts**

Calculation. A plant treats 3.2 million gallons per day at a chlorine dose of 1.8 mg/L. How many pounds of chlorine are needed per day?

11. **6 pts**

Why is a bird on a power line safe, and what should you do if you find a downed line?

12. **6 pts**

Write a short paragraph: Which infrastructure career described in this unit interests you most, and how does it serve other people?

ANSWER KEY

1. The grid stores very little energy, so power must be made as it is used. When demand rises, energy is drawn from the spinning generators, which slow down slightly, so the frequency drops below 60 Hz until control systems add more power.
2. Causes (any two): lines sagging into overgrown trees; a failed alarm program so operators did not know; poor situational awareness and coordination. Changes (any two): mandatory, enforceable reliability standards; strict tree-trimming rules; better operator training and backup tools; better real-time monitoring.
3. $I = P \div V = 200,000,000 \div 500,000 = 400 \text{ A}$. $\text{Loss} = I^2R = 400^2 \times 5 = 800,000 \text{ W} = 0.8 \text{ MW}$. At 50,000 V the current is 10 times larger, so the loss is 100 times larger (80 MW).
4. A chain reaction in which one failure shifts load onto other parts, which overload and fail in turn. N-1 means the grid must keep working normally if any single major element (one line, generator or transformer) is lost.
5. $P = \rho gh = 1,000 \times 9.8 \times 45 = 441,000 \text{ Pa} = 441 \text{ kPa}$. $441 \div 6.9 \approx 64 \text{ psi}$. (Or $45 \text{ m} \approx 148 \text{ ft} \times 0.433 \approx 64 \text{ psi}$.)
6. $Q = Av = 0.010 \times 2.0 = 0.020 \text{ m}^3/\text{s} = 20 \text{ L/s}$.
7. Use a larger diameter pipe; use a shorter route; use smoother pipe; keep velocity lower (any two). A tower stores water high up, giving steady pressure from its height and a reserve for fires and peak demand, so pumps can run steadily.
8. $\sin \theta_c = 1.00 \div 1.33 = 0.752$, $\theta_c \approx 49^\circ$. $v = 300,000 \div 1.47 \approx 204,000 \text{ km/s}$; $t = 3,000 \div 204,000 \approx 0.015 \text{ s}$ (15 ms).
9. That losses came from impurities, not the glass itself, so very pure glass could carry light signals for kilometers. Packets are small numbered blocks of data with headers (source, destination, sequence), sent separately through the network and reassembled.
10. $\text{lb/day} = \text{MGD} \times \text{mg/L} \times 8.34 = 3.2 \times 1.8 \times 8.34 \approx 48 \text{ lb/day}$.
11. The bird touches only one wire, so its body is all at the same voltage and no current flows through it. Stay far away (at least 35 feet), do not touch anything near it, keep others away, and call 911 and the utility; if near one, shuffle away with small steps, feet together.
12. Answers vary; a good answer names the career, describes its work and training accurately, and explains a specific way it protects or serves the public.

PORTFOLIO PIECE: A TOWN UTILITY PLAN

Design the water and power systems for a small imaginary town of about 500 homes on a map you draw, with a hill, a river and a valley. Place a water source, treatment plant, pump and water tower, and calculate the static pressure at the highest and lowest homes. Choose a main pipe size and justify it with $Q = Av$ and friction. Lay out power from a substation with at least two supply paths (N-1), and calculate line loss for one feeder at two voltages. Add a fiber line to the town center. Then build one working piece (the siphon water system or the motor-generator model) and include its test data. Present it as an engineer's report with the map, calculations and photographs.

LOOK FOR	WHAT IT MEANS
Town map	Neat, labeled map with source, treatment, pump, tower, mains, substation, two power paths and fiber route; elevations marked.
Water calculations	Static pressures at high and low homes in psi and kPa; pipe flow sized with $Q = Av$; pressure zones or valves considered.
Power calculations	Line loss calculated at two voltages with $P = I^2R$; redundancy explained using the N-1 rule.
Working model and data	Siphon or motor-generator model built and tested with a data table and graph.
Report	Clear explanations with units, an honest comparison of model results with calculations, and one improvement.

UNIT 6

SHIPS

You already know why ships float. This year you will learn what naval architects and marine engineers worry about once a ship is afloat: how to push it through the water with as little power as possible, how to make its propellers bite without destroying themselves, how to take a vessel to the deepest place in the ocean and bring it back, and how to build giant steel ships quickly and safely. You will meet William Froude and his towing tank, Charles Parsons and his record-breaking *Turbinia*, Jacques Piccard and Don Walsh in the bathyscaphe *Trieste*, and the shipyard workers and scientists of the Liberty ships.

Each lesson has real numbers: hull speed from wave physics ($v \approx 1.34\sqrt{L}$), drag and thrust, the pressure at the bottom of the Mariana Trench ($P = \rho gh$), Boyle's law, and the temperature at which steel turns brittle. Your builds include a rain-gutter towing tank, water boiling in a syringe at room temperature, a Boyle's-law pressure test and a cold-brittleness test, each with a fair test and an improvement round.

PREREQUISITES

- Knows Archimedes' principle and density (earlier grades)
- Can use $P = \rho gh$ and the idea of stress (Units 2 and 5)
- Knows Newton's third law and momentum (Unit 1)
- Can take square roots and work with scientific notation

MASTERY CHECKLIST

- ☐ I can explain wave-making and friction drag and calculate hull speed ($v \approx 1.34\sqrt{L}$ in knots and feet).
- ☐ I can explain how a bulbous bow reduces drag and how Froude used scale models.
- ☐ I can explain cavitation as boiling at low pressure and how propeller designers avoid it, and calculate thrust from $F = \dot{m}\Delta v$.
- ☐ I can calculate deep-sea pressure and the force on a window, use Boyle's law, and explain how the *Trieste* controlled its buoyancy.
- ☐ I can explain brittle fracture, the ductile-to-brittle transition and stress concentrations, and describe modern block shipbuilding.

OPTIONAL KITS FOR THIS UNIT

- **LEGO Technic:** Ages 9 and up. Technic motors, gears and propellers can drive model boats and a thrust stand for Lesson 6.2.
- **KiwiCo Tinker Crate:** Ages 9–16 (Tinker line). Some crates include hydraulic and boat projects that make good warm-ups for this unit.

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

LESSONS IN THIS UNIT

6.1 Drag, Hull Speed and the Bulbous Bow: Froude's Towing Tank

2 sessions of 60 minutes

6.2 Propellers and Cavitation: Parsons and the Turbinia

2 sessions of 60 minutes

6.3 Submarines and Pressure: The Trieste Reaches the Deepest Sea

2 sessions of 60 minutes

6.4 Modern Shipbuilding: Liberty Ships, Brittle Steel and the Block Method

2 sessions of 60 minutes

UNIT 6 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use $g = 9.8 \text{ m/s}^2$ and seawater density $1,025 \text{ kg/m}^3$. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Name the two main kinds of hull resistance and explain why wave drag rises so steeply near hull speed.

2. 10 pts

Calculation. Find the hull speed of a boat with a 49-foot waterline. If a ship needs 2,000 kW at 15 knots, about how much power does it need at 20 knots if power grows with speed cubed?

3. 8 pts

What was Froude's key idea for testing models, and how does a bulbous bow reduce drag?

4. 8 pts

Calculation. A propeller moves 800 kg of water per second and increases its speed by 5 m/s. What is the thrust?

5. 8 pts

Explain cavitation and give two ways propeller designers reduce it.

6. 8 pts

What problem did Parsons find with *Turbinia*, and how did he solve it?

7. 10 pts

Calculation. Find the water pressure (not counting air) at 6,000 m depth in MPa. What force acts on a window with area 0.02 m^2 ?

8. 8 pts

Calculation. A balloon holds 6.0 L of air at the surface (100 kPa). What is its volume at a total pressure of 400 kPa (about 30 m deep)?

9. 8 pts

Why did the *Trieste* use gasoline instead of air in its float, and what made its iron-shot ballast fail-safe?

10. 8 pts

Why were some Liberty ships and other welded ships of the 1940s prone to cracking in two?

11. 8 pts

What is a stress concentration, and why are hatch corners and airplane windows rounded?

12. 8 pts

Describe block construction in modern shipyards and give two reasons it is faster and safer than building a hull piece by piece.

ANSWER KEY

1. Friction (skin) drag and wave-making drag. Near hull speed the bow wave becomes as long as the hull, so the hull sits in its own trough and would have to climb its bow wave to go faster, which takes rapidly increasing energy.
2. $v \approx 1.34 \times \sqrt{49} = 1.34 \times 7 \approx 9.4$ knots. Power ratio = $(20 \div 15)^3 = 2.37$, so about 2,000 $\times 2.37 \approx 4,700$ kW.
3. A model and a ship make the same wave pattern at the same Froude number ($v \div \sqrt{gL}$), so model wave drag can be measured and scaled up, with friction drag handled separately. A bulbous bow makes its own wave whose crest falls in the bow wave's trough, partly canceling it at the design speed.
4. $F = \dot{m}\Delta v = 800 \times 5 = 4,000$ N.
5. Where water moves fast over the blade, pressure falls below the vapor pressure and the water boils into vapor bubbles, which collapse violently, damaging the metal and wasting thrust. Reduce it by more or wider blades (more area), slower rotation with larger diameter, carefully shaped and skewed blades, and placing propellers deeper.
6. Her single fast propeller cavitated and churned the water without pushing well. He studied it in the first cavitation tunnel and rebuilt her with three shafts carrying nine propellers, spreading the thrust over more blade area so she reached about 34 knots.
7. $P = \rho gh = 1,025 \times 9.8 \times 6,000 \approx 60,300,000$ Pa ≈ 60 MPa. $F = PA \approx 60,300,000 \times 0.02 \approx 1.2$ million N.
8. $P_1 V_1 = P_2 V_2$: $100 \times 6.0 = 400 \times V_2$, $V_2 = 1.5$ L.
9. Gasoline is lighter than water and hardly compresses, so it gives the same lift at any depth; air would be squeezed to a tiny volume. The shot was held by electromagnets, so if power failed, the shot would drop automatically and the vessel would rise.
10. Their steel became brittle at low temperatures (below its transition temperature); cracks started at stress concentrations such as square hatch corners and weld defects; and in an all-welded hull there were no riveted joints to stop a running crack.
11. A local increase in stress at a sharp corner, notch or crack. Rounding the corner spreads the stress more evenly, lowering the peak so cracks are less likely to start.

12. The ship is built as large steel blocks, each fitted with pipes, cables and paint, then lifted by cranes and welded together in a dry dock. Faster: many blocks are built at the same time; work is done indoors and at ground level where it is easier. Safer and better quality: less work at height or in cramped spaces; easier inspection of welds.

PORTFOLIO PIECE: A TANK-TESTED MODEL HULL

Design a model cargo hull to carry a set load (for example, 200 g of pennies) as fast as possible in your rain-gutter towing tank, using a fixed towing weight. Before building, draw the lines plan (side view, top view and three cross sections), calculate the model's hull speed, and predict its waterline from Archimedes' principle. Build at least two versions, one with a bulbous bow, and test each three times. Present a one-page engineer's report with drawings, data, a graph of speed against design, photographs of the wave patterns, and your recommendation, as a naval architect would present it to a ship owner.

LOOK FOR	WHAT IT MEANS
Lines plan	Side, top and section views drawn to scale with dimensions; predicted waterline and hull speed calculated.
Construction	Hulls of equal mass and load, smooth and symmetrical; bulb shaped and placed deliberately.
Fair testing	Same towing weight and distance; three runs per design; times and speeds recorded with units.
Analysis	Explains results using friction drag, wave drag, hull speed and the bulb's wave cancellation.
Recommendation	Clear, honest report with a specific recommendation and one further improvement.

6.1 DRAG, HULL SPEED AND THE BULBOUS BOW: FROUDE'S TOWING TANK

OBJECTIVES

- Explain friction drag and wave-making drag, and why wave drag rises steeply near hull speed.
- Calculate hull speed ($v \approx 1.34\sqrt{L}$, knots and feet) and explain how Froude used models at the same Froude number.
- Build a rain-gutter towing tank and compare bow shapes, including a bulbous bow, in a fair test.

Warm-up. Drag your finger slowly through a pan or tub of water, then faster. Watch the waves it makes. Then drag a flat spoon edge-first and flat-side-first. Which takes more force? Which makes bigger waves? Sketch the wave pattern behind your finger from above.

WATCH

Why Are Big Ships Faster Than Small Ships?

Casual Navigation · 5:56

<https://www.youtube.com/watch?v=URgSFglbl5g>

WHEN TO WATCH

After the physics paragraph. Watch the bow wave and stern wave and when they line up with the hull.

BACKUP VIDEO

What is the BULBOUS BOW for?

Casual Navigation · 4:08

<https://www.youtube.com/watch?v=6FrCusDG41U>

With the engineering paragraph: how the bulb's wave cancels the bow wave.

KEY TERMS

friction (skin) drag

Resistance from water rubbing along the wetted surface of the hull. It grows with wetted area and roughly with speed squared.

hull speed

The speed at which the ship's own bow wave is as long as its waterline, so the hull sits in its own wave trough: about $1.34 \times \sqrt{\text{waterline length in feet}}$ knots.

bulbous bow

A rounded bulb below the waterline at the front of a ship, shaped to make a wave that partly cancels the bow wave at the ship's cruising speed.

wave-making drag

Resistance from the energy a moving hull spends making waves. It rises very steeply as speed approaches hull speed.

Froude number

$Fr = v \div \sqrt{gL}$. A model and a full-size ship at the same Froude number make the same pattern of waves.

knot

One nautical mile per hour, about 1.15 mph or 0.514 m/s.

CORE IDEAS

The story. In the 1860s the Royal Navy was changing from wooden sailing ships to iron steamships, and nobody could reliably predict how much power a new ship would need. Ships were built, tried, and sometimes found too slow. William Froude, an English railway engineer turned naval researcher, proposed testing scale models first. In 1871 he towed the real warship HMS *Greyhound* behind another ship and measured the pull, to check his methods, and in 1872, with Admiralty money, he opened the first ship-model test tank at Torquay: a long indoor tank where models of paraffin wax were towed by a carriage at carefully measured speeds.

How they figured it out. Froude's great insight was that a model's resistance has two parts that scale differently. Friction drag depends on the wetted surface and could be estimated from tests on towed planks. Wave-making drag depends on the pattern of waves, and that pattern is the same for a model and a ship when the speed divided by $\sqrt{gL}$ is the same; we now call that ratio the Froude number. So he could test a 12-foot model at the right, slower speed, subtract the friction part, scale up the wave part, and add back the ship's friction. His predictions matched the *Greyhound's* full-

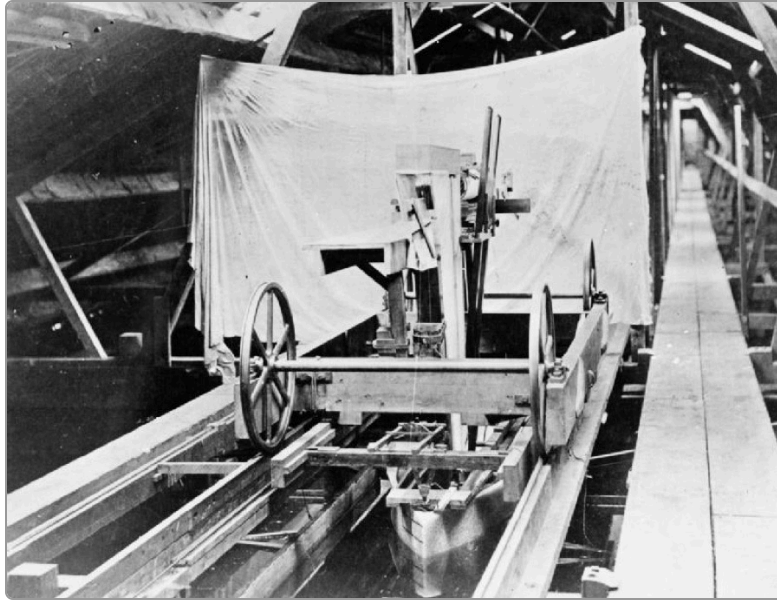
size test. Towing tanks spread around the world. In the United States, naval constructor David W. Taylor built a large model basin in Washington in 1898, and his tests led to the bulbous bow, first used on the battleship USS *Delaware* in 1910.

The physics. A moving hull makes a bow wave and a stern wave. Deep-water waves travel at a speed set by their length: $v = \sqrt{g\lambda \div 2\pi}$. When the ship speeds up, its bow wave lengthens until the wavelength equals the waterline length. Then the hull sits in the trough between its own bow and stern waves and would have to climb its own bow wave to go faster. That is **hull speed**: in feet and knots, $v \approx 1.34\sqrt{L}$; in meters and meters per second, $v \approx 1.25\sqrt{L}$. Worked example: a sailboat with a 25-foot waterline has hull speed $\approx 1.34 \times 5 = 6.7$ knots. A container ship with a 1,200-foot waterline has hull speed $\approx 1.34 \times 34.6 \approx 46$ knots, far above its cruising speed of about 16–24 knots. That is why big ships are fast: their long hulls stay well below hull speed, where wave drag is small. Drag force grows with speed squared, $F_d = \frac{1}{2}\rho v^2 C_d A$, and the power needed grows with speed cubed ($P = F_d v$), so going 20% faster can take about 70% more power.

The engineering. Naval architects shape hulls to fit their speed. Displacement hulls (tankers, container ships, sailboats) are long and slender to stay below hull speed. Planing hulls (speedboats) are flat-bottomed and climb onto the surface to escape the problem. The **bulbous bow** makes its own small wave just ahead of the bow wave, timed so its crest falls in the bow wave's trough, partly canceling it. At its design speed a bulb can cut fuel use by several percent, a huge saving over a ship's life; at other speeds it can help less or even add drag, so some ships have had their bulbs reshaped when they began sailing more slowly to save fuel. Hull coatings that stay smooth reduce friction drag too.

Try it. Your towing tank will pull model hulls with a falling weight, so every model feels the same force. The fastest model has the least drag.

PICTURE STUDY



Froude's Test Tank at Torquay, Unknown photographer, about 1872 · Photograph · Imperial War Museums, London

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

This was the world's first ship-model test tank. Every modern ship design still passes through a tank like it, or a computer program checked against one.

Look closely

- Find the rails along the tank. What rode on them?
- Look at the length of the tank compared with its width. Why make it so long?
- Look for any instruments or recording machines.
- Find the water surface. Why would the tank need to be kept very calm between tests?

Talk about it

1. Why was it cheaper and safer to test a model than to build a full-size ship and try it?
2. If a model $\frac{1}{25}$ the length of the ship is tested, the Froude rule says it should move at $\sqrt{\frac{1}{25}} = \frac{1}{5}$ the ship's speed. How fast should the model go for a ship of 20 knots?
3. What measurements would you take in a tank like this?

Safety first. Have an adult present near any tub or gutter of water, and mop up spills. Hang the towing weight low over a soft surface so it cannot drop on toes.

BUILD

A Rain-Gutter Towing Tank

You will build a small towing tank from a length of vinyl rain gutter (or a bathtub), tow foam model hulls with a falling weight on a string, time them over a measured distance, and test how bow shape, including a bulb, changes their speed.

You will need

- A 3 m length of vinyl rain gutter with two end caps (hardware store), or a bathtub
- Blocks of foam (craft foam or insulation foam board), a serrated knife or hot-wire foam cutter (adult) and sandpaper
- Fishing line or thread, a spool or pencil as a pulley at the end of the tank, and washers as the towing weight
- A stopwatch or phone video, a tape measure and modeling clay for adding weight and bulbs

Steps

1. Set the gutter level on chairs or the floor and fill it with water to 8 cm deep. Mark a start line and a finish line 2.0 m apart.
2. Cut three hulls the same length (25 cm), width (6 cm) and depth from foam: (1) a blunt box bow, (2) a pointed V bow, (3) the pointed bow with a clay bulb (about 2 cm across) stuck on below the waterline at the front. Weigh them and add clay inside so all three have the same mass.
3. Tie the line to each hull's bow, run it over the pulley at the far end, and hang the same number of washers each time from a fixed height.
4. **Predict.** Rank the three hulls by speed. Then release each hull from rest behind the start line and time it from start to finish. Do three runs each and average.
5. Calculate each hull's average speed. Watch and sketch the waves each makes.
6. **Fair test 2.** Make a long, slender hull (40 cm × 4 cm) with the same mass as hull 2. Compare speeds with the same towing weight. Explain using hull

speed.

7. Calculate the hull speed of your 25 cm and 40 cm models with $v \approx 1.25\sqrt{L}$ (m/s, m). Are your models near hull speed?
8. **Improve.** Change the bulb's size or position (higher, lower, farther forward) and retest. Find the best bulb for your towing weight, then double the weight and see if the same bulb still wins.

Tips

- Start each run with the hull centered and the line straight so it does not rub the gutter walls.
- Wipe the line dry between runs; wet line can stick on the pulley.
- Very light towing weights give the clearest differences. Too heavy, and every hull simply skids along.

Check your work

- ☐ I can explain friction drag, wave drag and hull speed, and calculate hull speed.
- ☐ My towing-tank data compared bow shapes fairly, with equal mass and towing force.
- ☐ I tested a bulbous bow and found how its size or position changed the result.

ENGINEER'S NOTEBOOK

1. Top-view sketch of the wave pattern behind each of your models, with the bow and stern waves labeled.
2. Towing-tank data table and a bar graph of average speed for each hull.
3. Draw a side view of a ship at hull speed, sitting between its bow wave and stern wave.
4. Solve: what is the hull speed of a 36-foot waterline sailboat? Of a 900-foot ship? If drag power goes with speed cubed, how many times more power does a ship need at 22 knots than at 16?

From history. William Froude's son, Robert Edmund Froude, carried on the work, and the Admiralty built a larger tank at Haslar in 1886. Today's model basins, such as the David Taylor Model Basin in Maryland, can be more than half a mile long, and their results are combined with computer fluid-dynamics simulations before a hull is built.

COMMON MISTAKES

- Thinking hull speed is an absolute speed limit. Powerful or planing boats can go faster; they just need far more power to climb their bow wave.
- Believing a bulbous bow helps at every speed. It is tuned for a design speed.
- Testing models of different masses. A heavier model sits deeper and has more drag, so the test is no longer fair.

Make it a game • Hull Speed Duel. Pick a boat length in feet. Each of you calculates its hull speed with $v \approx 1.34\sqrt{L}$ and writes it down before comparing. Closest to the true answer wins the round. Then explain, in thirty seconds each, why wave drag rises steeply near hull speed and what a bulbous bow does. First to three wins.

Scripture. “The way of an eagle in the air; the way of a serpent upon a rock; the way of a ship in the midst of the sea;” (Proverbs 30:19, KJV)

Agur, the writer of this proverb, counted the way of a ship through the sea among the things too wonderful for him. Froude spent his life studying it with patience, models and careful measurement.

6.2 PROPELLERS AND CAVITATION: PARSONS AND THE TURBINIA

OBJECTIVES

- Explain how a propeller makes thrust and calculate thrust with $F = \dot{m}\Delta v$.
- Explain cavitation as water boiling at low pressure and describe the damage it causes and how designers prevent it.
- Boil water at room temperature in a syringe, and test how blade angle changes the thrust of a model propeller.

Warm-up. Water boils at 100 °C at sea level. On a high mountain it boils at a lower temperature. Predict: could water boil at room temperature? What would you have to change? Write your prediction, then test it in Session 2 with a syringe.

WATCH

Cavitation - Easily explained!

IET Institute for Energy Technology · 10:11

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

WHEN TO WATCH

After the physics paragraph. Pay attention to the phase diagram and the pictures of damaged propellers and pump impellers.

BACKUP VIDEO

Steam Turbine Ship Gate-crashing the Queen 1897 Charles Parsons Turbinia | Season 1 - Episode 42

Ireland Made - stories of Irish transport · 3:02

<https://www.youtube.com/watch?v=MOY1BNUqSMs>

With the story paragraph: archive photographs of the *Turbinia* and the 1897 naval review.

KEY TERMS

thrust

The forward force a propeller makes by pushing water backward (Newton's third law): $F = \dot{m}\Delta v$, mass flow rate times the change in the water's speed.

pitch

How far a propeller would move forward in one turn if it screwed through the water like a bolt through a nut.

vapor pressure

The pressure at which a liquid boils at a given temperature. For water at 20 °C it is only about 2.3 kPa, about 1/40 of air pressure.

cavitation

The forming of vapor bubbles in a liquid where its pressure drops below the vapor pressure, and their violent collapse when pressure rises again.

steam turbine

An engine in which high-pressure steam spins rows of blades on a shaft, turning heat into rotation smoothly and at high speed.

CORE IDEAS

The story. In 1884 the English engineer Charles Parsons patented the steam turbine, an engine that spun smoothly at very high speed instead of pumping pistons back and forth. To prove it could drive a ship, he built a slender launch about 100 feet long named *Turbinia*, launched in 1894. At first she was a disappointment: the propeller seemed to churn the water without pushing well. Parsons found the cause and fixed it, and on June 26, 1897, at the great naval review at Spithead held for Queen Victoria's Diamond Jubilee, *Turbinia* raced uninvited between the lines of warships at about 34 knots, faster than any ship in the navy could chase her. Within a few years turbines drove warships and great ocean liners such as the *Mauretania*.

How they figured it out. Parsons saw that his fast-spinning propeller was surrounded by a cloud of bubbles. The blades were moving so fast that the water pressure on them dropped low enough for the water to boil, even though it was cold. He named the problem **cavitation** (from the cavities, or empty spaces, it made) and around 1895 built a small glass-sided tunnel in which he could watch a model propeller spinning under a flashing light, the first cavitation tunnel. His solution was to spread the work over more blade area at lower speed: he rebuilt *Turbinia* with three shafts, each driven by its own turbine, and three propellers on each shaft, nine in all. The thrust no longer had to be squeezed through one small propeller.

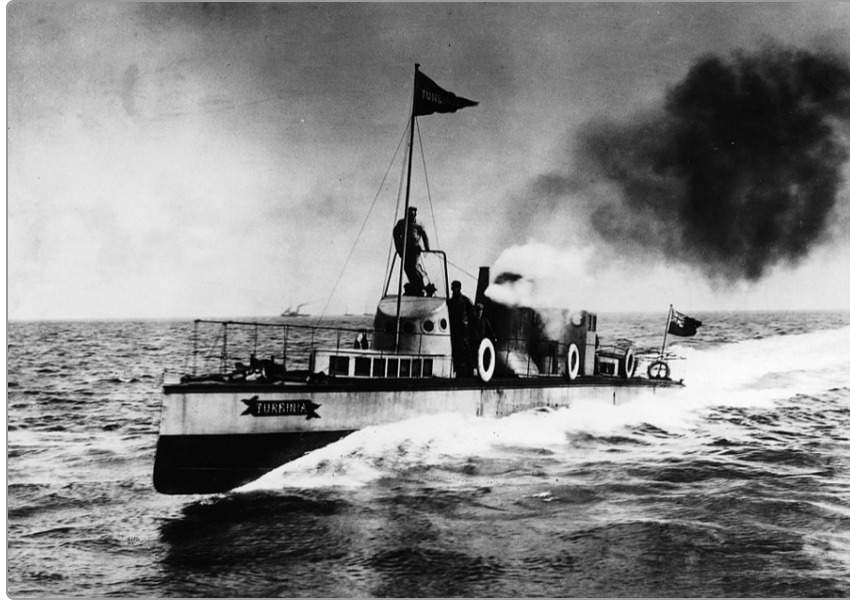
The physics. A propeller blade is a rotating wing. It pushes water backward, and the water pushes the propeller (and the ship) forward. Thrust is the rate of change of the water's momentum: $F = \dot{m}\Delta v$. Worked example: a propeller that moves 500 kg of water each second from 5 m/s to 9 m/s makes a thrust of $F = 500 \text{ kg/s} \times 4 \text{ m/s} = 2,000$

N. On the back face of each blade the water speeds up and its pressure falls. If the pressure drops below the vapor pressure (about 2.3 kPa at 20 °C), the water boils into bubbles of vapor. As the bubbles are carried into higher pressure, they collapse in a few millionths of a second, making tiny jets and shock waves that pit metal, waste thrust and make noise. Depth helps: at 5 m below the surface the pressure is about $101 + 1,025 \times 9.8 \times 5 \div 1,000 \approx 151$ kPa, so propellers are placed as deep as possible.

The engineering. Propeller designers fight cavitation by spreading thrust over a larger blade area (more or wider blades), turning slower with a larger diameter, curving and skewing the blades so the pressure changes gently, and placing the propeller deep and in smooth water. Every new design is tested in a cavitation tunnel, where the pressure can be lowered to match full-size conditions. Cavitation also matters in pumps, hydroelectric turbines, and even dams, where fast spillway water can cavitate and erode concrete. For submarines, a quiet, cavitation-free propeller is especially important.

Try it. In your syringe, pulling the plunger lowers the pressure on the water. If the pressure gets low enough, warm tap water will boil in your hand without being heated.

PICTURE STUDY



Turbinia at Speed, Alfred John West (attributed), 1897 · Photograph · Newcastle upon Tyne; Turbinia is preserved at the Discovery Museum

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

This famous photograph shows *Turbinia* at full speed. She was the fastest ship in the world when she was built.

Look closely

- Find the bow wave. How high does it rise compared with the hull?
- Look at the hull's shape. Is it long and slender or short and wide? Why?
- Find the wake behind the stern. What does its whiteness tell you about the propellers?
- Look at the smoke. Which way is it blowing, and why?

Talk about it

1. *Turbinia's* waterline was about 100 feet. What is her hull speed? She reached about 34 knots. What does that tell you about her hull?
2. Why did one small propeller not work, and why did nine propellers on three shafts work better?
3. Why might a navy be impressed and worried at the same time by a ship like this?

Safety first. Use warm tap water only, never hot or boiling water, in the syringe. Wear safety glasses for the thrust test, keep fingers clear of the spinning propeller, and use only batteries for the motor.

BUILD

Boiling Cold Water and a Propeller Thrust Stand

First you will make water boil at room temperature by lowering its pressure in a syringe, as happens on a cavitating propeller blade. Then you will build a thrust stand on a kitchen scale and test how a model propeller's blade angle changes its thrust.

You will need

- A large plastic syringe (30–60 mL) without a needle, and warm tap water
- A small DC hobby motor, a 2-AA or 3-AA battery holder with switch
- Craft sticks or card stock, a cork or bottle cap hub, glue, and a protractor
- A kitchen scale, a ruler, tape and a heavy book
- Safety glasses

Steps

1. **Boiling test.** Draw 5 mL of warm tap water into the syringe and push out the air. Seal the tip firmly with a fingertip, then pull the plunger out hard and hold it. Watch for bubbles forming and growing throughout the water. Release slowly and watch them collapse.
2. Repeat with cold water and with warm water. Record which forms bubbles most easily and explain using vapor pressure.
3. **Thrust stand.** Tape the motor to the end of a ruler so its shaft points sideways along the ruler. Rest the other end of the ruler on the scale's pan and the middle on a pencil as a pivot taped to a book, so the propeller's push presses the ruler's end onto the scale. Zero the scale with the motor off.
4. Make three two-blade propellers the same diameter (10 cm) with blades set at 15°, 30° and 45° to the plane of rotation (measure with a protractor).
5. **Fair test.** Run each propeller with the same fresh batteries for 5 seconds and record the steady scale reading. Repeat three times. Convert grams to newtons ($\text{g} \div 1,000 \times 9.8$). Remember the lever: if the motor is twice as far from the pivot as the scale contact, the thrust is half the scale's force; measure and correct.

6. Graph thrust against blade angle.

7. **Improve.** Using your best angle, test two blades against four blades of the same size and angle. More blade area, like Parsons's nine propellers, should spread the load. Does it raise the thrust, or does the small motor slow down? Explain.

8. Write a paragraph connecting your syringe test to cavitation on a ship's propeller.

Tips

- If you feel no bubbles in the syringe, make sure no air is left inside and pull harder; small syringes are easiest.
- Keep the propeller at least 5 cm from the scale and table so its own wind does not push on them.
- Mark the front of each propeller so you mount them all the same way round.

Check your work

- ☐ I made water boil at room temperature by lowering its pressure, and I can explain cavitation.
- ☐ I can calculate thrust with $F = \dot{m}\Delta v$.
- ☐ My thrust-stand data show how blade angle and number of blades changed thrust.

ENGINEER'S NOTEBOOK

1. Sketch of a propeller blade in cross section, showing high pressure on one face, low pressure on the other, and where cavitation bubbles form.
2. Syringe observations and a sentence explaining them with vapor pressure.
3. Thrust-stand data table and graph.
4. Solve: a ship's propeller pushes 12,000 kg of water per second and speeds it up by 3 m/s. Find the thrust. What is the pressure at a propeller 8 m below the surface?

From history. Parsons's turbines did more than drive ships. Turbine-driven generators soon made most of the world's electricity, and steam turbines in power plants (coal, gas and nuclear) still generate a large share of it today. *Turbinia* herself is preserved in the Discovery Museum in Newcastle upon Tyne.

COMMON MISTAKES

- Thinking cavitation bubbles are air. They are water vapor, formed by boiling at low pressure.
- Believing a faster-spinning propeller always gives more thrust. Past a point, it cavitates and thrust falls.
- Forgetting that thrust comes from pushing water backward; a propeller does not “pull” a ship through the water.

Make it a game · Why Does It Cavitates? Teach-back game. You are the Turbinia's engineer explaining cavitation to a skeptical parent: water boiling at low pressure, damage to blades, and how designers prevent it. Your parent interrupts with one false claim, such as water only boils when hot, and you must catch it. Reverse roles, and explain thrust, $F = \dot{m}\Delta v$, in one sentence.

6.3 SUBMARINES AND PRESSURE: THE TRIESTE REACHES THE DEEPEST SEA

OBJECTIVES

- Calculate pressure at great depth ($P = \rho gh$) and the force on a window, and explain why deep-sea crew cabins are spheres.
- Use Boyle's law ($P_1V_1 = P_2V_2$) and explain why the *Trieste* used gasoline, not air, for buoyancy.
- Measure how the volume of trapped air changes with pressure in a syringe and graph the result.

Warm-up. Push a plastic cup, open end down, straight into a tub or deep bowl of water. Look through the side: what happens to the air inside as you push deeper? Now imagine a submarine 11 kilometers down. What would happen to air in a soft bag at that depth? Write your prediction.

WATCH

Inside the Sub That Reached Earth's Deepest Point | Bathyscaphe Trieste

Deconstructed · 15:55

<https://www.youtube.com/watch?v=0KKHYtSLI1g>

WHEN TO WATCH

After the story paragraph. Note how the float, ballast and crew sphere each do one job.

KEY TERMS

bathyscaphe

A deep-diving vessel made of a large float filled with a liquid lighter than water, with a small, thick crew sphere hung beneath it.

Boyle's law

For a gas at constant temperature, pressure times volume stays the same: $P_1V_1 = P_2V_2$. Double the pressure and the volume halves.

ballast

Heavy material carried to make a vessel sink or keep it stable, which can be released to make it rise.

neutral buoyancy

When a submerged vessel's weight exactly equals the buoyant force, so it neither rises nor sinks.

pressure hull

The strong, sealed shell that keeps the crew at normal air pressure while the sea pushes on it from outside.

fail-safe

Designed so that if something fails (such as electric power), the system moves to a safe state by itself.

CORE IDEAS

The story. On January 23, 1960, the bathyscaphe *Trieste*, owned by the U.S. Navy, descended into the Challenger Deep in the Mariana Trench of the Pacific, the deepest known place in the ocean, nearly 11,000 meters (about 36,000 feet) down. Aboard were Jacques Piccard, the son of the vessel's Swiss designer Auguste Piccard, and U.S. Navy Lieutenant Don Walsh. The descent took almost five hours. At about 9,000 meters they heard a loud crack: one of the outer acrylic window panes had cracked, but the main window held. They spent about twenty minutes on the bottom, saw that the floor was soft ooze, and rose back to the surface. No one returned to the Challenger Deep with a crew for 52 years.

How they figured it out. Auguste Piccard had already built a pressurized gondola for high-altitude balloon flights in 1931, and he designed the bathyscaphe on the same idea: a sealed cabin hung from a lifting body. The lifting body could not be filled with air, because air would be squeezed to a tiny volume by the pressure. Instead, the 15-meter float was filled with about 85,000 liters of gasoline, which is lighter than water and barely compresses. To descend, the crew let seawater into small tanks; to stop or rise, they released tons of iron shot held in hoppers by electromagnets. If the electric power failed, the magnets would let go and the shot would fall, so the vessel would rise by itself: a fail-safe design. The crew sphere was forged steel about 12.7 cm (5 inches) thick, and the windows were cone-shaped blocks of acrylic that the pressure pushed tighter into their seats.

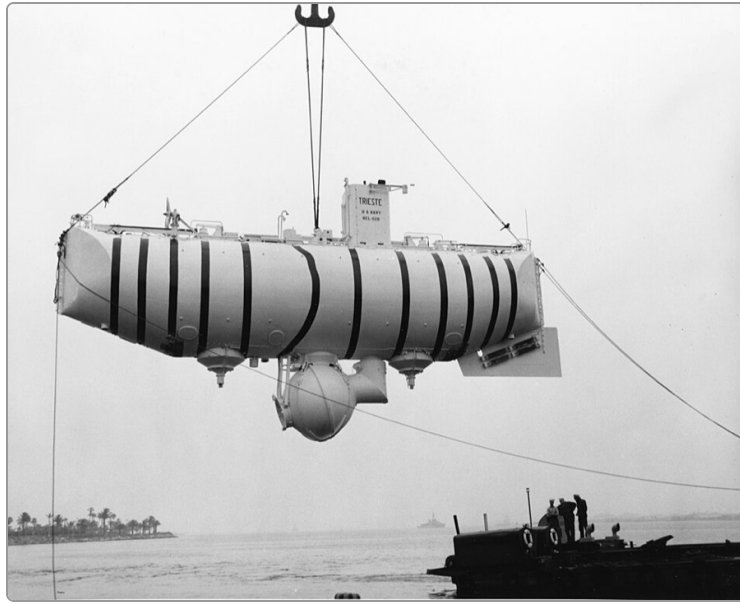
The physics. At the bottom of the Challenger Deep the pressure is $P = \rho gh \approx 1,025 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 10,900 \text{ m} \approx 110,000,000 \text{ Pa} = 110 \text{ MPa}$, about 1,000 times air pressure, or about 16,000 psi. Worked example: on a window 20 cm across, with area $A = \pi \times (0.10 \text{ m})^2 \approx 0.031 \text{ m}^2$, the force is $F = PA \approx 110,000,000 \times 0.031 \approx 3.4 \text{ million}$

newtons, the weight of about 350 metric tons. A sphere is the best shape for resisting pressure because the sea pushes equally all around it and the shell is in pure compression, with no corners or flat sides to bend. Gas is very different from liquid: by **Boyle's law**, air at 1,000 times surface pressure takes up 1/1,000 of its surface volume. That is why a submarine that controls its depth with air in ballast tanks can work only at moderate depths.

The engineering. Military and research submarines use ballast tanks: flood them with seawater to dive, and blow compressed air into them to surface, with small trim tanks to fine-tune neutral buoyancy. Their hulls are cylinders stiffened by ring frames, designed for a test depth with a margin of safety. Modern deep submersibles use titanium spheres and syntactic foam, a material made of tiny hollow glass spheres in resin that floats and resists crushing. Deep-sea engineers test every pressure hull in a pressure chamber before anyone rides in it, follow classification rules written by experienced engineers, and use fail-safe drop weights. The deep ocean gives no second chances, so careful design, independent checking and testing are a matter of life.

Try it. In your build you will squeeze trapped air in a syringe by stacking books on the plunger and see Boyle's law in your own data.

PICTURE STUDY



The Bathyscaphe Trieste, U.S. Navy photograph, about 1958–1959 · Photograph · U.S. Navy, Naval History and Heritage Command

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

The *Trieste* looks more like a blimp than a submarine, and in a way it was one: a large float lifting a small cabin, but in water instead of air.

Look closely

- Find the crew sphere. How big is it compared with the float above?
- Find the float. What was inside it, and why so much?
- Look for the ballast hoppers that held the iron shot.
- Look for any windows or lights on the sphere.

Talk about it

1. Why was the crew cabin a sphere instead of a cylinder or box?
2. Why would a float full of air be useless at the bottom of the ocean?
3. What would happen if the electromagnets holding the iron shot lost power, and why was that a good design?

Safety first. Use a syringe without a needle. Stack books gently and keep fingers and faces clear of the plunger, which can snap upward if the books slip. Wear safety glasses.

BUILD

Boyle's Law in a Syringe

You will trap air in a sealed syringe and stack known masses on the plunger, measuring the volume each time. From the force and the plunger's area you will calculate the pressure and test whether pressure $\times$ volume stays constant.

You will need

- A large plastic syringe (30–60 mL) without a needle, with a tight cap or a blob of hot glue (adult) or modeling clay to seal the tip
- Several similar books or bags of rice, weighed on a kitchen scale
- A small board or stiff cardboard square on top of the plunger to hold the masses
- A ruler or calipers, tape, and a sturdy support so the syringe stands upright
- Safety glasses

Steps

1. Set the plunger at the 30 mL mark (or the largest even mark) and seal the tip airtight. Tape the syringe upright inside a box or between two blocks so it cannot tip.
2. Measure the inside diameter of the barrel (or the plunger's rubber diameter) and calculate its area A in m^2 .
3. **Predict.** Air pressure is about 101 kPa. If you add enough mass to double the pressure on the air, what volume should you read?
4. Add the board and record the volume. Add masses one at a time, gently, recording total mass and volume each time. Twist the plunger slightly before each reading to free it from friction. Go up to the heaviest load you can safely balance.
5. For each load, calculate the added pressure $\Delta P = mg \div A$, the total pressure $P = 101,000 \text{ Pa} + \Delta P$, and the product $P \times V$.
6. Graph V against P , then V against $1 \div P$. If Boyle's law holds, the second graph is a straight line through the origin.

7. **Deep-sea math.** Use your data to answer: at what water depth would the pressure be the same as your largest P? (Use $\Delta P = \rho gh$.)
8. **Improve.** Friction makes the plunger stick. Take readings both while loading and while unloading and average them, and see whether your $P \times V$ values agree better.

Tips

- Wait a few seconds after each new load for the air to return to room temperature; squeezing gas warms it slightly.
- A 60 mL syringe has a large area, so it needs much more mass for the same pressure. A 10–20 mL syringe reaches higher pressures with books.
- If the volume slowly creeps smaller, the seal is leaking. Reseal and start again.

Check your work

- ☐ I can calculate pressure at depth and the force on a window, and explain why deep-sea cabins are spheres.
- ☐ My syringe data show Boyle's law, with $P \times V$ nearly constant.
- ☐ I can explain how the

Trieste used gasoline, ballast tanks and iron shot to sink and rise safely.

est

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ENGINEER'S NOTEBOOK

1. Labeled cutaway of the *Trieste*: float, gasoline tanks, water ballast tanks, iron-shot hoppers, electromagnets, crew sphere, window.
2. Boyle's law data table and both graphs.
3. Solve: what is the pressure at 4,000 m (the average ocean depth)? What force acts on a 15 cm-diameter window there?
4. Write a paragraph on the fail-safe ballast. Name one other fail-safe design you use every day (hint: elevators, trains, or a lawn mower's handle).

From history. In 2012 the filmmaker James Cameron dove alone to the Challenger Deep in the *Deepsea Challenger*, and since 2019 the submersible *Limiting Factor*, with a titanium sphere, has made many dives there. Don Walsh lived to see them; he died in 2023, aged 92.

COMMON MISTAKES

- Thinking a submarine sinks because it is heavy. It sinks when its total weight exceeds the buoyant force, which it controls by taking in water.
- Using only water pressure (ρgh) and forgetting the air pressure on top, or the reverse. Total pressure = air pressure + ρgh .
- Believing gases and liquids compress the same way. Gases compress greatly; water and gasoline hardly compress at all.

Make it a game • Down to the Trieste. Depth countdown. Your parent calls a depth in feet or meters. You write the pressure from $P = \rho gh$ and decide, aloud, whether a sphere or a cylinder is stronger and why. Then explain Boyle's law and why the Trieste floated on gasoline, not air. Five depths gets you a gold bean. Switch and quiz each other.

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)

Piccard and Walsh went to the uttermost part of the sea, nearly seven miles down. The psalmist knew that no depth is beyond God's care.

6.4 MODERN SHIPBUILDING: LIBERTY SHIPS, BRITTLE STEEL AND THE BLOCK METHOD

OBJECTIVES

- Describe how the Liberty ships were built quickly by welding and prefabrication, and how modern shipyards build ships in blocks.
- Explain brittle fracture, stress concentrations and the ductile-to-brittle transition, and how Constance Tipper's work fixed the problem.
- Test how temperature and a notch change the way plastic breaks, and compare assembly-line and one-at-a-time building.

Warm-up. Take two identical plastic spoons. Put one in the freezer for an hour. Then, wearing safety glasses, bend each slowly. Which bends before breaking? Which snaps? Look at the broken edges. Write what you observe. (You will do this more carefully in the build.)

WATCH

The Big Bang - The facts behind brittle fracture

TWI Ltd • 7:59

<https://www.youtube.com/watch?v=ru8zXGoVRDk>

WHEN TO WATCH

After the story paragraph. Watch the Charpy impact test and the graph of energy against temperature.

BACKUP VIDEO

Inside shipyard - The process of building the ship.

Naval Architecture • 14:26

<https://www.youtube.com/watch?v=gtgQu3DRQbl>

With the engineering paragraph: watch the blocks being built, painted, lifted and joined.

KEY TERMS

prefabrication

Building large parts of a structure in a factory or yard area and then assembling them in place.

brittle fracture

Sudden cracking with little bending or warning, in which a crack can run through steel at hundreds of meters per second.

toughness

A material's ability to absorb energy before breaking. It is measured with tests such as the Charpy impact test.

block construction

The modern shipbuilding method: the hull is built as large steel blocks, each fitted with pipes, cables and paint, then lifted by giant cranes and welded together.

ductile-to-brittle transition

The temperature range below which some steels lose their toughness and break in a brittle way.

stress concentration

A local rise in stress at a sharp corner, notch or crack, which can start a fracture.

CORE IDEAS

The story. During the Second World War, the United States needed cargo ships faster than they had ever been built. The answer was the Liberty ship, a plain 441-foot freighter based on a British design. Eighteen American shipyards built 2,710 of them between 1941 and 1945. Instead of riveting, workers (many of them women new to the trade) welded the steel plates, and large sections were prefabricated and then lifted into place. In November 1942 a yard in Richmond, California, assembled the SS *Robert E. Peary* in 4 days and 15½ hours to show what was possible. But some welded ships developed sudden cracks, especially in cold seas, and a few broke completely in two. In January 1943 the new tanker *Schenectady*, a different welded design, cracked across its deck and split while tied up at its dock in Portland, Oregon.

How they figured it out. A board of investigation studied hundreds of fractures. Constance Tipper, a metallurgist at the University of Cambridge, tested small notched bars of the ships' steel at different temperatures and showed that the steel had a transition temperature: above it, the steel bent and absorbed energy; below it, the same steel snapped like glass. Many of the ships' cracks had started at square

corners of hatch openings or at weld defects, where stress concentrated, and then raced through the welded hull because there were no riveted joints to stop them. The fixes were practical: rounder hatch corners, riveted “crack-arrester” strips in the hull, better welding procedures, and later, steels chosen and tested for toughness at low temperature. Notched-bar impact tests such as the Charpy test became standard for ship steel.

The physics. Metals deform by layers of atoms slipping past one another, which absorbs energy (ductile behavior). In some steels, at low temperature, slipping becomes difficult and atoms split apart instead (brittle cleavage), so a crack runs with little energy absorbed. A sharp notch raises the stress at its tip: the stress at the tip of a narrow crack can be many times the average stress in the plate. In a riveted hull a crack usually stopped at the edge of a plate; in an all-welded hull, the plates are one continuous piece, so a crack could keep running. Worked example: if a hull plate carries an average stress of 80 MPa, a hatch corner with a stress concentration factor of 3 sees about 240 MPa, close to the yield strength of ordinary steel; rounding the corner to a stress concentration factor of 1.5 drops it to 120 MPa.

The engineering. Modern shipyards build in blocks, the method that grew from wartime prefabrication. Ships are designed completely in 3D CAD; steel plates are cut by computer-controlled plasma or laser cutters; robots and skilled welders join panels into blocks that can weigh hundreds of tons; pipes, cables and paint are added while each block is still easy to reach; and giant gantry cranes lift the blocks into a dry dock to be welded together. Every weld is inspected, often with ultrasound or X-rays, and independent classification societies check the design and construction. The largest container ships are now about 400 meters long and carry more than 24,000 containers, built in about a year.

Today. The Liberty ships’ lessons are now everyday engineering: steel is tested for toughness at its service temperature, corners are rounded, welds are inspected, and designs include ways for a crack to stop. Two Liberty ships, the SS *Jeremiah O’Brien* and SS *John W. Brown*, are still afloat as museum ships.

PICTURE STUDY



Fitting Out a Liberty Ship, U.S. government photograph, about 1942–1943 · Photograph · U.S. shipyard; National Archives

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

After launch, each Liberty ship was finished alongside a pier: engines, masts, winches and fittings were installed. This photograph shows the scale and speed of wartime shipbuilding.

Look closely

- Find the cranes. What do you think they are lifting?
- Look at the hull. Can you see rows of rivets, or smooth welded seams?
- Find the hatches on the deck. Are their corners square or rounded?
- Count the people you can see. How many workers might one ship need?

Talk about it

1. Why did welding let ships be built faster than riveting?
2. Why did square hatch corners become a problem in cold water?
3. What did shipbuilders change so that later welded ships did not crack?

Safety first. Wear safety glasses for every breaking test; cold plastic snaps and pieces can fly. Use only the freezer, the refrigerator and warm tap water for temperatures. An adult makes any notches with a craft knife.

BUILD

Cold-Brittleness and Block-Building Tests

You will test identical plastic spoons (or strips cut from one plastic lid) at four temperatures, with and without a notch, to see a ductile-to-brittle change and the effect of a stress concentration. Then you will compare two ways of building a cardboard hull: one piece at a time, or in prefabricated blocks.

You will need

- At least 16 identical plastic spoons or strips cut from the same plastic container (polystyrene works well)
- A freezer, a refrigerator, a bowl of warm tap water, a thermometer
- A protractor, a vise or a heavy book to clamp one end, pliers
- A craft knife (adult) for notches
- Card stock, tape and scissors for the block-building contest; a stopwatch
- Safety glasses

Steps

1. Label four sets of four spoons: freezer (about -18°C), refrigerator (about 4°C), room (about 20°C), and warm water (about 40°C). Have an adult cut a small notch in the middle of the handle of two spoons in each set.
2. Condition each set at its temperature for at least 30 minutes (keep the warm set in warm water until the moment of testing).
3. **Predict.** Which sets will snap and which will bend? Will the notch matter more in the cold?
4. **Fair test.** Clamp the bowl end of each spoon under the book at the table edge. Wearing safety glasses, bend the handle slowly with the pliers, measuring the angle at which it breaks (or note “bent without breaking” at 90°). Test quickly after removing each from its temperature. Record the angle and whether the break looked brittle (clean, shiny, flat) or ductile (whitened, stretched).
5. Make a table and graph of break angle against temperature, with separate lines for notched and plain spoons. Find your plastic’s “transition” range.

6. **Block contest.** Design a simple box-shaped cardboard hull 30 cm long made of six panels with two internal bulkheads. Team 1 (or you, the first time) builds it one piece at a time in order. Team 2 builds three blocks separately (bow, middle, stern, each with its bulkhead), then joins them. Time each method, including joining.
7. Check both hulls for accuracy (straight, square, no gaps) and float them with a load of pennies to test for leaks.
8. **Improve.** Change one thing in your block method (for example, add alignment marks, or prepare all parts before starting) and try again. Write what made the biggest difference.

Tips

- Bend at the same speed every time; a fast bend can make even a ductile plastic snap.
- Look closely at each broken edge with a magnifier. Brittle breaks are smooth and glassy; ductile ones are white and stretched.
- In the block contest, the joining step is where real shipyards spend great care: blocks must line up within millimeters.

Check your work

- ☐ I can explain brittle fracture, the transition temperature and stress concentrations.
- ☐ My data show how temperature and a notch changed the way the plastic broke.
- ☐ I can explain how block construction speeds up shipbuilding, and I tested it.

ENGINEER'S NOTEBOOK

1. Graph of break angle against temperature for notched and plain spoons, with the transition range marked.
2. Sketch a square hatch corner and a rounded one, and shade where stress concentrates in each.
3. Flow chart of modern block shipbuilding from CAD design to sea trials.
4. Solve: a hull plate has an average stress of 60 MPa. What is the stress at a corner with a stress concentration factor of 3.5? If the steel yields at 250 MPa, is it safe? What factor would make it safe with a margin of 1.5?

From history. Constance Tipper became the first woman to hold a full-time faculty post in Cambridge University's engineering department, and the Tipper test, a notched-bar test she developed, was used for years to qualify ship steel. Lloyd's Register, the first classification society, began in a London coffee house in the 1760s, recording the condition of ships for merchants and insurers.

COMMON MISTAKES

- Thinking welding itself was the mistake. Welding was a great advance; the problems came from steel that was brittle in the cold, sharp corners and weld defects.
- Believing that stronger always means tougher. A very hard, strong material can still be brittle.
- Forgetting that temperature matters. The same steel can be tough in summer and brittle in a winter sea.

Make it a game · Block Builders. Memory challenge. List from memory, in sixty seconds, everything that made Liberty ships fast to build and everything that made some of them crack. Your parent counts the correct ideas. Then act out a brittle fracture: crack a dry cracker or pasta stick, compare to a bent cooked noodle, and name the ductile-to-brittle idea aloud.

Scripture. “Make thee an ark of gopher wood; rooms shalt thou make in the ark, and shalt pitch it within and without with pitch. 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 6:14-15, KJV)

Noah was given a material, internal rooms, a waterproof coating and exact proportions: a ship specification. Good shipbuilding still begins with clear specifications faithfully followed.

SHIPS

You already know why ships float. This year you will learn what naval architects and marine engineers worry about once a ship is afloat: how to push it through the water with as little power as possible, how to make its propellers bite without destroying themselves, how to take a vessel to the deepest place in the ocean and bring it back, and how to build giant steel ships quickly and safely. You will meet William Froude and his towing tank, Charles Parsons and his record-breaking *Turbinia*, Jacques Piccard and Don Walsh in the bathyscaphe *Trieste*, and the shipyard workers and scientists of the Liberty ships.

Each lesson has real numbers: hull speed from wave physics ($v \approx 1.34\sqrt{L}$), drag and thrust, the pressure at the bottom of the Mariana Trench ($P = \rho gh$), Boyle's law, and the temperature at which steel turns brittle. Your builds include a rain-gutter towing tank, water boiling in a syringe at room temperature, a Boyle's-law pressure test and a cold-brittleness test, each with a fair test and an improvement round.

PREREQUISITES

- Knows Archimedes' principle and density (earlier grades)
- Can use $P = \rho gh$ and the idea of stress (Units 2 and 5)
- Knows Newton's third law and momentum (Unit 1)
- Can take square roots and work with scientific notation

MASTERY CHECKLIST

- ☐ I can explain wave-making and friction drag and calculate hull speed ($v \approx 1.34\sqrt{L}$ in knots and feet).
- ☐ I can explain how a bulbous bow reduces drag and how Froude used scale models.
- ☐ I can explain cavitation as boiling at low pressure and how propeller designers avoid it, and calculate thrust from $F = \dot{m}\Delta v$.
- ☐ I can calculate deep-sea pressure and the force on a window, use Boyle's law, and explain how the *Trieste* controlled its buoyancy.
- ☐ I can explain brittle fracture, the ductile-to-brittle transition and stress concentrations, and describe modern block shipbuilding.

OPTIONAL KITS FOR THIS UNIT

- **LEGO Technic:** Ages 9 and up. Technic motors, gears and propellers can drive model boats and a thrust stand for Lesson 6.2.
- **KiwiCo Tinker Crate:** Ages 9–16 (Tinker line). Some crates include hydraulic and boat projects that make good warm-ups for this unit.

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

LESSONS IN THIS UNIT

6.1 Drag, Hull Speed and the Bulbous Bow: Froude's Towing Tank

2 sessions of 60 minutes

6.2 Propellers and Cavitation: Parsons and the Turbinia

2 sessions of 60 minutes

6.3 Submarines and Pressure: The Trieste Reaches the Deepest Sea

2 sessions of 60 minutes

6.4 Modern Shipbuilding: Liberty Ships, Brittle Steel and the Block Method

2 sessions of 60 minutes

UNIT 6 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use $g = 9.8 \text{ m/s}^2$ and seawater density $1,025 \text{ kg/m}^3$. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Name the two main kinds of hull resistance and explain why wave drag rises so steeply near hull speed.

2. 10 pts

Calculation. Find the hull speed of a boat with a 49-foot waterline. If a ship needs 2,000 kW at 15 knots, about how much power does it need at 20 knots if power grows with speed cubed?

3. 8 pts

What was Froude's key idea for testing models, and how does a bulbous bow reduce drag?

4. 8 pts

Calculation. A propeller moves 800 kg of water per second and increases its speed by 5 m/s. What is the thrust?

5. 8 pts

Explain cavitation and give two ways propeller designers reduce it.

6. 8 pts

What problem did Parsons find with *Turbinia*, and how did he solve it?

7. 10 pts

Calculation. Find the water pressure (not counting air) at 6,000 m depth in MPa. What force acts on a window with area 0.02 m^2 ?

8. 8 pts

Calculation. A balloon holds 6.0 L of air at the surface (100 kPa). What is its volume at a total pressure of 400 kPa (about 30 m deep)?

9. 8 pts

Why did the *Trieste* use gasoline instead of air in its float, and what made its iron-shot ballast fail-safe?

10. 8 pts

Why were some Liberty ships and other welded ships of the 1940s prone to cracking in two?

11. 8 pts

What is a stress concentration, and why are hatch corners and airplane windows rounded?

12. 8 pts

Describe block construction in modern shipyards and give two reasons it is faster and safer than building a hull piece by piece.

ANSWER KEY

1. Friction (skin) drag and wave-making drag. Near hull speed the bow wave becomes as long as the hull, so the hull sits in its own trough and would have to climb its bow wave to go faster, which takes rapidly increasing energy.
2. $v \approx 1.34 \times \sqrt{49} = 1.34 \times 7 \approx 9.4$ knots. Power ratio = $(20 \div 15)^3 = 2.37$, so about 2,000 $\times 2.37 \approx 4,700$ kW.
3. A model and a ship make the same wave pattern at the same Froude number ($v \div \sqrt{gL}$), so model wave drag can be measured and scaled up, with friction drag handled separately. A bulbous bow makes its own wave whose crest falls in the bow wave's trough, partly canceling it at the design speed.
4. $F = \dot{m}\Delta v = 800 \times 5 = 4,000$ N.
5. Where water moves fast over the blade, pressure falls below the vapor pressure and the water boils into vapor bubbles, which collapse violently, damaging the metal and wasting thrust. Reduce it by more or wider blades (more area), slower rotation with larger diameter, carefully shaped and skewed blades, and placing propellers deeper.
6. Her single fast propeller cavitated and churned the water without pushing well. He studied it in the first cavitation tunnel and rebuilt her with three shafts carrying nine propellers, spreading the thrust over more blade area so she reached about 34 knots.
7. $P = \rho gh = 1,025 \times 9.8 \times 6,000 \approx 60,300,000$ Pa ≈ 60 MPa. $F = PA \approx 60,300,000 \times 0.02 \approx 1.2$ million N.
8. $P_1 V_1 = P_2 V_2$: $100 \times 6.0 = 400 \times V_2$, $V_2 = 1.5$ L.
9. Gasoline is lighter than water and hardly compresses, so it gives the same lift at any depth; air would be squeezed to a tiny volume. The shot was held by electromagnets, so if power failed, the shot would drop automatically and the vessel would rise.
10. Their steel became brittle at low temperatures (below its transition temperature); cracks started at stress concentrations such as square hatch corners and weld defects; and in an all-welded hull there were no riveted joints to stop a running crack.
11. A local increase in stress at a sharp corner, notch or crack. Rounding the corner spreads the stress more evenly, lowering the peak so cracks are less likely to start.

12. The ship is built as large steel blocks, each fitted with pipes, cables and paint, then lifted by cranes and welded together in a dry dock. Faster: many blocks are built at the same time; work is done indoors and at ground level where it is easier. Safer and better quality: less work at height or in cramped spaces; easier inspection of welds.

PORTFOLIO PIECE: A TANK-TESTED MODEL HULL

Design a model cargo hull to carry a set load (for example, 200 g of pennies) as fast as possible in your rain-gutter towing tank, using a fixed towing weight. Before building, draw the lines plan (side view, top view and three cross sections), calculate the model's hull speed, and predict its waterline from Archimedes' principle. Build at least two versions, one with a bulbous bow, and test each three times. Present a one-page engineer's report with drawings, data, a graph of speed against design, photographs of the wave patterns, and your recommendation, as a naval architect would present it to a ship owner.

LOOK FOR	WHAT IT MEANS
Lines plan	Side, top and section views drawn to scale with dimensions; predicted waterline and hull speed calculated.
Construction	Hulls of equal mass and load, smooth and symmetrical; bulb shaped and placed deliberately.
Fair testing	Same towing weight and distance; three runs per design; times and speeds recorded with units.
Analysis	Explains results using friction drag, wave drag, hull speed and the bulb's wave cancellation.
Recommendation	Clear, honest report with a specific recommendation and one further improvement.

UNIT 7

FLIGHT AND SPACE

Every flying machine is a set of trade-offs. A wing big enough to lift a slow, light human-powered airplane would be far too draggy for a jet airliner; a rocket powerful enough to reach the Moon must throw away most of itself on the way. In this unit you will use the lift equation and wing loading to compare aircraft as different as the pedal-powered *Gossamer Albatross* and the Boeing 747, follow Igor Sikorsky as he finally made the helicopter practical, and ride the Saturn V into orbit with Newton's laws and a little orbital mechanics.

The unit ends with the newest flying machines most of you will actually handle: drones. You will learn how four spinning rotors and a fast feedback loop keep a quadcopter steady, how NASA flew a helicopter on Mars, and the FAA rules every recreational pilot must follow. Builds include gliders with measured wing loading, paper rotors and a torque test, a water-bottle rocket flown with an adult, and a rotor thrust stand.

PREREQUISITES

- Knows the four forces of flight and that a wing turns air downward (earlier grades)
- Knows Newton's three laws, momentum and $F = \dot{m}\Delta v$ (Units 1 and 6)
- Can use square roots, exponents and scientific notation
- Knows wind pressure $q = \frac{1}{2}\rho v^2$ (Unit 3)

MASTERY CHECKLIST

- ☐ I can use the lift equation ($L = \frac{1}{2}\rho v^2 SC$) and calculate wing loading and stall speed, and explain design trade-offs between slow and fast aircraft.
- ☐ I can explain how a helicopter's collective, cyclic and tail rotor control it, and why helicopters have large rotors.
- ☐ I can calculate rocket thrust ($F = \dot{m}v$) and orbital speed ($v = \sqrt{GM \div r}$), and explain why rockets use stages.
- ☐ I can explain how a quadcopter controls pitch, roll and yaw with rotor speeds and a feedback loop.
- ☐ I can state the FAA rules for recreational drone flying and plan a safe, legal flight.

OPTIONAL KITS FOR THIS UNIT

- **Estes model rockets**: Grades 6–8 only, with an adult, outdoors in an open field, following the National Association of Rocketry Model Rocket Safety Code. Starter sets with a launch pad and controller are a step up from the water rocket in Lesson 7.3.
- **Ryze Tello drone**: Ages 13 and up with an adult. A small indoor drone under 250 grams that can be programmed with block code or Python; fits Lesson 7.4. Follow the FAA rules in that lesson whenever you fly outdoors.
- **LEGO Technic**: Ages 9 and up. Technic sets with rotor and swashplate mechanisms show helicopter controls clearly (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 Aircraft Design Trade-offs: Wing Loading from the Gossamer Albatross to the 747

2 sessions of 60 minutes

7.2 Helicopters: Sikorsky and the Rotating Wing

2 sessions of 60 minutes

7.3 Rocketry and Orbits: Apollo and the Saturn V

2 sessions of 60 minutes

7.4 Drones and FAA Rules: Four Rotors and a Feedback Loop

2 sessions of 60 minutes

UNIT 7 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use $g = 9.8 \text{ m/s}^2$ and $\rho = 1.225 \text{ kg/m}^3$ at sea level. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Write the lift equation and name each term. Which term did MacCready make very large to allow human-powered flight?

2. 10 pts

Calculation. An airplane weighs 12,000 N with a wing area of 15 m^2 . Find its wing loading and its stall speed if $C_{L,\max} = 1.5$.

3. 8 pts

Give two advantages and two disadvantages of a high wing loading.

4. 8 pts

Explain what the collective, the cyclic and the tail rotor each do.

5. 8 pts

Why do helicopters have long rotor blades? Use momentum theory in your answer.

6. **10 pts**

Calculation. A rocket engine burns 300 kg of propellant per second with an exhaust speed of 3,000 m/s. Find its thrust. Can it lift a rocket with a mass of 80,000 kg off the pad?

7. **10 pts**

Calculation. Find the orbital speed and period of a satellite 600 km above Earth (Earth radius 6,371 km, $GM = 3.99 \times 10^{14} \text{ m}^3/\text{s}^2$).

8. **8 pts**

Why does a rocket use stages? Why was the F-1 engine's combustion instability such a serious problem, and how did engineers solve it?

9. **8 pts**

Describe how a quadcopter yaws (turns its nose) without tilting.

10. **6 pts**

Calculation. A drone has a mass of 0.80 kg. What total thrust must its four rotors make to hover, and to climb with an acceleration of 1.5 m/s^2 ?

11. **8 pts**

List five FAA rules a recreational drone pilot in the United States must follow.

12. **8 pts**

Write a short paragraph: How does a feedback loop keep a drone steady, and what happens if the controller is tuned too strongly?

ANSWER KEY

1. $L = \frac{1}{2}\rho v^2 S C_L$: air density ρ , airspeed v , wing area S , lift coefficient C_L . He made the wing area S very large for a very light aircraft, giving very low wing loading so it could fly slowly on little power.
2. $W \div S = 12,000 \div 15 = 800 \text{ N/m}^2$. $v_s = \sqrt{(2 \times 800 \div (1.225 \times 1.5))} = \sqrt{(1,600 \div 1.84)} \approx \sqrt{871} \approx 29.5 \text{ m/s}$.
3. Advantages: faster cruise; smaller, lighter, less draggy wing; smoother ride in gusts. Disadvantages: higher stall and landing speeds; longer runways; needs flaps and slats (any two each).
4. Collective changes the pitch of all main blades together to raise or lower lift. Cyclic changes each blade's pitch as it goes around, tilting the rotor disk to move the helicopter in a direction. The tail rotor cancels the main rotor's torque reaction and lets the pilot turn (yaw).
5. Hover power $P = T^{3/2} \div \sqrt{(2\rho A)}$ falls as the rotor disk area A grows. A larger rotor moves more air more slowly to make the same thrust, which takes less power; halving the rotor diameter would double the power needed.
6. $F = \dot{m}v_e = 300 \times 3,000 = 900,000 \text{ N}$. Weight = $80,000 \times 9.8 = 784,000 \text{ N}$. Thrust is larger, so yes, it can lift off (net force 116,000 N upward).
7. $r = 6.971 \times 10^6 \text{ m}$. $v = \sqrt{(3.99 \times 10^{14} \div 6.971 \times 10^6)} \approx \sqrt{(5.72 \times 10^7)} \approx 7,560 \text{ m/s}$. $T = 2\pi r \div v \approx 4.38 \times 10^7 \div 7,560 \approx 5,790 \text{ s} \approx 97 \text{ minutes}$.
8. Dropping empty stages means the remaining engines do not waste thrust pushing empty tanks, so the rocket can reach a higher final speed. Unstable combustion shook engines apart in a fraction of a second; engineers deliberately disturbed the flame in test engines and redesigned the injector with baffles and new hole patterns until the engine damped disturbances on its own.
9. It speeds up the two rotors that spin one way and slows the two that spin the other way. Total lift stays the same, but the torques no longer cancel, so the reaction torque turns the drone.
10. Hover: $T = mg = 0.80 \times 9.8 = 7.84 \text{ N}$ (1.96 N per rotor). Climb: $T = m(g + a) = 0.80 \times 11.3 = 9.04 \text{ N}$.
11. Any five: pass TRUST and carry proof; register a drone of 250 g or more and mark it (and broadcast Remote ID if registered); fly at or below 400 ft in uncontrolled airspace; get authorization before flying in controlled airspace near airports; keep the drone in visual line of sight; do not fly over people or

moving vehicles; do not interfere with manned aircraft or emergency operations; fly only for recreation (commercial flying requires Part 107).

12. The IMU measures tilt many times a second; the controller compares it with the wanted tilt and changes each motor's speed to correct the error, repeating continuously. If tuned too strongly, it over-corrects and the drone oscillates or shakes; too weakly, it drifts and responds slowly.

PORTFOLIO PIECE: A MISSION-DESIGNED GLIDER

Choose a mission for a hand-launched glider: the longest time aloft from a 2 m launch, or the farthest distance, or carrying a payload of 5 paper clips as far as possible. Before building, calculate your planned wing area, mass, wing loading and expected glide speed, and choose an aspect ratio with reasons. Build it, trim it, and test it at least ten times, changing only one thing between rounds. Present a design report with a three-view drawing, the calculations, a data table and graph, photographs, and a final paragraph explaining the trade-offs you made, as an aircraft designer would present to a customer.

LOOK FOR	WHAT IT MEANS
Mission and calculations	Mission stated clearly; wing area, mass, wing loading and expected speed calculated with units; aspect ratio chosen with reasons.
Drawing and construction	Neat three-view drawing with dimensions; straight, symmetrical glider that matches the drawing.
Testing and data	At least ten flights recorded with one variable changed at a time; table and graph with units.
Trade-off analysis	Explains using the lift equation and wing loading why the final design suits its mission and what it gave up.
Improvement	At least one improvement made from test data, with before-and-after results.

7.1 AIRCRAFT DESIGN TRADE-OFFS: WING LOADING FROM THE GOSSAMER ALBATROSS TO THE 747

OBJECTIVES

- Use the lift equation to explain how speed, air density, wing area and lift coefficient set how much a wing can lift.
- Calculate wing loading and stall speed for real aircraft and explain the trade-offs of high and low wing loading.
- Fly gliders of different wing loading in a fair test and measure how glide speed changes.

Warm-up. Make two identical paper airplanes. Tape four paper clips to the nose of one, centered. Before you throw, predict: which will glide faster? Which will glide farther? Throw each gently and level from the same height three times. Record what happens. Did adding weight change the speed, the distance, or both?

WATCH

How to design an aircraft: Wing Loading

Aircraft Design Toolbox • 3:34

<https://www.youtube.com/watch?v=yA0x3K98Es8>

WHEN TO WATCH

After the physics paragraph. Write down the formula for stall speed shown in the video and compare it with ours.

Note: A small channel from a model-aircraft designer; clear slides and correct formulas.

BACKUP VIDEO

Paul MacCready - Gossamer Albatross

Academy of Achievement • 3:37

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

With the story paragraph: film of the English Channel crossing in 1979.

KEY TERMS

lift equation

$L = \frac{1}{2}\rho v^2 SC_L$, where ρ is air density, v is airspeed, S is wing area and C_L is the lift coefficient (set by wing shape and angle of attack).

stall speed

The slowest speed at which the wing can still make enough lift to hold the aircraft up: $v_s = \sqrt{2W \div (\rho SC_{L,max})}$.

trade-off

A choice in which improving one thing (such as speed) makes another worse (such as takeoff distance).

wing loading

An aircraft's weight divided by its wing area, $W \div S$, in N/m^2 or pounds per square foot.

aspect ratio

Wingspan squared divided by wing area. Long, narrow wings (high aspect ratio) make less drag for the lift they produce.

Kremer Prize

A prize offered in 1959 by industrialist Henry Kremer for the first human-powered aircraft to fly a figure-eight course around two markers half a mile apart.

CORE IDEAS

The story. For nearly twenty years after the Kremer Prize was offered in 1959, teams around the world built human-powered airplanes, and none could fly the figure-eight course. In 1976 Paul MacCready, an American aeronautical engineer, started over with a different idea. He reasoned that if an airplane were very large and very light, it would fly so slowly that one person pedaling could keep it up. His *Gossamer Condor*, built of thin aluminum tubes, piano wire and clear plastic film, had a wingspan of about 96 feet but weighed only about 70 pounds. On August 23, 1977, the cyclist and hang-glider pilot Bryan Allen pedaled it around the course in California and won the prize. On June 12, 1979, Allen pedaled its successor, the *Gossamer Albatross*, across the English Channel in just under three hours.

How they figured it out. MacCready's real breakthrough was in the design process. Earlier teams had built beautiful, carefully crafted aircraft that took months to repair after a crash. MacCready designed the *Condor* to be easy to fix: when it crashed, the team could rebuild it in hours or days and fly again. They made hundreds of test

flights, changing one thing at a time, learning from every failure. He later said the problem was not building one perfect airplane but learning fast. That habit, quick prototypes and many tests, is now how engineers design everything from drones to software.

The physics. In level flight lift equals weight: $W = \frac{1}{2}\rho v^2 S C_L$. Rearranged, the speed needed is $v = \sqrt{(2(W \div S) \div (\rho C_L))}$, so the key number is the **wing loading**, $W \div S$.

Worked examples: a Cessna 172 weighs about 2,400 lb with 174 ft² of wing, a wing loading of about 14 lb/ft². A Boeing 747-400 at maximum takeoff weight, about 875,000 lb on 5,650 ft² of wing, carries about 155 lb/ft², eleven times as much. The *Gossamer Albatross* with its pilot weighed about 100 kg (about 220 lb) on roughly 45 m² (about 490 ft²) of wing: less than half a pound per square foot. In metric units: for the Cessna, $W \approx 10,700$ N and $S \approx 16.2$ m²; with $\rho = 1.225$ kg/m³ and $C_{L,max} \approx 1.6$, $v_s = \sqrt{(2 \times 10,700 \div (1.225 \times 16.2 \times 1.6))} \approx 26$ m/s (about 50 knots). For the *Albatross*, with $W \approx 930$ N, $S \approx 45$ m² and $C_L \approx 1.2$, $v \approx \sqrt{(2 \times 930 \div (1.225 \times 45 \times 1.2))} \approx 5.3$ m/s, about a fast jogging pace.

The engineering. Wing loading drives many other choices. **Low wing loading** (large wing for the weight) means slow flight, short takeoffs and landings, and good climbing, but a bumpy ride in gusts, more drag at high speed and a large, heavy structure. **High wing loading** means a small, efficient wing for fast cruise and a smooth ride, but long runways and high landing speeds, so airliners add slats and flaps that enlarge the wing and raise C_L for takeoff and landing. Designers also choose aspect ratio (gliders and the *Albatross* have long, narrow wings for low drag; fighters have short wings for strength and roll rate), and they balance structural weight, fuel, payload and cost. Every airplane is a set of compromises chosen for its mission.

Try it. In your build you will add paper clips to a glider to change only its wing loading. The lift equation predicts that glide speed should grow with the square root of wing loading.

PICTURE STUDY



The Gossamer Albatross II in Flight, NASA Dryden Flight Research Center, 1980 · Photograph · NASA, Edwards, California

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

After the Channel crossing, a second *Albatross* was flown by NASA to study very slow, very light flight. Notice how much wing there is for so little airplane.

Look closely

- Find the pilot. How big is he compared with the wing?
- Find the propeller. Where is it, and what turns it?
- Look at the wing's structure through the clear covering. What holds it in shape?
- Find the small wing in front (the canard). What do you think it is for?

Talk about it

1. Why does such a large wing allow a person to fly by pedaling?
2. What would happen to this aircraft in a gusty wind? Why did they fly early in the morning?
3. What did MacCready trade away to get such a low wing loading?

Safety first. Throw gliders only where nobody can be hit, away from windows, and never toward faces. Wear safety glasses if you use a rubber-band launcher.

BUILD

The Wing-Loading Glider Test

You will build a simple glider from a foam meat tray or foam plate (or card stock), measure its wing area and mass, and add paper clips to change its wing loading. You will launch it the same way each time from a fixed height and measure glide speed and distance.

You will need

- Clean foam trays or foam plates (or card stock), a ruler, a pencil and scissors
- Paper clips (weigh 10 together to find one clip's mass) and a kitchen scale
- Modeling clay for balance, tape, a tape measure and a stopwatch or phone video
- A launch spot such as a landing or a step stool (with an adult), in a large room or a calm outdoor area

Steps

1. Cut a glider with a straight wing (for example, 30 cm span $\times$ 6 cm chord), a fuselage strip and a tail. Calculate the wing area S in m^2 . Add clay to the nose until it glides smoothly. Weigh it and calculate the wing loading $W \div S$ in N/m^2 .
2. Choose a fixed launch height (for example, 1.5 m) and a gentle, level launch. Practice until the flights are consistent.
3. **Predict.** If you double the wing loading, by what factor should the glide speed change? (Hint: $v \propto \sqrt{(W \div S)}$.)
4. **Fair test.** Fly the glider with 0, 2, 4 and 8 paper clips taped at the balance point (so the balance does not change). For each, fly five times. Measure the distance flown and the time in the air, and calculate the average glide speed (distance $\div$ time).
5. Make a table: number of clips, mass (g), wing loading (N/m^2), average distance (m), average time (s), speed (m/s).

6. Graph speed against $\sqrt{(\text{wing loading})}$. Is it close to a straight line? Did distance change much?
7. **Wing area test.** Build a second glider with the same mass but a wing 50% larger. Predict and test its glide speed.
8. **Improve.** Design a glider for one mission: the longest time aloft, or the fastest flight to a target 5 m away. Explain your wing loading and aspect ratio choices and test it.

Tips

- Tape added weight exactly at the balance point; weight placed forward or back changes the trim and spoils the fair test.
- Indoors with no drafts gives the most consistent flights.
- The glide ratio (distance $\div$ height) should stay roughly the same as you add weight, even though speed rises. Gliders carry water ballast for that reason.

Check your work

- ☐ I can calculate wing loading and stall speed with units.
- ☐ My data show glide speed rising as wing loading rose, and I compared it with the lift equation.
- ☐ I can explain the trade-offs between low and high wing loading.

ENGINEER'S NOTEBOOK

1. Top-view sketch of your glider with dimensions and wing area calculation.
2. Data table and graph of speed against $\sqrt{(\text{wing loading})}$.
3. Make a comparison chart: *Gossamer Albatross*, Cessna 172, Boeing 747: weight, wing area, wing loading, cruise speed, runway needed.
4. Solve: a glider weighs 3,500 N with 14 m² of wing. Find its wing loading and stall speed if $C_{L,\text{max}} = 1.4$.

From history. MacCready's team went on to build the *Gossamer Penguin* and the *Solar Challenger*, which crossed the English Channel on sunlight alone in 1981, and his company later built solar-powered and long-endurance aircraft for NASA. The *Gossamer Condor* hangs in the Smithsonian National Air and Space Museum near the Wright brothers' Flyer.

COMMON MISTAKES

- Thinking a heavier glider always glides a shorter distance. It glides faster at about the same angle, so distance changes little.
- Mixing pounds-force and kilograms in wing loading. Use newtons with square meters, or pounds with square feet.
- Believing bigger wings are always better. They add weight and drag; the right size depends on the mission.

Make it a game · Wing-Loading Trade. Draw a quick table with four aircraft you choose, from a glider to a jet. Guess each one's wing loading, in order from lowest to highest, then calculate for two of them. Your parent grades your order. Finish by explaining one trade-off of high wing loading, like higher stall speed, in a single sentence.

Scripture. “Doth the hawk fly by thy wisdom, and stretch her wings toward the south?” (Job 39:26, KJV)

God asked Job whether the hawk’s flight came from human wisdom. The best human aircraft are still humble copies of the wings God designed.

7.2 HELICOPTERS: SIKORSKY AND THE ROTATING WING

OBJECTIVES

- Explain how a rotor makes lift and how the collective, cyclic and tail rotor control a helicopter.
- Explain torque reaction with Newton's third law and estimate the power needed to hover using momentum theory.
- Test paper rotors in a fair test of blade length, and show torque reaction with a hanging motor.

Warm-up. Sit on a spinning office chair with your feet off the floor, holding a heavy book. Swing the book quickly to your right. Which way does your chair turn? Write a sentence explaining why with Newton's third law. Then think: what would happen to a helicopter body if its rotor were spun by an engine inside it?

WATCH

Igor Sikorsky's First Successful Helicopter | The Henry Ford's Innovation Nation

The Henry Ford • 4:23

<https://www.youtube.com/watch?v=-OGDVyj9mrY>

WHEN TO WATCH

After the story. This is the actual VS-300, which hangs in The Henry Ford museum.

BACKUP VIDEO

How helicopter controls work

Micah Muzio • 6:47

<https://www.youtube.com/watch?v=r0A5ig39yg0>

After the physics paragraph: a pilot shows the collective, cyclic and pedals from the cockpit while hovering.

KEY TERMS

rotor

The set of spinning blades on a helicopter. Each blade is a long, narrow wing.

cyclic

The control that changes each blade's pitch as it goes around, tilting the rotor disk so the helicopter moves forward, back or sideways.

torque reaction

The equal and opposite twist on the helicopter body when the engine turns the rotor (Newton's third law). The tail rotor cancels it.

collective

The control that changes the pitch (angle) of all main-rotor blades together, raising or lowering total lift.

swashplate

The mechanism of two linked plates below the rotor that passes the collective and cyclic commands to the spinning blades.

autorotation

Gliding descent with the engine off, in which upward airflow keeps the rotor spinning so the pilot can land safely.

CORE IDEAS

The story. As a young man in Kiev, Igor Sikorsky built two helicopters in 1909 and 1910. Neither could lift a pilot. He turned to airplanes and in 1913 built the world's first four-engine airplane, the *Russky Vityaz*. After the upheavals of 1917 in Russia he came to the United States in 1919 with almost nothing, started a company, and built famous flying boats. He never forgot the helicopter. In 1939 his VS-300, an open frame of steel tubes with a single main rotor and a small tail rotor, made its first tethered hop on September 14. On May 13, 1940, it made its first free flight, and on May 6, 1941, it set a world endurance record of 1 hour 32 minutes. Sikorsky, a devout Christian who wrote books about the Lord's Prayer, often said the helicopter's greatest work would be saving lives, and it has been: in rescues at sea, on mountains and in floods.

How they figured it out. The VS-300 flew in many forms. At first it would fly sideways and backward well but did not want to fly forward; Sikorsky joked that it flew every direction except the one he wanted. He and his engineers tried one, two and three tail rotors, auxiliary rotors on outriggers and different control linkages, flying, measuring and rebuilding again and again, with Sikorsky himself at the controls in

his felt hat. In the end they settled on one main rotor with cyclic and collective control and one tail rotor for torque and direction, the layout that most helicopters still use. Its success led to the R-4, the first mass-produced helicopter, in 1942.

The physics. A rotor blade makes lift like a wing; because it spins, it meets fast air even when the helicopter hovers. By Newton's third law the rotor pushes air down and the air pushes the rotor up. When the engine spins the rotor one way, the body tries to spin the other way, the torque reaction, so a tail rotor pushes sideways to stop it. In forward flight the blade moving forward (advancing) meets faster air than the blade moving backward (retreating), so blades are hinged or flexible and change pitch as they go around to even out the lift. Momentum theory estimates the ideal power to hover: $P = T^{3/2} \div \sqrt{(2\rho A)}$, where T is thrust and A is the rotor disk area. Worked example: a 1,000 kg helicopter ($T \approx 9,800$ N) with a rotor 10 m across ($A = \pi \times 5^2 \approx 78.5$ m²) needs $P \approx 9,800^{1.5} \div \sqrt{(2 \times 1.225 \times 78.5)} \approx 970,000 \div 13.9 \approx 70,000$ W (70 kW, about 94 horsepower) in an ideal world; real helicopters need roughly half again as much. With a rotor half as wide, the area would be one-quarter and the power twice as great. That is why helicopters have long blades.

The engineering. Helicopter engineers balance rotor size, blade speed (tip speed must stay well below the speed of sound), weight, vibration and noise. The swashplate passes the pilot's commands to blades turning hundreds of times a minute, and every bearing, link and blade must resist fatigue from millions of load cycles, so parts are given strict replacement times and frequent inspections. Some designs avoid a tail rotor with two rotors turning opposite ways, either one above the other (coaxial) or front and back (tandem, like the Chinook). Because they can hover and land almost anywhere, helicopters serve as air ambulances, rescue craft, firefighting aircraft and cranes.

Try it. A paper rotor falling through the air is a helicopter in autorotation: the air flowing up through it spins the blades, and the spinning blades make lift that slows the fall.

PICTURE STUDY



Igor Sikorsky Flying the VS-300, Unknown photographer, about 1940–1941 · Photograph · Stratford, Connecticut

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

The VS-300 flew in many versions as Sikorsky tested and rebuilt it. Here it has a small fabric-covered nose and floats. Sikorsky usually flew it himself in his hat.

Look closely

- Find the main rotor and count its blades.
- Find the tail boom and the small rotors at its end. Which way must they push to stop the body from turning?
- Find the floats. Why might a helicopter be built to land on water?
- Look at the lattice frame of the tail. Why use a frame of thin tubes instead of a solid boom?

Talk about it

1. Why does a helicopter with one main rotor need a tail rotor?
2. Why would an open frame be a good choice for an experimental machine that was rebuilt many times?
3. What jobs can a helicopter do that an airplane cannot?

Safety first. Drop paper rotors from a landing or a sturdy step stool only with an adult holding it, never from a railing or window. Keep fingers away from spinning propellers, and use only batteries for the motor.

BUILD

Paper Rotors and the Torque Test

You will make paper rotors (rotocopters), drop them from a fixed height, and run a fair test of blade length. Then you will hang a battery-powered motor and propeller from a thread to see torque reaction, and design a fix like a tail rotor.

You will need

- Card stock or printer paper, scissors, a ruler and paper clips
- A tape measure, a stopwatch or phone, and a safe place to drop from about 2–2.5 m
- A small hobby motor with a propeller, a 1-AA or 2-AA battery holder, tape and a craft stick
- A 1 m length of thread, and card stock for “tail” fins

Steps

1. Cut paper rotors from a template: a strip with two blades at the top and a folded stem with one paper clip at the bottom. Make blade lengths of 4, 6, 8 and 10 cm with the same width and stem.
2. **Predict.** Which will fall slowest? Write your reasoning.
3. **Fair test.** Drop each rotor from the same height (measure it) five times and time each fall. Calculate the average descent speed (height $\div$ time).
4. Make a table and graph descent speed against blade length (or against blade area). Describe the pattern. Is there a best length, after which longer blades bend or wobble?
5. Test the best rotor with 1, 2 and 3 paper clips. Use $T \approx \text{weight}$ to explain why the rotor must fall faster to hold up more weight.
6. **Torque test.** Tape the motor and battery holder to a craft stick so the propeller faces down and the whole unit is balanced. Hang it from the thread by its middle. Switch on the motor and watch the stick: which way does it turn compared with the propeller?
7. **Improve.** Stop the stick from spinning by adding a card-stock fin in the propeller’s downwash, or a second motor and propeller spinning the other

way. Explain which helicopter design (tail rotor, coaxial, tandem) your fix resembles.

Tips

- Crease the blades in opposite directions so the rotor spins steadily.
- Drop rotors in still air; even a small draft changes the time.
- Film the drops in slow motion to see how long the rotor takes to start spinning.

Check your work

- ☐ I can explain how collective, cyclic and the tail rotor control a helicopter.
- ☐ My data show how blade length changed descent speed, and I can explain autorotation.
- ☐ I showed torque reaction and fixed it, and I can explain why helicopters have large rotors.

ENGINEER'S NOTEBOOK

1. Labeled diagram of a helicopter: main rotor, swashplate, tail rotor, engine, transmission, with arrows for lift, weight and torque reaction.
2. Paper-rotor data table and graph.
3. Top-view sketch of a rotor in forward flight showing the advancing and retreating blades and their relative airspeeds.
4. Solve: using $P = T^{3/2} \div \sqrt{(2\rho A)}$, find the ideal hover power for a 2,000 kg helicopter with a rotor 12 m across.

From history. In 1944 a Sikorsky R-4 made one of the first helicopter rescues, carrying injured men out of the jungle in Burma, and in 1945 a Sikorsky helicopter made the first hoist rescue, lifting two men from a stranded oil barge in Long Island Sound. Sikorsky lived until 1972 and saw helicopters save many thousands of lives.

COMMON MISTAKES

- Thinking the tail rotor is mainly for steering forward flight. Its first job is to cancel the main rotor's torque; it also lets the pilot turn by pushing more or less.
- Believing a helicopter falls like a stone if its engine stops. In autorotation the rotor keeps spinning and the pilot can land.

- Confusing collective and cyclic. Collective changes all blades together (up and down); cyclic changes them as they go around (tilting the disk).

Make it a game • Helicopter Charades. Charades without speaking. Act out the collective, the cyclic, the tail rotor, torque reaction and autorotation using your arms and body. Your parent guesses each one and then must explain in one sentence what that control does. Swap roles. Score a point for each correct guess and each correct explanation. First to eight wins.

7.3 ROCKETRY AND ORBITS: APOLLO AND THE SATURN V

OBJECTIVES

- Calculate rocket thrust ($F = \dot{m}v_e$) and explain why rockets use stages, using the rocket equation in words.
- Explain an orbit with Newton's cannonball and calculate orbital speed and period ($v = \sqrt{GM \div r}$, $T = 2\pi r \div v$).
- Fly a water-bottle rocket with an adult in a fair test of water volume and estimate its height from flight time.

Warm-up. Stand outside and throw a ball level, softly, then harder, then as hard as you can (in an open area). Each time it lands farther away. Now imagine throwing it so hard that the ground curves away beneath it as fast as it falls. Sketch what would happen. You have just drawn Isaac Newton's idea of an orbit from 1687.

WATCH

How the Apollo Spacecraft works: Part 1

Jared Owen · 3:39

<https://www.youtube.com/watch?v=8dpkmUjJ8xU>

WHEN TO WATCH

Before the engineering paragraph. Name each stage and its engines as they fall away.

BACKUP VIDEO

The Only Video Needed to Understand Orbital Mechanics

Animations Xplained · 7:38

<https://www.youtube.com/watch?v=bcvnfQlz1x4>

After the physics paragraph: why a spacecraft must slow down to speed up in orbit.

KEY TERMS

thrust

The force a rocket engine makes by throwing exhaust backward: $F = \dot{m}v_e$, mass flow rate times exhaust speed.

exhaust velocity

How fast the hot gases leave the nozzle. Higher exhaust velocity means more push from each kilogram of propellant.

staging

Building a rocket in sections that drop off when their propellant is used up, so the rest does not carry empty tanks.

orbit

The curved path of an object that is falling around a planet while moving sideways fast enough that the surface curves away beneath it.

orbital speed

The speed needed for a circular orbit: $v = \sqrt{GM \div r}$. For low Earth orbit it is about 7.8 km/s.

rocket equation

$\Delta v = v_e \ln(m_{\text{full}} \div m_{\text{empty}})$: the change in speed a rocket can reach depends on exhaust speed and how much of the rocket is propellant.

CORE IDEAS

The story. The Saturn V was the largest rocket ever flown when it was built: 363 feet tall, weighing about 6.2 million pounds when fueled. Its first stage had five F-1 engines that together produced about 7.5 million pounds of thrust. Between 1967 and 1973 it flew thirteen times. On December 21, 1968, a Saturn V launched Apollo 8, and Frank Borman, Jim Lovell and Bill Anders became the first people to leave Earth's orbit and circle the Moon. On Christmas Eve, as they orbited the Moon, they took turns reading to the world the first ten verses of Genesis. In July 1969 another Saturn V carried Apollo 11, and Neil Armstrong and Buzz Aldrin walked on the Moon.

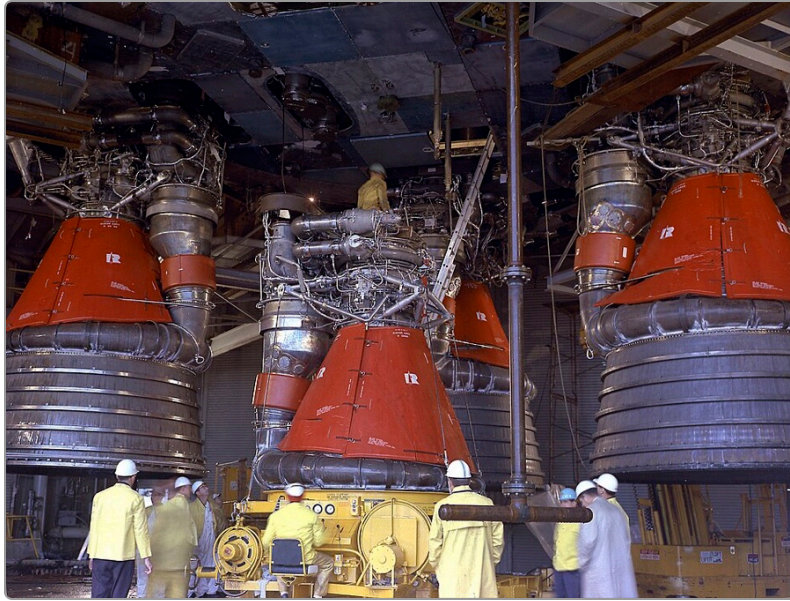
How they figured it out. The F-1 engine nearly stopped the program. In early tests, the burning in its huge combustion chamber became unstable, shaking violently and destroying engines in less than a second. Engineers at Rocketdyne and NASA could not wait for the problem to happen by chance, so they set off small charges inside test engines on purpose to disturb the flame, then measured how quickly the engine recovered. They tried design after design of the injector plate (which sprays in the fuel and oxygen), adding baffles and changing hole patterns, until the engine damped any disturbance on its own within a fraction of a second. NASA manager George Mueller also made a bold decision called “all-up” testing: rather than testing one stage at a time, the very first Saturn V flight in November 1967 flew all three live stages together. It worked, and it saved many months.

The physics. A rocket pushes its exhaust backward, and the exhaust pushes the rocket forward (Newton's third law). Thrust is $F = \dot{m}v_e$. Worked example: each F-1 engine burned about 2,600 kg of kerosene and liquid oxygen each second, with an exhaust speed of about 2,600 m/s at sea level, so $F \approx 2,600 \times 2,600 \approx 6.8$ million N per engine. Five engines gave about 34 million N, about 7.5 million pounds. To stay in orbit, a spacecraft must move sideways fast enough: $v = \sqrt{GM \div r}$, where GM for Earth is $3.99 \times 10^{14} \text{ m}^3/\text{s}^2$. At 200 km altitude, $r = 6,371 \text{ km} + 200 \text{ km} = 6.57 \times 10^6 \text{ m}$, so $v = \sqrt{(3.99 \times 10^{14} \div 6.57 \times 10^6)} \approx 7,800 \text{ m/s}$, about 17,500 mph. One orbit takes $T = 2\pi r \div v \approx 2\pi \times 6.57 \times 10^6 \div 7,800 \approx 5,300 \text{ s}$, about 88 minutes.

The engineering. The rocket equation explains why the Saturn V was so huge and why it had three stages. To reach orbit a rocket needs about 9.4 km/s of Δv (orbital speed plus losses to gravity and air), and with exhaust speeds of 2.6–4.2 km/s, most of the rocket must be propellant. Dropping each empty stage means the next engines push less dead weight. The Saturn V's first stage burned for about 2½ minutes and lifted the rocket about 40 miles high; the second and third stages used liquid hydrogen, which gives a higher exhaust speed. Every one of its millions of parts had to work, so engineers used careful testing, redundancy where possible, and detailed records of every part and every test.

Today. Modern rockets land and reuse their first stages, which changes the economics of spaceflight, but they still obey the same equations, and engineers still test engines on the ground long before anyone rides on them.

PICTURE STUDY



F-1 Engines Being Installed on a Saturn V, NASA, 1960s · Photograph · NASA

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

Each F-1 engine stood about 19 feet tall, and five were mounted at the base of the Saturn V's first stage. Look at the people for scale.

Look closely

- Find the workers. How many times taller is one engine nozzle than a person?
- Count the engines you can see. Where is the fifth one placed?
- Look at the tubes running around the nozzles. Some carried cold fuel to cool the nozzle walls.
- Find the thrust structure above the engines. What load does it carry?

Talk about it

1. The five engines pushed with about 34 million newtons. Through what part of the rocket must that force be carried to lift the whole vehicle?
2. Why would engineers test each engine on the ground many times before flight?
3. Why do you think four of the engines could swivel but the center one was fixed?

Safety first. Water rockets must be flown outdoors in a large open field with an adult in charge, far from people, roads, trees and power lines. Wear safety glasses; stand to the side, never over the rocket. Use only air pressure (a bicycle pump), never more than about 60 psi, and only plastic soda bottles made for carbonated drinks. Never use chemical reactions, fire or model rocket motors without an adult and the NAR safety code.

BUILD

Water-Bottle Rocket Fair Test

You will fly a water rocket made from a 2-liter soda bottle and launched with a bicycle pump, run a fair test of how much water to load, and estimate the height reached from the time of flight, with an adult in charge of the launch.

You will need

- Several clean 2-liter carbonated-drink bottles, card stock for fins and a nose cone, duct tape
- A launcher: a rubber stopper or cork that fits the bottle mouth, drilled by an adult to hold a ball-inflation needle, and a bicycle pump with a pressure gauge (or a purchased water-rocket launcher)
- A measuring cup, a stopwatch, a tape measure and safety glasses
- A large open field and an adult launch director

Steps

1. Add three or four fins near the bottle's neck (which becomes the bottom) and a cone on the base (the top). Check that the rocket is straight and balanced.
2. **Predict.** Which water volume will fly highest: 0 mL, 250 mL, 500 mL, 750 mL or 1,000 mL? Explain using $F = mv_e$ and the weight of the water.
3. With the adult in charge, load the water, insert the stopper, set the rocket on its stand pointing straight up, and pump to the same pressure each time (for example, 40 psi). Everyone stands back and the adult counts down.
4. Time the whole flight from launch to landing. If drag is small, height $\approx g t^2 \div 8$ (because the rocket spends half the time going up). Record three flights for each water volume.
5. Make a table: water volume, flight time (average of three), estimated height. Graph height against water volume. Find the best volume.
6. Discuss why too little water gives little thrust and too much water is heavy to lift. Connect this to the rocket equation.
7. **Staging thought experiment.** Sketch how a two-stage water rocket could work, and explain why dropping the empty first bottle would help.

8. **Improve.** Change one feature (fin size, nose weight or nozzle shape) and fly it at the best water volume. Compare the flight time.

Tips

- Stop at the pressure the adult sets, every time; pressure is the variable you are holding constant.
- A little modeling clay in the nose cone makes the rocket fly straighter, like moving a dart's weight forward.
- Check bottles for scratches or dents and retire any that look damaged.

Check your work

- ☐ I can calculate rocket thrust and orbital speed with units.
- ☐ I can explain why rockets use stages and why most of a rocket is propellant.
- ☐ My fair test found the best water volume, and I explained the result with physics.

ENGINEER'S NOTEBOOK

1. Cutaway sketch of the Saturn V with its three stages, engines, propellants and the Apollo spacecraft labeled.
2. Water-rocket data table and graph.
3. Draw Newton's cannonball: a mountain on a round Earth with paths for slow, faster and orbital speeds.
4. Solve: find the orbital speed and period at 400 km altitude (where the International Space Station flies).

From history. Robert Goddard, an American physics professor, launched the first liquid-fueled rocket on March 16, 1926, in a snowy field in Massachusetts. It flew for about 2½ seconds and rose 41 feet. Forty-three years later, a liquid-fueled rocket carried people to the Moon. Isaac Newton, a believing Christian, had explained the orbit with his imagined cannon on a mountaintop in his *Principia* of 1687.

COMMON MISTAKES

- Thinking a rocket pushes against the air or the ground. It pushes on its own exhaust, which is why it works best in the vacuum of space.
- Believing astronauts in orbit float because there is no gravity. Gravity at the Space Station is about 90% as strong as on the ground; they float because they are falling around the Earth.

- Forgetting that most of a rocket's mass is propellant, so its acceleration grows as it burns.

Make it a game · Stage It, Orbit It. Beat the clock. In ninety seconds, explain why rockets use stages and how Newton's cannonball describes an orbit. Your parent counts the correct ideas. Then each of you picks a planet radius and guesses an orbital speed before calculating $v = \sqrt{GM \div r}$. Closest guess wins the round. Best of three.

Scripture. “In the beginning God created the heaven and the earth.” (Genesis 1:1, KJV)

These were the first words the Apollo 8 crew read to the world on Christmas Eve 1968, as they orbited the Moon and saw the whole Earth from far away.

7.4 DRONES AND FAA RULES: FOUR ROTORS AND A FEEDBACK LOOP

OBJECTIVES

- Explain how a quadcopter controls climb, pitch, roll and yaw by changing the speeds of its four rotors.
- Explain the feedback loop (sensors, controller, motors) that keeps a drone steady, and calculate the thrust needed to hover and climb.
- State the FAA rules for recreational drone flying, plan a legal flight, and measure rotor thrust on a test stand.

Warm-up. Balance a broom or a long stick upright on the palm of your hand. Notice what your eyes and hand are doing: watch, detect a tilt, move the hand under it, again and again. Write down each step. Then count how many corrections you make in 10 seconds. A drone does the same thing hundreds of times a second.

WATCH

Drones | The complete flight dynamics

Sabin Civil Engineering · 6:37

<https://www.youtube.com/watch?v=C0KBu2ihp-s>

WHEN TO WATCH

After the physics paragraph. Watch which rotors speed up for each maneuver.

BACKUP VIDEO

Flying a Drone for Fun? Know These FAA Rules First

UAV Coach · 6:43

<https://www.youtube.com/watch?v=Rq4xUXk5jYo>

With the engineering paragraph: a drone instructor walks through the recreational rules and the TRUST test.

KEY TERMS

quadcopter

A drone with four rotors, two spinning clockwise and two counterclockwise, so their torques cancel.

inertial measurement unit (IMU)

A chip with gyroscopes and accelerometers that measures rotation and acceleration many times a second.

PID controller

A common controller that responds to the error now (proportional), the error built up over time (integral), and how fast the error is changing (derivative).

pitch, roll, yaw

Rotations about three axes: pitch tips the nose up or down, roll tips one side down, and yaw turns the nose left or right.

feedback control

A loop in which a sensor measures what is happening, a controller compares it with what is wanted, and the motors correct the difference.

TRUST

The FAA's free Recreational UAS Safety Test, which every recreational drone pilot in the United States must pass, carrying proof when flying.

CORE IDEAS

The story. The four-rotor idea is old. In 1907 in France, the brothers Louis and Jacques Bréguet, with Professor Charles Richet, built the *Gyroplane No. 1*, with four large rotors on a cross-shaped frame. It lifted its pilot about two feet off the ground, but men had to steady it with poles, because no human could control four rotors at once. A century later, cheap tiny gyroscope chips, fast microcontrollers and powerful small motors and batteries made the quadcopter practical. Then on April 19, 2021, NASA's *Ingenuity* helicopter, which rode to Mars with the *Perseverance* rover, made the first powered, controlled flight on another planet. It was designed for five flights and made 72.

How they figured it out. The Bréguets' problem was control, not lift. A machine with several rotors is unstable: a tiny tilt makes one side lift less, and it tips further. The answer came from electronics: an inertial measurement unit senses the tilt in a thousandth of a second, and a computer adjusts each motor's speed before a human could even notice. *Ingenuity* faced an even harder version. Mars's air is only about 1% as dense as Earth's, so its two stacked rotors, 1.2 m across, had to spin at about

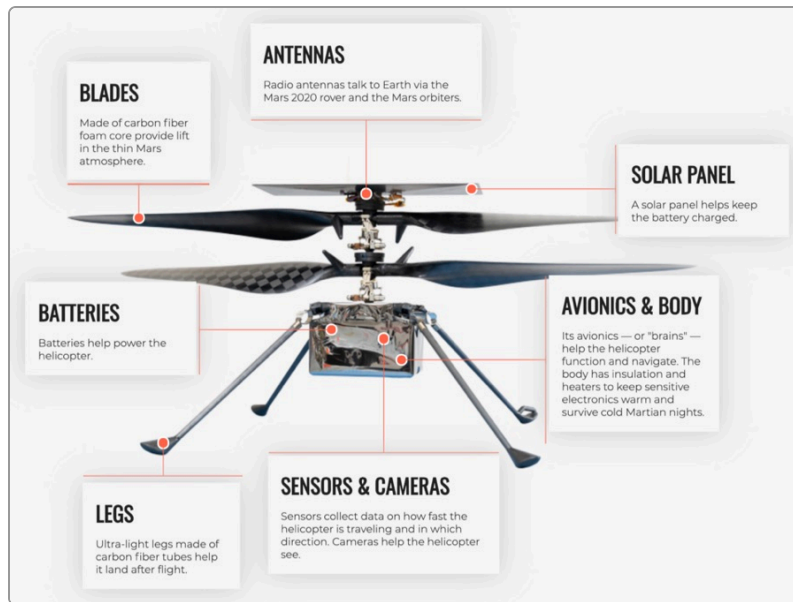
2,400 rpm (turns per minute), and because radio signals take minutes to travel between Earth and Mars, it had to fly completely on its own. Engineers tested it in a large vacuum chamber at the Jet Propulsion Laboratory filled with thin carbon dioxide, with a cable pulling upward to imitate Mars's weaker gravity.

The physics. Each rotor's thrust grows roughly with the square of its spin speed. To hover, total thrust must equal weight. Worked example: a 249 g drone weighs $0.249 \text{ kg} \times 9.8 \text{ m/s}^2 \approx 2.44 \text{ N}$, so each of four rotors must make about 0.61 N. To climb with an acceleration of 2 m/s^2 , total thrust must be $m(g + a) = 0.249 \times 11.8 \approx 2.94 \text{ N}$. To **pitch** forward, the rear rotors speed up and the front ones slow; to **roll**, one side speeds up; to **yaw**, the two clockwise rotors speed up and the two counterclockwise ones slow, so the uncanceled torque turns the drone (Newton's third law again). Once tilted, part of the thrust points sideways and the drone moves. Most drones are designed with a thrust-to-weight ratio of about 2:1 so they have power to spare for control and wind.

The engineering. A drone's flight controller runs a **feedback loop** hundreds or thousands of times a second: read the IMU, compare the actual tilt with the wanted tilt, and adjust the motors with a PID controller. Engineers "tune" the controller: too gentle, and the drone drifts; too strong, and it oscillates. GPS, barometers and downward cameras add position and height hold. Drones now inspect bridges and power lines, map farms, film, deliver supplies and help in search and rescue, and drone pilot, controls engineer and aerospace engineer are growing careers. **In the United States, recreational pilots must:** pass the free TRUST test and carry proof; register any drone that weighs 250 grams (0.55 lb) or more and mark it with its registration number (registered drones must also broadcast Remote ID); fly at or below 400 feet in uncontrolled airspace; get authorization (for example, through LAANC) before flying in controlled airspace near airports; keep the drone within visual line of sight; and never fly over people or moving vehicles, near emergency scenes, or anywhere that interferes with manned aircraft. Flying for pay or for a business requires a Part 107 remote pilot certificate, available from age 16.

Today. The FAA's free B4UFLY app shows where you may fly. Always check it, and the FAA's Recreational Flyers web page, before flying, because rules and airspace can change.

PICTURE STUDY



Anatomy of the Mars Helicopter Ingenuity, NASA/JPL-Caltech, 2020 · Labeled engineering illustration · NASA Jet Propulsion Laboratory
Image: [Wikimedia Commons](#), public domain

Ingenuity weighed about 1.8 kg on Earth. This drawing shows how its engineers fitted rotors, motors, batteries, sensors, computers and a heater into something small and light enough to fly in Mars’s thin air.

Look closely

- Find the two rotors. Why do they spin in opposite directions?
- Find the solar panel. What does it charge, and why does the helicopter need a heater at night?
- Find the sensors and cameras. Which ones would tell it its height and tilt?
- Look at the legs. Why are they so thin?

Talk about it

1. *Ingenuity* weighed about 1.8 kg. Mars gravity is about 3.7 m/s^2 . What thrust did it need to hover?
2. Why did *Ingenuity* have to fly itself without a human pilot at the controls?
3. How is this helicopter like a quadcopter, and how is it different?

Safety first. Never fly a drone near people, roads, airports, power lines, emergency scenes or over neighbors' property; follow every FAA rule in this lesson and an adult's directions. Keep fingers clear of spinning propellers and use propeller guards indoors. In the build, use only AA batteries; never puncture, crush, short or charge a damaged lithium drone battery.

BUILD

A Rotor Thrust Stand and a Legal Flight Plan

You will measure the thrust of a small motor and propeller on a kitchen scale at different battery voltages and find how thrust depends on spin speed. Then you will use your measurements to size a drone and write a complete, legal flight plan using the FAA rules.

You will need

- A small DC hobby motor with a plastic propeller, a 1-, 2- and 3-AA battery holder (or one holder with clips to choose cells)
- A kitchen scale, a ruler, a pencil (pivot), tape and a heavy book (the thrust stand from Lesson 6.2 works)
- A digital multimeter, safety glasses
- A smartphone with the free FAA B4UFLY app (or the FAA website) and a map of a park near you
- Optional: a small indoor drone under 250 g, with an adult

Steps

1. Build or reuse the lever thrust stand so the propeller blows away from the scale. Zero the scale with the motor off. Measure the lever arms and work out the correction factor.
2. **Fair test.** Run the motor on 1, 2 and 3 AA cells, measuring the battery voltage under load each time with the multimeter. Record the scale reading for 5 seconds and convert to thrust in newtons. Repeat three times each.
3. If you have a phone tuner or spectrum app, record the pitch of the propeller hum as a measure of spin speed (frequency is proportional to rpm).
4. Graph thrust against voltage, and if you can, thrust against (spin frequency)². Which is closer to a straight line?
5. **Size a drone.** Using your best thrust per motor, how heavy could a four-motor drone be and still have a 2:1 thrust-to-weight ratio? Is that more or less than your motor-and-battery mass? What does this tell you about real drone motors?

6. **Flight plan.** Choose a park. Use B4UFLY to check the airspace. Write a one-page plan: drone weight and registration need, TRUST status, takeoff spot, maximum height (no more than 400 ft), how you will keep it in sight, people and roads to avoid, weather limits, and what you will do if the drone loses signal.
7. **Optional flight.** With an adult, fly a sub-250 g drone indoors or in a legal open area following your plan. Practice hovering and one square pattern. Record the battery time.
8. **Improve.** Test a propeller of a different size or pitch on the stand with the same battery and compare thrust. Explain which one a heavy-lift drone should use.

Tips

- Hobby motors are not made for long runs; give each test only a few seconds and let the motor cool.
- Keep the propeller well away from the scale and walls so its wind does not push on them.
- Real drone motors are brushless and far more powerful for their weight; that is why your homemade drone would struggle to lift itself.

Check your work

- ☐ I can explain how a quadcopter pitches, rolls and yaws and how a feedback loop keeps it steady.
- ☐ I measured rotor thrust on a test stand and used it to size a drone.
- ☐ I can state the FAA recreational rules and wrote a legal, safe flight plan.

ENGINEER'S NOTEBOOK

1. Top-view diagram of a quadcopter with rotor numbers and spin directions, and four small diagrams showing which rotors speed up for climb, pitch, roll and yaw.
2. Block diagram of a drone's feedback loop: wanted tilt → controller → motors → drone → IMU → back to controller.
3. Thrust-stand data table and graph.
4. Your flight plan and a list of the FAA rules in your own words.

From history. *Ingenuity's* last flight was in January 2024, when a rotor blade was damaged on landing. Over nearly three years it flew more than two hours in total and traveled about 17 kilometers, scouting routes for the *Perseverance* rover, and it proved that flight on other worlds is possible. NASA is now designing larger rotorcraft for Mars and the *Dragonfly* rotorcraft for Saturn's moon Titan.

COMMON MISTAKES

- Thinking a quadcopter turns (yaws) by tilting. It yaws by changing the balance of torque between its clockwise and counterclockwise rotors.
- Believing small drones need no rules. Every recreational pilot must pass TRUST and follow the safety rules, whatever the drone's weight; registration is required at 250 grams and above.
- Forgetting that a drone tilted to move forward has less upward thrust, so it must speed up its rotors or it will sink.

Make it a game · Be the Quadcopter. Stand and act as a quadcopter with your arms as rotors. Your parent calls climb, pitch, roll or yaw, and you show which rotors speed up and which slow down. Then explain the feedback loop of sensors, controller and motors in one breath. Three mistakes ends the round. Beat your own streak and keep a record.

UNIT 7

FLIGHT AND SPACE

Every flying machine is a set of trade-offs. A wing big enough to lift a slow, light human-powered airplane would be far too draggy for a jet airliner; a rocket powerful enough to reach the Moon must throw away most of itself on the way. In this unit you will use the lift equation and wing loading to compare aircraft as different as the pedal-powered *Gossamer Albatross* and the Boeing 747, follow Igor Sikorsky as he finally made the helicopter practical, and ride the Saturn V into orbit with Newton's laws and a little orbital mechanics.

The unit ends with the newest flying machines most of you will actually handle: drones. You will learn how four spinning rotors and a fast feedback loop keep a quadcopter steady, how NASA flew a helicopter on Mars, and the FAA rules every recreational pilot must follow. Builds include gliders with measured wing loading, paper rotors and a torque test, a water-bottle rocket flown with an adult, and a rotor thrust stand.

PREREQUISITES

- Knows the four forces of flight and that a wing turns air downward (earlier grades)
- Knows Newton's three laws, momentum and $F = \dot{m}\Delta v$ (Units 1 and 6)
- Can use square roots, exponents and scientific notation
- Knows wind pressure $q = \frac{1}{2}\rho v^2$ (Unit 3)

MASTERY CHECKLIST

- ☐ I can use the lift equation ($L = \frac{1}{2}\rho v^2 SC$) and calculate wing loading and stall speed, and explain design trade-offs between slow and fast aircraft.
- ☐ I can explain how a helicopter's collective, cyclic and tail rotor control it, and why helicopters have large rotors.
- ☐ I can calculate rocket thrust ($F = \dot{m}v$) and orbital speed ($v = \sqrt{GM \div r}$), and explain why rockets use stages.
- ☐ I can explain how a quadcopter controls pitch, roll and yaw with rotor speeds and a feedback loop.
- ☐ I can state the FAA rules for recreational drone flying and plan a safe, legal flight.

OPTIONAL KITS FOR THIS UNIT

- **Estes model rockets**: Grades 6–8 only, with an adult, outdoors in an open field, following the National Association of Rocketry Model Rocket Safety Code. Starter sets with a launch pad and controller are a step up from the water rocket in Lesson 7.3.
- **Ryze Tello drone**: Ages 13 and up with an adult. A small indoor drone under 250 grams that can be programmed with block code or Python; fits Lesson 7.4. Follow the FAA rules in that lesson whenever you fly outdoors.
- **LEGO Technic**: Ages 9 and up. Technic sets with rotor and swashplate mechanisms show helicopter controls clearly (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 Aircraft Design Trade-offs: Wing Loading from the Gossamer Albatross to the 747

2 sessions of 60 minutes

7.2 Helicopters: Sikorsky and the Rotating Wing

2 sessions of 60 minutes

7.3 Rocketry and Orbits: Apollo and the Saturn V

2 sessions of 60 minutes

7.4 Drones and FAA Rules: Four Rotors and a Feedback Loop

2 sessions of 60 minutes

UNIT 7 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use $g = 9.8 \text{ m/s}^2$ and $\rho = 1.225 \text{ kg/m}^3$ at sea level. Use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Write the lift equation and name each term. Which term did MacCready make very large to allow human-powered flight?

2. 10 pts

Calculation. An airplane weighs 12,000 N with a wing area of 15 m^2 . Find its wing loading and its stall speed if $C_{L,\max} = 1.5$.

3. 8 pts

Give two advantages and two disadvantages of a high wing loading.

4. 8 pts

Explain what the collective, the cyclic and the tail rotor each do.

5. 8 pts

Why do helicopters have long rotor blades? Use momentum theory in your answer.

6. **10 pts**

Calculation. A rocket engine burns 300 kg of propellant per second with an exhaust speed of 3,000 m/s. Find its thrust. Can it lift a rocket with a mass of 80,000 kg off the pad?

7. **10 pts**

Calculation. Find the orbital speed and period of a satellite 600 km above Earth (Earth radius 6,371 km, $GM = 3.99 \times 10^{14} \text{ m}^3/\text{s}^2$).

8. **8 pts**

Why does a rocket use stages? Why was the F-1 engine's combustion instability such a serious problem, and how did engineers solve it?

9. **8 pts**

Describe how a quadcopter yaws (turns its nose) without tilting.

10. **6 pts**

Calculation. A drone has a mass of 0.80 kg. What total thrust must its four rotors make to hover, and to climb with an acceleration of 1.5 m/s^2 ?

11. **8 pts**

List five FAA rules a recreational drone pilot in the United States must follow.

12. **8 pts**

Write a short paragraph: How does a feedback loop keep a drone steady, and what happens if the controller is tuned too strongly?

ANSWER KEY

1. $L = \frac{1}{2}\rho v^2 S C_L$: air density ρ , airspeed v , wing area S , lift coefficient C_L . He made the wing area S very large for a very light aircraft, giving very low wing loading so it could fly slowly on little power.
2. $W \div S = 12,000 \div 15 = 800 \text{ N/m}^2$. $v_s = \sqrt{(2 \times 800 \div (1.225 \times 1.5))} = \sqrt{(1,600 \div 1.84)} \approx \sqrt{871} \approx 29.5 \text{ m/s}$.
3. Advantages: faster cruise; smaller, lighter, less draggy wing; smoother ride in gusts. Disadvantages: higher stall and landing speeds; longer runways; needs flaps and slats (any two each).
4. Collective changes the pitch of all main blades together to raise or lower lift. Cyclic changes each blade's pitch as it goes around, tilting the rotor disk to move the helicopter in a direction. The tail rotor cancels the main rotor's torque reaction and lets the pilot turn (yaw).
5. Hover power $P = T^{3/2} \div \sqrt{(2\rho A)}$ falls as the rotor disk area A grows. A larger rotor moves more air more slowly to make the same thrust, which takes less power; halving the rotor diameter would double the power needed.
6. $F = \dot{m}v_e = 300 \times 3,000 = 900,000 \text{ N}$. Weight = $80,000 \times 9.8 = 784,000 \text{ N}$. Thrust is larger, so yes, it can lift off (net force 116,000 N upward).
7. $r = 6.971 \times 10^6 \text{ m}$. $v = \sqrt{(3.99 \times 10^{14} \div 6.971 \times 10^6)} \approx \sqrt{(5.72 \times 10^7)} \approx 7,560 \text{ m/s}$. $T = 2\pi r \div v \approx 4.38 \times 10^7 \div 7,560 \approx 5,790 \text{ s} \approx 97 \text{ minutes}$.
8. Dropping empty stages means the remaining engines do not waste thrust pushing empty tanks, so the rocket can reach a higher final speed. Unstable combustion shook engines apart in a fraction of a second; engineers deliberately disturbed the flame in test engines and redesigned the injector with baffles and new hole patterns until the engine damped disturbances on its own.
9. It speeds up the two rotors that spin one way and slows the two that spin the other way. Total lift stays the same, but the torques no longer cancel, so the reaction torque turns the drone.
10. Hover: $T = mg = 0.80 \times 9.8 = 7.84 \text{ N}$ (1.96 N per rotor). Climb: $T = m(g + a) = 0.80 \times 11.3 = 9.04 \text{ N}$.
11. Any five: pass TRUST and carry proof; register a drone of 250 g or more and mark it (and broadcast Remote ID if registered); fly at or below 400 ft in uncontrolled airspace; get authorization before flying in controlled airspace near airports; keep the drone in visual line of sight; do not fly over people or

moving vehicles; do not interfere with manned aircraft or emergency operations; fly only for recreation (commercial flying requires Part 107).

12. The IMU measures tilt many times a second; the controller compares it with the wanted tilt and changes each motor's speed to correct the error, repeating continuously. If tuned too strongly, it over-corrects and the drone oscillates or shakes; too weakly, it drifts and responds slowly.

PORTFOLIO PIECE: A MISSION-DESIGNED GLIDER

Choose a mission for a hand-launched glider: the longest time aloft from a 2 m launch, or the farthest distance, or carrying a payload of 5 paper clips as far as possible. Before building, calculate your planned wing area, mass, wing loading and expected glide speed, and choose an aspect ratio with reasons. Build it, trim it, and test it at least ten times, changing only one thing between rounds. Present a design report with a three-view drawing, the calculations, a data table and graph, photographs, and a final paragraph explaining the trade-offs you made, as an aircraft designer would present to a customer.

LOOK FOR	WHAT IT MEANS
Mission and calculations	Mission stated clearly; wing area, mass, wing loading and expected speed calculated with units; aspect ratio chosen with reasons.
Drawing and construction	Neat three-view drawing with dimensions; straight, symmetrical glider that matches the drawing.
Testing and data	At least ten flights recorded with one variable changed at a time; table and graph with units.
Trade-off analysis	Explains using the lift equation and wing loading why the final design suits its mission and what it gave up.
Improvement	At least one improvement made from test data, with before-and-after results.

UNIT 8

CAPSTONE: THE ENGINEER'S CALLING

This last unit brings the whole year together and looks ahead to high school and beyond. It begins with the hardest question in engineering: what does an engineer owe the people who will use what he or she designs? You will study the Hyatt Regency walkway collapse of 1981, one of the most important ethics cases in American engineering, and model with rubber bands how one small design change doubled the load on a connection. You will think about engineering as a vocation, a calling to serve others with skill and honesty.

Then you will plan and carry out a capstone design project of your own, the way real engineers do: with a schedule and a budget (counting the cost, as Jesus said, before building the tower), clear requirements, a decision matrix, prototypes, tests and improvements. The year ends with a family engineering fair, where, like Michael Faraday at his Christmas lectures, you will explain your work clearly to an audience and answer their questions.

PREREQUISITES

- Has completed the builds and notebook pages of Units 1–7
- Can calculate reactions and loads in simple structures (Unit 2)
- Can make data tables, graphs and averages, and calculate percent error
- Has a parent or mentor willing to act as “client” and reviewer for the capstone

MASTERY CHECKLIST

- ☐ I can explain the engineering failure and the ethical failures in the Hyatt Regency collapse, and state the engineer’s first duty to the public.
- ☐ I can make a work breakdown, a Gantt chart and a critical-path network, and build a budget with a contingency.
- ☐ I can write requirements and constraints, compare options in a weighted decision matrix, and prototype, test and improve a design.
- ☐ I can calculate mean, range and percent error and report results honestly with their uncertainty.
- ☐ I can present an engineering project clearly with a poster or display, a live demo and answers to questions.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober)**: Ages 8 and up (the Hack Pack line is for ages 12 and up). Monthly build-and-modify projects that can seed capstone ideas in Lesson 8.3.
- **BBC micro:bit**: Ages 10 and up. A small programmable board with built-in sensors and free MakeCode software; a good brain for sensing and logging capstone projects.
- **Raspberry Pi Pico**: Ages 12 and up with an adult. The microcontroller from Lesson 4.3, inexpensive and powered by USB, for capstones that sense, decide and act.

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 Engineering Ethics and Vocation: The Hyatt Regency Walkways

2 sessions of 60 minutes

8.2 Project Management: Counting the Cost at Hoover Dam

2 sessions of 60 minutes

8.3 A Capstone Design Project: From Problem to Prototype

2 sessions of 60 minutes

8.4 The Engineering Fair and Presentation: Faraday's Christmas Lectures

2 sessions of 60 minutes

UNIT 8 REVIEW

This final review covers this unit and draws on the whole year. Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. 10 pts

Calculation and explanation. In the Hyatt Regency walkways, suppose each walkway put a load of 40 kN on each hanger. What load did the fourth-floor connection carry in the original design and in the as-built design? Explain with a free-body diagram in words.

2. 8 pts

Name two ethical failures in the Hyatt Regency case and state the first duty of engineers in professional codes of ethics.

3. 6 pts

What does it mean to see engineering as a vocation?

4. 10 pts

Calculation. Tasks: A (2 weeks); B (4 weeks, after A); C (3 weeks, after A); D (2 weeks, after C); E (1 week, after B and D). Find the critical path, the project length and the float of task B.

5. (8 pts)

A project's base cost estimate is \$64,000. What is the budget with a 15% contingency? Why include contingency?

6. (8 pts)

Why was Hoover Dam poured in separate blocks with cooling pipes, and how did Frank Crowe finish early?

7. (8 pts)

Write one testable requirement and one constraint for a garden watering system.

8. (10 pts)

Calculation. Three concepts are scored 1–5 on Performance (weight 4), Cost (weight 3) and Ease of building (weight 2). A scores 4, 2, 3; B scores 3, 4, 4; C scores 5, 1, 2. Find each total and choose.

9. (8 pts)

Calculation. Find the wind power passing through a rotor 3.0 m across in an 8 m/s wind ($\rho = 1.2 \text{ kg/m}^3$). How much might a turbine with 30% efficiency produce?

10. (8 pts)

Calculation. Four trials of a bridge's failure load are 5.2, 5.6, 5.0 and 5.4 kg. Find the mean and range, report the result with an uncertainty, and find the percent error if you predicted 6.0 kg.

11. (8 pts)

List the main sections of an engineering report and three habits of a good presenter, as Faraday practiced them.

12. (8 pts)

Write a paragraph: Choose one story from this year (for example, the Wright brothers, the Roebblings, Froude, Leal and Fuller, or the *Trieste*) and explain what it teaches about how engineers learn and serve.

ANSWER KEY

1. Original: 40 kN (the second-floor load went up the continuous rod to the ceiling). As-built: 80 kN, because the lower rod hung from the fourth-floor beam, so that connection carried its own walkway plus the second-floor walkway.
2. Any two: approving the design change without calculating it; not checking shop drawings and connections carefully; each party assuming someone else had checked; an original design already weaker than the code required. First duty: hold paramount the safety, health and welfare of the public.
3. To see the work as a calling to serve God and neighbor with skill and honesty, not just a job; for example, doing careful work even when no one checks, because the people who use it matter.
4. Paths: A–B–E = $2 + 4 + 1 = 7$ weeks; A–C–D–E = $2 + 3 + 2 + 1 = 8$ weeks. Critical path A–C–D–E, 8 weeks. Task B has 1 week of float.
5. $\$64,000 \times 1.15 = \$73,600$. Because some things always go wrong or cost more than expected; contingency keeps the project from cutting quality or safety or running out of money.
6. Concrete gives off heat as it cures; a single huge mass would take a very long time to cool and would crack. Crowe planned the critical path carefully (diversion tunnels, cofferdams, excavation, concrete), concentrated people and equipment on critical tasks, and built a fast concrete-delivery system of cableways.
7. Example requirement: delivers at least 2 liters of water evenly to a 1 m^2 bed in 30 minutes. Example constraint: costs less than \$15 and uses no electricity from the wall. (Any measurable requirement and real limit accepted.)
8. $A = 16 + 6 + 6 = 28$. $B = 12 + 12 + 8 = 32$. $C = 20 + 3 + 4 = 27$. Concept B scores highest.
9. $A = \pi \times 1.5^2 \approx 7.07 \text{ m}^2$. $P = \frac{1}{2} \times 1.2 \times 7.07 \times 8^3 \approx 0.6 \times 7.07 \times 512 \approx 2,170 \text{ W}$. At 30%: about 650 W.
10. Mean = $21.2 \div 4 = 5.3 \text{ kg}$. Range = $5.6 - 5.0 = 0.6 \text{ kg}$; report $5.3 \pm 0.3 \text{ kg}$. Percent error = $|5.3 - 6.0| \div 6.0 \times 100\% \approx 11.7\%$.
11. Sections: summary; problem; requirements and constraints; concepts and decision; design; testing and results; conclusions and recommendations. Habits (any three): speak slowly and clearly; show real live demos; keep apparatus large and simple; connect to what the audience knows; rehearse; finish on time; invite questions.

12. Answers vary; a strong answer tells the story accurately, names the problem, the tests or measurements, the failure or difficulty overcome, and how the result served people.

PORTFOLIO PIECE: THE CAPSTONE PROJECT AND ENGINEERING FAIR

Complete, document and present your capstone design project: a real solution to a real problem for a real client, planned with a schedule and budget, chosen with a weighted decision matrix, built, tested against measurable requirements, and improved at least once. Present it at the family engineering fair with a display, a 3–5 minute talk and a live demo, alongside your best build from each unit. Hand in the engineering report, the plan, the decision matrix, all test data and your end-of-year reflection, with your client’s signed comments.

LOOK FOR	WHAT IT MEANS
Problem and requirements	Clear problem statement from a real client; at least four measurable requirements and three constraints.
Design process	At least three concepts compared in a weighted decision matrix; reasons for the choice explained; design review held.
Planning	Gantt chart, critical path and budget with contingency; planned and actual time and cost compared honestly.
Testing and improvement	Prototype tested against every requirement with repeated trials, mean and uncertainty; at least one improvement with before-and-after data.
Communication	Clear report and display; timed talk with live demo; questions answered with data; reflection completed.

8.1 ENGINEERING ETHICS AND VOCATION: THE HYATT REGENCY WALKWAYS

OBJECTIVES

- Explain how a design change in the Hyatt Regency walkway hangers doubled the load on a connection, using a free-body diagram.
- Identify the ethical failures that allowed the change to be built, and state the engineer's first duty under professional codes.
- Model both hanger designs with rubber-band "connections" and measure the difference in load.

Warm-up. Hang two cups, one below the other, from a single string tied to a hook: cup A on top, cup B below, the string passing straight down through a knot under cup A. Then rebuild it with two strings: one from the hook to cup A, and a second from cup A down to cup B. Put coins in both cups. In each design, what is cup A's handle carrying? Sketch both and write your answer before reading the story.

WATCH

Hyatt Regency Walkway Collapse: Ethics Case Study No. 4

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

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

WHEN TO WATCH

After the story paragraph. List every point where someone could have stopped the error.

Note: Produced by the American Society of Civil Engineers. It shows newspaper headlines and photographs of the collapsed walkways (no graphic injuries). Watch together.

KEY TERMS

connection

The part of a structure where members are joined, such as a bolt, weld or nut on a rod. Many failures begin at connections.

shop drawings

Detailed drawings made by a fabricator showing exactly how each piece will be made and joined. The engineer of record must review them.

engineer of record

The licensed engineer whose seal is on the structural design and who is responsible for it.

code of ethics

A profession's written rules of conduct. Engineering codes put the safety, health and welfare of the public first.

vocation

A calling; work understood as service to God and neighbor, not only as a way to earn a living.

whistleblowing

Reporting a danger or wrongdoing to those with authority to stop it, even at personal cost.

CORE IDEAS

The story. On the evening of July 17, 1981, about 1,600 people gathered for a dance in the atrium of the new Hyatt Regency hotel in Kansas City, Missouri. Spectators stood on walkways suspended from the ceiling across the atrium: one on the fourth floor directly above one on the second floor. At 7:05 p.m. the fourth-floor walkway's connections failed, and both walkways fell onto the crowd. One hundred fourteen people died and more than 200 were injured. It remains one of the deadliest structural failures in American history.

How they figured it out. Investigators from the National Bureau of Standards tested the steel and studied the design. In the original drawings, long steel rods ran from the ceiling straight through the fourth-floor walkway's box beams down to the second-floor walkway, with nuts holding each walkway onto the rods. That detail was hard to build, so the steel fabricator proposed using two sets of shorter rods instead: one from the ceiling to the fourth-floor walkway, and a second from the fourth-floor beams down to the second-floor walkway. The structural engineers approved the change without calculating its effect. Investigators found that even the original detail was weaker than the building code required, and the change made it far worse. The engineers of record lost their licenses to practice in Missouri. One of them, Jack Gillum, spent years afterward lecturing engineering students about what went wrong and the responsibility that comes with an engineer's seal.

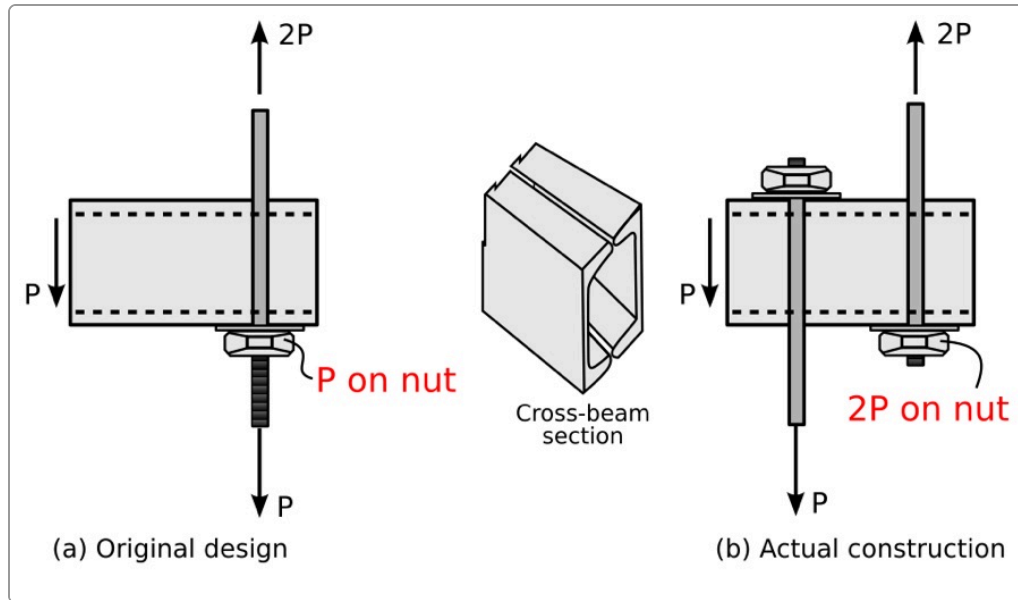
The physics. Draw a free-body diagram of the nut and beam under the fourth-floor walkway. Suppose each walkway puts a load P on each hanger. In the **original design**, the second-floor load travels up the continuous rod to the ceiling; the fourth-floor nut carries only its own walkway, P . In the **revised design**, the lower rod hangs from the fourth-floor beam, so the second-floor walkway's load P is added to the

fourth-floor beam, and the upper nut and beam connection must carry $2P$. With illustrative numbers, if $P = 50 \text{ kN}$, the connection that was meant to carry 50 kN had to carry 100 kN . The nuts pulled through the box beams, which were made of two thin channels welded together at their edges, exactly where the doubled force was concentrated.

The engineering. The failure was not mainly a calculation mistake; it was a failure of responsibility. The change was proposed by one firm, approved by another, and passed through reviews, with each party assuming someone else had checked it. Engineering codes of ethics, such as that of the National Society of Professional Engineers, begin with the same duty: engineers shall hold paramount the safety, health and welfare of the public. That means checking connections, reviewing shop drawings with real calculations, refusing to sign what you have not checked, and speaking up when something is unsafe, even if it costs time, money or friendship. For a Christian, this is part of a larger calling. Bezalel was filled with skill “in all manner of workmanship” to build the tabernacle, and Paul tells all workers to work heartily, as to the Lord. Engineering done that way is a form of loving your neighbor.

Today. After the Hyatt collapse, the American Society of Civil Engineers and state licensing boards clarified that the engineer of record is responsible for reviewing and approving connection designs and shop drawings. The case is taught in nearly every engineering ethics course in the country.

PICTURE STUDY



The Hyatt Regency Walkway Hanger Designs, Diagram based on the National Bureau of Standards investigation, drawn after 1982 · Engineering diagram · Wikimedia Commons

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

This diagram compares the two hanger designs. It is the kind of simple sketch that, drawn and checked before the change was approved, could have stopped the disaster.

Look closely

- Find the ceiling, the fourth-floor walkway and the second-floor walkway in each design.
- Trace the path of the second-floor walkway's weight to the ceiling in the original design.
- Trace it again in the as-built design. Where does it pass through the fourth-floor beam?
- Find the nut under the fourth-floor box beam in each design. How many walkways does it hold up?

Talk about it

1. Using a free-body diagram, explain why the as-built nut carried twice the load.
2. Why might the change have looked harmless to someone who did not draw a diagram?

3. Who had the responsibility to check the change, and what should that person have done?

Safety first. Hang the model from a sturdy rod across two chairs, low over a table, so nothing can fall far. Keep faces back from stretched rubber bands and wear safety glasses.

BUILD

The Two-Hanger Model with Rubber-Band Gauges

You will build both Hyatt hanger designs at small scale using string as the rods, cardboard strips as the walkways and calibrated rubber bands as the fourth-floor connections. The stretch of each rubber band shows how much load the connection carries.

You will need

- A broom handle or dowel laid across two chairs as the “ceiling”
- String, two stiff cardboard strips (about 30 cm × 5 cm) as walkways, and paper clips
- Several identical small rubber bands, a ruler, and two small bags or cups for loads
- Coins or washers and a kitchen scale; tape; safety glasses

Steps

1. **Calibrate.** Hang one rubber band from the dowel and hang known masses from it (50 g, 100 g, 200 g). Measure its stretched length each time and make a calibration graph of length against force (N).
2. **Original design.** Hang a continuous string from the dowel through a hole in the upper walkway strip and on down through the lower strip. Attach each strip to the string with a rubber band looped onto the string at a knot (the “nut”), so each walkway hangs from its own rubber band on the continuous string. Load each walkway with the same mass.
3. Measure the stretch of the upper walkway’s rubber band and use your calibration graph to find the force it carries.
4. **As-built design.** Now use two strings: one from the dowel to the upper walkway (connected by its rubber band), and a second string tied to the upper walkway strip and running down to the lower walkway. Load both walkways with the same masses as before.
5. Measure the upper connection’s stretch again and find its force. Compare with the original. Make a table: design, load on each walkway (N), measured force at upper connection (N), predicted force (P or 2P).

6. Draw a free-body diagram of the upper walkway in each design, with every force labeled.
7. **Improve.** Suggest a third design that would have been easy to build and kept the load on the upper connection at P. Build and test it. (Hint: what if the lower walkway hung from its own rods from the ceiling, passing beside the upper walkway?)
8. Write a one-page memo, as if you were the engineer of record asked to approve the change, explaining with numbers why you would or would not sign.

Tips

- Use rubber bands of the same size from the same bag; calibrate the one you will use as the gauge.
- Measure lengths with the ruler held beside, not touching, the rubber band.
- Your model will not match exactly because cardboard bends and string stretches. The doubling should still be clear.

Check your work

- ☐ I can explain with a free-body diagram why the revised Hyatt detail doubled the load on the upper connection.
- ☐ My rubber-band measurements showed the difference, and I designed a better alternative.
- ☐ I can state the engineer's first duty to the public and explain engineering as a vocation.

ENGINEER'S NOTEBOOK

1. Free-body diagrams of the upper walkway connection in the original, as-built and your improved designs.
2. Calibration graph and data table.
3. Your engineer's memo approving or rejecting the change.
4. Write a paragraph: What does it mean to work "heartily, as to the Lord" as an engineer? Give two specific examples.

From history. A better-known ethics story ended well. In 1978, engineer William LeMessurier discovered that his own design for New York's new Citicorp Center tower was weaker against certain winds than he had thought. Instead of hiding it, he reported it to the owners and city officials, and the connections were secretly reinforced by welding crews at night before a hurricane season. He is remembered for his honesty.

COMMON MISTAKES

- Blaming only the steel. The steel behaved exactly as physics says; people failed to check the design.
- Thinking ethics means only not lying. It also means checking work, speaking up and refusing to pass along risk to the public.
- Assuming that if a reviewer approved it, it must be safe. Every engineer who signs is responsible.

Make it a game • Which Load Is Bigger?. Two-truths-and-a-tall-tale on the Hyatt Regency walkways. State three claims about the hangers and the connection: two true, one false. Your parent must find the false one using a free-body diagram drawn on paper. Swap. Finally, say the engineer's first duty and name one way a whistle could have been blown.

Scripture. “And whatsoever ye do, do it heartily, as to the Lord, and not unto men;” (Colossians 3:23, KJV)

An engineer who works as to the Lord checks the connection even when no one else will, because the people on the walkway matter to God.

8.2 PROJECT MANAGEMENT: COUNTING THE COST AT HOOVER DAM

OBJECTIVES

- Make a work breakdown structure, a Gantt chart and a critical-path network, and find a project's critical path and float.
- Build a project budget with a contingency, and compare planned and actual cost and time.
- Write the schedule and budget for your own capstone project.

Warm-up. List every step needed to make a family pancake breakfast, from buying eggs to washing the last pan. Estimate how many minutes each takes. Which steps can happen at the same time (for example, heating the griddle while mixing the batter)? Which must happen in order? What is the shortest possible time to get everyone fed? Write your answer and keep the list.

WATCH

What is the Critical Path Method (CPM)?

Online PM Courses - Mike Clayton • 5:26

<https://www.youtube.com/watch?v=rxGcV0tuxRU>

WHEN TO WATCH

After the physics paragraph. Then go back to your pancake list and find its critical path.

BACKUP VIDEO

Constructing the Hoover Dam

Science Channel • 2:54

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

With the story paragraph: how the dam's concrete was cooled as it was poured.

KEY TERMS

work breakdown structure (WBS)

A list that breaks a project into smaller and smaller pieces of work until each can be estimated and assigned.

critical path

The longest chain of dependent tasks in a project. Any delay on it delays the whole project.

contingency

Extra time and money set aside in a plan for things that go wrong.

Gantt chart

A bar chart of tasks against time, showing when each starts and ends. It was developed by Henry Gantt in the 1910s.

float (slack)

How long a task not on the critical path can be delayed without delaying the project.

milestone

An important point in a project, such as finishing the foundation, used to check progress.

CORE IDEAS

The story. In 1931 a group of companies called Six Companies won the contract to build Hoover Dam (then called Boulder Dam) on the Colorado River for about \$49 million, the largest construction contract the U.S. government had ever let. The superintendent was Frank Crowe, a civil engineer who had spent his life building dams for the Bureau of Reclamation. The contract set a deadline and heavy penalties for every day late. Crowe finished the dam in early 1936, more than two years ahead of schedule. It was then the largest concrete structure in the world, about 726 feet high, with about 3.25 million cubic yards of concrete.

How they figured it out. Crowe planned the job as a chain of steps in which each one had to be finished before the next could begin: first, four diversion tunnels, each 56 feet across, blasted through the canyon walls to carry the river around the site; then cofferdams to keep the river out; then excavation down to solid rock; then the concrete. He knew which tasks were on the critical path and put most of his men and machines there. To deliver concrete fast enough, his team designed a system of cableways that carried 8-cubic-yard buckets across the canyon to the exact block being poured. The first bucket was placed on June 6, 1933. Concrete gives off heat as it hardens, and engineers calculated that a dam poured in one solid mass would take

more than a century to cool and would crack. So the dam was poured in hundreds of separate column blocks, cooled by water pumped through about 582 miles of embedded one-inch steel pipe from a refrigeration plant.

The physics. Project planning is mathematics. In a critical-path network, each task has a duration and a list of tasks that must come before it. Worked example: a small bridge project has (A) design, 4 weeks; (B) order steel, 6 weeks, after A; (C) build foundations, 5 weeks, after A; (D) erect steel, 3 weeks, after B and C; (E) pave deck, 2 weeks, after D. Path A–B–D–E takes $4 + 6 + 3 + 2 = 15$ weeks; path A–C–D–E takes $4 + 5 + 3 + 2 = 14$ weeks. The critical path is A–B–D–E (15 weeks), and task C has 1 week of float. Budgets add up the same way: if materials cost \$42,000, labor \$36,000 and equipment \$12,000, the base estimate is \$90,000; with a 15% contingency, the budget is $\$90,000 \times 1.15 = \$103,500$.

The engineering. Engineers and construction managers plan with a work breakdown structure, a schedule (often a Gantt chart produced from a critical-path network), a budget with contingency, and a list of risks. During the work they track progress against the plan and act early when a critical task slips. The critical-path method was developed in 1957 by engineers at the DuPont company, and similar methods are now used on everything from bridges to space missions. Good project management is also a matter of honesty: reporting delays and cost overruns truthfully, as soon as they are known. Jesus taught the same thing: no one starts a tower without first sitting down to count the cost.

Today. Hoover Dam still generates electricity and stores water for millions of people in the Southwest. Frank Crowe went on to build Shasta Dam in California. His schedule is still studied as a model of planning.

PICTURE STUDY



The First Bucket of Concrete at Boulder Dam, U.S. Bureau of Reclamation, June 6, 1933 · Photograph · National Archives

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

This photograph records a milestone: the first bucket of concrete placed in the dam itself. Every task before it, tunnels, cofferdams and excavation, had to be finished first.

Look closely

- Find the bucket. How was it carried across the canyon?
- Find the wooden forms that shaped the concrete block.
- Look at the canyon walls. What had to be removed before concrete could be placed?
- Count the workers. What job might each one have?

Talk about it

1. Which tasks had to come before this moment? Draw them as a chain.
2. Why did the engineers pour the dam in many separate blocks instead of all at once?
3. How would a photograph like this help managers track progress?

BUILD

Plan and Track a Real Project

You will practice project management on a small real job, then write the schedule and budget for your capstone project. First you will plan a short build (a craft-stick truss or the family pancake breakfast), predict its time and cost, do it, and compare actual with planned. Then you will plan your capstone.

You will need

- Graph paper or a free spreadsheet program
- A small project to plan and carry out (for example, a craft-stick truss from Unit 2, or the family pancake breakfast), with its materials
- A stopwatch and receipts or price lists
- Your capstone ideas from your notebook

Steps

1. **WBS.** Break the small project into 8–12 tasks. For each, write its duration estimate, what must come before it, and its materials and cost.
2. **Network and critical path.** Draw the tasks as a network of boxes and arrows. Add up each path and find the critical path and any float.
3. **Gantt chart.** Draw the tasks as bars along a time line, showing which happen at the same time. Mark one milestone.
4. **Budget.** Add up costs and add a 15% contingency.
5. Carry out the project. Record the actual time for each task and the actual cost.
6. Make a table: task, planned time, actual time, difference. Calculate the total schedule variance and cost variance (actual – planned). Which estimates were worst, and why?
7. **Capstone plan.** Now write the WBS, critical-path network, Gantt chart and budget for your capstone project (Lesson 8.3), with milestones for “design chosen,” “first prototype tested” and “final ready for the fair.”
8. **Improve.** Using what you learned from your small project, add contingency where your estimates were weakest. Have a parent review your plan as the

“client” and sign it.

Tips

- Most beginners underestimate. Add time for gathering materials, waiting for glue to dry and cleaning up.
- Tasks that can happen at the same time shorten a project; look for them.
- Keep the plan where you can see it and mark progress each session.

Check your work

- ☐ I can find a critical path and float in a network.
- ☐ I made a Gantt chart and budget with contingency, and compared plan with reality honestly.
- ☐ I have a reviewed and signed schedule and budget for my capstone.

ENGINEER'S NOTEBOOK

1. Network diagram and Gantt chart for your small project, with the critical path highlighted.
2. Planned-versus-actual table with schedule and cost variance.
3. Your capstone WBS, Gantt chart and budget.
4. Solve: tasks A (3 days), B (5 days, after A), C (2 days, after A), D (4 days, after C), E (1 day, after B and D). Find the critical path, the project length, and the float of each task not on it.

From history. Henry Gantt, an American mechanical engineer, developed his bar charts in the 1910s while working to make factories more efficient, and they were used to plan shipbuilding during the First World War. Hoover Dam's builders worked in brutal heat, and the project's safety record, though better than many jobs of its time, was poor by today's standards; 96 men died in industrial accidents during construction, one reason modern projects plan safety as carefully as schedule and cost.

COMMON MISTAKES

- Adding up all task times to find the project length. Tasks done at the same time overlap; the project length is the longest path.
- Leaving out contingency, then having to cut quality or safety when something goes wrong.
- Hiding a delay. A delay reported early can be fixed; a hidden one grows.

Make it a game • Critical Path Cards. Make cards for six tasks of a project, with durations: draw a dependency map and lay them out. Your parent shuffles them and you rebuild the network from memory, then name the critical path and the float. Add a ten percent contingency to a made-up budget. Fastest correct rebuild earns a point; best of three.

Scripture. “For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he have sufficient to finish it? Lest haply, after he hath laid the foundation, and is not able to finish it, all that behold it begin to mock him, Saying, This man began to build, and was not able to finish.” (Luke 14:28-30, KJV)

Jesus used project planning to teach about counting the cost of following Him. Every engineer and builder knows how true His picture is.

8.3 A CAPSTONE DESIGN PROJECT: FROM PROBLEM TO PROTOTYPE

OBJECTIVES

- Write a problem statement, requirements and constraints for a real need.
- Compare at least three concepts in a weighted decision matrix and choose one with reasons.
- Build, test and improve a prototype, using at least one equation from this year to predict its performance.

Warm-up. Think of one small problem in your home, church or neighborhood that annoys or burdens someone: a garden that dries out, a grandparent who struggles to open jars, a gate that will not stay shut, a dark path at night. Write three problems. For each, write who has the problem and what a good solution would need to do. You may choose one of these for your capstone.

WATCH

William Kamkwamba: How I built a windmill

TED • 6:09

<https://www.youtube.com/watch?v=G8yKFVPOD6o>

WHEN TO WATCH

After the story paragraph. Listen for the materials he used and how he learned to build.

BACKUP VIDEO

Engineering Basics - What is a Decision Matrix?

Mr. Z (3D CAD Extraordinaire!) • 3:32

<https://www.youtube.com/watch?v=e0ViXMexuo0>

Before you build your decision matrix. Pause and set up your own columns as he explains each one.

KEY TERMS

problem statement

One or two sentences that say who has a need, what the need is and why it matters, without naming the solution.

constraint

A limit the design must stay within, such as cost, size, weight, materials, safety or time.

prototype

An early working model built to test whether a design idea works.

requirement

Something the design must do, stated so it can be tested (for example, “lifts 200 g at least 30 cm in under 60 seconds”).

decision matrix

A table that scores several concepts against weighted criteria to help choose the best one.

design review

A meeting where others examine a design and ask hard questions before it moves to the next stage.

CORE IDEAS

The story. In 2001 and 2002, a severe famine struck Malawi, in southeastern Africa. William Kamkwamba, then about fourteen, had to drop out of secondary school because his family could not pay the fees. He kept learning at a small village library, where he found a book called *Using Energy* with a picture of windmills on the cover. Using its diagrams, a broken bicycle, a tractor fan, PVC pipe that he heated and flattened into blades, a bicycle dynamo and poles cut from blue gum trees, he built a windmill that lit light bulbs and charged phones for his family and neighbors. People had laughed at him; then they came to charge their phones. He later built a windmill-powered water pump and solar-powered wells for his village, finished school, and graduated from Dartmouth College in 2014.

How they figured it out. William had no engineering training, but he followed the same process every engineer follows. He understood the need (light and water for his family), studied what others had done (the library book), worked within hard constraints (no money, only scrap materials), built a prototype, tested it, and improved it. His first small model was made with a radio motor; his full windmill went through many changes as he learned what worked. Engineers call this the

design process, and it is the same process you followed with every build this year: define, research, imagine, plan, build, test, improve.

The physics. Every capstone should rest on at least one equation that predicts how the design will perform. For a wind turbine, the power in the wind passing through the blades is $P = \frac{1}{2}\rho A v^3$. Worked example: a rotor 2.0 m across ($A = \pi \times 1.0^2 \approx 3.14 \text{ m}^2$) in a 5 m/s wind receives $P = \frac{1}{2} \times 1.2 \times 3.14 \times 5^3 \approx 236 \text{ W}$. No turbine can capture more than 59% of this (the Betz limit), and a simple homemade one might capture 20–30%, about 50–70 W, enough for a few LED lights. Because power goes with v^3 , a wind of 10 m/s carries eight times as much power. Your own project might instead use $F = ma$, $mgh = \frac{1}{2}mv^2$, $P = I^2R$, $P = \rho gh$, the lift equation or $\text{stress} = F \div A$.

The engineering. Real engineering begins with clear, testable **requirements** and **constraints**. Then engineers brainstorm several concepts, because the first idea is rarely the best, and compare them in a **weighted decision matrix**: list criteria (for example, performance, cost, safety, ease of building, durability), give each a weight, score every concept, and multiply and add. The highest score is not automatically the winner, but the matrix makes the reasons clear and honest. After choosing, engineers build a prototype, test it against each requirement, hold a design review, and improve. They document everything so others can build, use and maintain the design.

Try it. Your capstone is your chance to solve a real problem for a real person. Choose something you can build safely in about four weeks with household and craft-store materials (and, if you have them, a microcontroller or kit), and plan to test it with numbers.

PICTURE STUDY



The Head and Wheel of a Water-Pumping Windmill, Historic American Engineering Record, survey photograph · Photograph · Kregel Windmill Company records, Nebraska City; Library of Congress

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

Thousands of small factories like the Kregel Windmill Company made farm windmills to pump water across the American plains. William Kamkwamba's library book showed windmills like these.

Look closely

- Count the blades on the wheel. Why do farm windmills have so many?
- Find the hub and the head where the wheel's shaft enters. What do you think is inside it?
- Look at how the blades are fixed to the rim and the spokes. How might they be repaired?
- Look at the weathered wood. What would an owner have to maintain?

Talk about it

1. A water-pumping windmill needs to start in light winds and push hard, not spin fast. How does its many-bladed wheel suit that job?
2. What would you need to change to make a windmill generate electricity instead of pumping water?

3. Why might a design that can be repaired with simple tools be the best design for a farm far from any town?

Safety first. Choose a project that uses only batteries or USB power, never the outlets in the wall or household wiring. An adult handles sharp tools, hot glue and drills. Wear safety glasses for anything that spins, flies or is under tension. Have an adult approve your design before you build.

BUILD

Your Capstone Design Project

Over the four weeks of this unit you will carry out a capstone engineering project from problem to tested prototype, following your plan from Lesson 8.2. If you need an idea, choose one of these: a small wind turbine that lifts a cup of washers or lights an LED; a gravity-fed drip watering system for a garden bed; a jar-opening aid for someone with weak hands; a sensing device with a Raspberry Pi Pico; a load-tested shelf or footbridge; or a model building that passes the wind and shake tests.

You will need

- Your engineer's notebook, graph paper and your project plan from Lesson 8.2
- Materials chosen in your design (household, craft-store, and any optional kit such as a micro:bit or Pico)
- Measuring tools: ruler, tape measure, kitchen scale, stopwatch, multimeter as needed
- A "client" (a parent, grandparent or neighbor who has the problem) and a reviewer

Steps

1. **Problem statement.** Interview your client. Write one or two sentences stating the need without naming a solution.
2. **Requirements and constraints.** List at least four measurable requirements and at least three constraints (cost limit, size, safety, time).
3. **Research.** Find how others have solved similar problems (books, museum pages, videos from this course). Note two ideas you could borrow.
4. **Concepts.** Sketch at least three different concepts. Label each and estimate its performance with an equation.
5. **Decision matrix.** Choose 4–6 weighted criteria. Score each concept from 1 to 5, multiply by the weights and total. Choose a concept and write two sentences explaining why.

6. **Design review.** Present your choice and drawings to your reviewer. Write down every question asked and how you will answer it.
7. **Prototype and test.** Build the first prototype. Test it against every requirement with measurements, at least three trials each. Record the results honestly, including failures.
8. **Improve.** Change the design to fix the biggest weakness, test again, and record the improvement. Repeat if time allows. Prepare the final version for the engineering fair.

Tips

- Pick a problem small enough to finish. A simple design that works and is well tested beats an ambitious one that is never finished.
- Write requirements with numbers: “holds 2 kg,” not “holds a lot.”
- Photograph every prototype and every failure. They are the most interesting part of your fair display.

Check your work

- ☐ I wrote a clear problem statement, measurable requirements and constraints.
- ☐ I compared at least three concepts in a weighted decision matrix and explained my choice.
- ☐ I built, tested and improved a prototype and recorded the results honestly.

ENGINEER'S NOTEBOOK

1. Problem statement, requirements and constraints, with your client's signature.
2. Concept sketches with performance estimates, and your weighted decision matrix.
3. Test data tables and graphs for each prototype, with what you changed between them.
4. Solve: what power is in a 6 m/s wind passing through a rotor 1.5 m across? What might a homemade turbine capture at 25% efficiency?

From history. William Kamkwamba's story was told in his book *The Boy Who Harnessed the Wind* (2009), written with Bryan Mealer. He has said that the most important thing he learned was to try, even when people laugh. His village library, a small room with donated books, is a reminder that a single good book in the right hands can start an engineer.

COMMON MISTAKES

- Falling in love with the first idea and skipping the comparison. The decision matrix is there to make you consider others honestly.
- Writing requirements that cannot be tested, such as “works well.”
- Changing several things at once between prototypes, so you cannot tell which change helped.

Make it a game • Matrix Judge. Invent a household problem, like a messy shoe pile. Write a problem statement, two requirements and a constraint in ninety seconds. Your parent proposes three concepts and you score them in a weighted decision matrix, defending each score. Then swap. Whoever's chosen design is questioned the least wins a pretend design review.

8.4 THE ENGINEERING FAIR AND PRESENTATION: FARADAY'S CHRISTMAS LECTURES

OBJECTIVES

- Organize an engineering report and a display: problem, requirements, design, testing, results and conclusions.
- Report measurements with their mean, range and percent error, and draw honest conclusions.
- Give a clear, short presentation and live demo at the family engineering fair and answer questions.

Warm-up. Explain one build from this year to a family member in exactly one minute, using a timer. Then ask them to tell it back to you. What did they remember? What did they miss? Write down one thing that made your explanation clear and one thing that made it confusing.

WATCH

Giving an Effective Poster Presentation

[georgerhess](#) · 11:55

<https://www.youtube.com/watch?v=vMSaFUrK-FA>

WHEN TO WATCH

Before you plan your display. Notice how the presenter uses the poster as a tool and invites questions.

Note: Made at North Carolina State University for college students; the advice works for any age.

BACKUP VIDEO

The History of the CHRISTMAS LECTURES - with Frank James

[The Royal Institution](#) · 22:43

<https://www.youtube.com/watch?v=duaC3JOxGYo>

With the story paragraph: a historian at the Royal Institution tells how Faraday's lectures began, with the original lecture theater and live demos.

KEY TERMS

engineering report

A written record of a project with a standard structure: summary, problem, requirements, design, testing, results, conclusions and recommendations.

uncertainty

How much a measured value might be off, often written as $\pm$ a number, for example 2.31 ± 0.04 s.

live demo

Showing a working design or experiment to an audience, so they see the result for themselves.

mean and range

The mean is the average of repeated measurements; the range (largest minus smallest) shows how much they varied.

percent error

$|\text{measured} - \text{predicted}| \div \text{predicted} \times 100\%$: how far a result is from the prediction.

CORE IDEAS

The story. In December 1825, the Royal Institution in London began a series of science lectures for young people during the holidays. Michael Faraday, the son of a blacksmith, who had started as a bookbinder's apprentice and became one of the greatest experimental scientists who ever lived, gave nineteen of the Christmas series himself. In his most famous, *The Chemical History of a Candle*, first given in 1848 and again in 1860, he explained combustion, air and water using nothing more than a candle and simple apparatus on the lecture table. A painting shows him lecturing in 1855 with Prince Albert and two young princes in the front row. The Christmas Lectures still continue every year. Faraday was a devout Christian all his life, and he saw his science as reading the book of God's works.

How they figured it out. Faraday worked hard at explaining. As a young man he attended lectures by Humphry Davy and wrote careful notes on what made a lecture good: speak slowly and clearly, show real experiments rather than just describing them, keep the audience's attention with a clear purpose, and finish on time. He rehearsed his live demos, kept his apparatus simple and large enough for the back

rows to see, and connected every idea to something his young audience already knew. Those habits are exactly what makes an engineering presentation work today.

The physics. An honest presentation reports measurements with their spread.

Worked example: three trials of a glider's flight time are 2.31 s, 2.35 s and 2.28 s. The mean is $(2.31 + 2.35 + 2.28) \div 3 = 2.31$ s; the range is $2.35 - 2.28 = 0.07$ s, so a fair way to report it is 2.31 ± 0.04 s (half the range). If you predicted 2.50 s, the percent error is $|2.31 - 2.50| \div 2.50 \times 100\% \approx 7.6\%$. A good conclusion says whether the difference is larger than your uncertainty and gives the most likely reasons, such as friction, air drag or measuring error, without hiding anything.

The engineering. Engineers spend a large part of their working lives communicating: writing reports, drawing plans, presenting designs to clients, explaining risks to the public, and teaching younger engineers. A good engineering display tells a clear story: the problem and who has it, the requirements, the options considered and why one was chosen, a labeled drawing, test data in a table and graph, what failed and what was improved, and a recommendation. A good talk is short (about three to five minutes), begins with the problem, shows a live demo, and ends by inviting questions. The ability to answer “How do you know?” with data is the mark of a real engineer.

Today. At your family engineering fair, you join a long line of makers who showed their work to others: Faraday at his lecture table, Benjamin Baker with his human cantilever, MacCready with his gossamer airplanes. *Fabricando fit faber*: by making, one becomes a maker, and by teaching, one becomes a teacher.

PICTURE STUDY



Faraday Lecturing at the Royal Institution, Alexander Blaikley, December 27, 1855 · Painting, later lithograph · The Royal Institution, London
Image: [Wikimedia Commons](#), public domain

This scene shows one of Faraday's Christmas Lectures for young people. Look at how he arranges the room and the apparatus so that everyone can see and understand.

Look closely

- Find Faraday. Is he reading from notes or talking to the audience?
- Find the apparatus on the lecture table. Is it large enough for the back rows to see?
- Find the front row. Who is sitting there?
- Look at the faces in the audience. Are they bored or interested? What makes you think so?

Talk about it

1. What habits of a good lecturer can you see in this picture?
2. Why would a real live demo be more convincing than a description?
3. How will you arrange your own display so visitors can see your design and data?

Safety first. Set up live demos so that guests stand back from anything that spins, flies or launches, and keep an adult in charge of any water, launching or tools. Use only batteries or USB power at the fair.

BUILD

The Family Engineering Fair

You will prepare a display and a short talk for your capstone project, and set out your best build from each unit with its notebook pages. Then you will hold a family engineering fair, show your work, answer questions and collect feedback.

You will need

- A trifold display board or a large poster, markers, printed graphs and photographs
- Your capstone prototype and your best build from each unit, with notebook pages
- Your engineer's notebook and a stopwatch
- Feedback cards and pencils for guests

Steps

1. **Report.** Write a two-page engineering report for your capstone with these headings: Summary; Problem and client; Requirements and constraints; Concepts and decision matrix; Final design (labeled drawing); Testing and results (table and graph with mean, range and percent error); Improvements; Conclusions and recommendations.
2. **Display.** Lay out your board so it reads left to right: problem → requirements → design → test data → improvements → conclusion. Use large titles and only short text; put the details in your report.
3. **Talk.** Write a 3–5 minute talk: begin with the problem and the client, show the design, give a live demo, show one graph, tell one failure and how you fixed it, and finish with your recommendation. Practice it three times with a timer.
4. **Anticipate questions.** Write five questions a visitor might ask (for example, “How do you know it is safe?” or “What would you change?”) and practice answering each with data.
5. **Unit display.** Set out your best build from each of Units 1–7 with one notebook page each, and write a one-sentence card for each saying what

physics it shows.

6. **Hold the fair.** Invite family, friends or your homeschool group. Give your talk, show it working, and answer questions. Ask each guest to fill in a feedback card: one thing that was clear, one question they still have.
7. **Reflect and improve.** Read the feedback cards. Write a one-page reflection: what you learned this year, which build taught you the most, what you would do differently, and what kind of engineering or making you might like to do next.

Tips

- Speak to your guests, not to your board. Use the board to point to what you are explaining.
- Practice the live demo until it works reliably, and have a backup photo or video if it fails on the day.
- When you do not know an answer, say so honestly and say how you could find out.

Check your work

- ☐ I wrote a complete engineering report with data, uncertainty and honest conclusions.
- ☐ I gave a clear, timed talk and live demo and answered questions with data.
- ☐ I collected feedback and wrote a reflection on my year as an engineer.

ENGINEER'S NOTEBOOK

1. A thumbnail sketch of your display layout before you build it.
2. Your talk outline and the five practice questions with answers.
3. Mean, range and percent-error calculations for your capstone test data.
4. Your end-of-year reflection.

From history. Faraday's Christmas lecture on the candle was written down and published in 1861 and has never gone out of print. Among later Christmas lecturers were the physicist William Henry Bragg and the engineer Eric Laithwaite, who in 1974 lectured on invention. Faraday turned down a knighthood and the presidency of the Royal Society, preferring, he said, to remain plain Michael Faraday to the end.

COMMON MISTAKES

- Putting too much text on the display. Visitors read titles, pictures and graphs; the talk and report carry the details.
- Hiding failures. Visitors and judges are most interested in what went wrong and how you fixed it.
- Reporting a single measurement as if it were exact. Report the mean and the spread.

Make it a game • Fair Report Card. Measure the same object five times, such as a table's length. Write down the mean, range and percent error against the true value. Your parent plays judge, asking one tough question about uncertainty. Then give a thirty-second live-demo pitch of your result. Judges award points for honest conclusions, not for the best-looking number.

Scripture. “And he hath put in his heart that he may teach, both he, and Aholiab, the son of Ahisamach, of the tribe of Dan.” (Exodus 35:34, KJV)

Bezalel and Aholiab were given skill not only to build but to teach others. Showing and explaining your work is part of the gift.

UNIT 8

CAPSTONE: THE ENGINEER'S CALLING

This last unit brings the whole year together and looks ahead to high school and beyond. It begins with the hardest question in engineering: what does an engineer owe the people who will use what he or she designs? You will study the Hyatt Regency walkway collapse of 1981, one of the most important ethics cases in American engineering, and model with rubber bands how one small design change doubled the load on a connection. You will think about engineering as a vocation, a calling to serve others with skill and honesty.

Then you will plan and carry out a capstone design project of your own, the way real engineers do: with a schedule and a budget (counting the cost, as Jesus said, before building the tower), clear requirements, a decision matrix, prototypes, tests and improvements. The year ends with a family engineering fair, where, like Michael Faraday at his Christmas lectures, you will explain your work clearly to an audience and answer their questions.

PREREQUISITES

- Has completed the builds and notebook pages of Units 1–7
- Can calculate reactions and loads in simple structures (Unit 2)
- Can make data tables, graphs and averages, and calculate percent error
- Has a parent or mentor willing to act as “client” and reviewer for the capstone

MASTERY CHECKLIST

- ☐ I can explain the engineering failure and the ethical failures in the Hyatt Regency collapse, and state the engineer’s first duty to the public.
- ☐ I can make a work breakdown, a Gantt chart and a critical-path network, and build a budget with a contingency.
- ☐ I can write requirements and constraints, compare options in a weighted decision matrix, and prototype, test and improve a design.
- ☐ I can calculate mean, range and percent error and report results honestly with their uncertainty.
- ☐ I can present an engineering project clearly with a poster or display, a live demo and answers to questions.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober)**: Ages 8 and up (the Hack Pack line is for ages 12 and up). Monthly build-and-modify projects that can seed capstone ideas in Lesson 8.3.
- **BBC micro:bit**: Ages 10 and up. A small programmable board with built-in sensors and free MakeCode software; a good brain for sensing and logging capstone projects.
- **Raspberry Pi Pico**: Ages 12 and up with an adult. The microcontroller from Lesson 4.3, inexpensive and powered by USB, for capstones that sense, decide and act.

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 Engineering Ethics and Vocation: The Hyatt Regency Walkways

2 sessions of 60 minutes

8.2 Project Management: Counting the Cost at Hoover Dam

2 sessions of 60 minutes

8.3 A Capstone Design Project: From Problem to Prototype

2 sessions of 60 minutes

8.4 The Engineering Fair and Presentation: Faraday's Christmas Lectures

2 sessions of 60 minutes

UNIT 8 REVIEW

This final review covers this unit and draws on the whole year. Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use complete sentences for explanations. The review is worth 100 points.

1. 10 pts

Calculation and explanation. In the Hyatt Regency walkways, suppose each walkway put a load of 40 kN on each hanger. What load did the fourth-floor connection carry in the original design and in the as-built design? Explain with a free-body diagram in words.

2. 8 pts

Name two ethical failures in the Hyatt Regency case and state the first duty of engineers in professional codes of ethics.

3. 6 pts

What does it mean to see engineering as a vocation?

4. 10 pts

Calculation. Tasks: A (2 weeks); B (4 weeks, after A); C (3 weeks, after A); D (2 weeks, after C); E (1 week, after B and D). Find the critical path, the project length and the float of task B.

5. (8 pts)

A project's base cost estimate is \$64,000. What is the budget with a 15% contingency? Why include contingency?

6. (8 pts)

Why was Hoover Dam poured in separate blocks with cooling pipes, and how did Frank Crowe finish early?

7. (8 pts)

Write one testable requirement and one constraint for a garden watering system.

8. (10 pts)

Calculation. Three concepts are scored 1–5 on Performance (weight 4), Cost (weight 3) and Ease of building (weight 2). A scores 4, 2, 3; B scores 3, 4, 4; C scores 5, 1, 2. Find each total and choose.

9. (8 pts)

Calculation. Find the wind power passing through a rotor 3.0 m across in an 8 m/s wind ($\rho = 1.2 \text{ kg/m}^3$). How much might a turbine with 30% efficiency produce?

10. (8 pts)

Calculation. Four trials of a bridge's failure load are 5.2, 5.6, 5.0 and 5.4 kg. Find the mean and range, report the result with an uncertainty, and find the percent error if you predicted 6.0 kg.

11. (8 pts)

List the main sections of an engineering report and three habits of a good presenter, as Faraday practiced them.

12. (8 pts)

Write a paragraph: Choose one story from this year (for example, the Wright brothers, the Roebings, Froude, Leal and Fuller, or the *Trieste*) and explain what it teaches about how engineers learn and serve.

ANSWER KEY

1. Original: 40 kN (the second-floor load went up the continuous rod to the ceiling). As-built: 80 kN, because the lower rod hung from the fourth-floor beam, so that connection carried its own walkway plus the second-floor walkway.
2. Any two: approving the design change without calculating it; not checking shop drawings and connections carefully; each party assuming someone else had checked; an original design already weaker than the code required. First duty: hold paramount the safety, health and welfare of the public.
3. To see the work as a calling to serve God and neighbor with skill and honesty, not just a job; for example, doing careful work even when no one checks, because the people who use it matter.
4. Paths: A-B-E = $2 + 4 + 1 = 7$ weeks; A-C-D-E = $2 + 3 + 2 + 1 = 8$ weeks. Critical path A-C-D-E, 8 weeks. Task B has 1 week of float.
5. $\$64,000 \times 1.15 = \$73,600$. Because some things always go wrong or cost more than expected; contingency keeps the project from cutting quality or safety or running out of money.
6. Concrete gives off heat as it cures; a single huge mass would take a very long time to cool and would crack. Crowe planned the critical path carefully (diversion tunnels, cofferdams, excavation, concrete), concentrated people and equipment on critical tasks, and built a fast concrete-delivery system of cableways.
7. Example requirement: delivers at least 2 liters of water evenly to a 1 m^2 bed in 30 minutes. Example constraint: costs less than \$15 and uses no electricity from the wall. (Any measurable requirement and real limit accepted.)
8. $A = 16 + 6 + 6 = 28$. $B = 12 + 12 + 8 = 32$. $C = 20 + 3 + 4 = 27$. Concept B scores highest.
9. $A = \pi \times 1.5^2 \approx 7.07 \text{ m}^2$. $P = \frac{1}{2} \times 1.2 \times 7.07 \times 8^3 \approx 0.6 \times 7.07 \times 512 \approx 2,170 \text{ W}$. At 30%: about 650 W.
10. Mean = $21.2 \div 4 = 5.3 \text{ kg}$. Range = $5.6 - 5.0 = 0.6 \text{ kg}$; report $5.3 \pm 0.3 \text{ kg}$. Percent error = $|5.3 - 6.0| \div 6.0 \times 100\% \approx 11.7\%$.
11. Sections: summary; problem; requirements and constraints; concepts and decision; design; testing and results; conclusions and recommendations. Habits (any three): speak slowly and clearly; show real live demos; keep apparatus large and simple; connect to what the audience knows; rehearse; finish on time; invite questions.

12. Answers vary; a strong answer tells the story accurately, names the problem, the tests or measurements, the failure or difficulty overcome, and how the result served people.

PORTFOLIO PIECE: THE CAPSTONE PROJECT AND ENGINEERING FAIR

Complete, document and present your capstone design project: a real solution to a real problem for a real client, planned with a schedule and budget, chosen with a weighted decision matrix, built, tested against measurable requirements, and improved at least once. Present it at the family engineering fair with a display, a 3–5 minute talk and a live demo, alongside your best build from each unit. Hand in the engineering report, the plan, the decision matrix, all test data and your end-of-year reflection, with your client’s signed comments.

LOOK FOR	WHAT IT MEANS
Problem and requirements	Clear problem statement from a real client; at least four measurable requirements and three constraints.
Design process	At least three concepts compared in a weighted decision matrix; reasons for the choice explained; design review held.
Planning	Gantt chart, critical path and budget with contingency; planned and actual time and cost compared honestly.
Testing and improvement	Prototype tested against every requirement with repeated trials, mean and uncertainty; at least one improvement with before-and-after data.
Communication	Clear report and display; timed talk with live demo; questions answered with data; reflection completed.

TOY LAB: THE PHYSICS OF PLAY

Some of the deepest physics in this whole course is hiding in the toy box. In this optional bonus unit you will study four toys the way a physicist and a product engineer would. A toy gyroscope that seems to defy gravity will teach you angular momentum, torque and precession, the same physics that steers ships and points the Hubble Space Telescope. A Slinky dropped from your hand will show, in slow motion, that a force takes time to travel through a material as a wave. A radio-controlled airplane will show how control surfaces, center of gravity and a radio link let a person fly a machine from the ground.

The last lesson is your own invention. You will invent, prototype and play-test a toy, check it against real toy-safety rules, work out what it would cost to make, and pitch it to a family panel, just as an inventor pitches to a toy company. Do this unit after the engineering fair, over the summer, or any week that needs something fun.

PREREQUISITES

- Has finished Units 1 and 7 (momentum, circular motion, energy, flight control)
- Can use $F = ma$, torque (force $\times$ distance) and a stopwatch with slow-motion video
- Can make data tables and graphs with units

MASTERY CHECKLIST

- ☐ I can explain gyroscopic precession using angular momentum and torque and calculate a precession rate.
- ☐ I can explain why the bottom of a dropped Slinky hangs still, using Hooke's law and wave travel, and measure a spring constant and a wave speed.
- ☐ I can explain how an RC airplane's control surfaces, center of gravity and radio system control its flight.
- ☐ I can invent, prototype, play-test and safety-check a toy, estimate its cost per unit and pitch it clearly.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up (Hack Pack for ages 12 and up). Each box is a toy built around one physics idea and designed to be taken apart and modified; excellent for Lessons 9.1 and 9.4.
- **KiwiCo crates:** Ages vary by line (Tinker and Eureka for ages 9–16 and up). Many crates are mechanical toys that work well as teardown and redesign projects for Lesson 9.4.
- **Snap Circuits (Elenco):** Ages 8 and up. Motors, switches and a spinning-disk launcher make it easy to prototype an electric toy for Lesson 9.4 without soldering.

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 Gyroscope and Precession	2 sessions of 60 minutes
9.2	The Slinky Drop: Waves in Slow Motion	2 sessions of 60 minutes
9.3	RC Airplanes and Toy Drones: Flying from the Ground	2 sessions of 60 minutes
9.4	Capstone Toy: Invent, Prototype, Test and Pitch	2 sessions of 60 minutes

UNIT 9 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use $g = 9.8 \text{ m/s}^2$. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Explain in your own words why a spinning gyroscope supported at one end precesses instead of falling.

2. **10 pts**

Calculation. A gyroscope rotor has $I = 3.0 \times 10^{-4} \text{ kg}\cdot\text{m}^2$ and spins at 250 rad/s. Its weight of 1.5 N acts 0.040 m from the pivot. Find L, the torque and the precession rate.

3. **6 pts**

What happens to the precession rate as a gyroscope slows down, and why?

4. **8 pts**

Name two engineering uses of gyroscopes and one safety rule for spinning toys.

5. **8 pts**

When you drop a hanging Slinky, why does its bottom stay still for a moment?

6. **10 pts**

Calculation. A 0.20 kg mass stretches a spring section by 0.08 m. Find k. How far would 0.50 kg stretch it?

7. **8 pts**

Calculation. A Slinky's bottom stays still for 0.28 s after release, and the stretched Slinky was 1.1 m long. Find the average speed of the collapse front and how far the center of mass fell in that time.

8. **8 pts**

List the main parts of an RC airplane's electronics and say what each does.

9. **10 pts**

Calculation and explanation. An elevator makes a 0.40 N force 0.50 m behind the CG. Find the pitching moment. Why must the CG of a model airplane be ahead of the wing's neutral point?

10. **8 pts**

Name four toy-safety checks and say why button batteries get special rules.

11. **10 pts**

Calculation. A toy mold costs \$24,000 and each toy costs \$1.20 in materials and labor. Find the unit cost for 8,000 toys and for 80,000 toys.

12. **6 pts**

Write a short paragraph: What makes a toy both good engineering and good for a child?

ANSWER KEY

1. Gravity makes a torque about the support. A torque changes angular momentum; because the rotor has a large angular momentum along its axle, the torque changes the direction of that angular momentum sideways, so the axle swings around the support (precesses) instead of tipping down.
2. $L = I\omega = 3.0 \times 10^{-4} \times 250 = 0.075 \text{ kg}\cdot\text{m}^2/\text{s}$. $\tau = 1.5 \times 0.040 = 0.060 \text{ N}\cdot\text{m}$. $\Omega = \tau \div L = 0.060 \div 0.075 = 0.80 \text{ rad/s}$.
3. It speeds up, because $\Omega = \tau \div L$ and $L = I\omega$ gets smaller as ω falls, while the torque stays the same.
4. Uses (any two): gyrocompasses; aircraft instruments and autopilots; ship stabilizers; reaction wheels for telescopes and spacecraft; MEMS gyros in phones and drones. Safety (any one): no small detachable parts for children under three; no sharp points; pull strings short enough not to be a strangling hazard.
5. The bottom coils are held in balance by tension above and gravity. Letting go changes the tension only at the top; the change travels down the Slinky as a wave of collapsing coils, and until it arrives the bottom's forces are still balanced, so it stays still.
6. $F = 0.20 \times 9.8 = 1.96 \text{ N}$; $k = 1.96 \div 0.08 = 24.5 \text{ N/m}$. For 0.50 kg: $x = (0.50 \times 9.8) \div 24.5 = 0.20 \text{ m}$.
7. $v = 1.1 \div 0.28 \approx 3.9 \text{ m/s}$. Center of mass: $\frac{1}{2}gt^2 = \frac{1}{2} \times 9.8 \times 0.28^2 \approx 0.38 \text{ m}$.
8. Transmitter (sends the pilot's commands); receiver (receives them); servos (move the control surfaces); ESC (controls motor power); motor and propeller (thrust); battery (power for all).
9. $M = 0.40 \times 0.50 = 0.20 \text{ N}\cdot\text{m}$. With the CG forward, a disturbance that pitches the nose up increases the tail's restoring force and brings the nose back down, so the airplane is stable; a tail-heavy airplane tends to keep pitching further and is unstable.
10. Any four: small-parts cylinder test (under three); sharp point and edge tests; cord length limits; drop, pull, twist and bite tests; limits on small powerful magnets; chemical tests (such as lead). Button batteries must be locked away because a swallowed one can quickly cause severe internal burns.
11. 8,000: $24,000 \div 8,000 + 1.20 = 3.00 + 1.20 = \$4.20$. 80,000: $24,000 \div 80,000 + 1.20 = 0.30 + 1.20 = \$1.50$.

12. Answers vary; a strong answer mentions that it works reliably, uses physics well, is safe for its age group, is durable and affordable, and invites real play, imagination or learning.

PORTFOLIO PIECE: A PHYSICS TOY, TESTED AND PITCHED

Present your Lesson 9.4 toy as a complete product package: a labeled drawing and working prototype; one physics calculation about how it works; play-test notes from a real child in its target age group, before and after your improvement; a safety-check table (small parts, edges and points, cords, drop test, batteries or magnets if any); a unit-cost calculation for two production quantities with a proposed price; and a short written pitch. If you prefer, you may instead build and fully test a gyroscope, Slinky or glider experiment from Lessons 9.1–9.3 and present it as a toy-company research report.

LOOK FOR	WHAT IT MEANS
Design and physics	Clear drawing and working prototype; at least one correct physics calculation with units.
Play test	Real user observed; specific notes recorded; design improved based on what was seen.
Safety	All relevant safety checks done and recorded; every problem fixed in the final design.
Cost	Unit cost calculated correctly for two quantities, with a sensible price.
Pitch	Clear, honest, evidence-based pitch that names the user, shows the toy working and answers questions.

9.1 THE GYROSCOPE AND PRECESSION

OBJECTIVES

- Explain angular momentum ($L = I\omega$) and how a torque changes its direction to cause precession.
- Calculate the precession rate of a toy gyroscope ($\Omega = mgr \div (I\omega)$) and explain why it speeds up as the gyroscope slows.
- Measure precession with a spinning bicycle wheel or a homemade gyroscope and test how spin rate changes it.

Warm-up. Spin a coin on its edge on a table and watch it as it slows. Then spin a top. Why does a spinning top stay upright while a still top falls over at once? Hold a bicycle wheel (off the bike) by its axle and tilt it, first still and then while someone spins it fast. Write down how the two feel different.

WATCH

Gyroscopic Precession

Veritasium · 3:49

<https://www.youtube.com/watch?v=ty9QSiVC2g0>

WHEN TO WATCH

After the physics paragraph. Watch the arrows for angular momentum and torque on the hanging wheel.

Note: Made with Destin Sandlin of SmarterEveryDay; the description mentions his channel.

KEY TERMS

angular momentum

The “quantity of spin” of a rotating object: $L = I\omega$, moment of inertia times angular speed. It points along the spin axis.

moment of inertia

How hard it is to change an object’s spin, I . Mass far from the axis counts most; for a solid disk $I = \frac{1}{2}mR^2$, for a ring $I \approx mR^2$.

torque

A turning force: $\tau = \text{force} \times \text{lever arm}$,
in newton-meters (N·m).

precession

The slow turning of a spinning object's
axis when a torque acts on it, at a rate
 $\Omega = \tau \div L$.

gyrocompass

A compass made from a gyroscope that
finds true north using the earth's
rotation instead of magnetism.

MEMS gyroscope

A tiny vibrating-structure gyroscope
etched in silicon, used in phones,
drones and game controllers.

CORE IDEAS

The story. In 1852 the French physicist Léon Foucault, who the year before had shown the earth's rotation with his famous pendulum, built a heavy brass wheel spinning very fast inside a set of rings that let its axis point any direction. Because a fast-spinning wheel keeps its axis pointed the same way in space, he could watch the earth slowly turn beneath it. He named it the *gyroscope*, from Greek words meaning “to see the turning.” By the early 1900s toy gyroscopes were sold everywhere, and engineers had turned the same physics into serious tools: the American inventor Elmer Sperry built a gyrocompass that was tested aboard a U.S. Navy battleship in 1911, and his son Lawrence showed off a gyroscopic autopilot in 1914 by standing up in the cockpit while the airplane flew level by itself.

How they figured it out. Foucault's difficulty was friction: a gyroscope slows down within minutes, and any small torque from friction or imbalance makes its axis wander. He used a heavy rim, precise bearings and a carefully balanced frame, and spun the wheel up with a gear train before each experiment. Toy makers faced the same problem at a smaller scale and much lower cost: a toy gyroscope works only if its rotor is balanced, its axle is straight and its pivots are sharp and smooth. Sperry's gyrocompass had to keep spinning for months at sea, so he drove it with an electric motor and added careful damping so it settled on north instead of swinging around it.

The physics. A spinning rotor has angular momentum $L = I\omega$, pointing along its axle. Rest one end of the axle on a stand, and gravity pulls down on the gyroscope, making a torque $\tau = mgr$ about the stand. A torque changes angular momentum, just as a force changes ordinary momentum, but here it changes the *direction* of L sideways, so instead of falling, the axle swings slowly around the stand. That is

precession, with rate $\Omega = \tau \div L = mgr \div (I\omega)$. Worked example: a toy rotor of mass 0.10 kg and radius 0.030 m has $I = \frac{1}{2}mR^2 = \frac{1}{2} \times 0.10 \times 0.030^2 = 4.5 \times 10^{-5} \text{ kg}\cdot\text{m}^2$. Spinning at 3,000 rpm (314 rad/s), $L = 4.5 \times 10^{-5} \times 314 \approx 0.014 \text{ kg}\cdot\text{m}^2/\text{s}$. If its weight acts 0.040 m from the pivot, $\tau = 0.10 \times 9.8 \times 0.040 = 0.039 \text{ N}\cdot\text{m}$, so $\Omega \approx 0.039 \div 0.014 \approx 2.8 \text{ rad/s}$, about one trip around the stand every 2.3 seconds. Because Ω gets larger as ω gets smaller, precession speeds up as the gyroscope slows, until it finally wobbles and falls.

The engineering. Engineers use gyroscopes to hold or measure direction: gyrocompasses on ships, gyroscopic instruments in aircraft, stabilizers that keep ships from rolling, and the reaction wheels and control-moment gyroscopes that point telescopes and the International Space Station without using fuel. Your phone and toy drones use MEMS gyroscopes, tiny vibrating silicon structures that sense rotation. A good toy gyroscope is a small piece of precision engineering: heavy rim for a large I , a balanced rotor, low-friction pivots and a pull string or starter to spin it fast. Toy-safety engineers check that the pivot points are not sharp enough to hurt, that pull strings cannot wrap around a small child's neck, and that no small parts can come loose for children under three.

Try it. In your build, a spinning bicycle wheel hung from one end of its axle will precess instead of falling. You will time its precession at different spin speeds and see $\Omega = \tau \div L$ at work.

PICTURE STUDY



Foucault's Gyroscope, Unknown photographer, instrument of 1852 · Photograph of the original instrument · Musée des Arts et Métiers, Paris

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

This is Foucault's own gyroscope, now in a Paris museum. The rings around the wheel are gimbals, which let the frame turn freely without twisting the wheel's axis. The small instrument beside it is a microscope for watching the slow drift.

Look closely

- Find the wheel inside its rings. Is its mass concentrated at the rim? Why?
- Find the gimbal rings. How many ways can the wheel's axis turn?
- Find the microscope beside it. Why would Foucault need a microscope to see the earth's rotation in an hour?
- Look for the leveling screws on the base. Why must the stand be level?

Talk about it

1. Why does a fast-spinning wheel keep pointing the same direction in space?
2. What would friction in the pivots do to Foucault's experiment?
3. How is a toy gyroscope like Foucault's, and how is it simpler?

Safety first. Spin the bicycle wheel only with an adult, holding the axle stubs, and keep fingers, hair and loose clothing away from the spokes. Wear safety glasses. Never spin a wheel near small children.

BUILD

Measuring Precession

You will hang a spinning bicycle wheel (or a homemade CD gyroscope) from one end of its axle and time its precession at different spin speeds. You will test whether faster spin gives slower precession, as $\Omega = \tau \div L$ predicts.

You will need

- A bicycle front wheel with axle stubs or handles on both sides (or a CD with a marble glued in its hole and a pencil axle as a small gyroscope)
- A strong rope or cord tied to a sturdy beam, door frame pull-up bar or tree branch, with an adult's help
- A stopwatch, a phone that records slow-motion video, tape and a marker
- A kitchen scale and tape measure

Steps

1. Weigh the wheel and measure its radius. Estimate $I \approx mR^2$ (most of a bicycle wheel's mass is in the rim and tire). Measure the distance r from the hanging point to the center of the wheel.
2. Put a strip of tape on the tire so you can count turns.
3. Tie a loop in the rope and hook one axle end into it. Have an adult spin the wheel fast by hand (or by pushing the tire), then let go of the other end gently, holding the axle level.
4. Film the wheel to count its spin rate (turns per second) from the tape mark, and time one full trip of the precession around the rope.
5. **Fair test.** Repeat at three different starting spin rates, keeping the hanging point and r the same. Record spin rate (rev/s and rad/s), precession time and precession rate $\Omega = 2\pi \div (\text{precession time})$.
6. Calculate $L = I\omega$ and the predicted $\Omega = mgr \div L$ for each trial. Make a table comparing predicted and measured Ω .
7. Graph Ω against $1 \div \omega$. If the theory is right, it is a straight line.
8. **Improve.** Change one thing: tape a small mass to the rim (bigger I) or hang the wheel closer to the axle end (smaller r). Predict, then test.

Tips

- Hold the axle level when you let go; tilting it at the start makes the wheel nod up and down (called nutation).
- Spin rates fall as you watch. Count spin over the same short interval during each precession trip.
- If you have a toy gyroscope with a stand, run the same test on it.

Check your work

- ☐ I can explain precession using angular momentum and torque.
- ☐ My measurements show precession slowing as spin rate increases, and I compared them with $\Omega = mgr \div (I\omega)$.
- ☐ I can describe two engineering uses of gyroscopes and two toy-safety checks for spinning toys.

ENGINEER'S NOTEBOOK

1. Side and top sketches of the hanging wheel with arrows for weight, torque, angular momentum and the direction of precession.
2. Data table and graph of Ω against $1 \div \omega$.
3. Solve: a gyroscope rotor has $I = 2.0 \times 10^{-4} \text{ kg}\cdot\text{m}^2$ and spins at 200 rad/s. Its mass is 0.20 kg with its center 0.05 m from the pivot. Find its precession rate and period.
4. Write a paragraph explaining to a younger child why a spinning top does not fall over.

From history. Elmer Sperry founded the Sperry Gyroscope Company in 1910, and gyrocompasses were soon fitted to warships and merchant ships around the world. The Hubble Space Telescope points to targets using spinning reaction wheels and steady gyroscopes so precise that it can hold on a distant galaxy for hours.

COMMON MISTAKES

- Thinking a gyroscope “cancels gravity.” The rope still holds up its full weight; gravity’s torque turns the axis sideways instead of tipping it down.
- Forgetting that precession gets faster as the spin slows.
- Using diameter instead of radius in $I = \frac{1}{2}mR^2$ or mR^2 .

Make it a game • Spin and Predict. Spin a top or coin on its edge. Predict aloud whether it will precess, wobble or fall, and why angular momentum and torque matter. Your parent marks your guess. Then explain why precession speeds up as the spin slows. Score points for correct predictions, and keep a record of how many spins you can explain in a row.

Scripture. “And the streets of the city shall be full of boys and girls playing in the streets thereof.” (Zechariah 8:5, KJV)

In Zechariah’s picture of a restored city, children at play are a sign of peace and blessing. Good toys, safely made, are part of that gift.

9.2 THE SLINKY DROP: WAVES IN SLOW MOTION

OBJECTIVES

- Tell how Richard and Betty James invented and sold the Slinky.
- Measure a spring constant with Hooke's law ($F = kx$) and measure the speed of a wave traveling along a spring.
- Film a hanging Slinky dropped in slow motion and explain why the bottom stays still until the top arrives.

Warm-up. Hold a Slinky by its top so it hangs and stretches. Predict: when you let go, what will the bottom do in the first instant: fall, rise, or stay still? Write your prediction and draw it. Do not drop it yet!

WATCH

Slinky Drop Answer

Veritasium · 3:30

<https://www.youtube.com/watch?v=eCMmmEEyOO0>

WHEN TO WATCH

After you write your warm-up prediction. Watch the bottom of the Slinky closely.

BACKUP VIDEO

Dropping a Slinky with VERITASIVM in SLOW MOTION!

Questacon · 1:43

https://www.youtube.com/watch?v=Tdh_R7po6Dw

After the physics paragraph: the same drop filmed at 1,000 frames per second at Australia's national science center.

KEY TERMS

Hooke's law

For a spring, the force is proportional to the stretch: $F = kx$, where k is the spring constant in N/m.

spring constant

How stiff a spring is: the force needed to stretch it by one meter, $k = F \div x$.

wave

A disturbance that travels through a material, carrying energy and information from one place to another.

longitudinal and transverse waves

In a longitudinal wave, coils move back and forth along the direction the wave travels (like sound); in a transverse wave they move sideways.

center of mass

The average position of an object's mass. When you drop the Slinky, its center of mass falls with acceleration g from the very start.

tension

The pulling force in a stretched spring or rope.

CORE IDEAS

The story. In 1943 Richard James, a mechanical engineer working for the U.S. Navy at a Philadelphia shipyard, was experimenting with springs meant to steady delicate instruments on ships at sea. One knocked off a shelf and seemed to walk, coil over coil, down onto the floor. He and his wife Betty saw a toy in it. Betty found the name “Slinky” in the dictionary. Richard spent about two years finding the right steel wire and coil size and building a machine to wind it. In November 1945 they showed it at Gimbel's department store in Philadelphia, and the first 400 sold in about ninety minutes. He patented it in 1947. Later Betty ran the company for decades and kept its price low so that families could afford it.

How they figured it out. Not every spring will walk down stairs. Richard tried many wires and shapes. It had to be flat, flexible wire that was stiff enough to spring back but soft enough that each coil would flop over onto the next step; the coils had to touch when relaxed; and the whole toy had to be light so the coils' momentum carried it on. The winding machine had to coil about 80 feet of flat wire evenly in seconds, cheaply enough to sell for a dollar. Like so many great toys, the Slinky was physics, engineering and manufacturing working together.

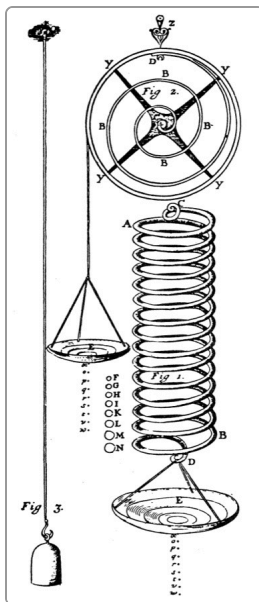
The physics. A hanging Slinky is a chain of springs, each coil pulled up by the tension above it and down by the weight below it. When you let go of the top, nothing tells the bottom coils that anything has changed until a wave of collapsing coils travels down to them. Until that front arrives, the tension and gravity on the bottom coils are still balanced, so the bottom hangs perfectly still in the air, while the top falls faster than g . The center of mass of the whole Slinky still falls with

acceleration g from the instant you let go. In slow motion the collapse of a typical metal Slinky takes about 0.3 seconds. Worked example: if the stretched Slinky was 1.2 m long and the collapse front reached the bottom in 0.30 s, the front moved at an average of $1.2 \div 0.30 = 4$ m/s. Meanwhile the center of mass fell $\frac{1}{2}gt^2 = \frac{1}{2} \times 9.8 \times 0.30^2 \approx 0.44$ m. The same idea applies to every material: a push or pull at one end reaches the other end only as a wave, at the speed of sound in that material.

The engineering. Springs are everywhere in engineering: in car suspensions, mattresses, clocks, valves and toys. Engineers choose spring wire for its stiffness, strength and resistance to fatigue (a spring flexed millions of times must not crack), and they calculate the spring constant from the wire size, coil diameter and number of coils. Wave travel matters in structures too: when a load is applied suddenly, the stress travels through the structure as a wave, which is why sudden impacts can break things that slow loads would not. Toy-safety engineers check that the wire ends of a metal spring toy are bent in and smooth, and that plastic spring toys for small children have no small parts and do not snap into sharp pieces.

Try it. In your build you will measure your Slinky's spring constant, send waves along it on the floor, and film the drop to see the bottom hang still.

PICTURE STUDY



Hooke's Springs, Robert Hooke, 1678 · Engraving · Frontispiece of *Lectures de Potentia Restitutiva*, London

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

Robert Hooke published his law of springs in 1678 with this engraving of his apparatus. Every spring toy, scale and car suspension still follows it.

Look closely

- Find the coiled spring with a weight hanging from it. What did Hooke measure?
- Find the scale pans. How would he add weight a little at a time?
- Find the coiled watch spring. How is it like and unlike the Slinky?
- Look for any measuring marks or rulers.

Talk about it

1. If one weight stretches the spring 2 cm, how far should three weights stretch it, if Hooke's law holds?
2. Why might a spring stop obeying Hooke's law if you hang too much on it?
3. How could you use Hooke's law to make a scale for weighing letters?

Safety first. Drop the Slinky only onto a soft surface such as a carpet or towel, and stand on the floor, not a chair, unless an adult holds it. Metal Slinkies can tangle and kink; do not stretch one beyond about 2 meters. Keep small plastic springs away from toddlers.

BUILD

Slinky Lab: Spring Constant, Waves and the Drop

You will measure your Slinky's spring constant with Hooke's law, send longitudinal and transverse waves along it and measure their speed, and film the hanging drop in slow motion to measure how long the bottom stays still.

You will need

- A metal Slinky (or a plastic one), a kitchen scale, small bags of coins or washers
- A tape measure, masking tape for marks, a smooth floor
- A phone that records slow-motion video (120 or 240 frames per second) and a tripod or a stack of books
- A partner

Steps

1. **Hooke's law.** Hold the top of the Slinky so a short section of about 20 coils hangs (pinch the coils above together). Hang masses of 50, 100, 150 and 200 g from the bottom and measure the stretch each time. Graph force (N) against stretch (m). The slope is k for that section.
2. **Waves.** With your partner, stretch the Slinky 3 m along a smooth floor. Push one end sharply forward once to make a longitudinal pulse, and time how long it takes to reach the other end and back. Do the same with a quick sideways flick (a transverse pulse). Calculate each speed: distance $\div$ time.
3. **Fair test.** Change only the stretched length (2 m, 3 m, 4 m) and measure the transverse wave speed each time. Does more tension make the wave faster?
4. **Drop.** Tape a bright mark on the bottom coil. Hang the Slinky from your hand against a plain wall, with a tape measure beside it, and have your partner film in slow motion. Let go cleanly.
5. Step through the video frame by frame. Count the frames from release until the bottom coil first moves, and convert to seconds (frames $\div$ frame rate).
6. Measure the hanging length and calculate the average speed of the collapse front. Calculate how far the center of mass fell in that time with $\frac{1}{2}gt^2$.

7. **Compare.** Repeat the drop with a heavier mass taped to the bottom. Predict, then measure, whether the bottom stays still for a longer or shorter time.
8. **Improve.** Repeat the drop three times and average. Identify your largest source of error (the release, frame rate, or hand movement) and change one thing to reduce it.

Tips

- Let go by opening your fingers quickly; pulling your hand up or down spoils the drop.
- Higher frame rates show the still bottom more clearly. 240 fps works well.
- Pulses fade quickly on a long Slinky; time several and average.

Check your work

- ☐ I measured a spring constant and can use $F = kx$.
- ☐ I measured wave speeds and tested how tension changed them.
- ☐ I filmed the Slinky drop and can explain why the bottom stays still until the wave arrives.

ENGINEER'S NOTEBOOK

1. Hooke's-law graph with the slope calculated as k .
2. Wave-speed table for longitudinal and transverse pulses at three lengths.
3. A five-frame sketch sequence of the Slinky drop, with the bottom coil's height marked in each frame.
4. Solve: a spring has $k = 25 \text{ N/m}$. How far does it stretch with a 0.30 kg mass hanging from it?

From history. The Slinky was named Pennsylvania's official state toy in 2001 and has been made in the same small town, Hollidaysburg, Pennsylvania, for decades. Soldiers in the Vietnam War reportedly tossed Slinkies over tree branches as makeshift radio antennas, an engineering use Richard James never imagined.

COMMON MISTAKES

- Thinking the whole Slinky starts falling at once. Information travels through it as a wave; the bottom cannot "know" you let go until the wave arrives.
- Believing the bottom floating means gravity has stopped. Gravity still pulls; the spring's tension still balances it until the wave arrives.

- Measuring stretch from the wrong place. Measure from the same coil each time.

Make it a game · Spring Memory Match. Make cards: Hooke's law, spring constant, wave, longitudinal, transverse, center of mass, tension. Add matching explanations on a second set. Lay them face down and flip pairs from memory. Then stretch a rubber band or a spring from a drawer and tell your parent how you would measure k . Fewest flips wins.

9.3 RC AIRPLANES AND TOY DRONES: FLYING FROM THE GROUND

OBJECTIVES

- Explain how an RC airplane's radio, receiver, servos, speed controller and motor work together.
- Explain how ailerons, elevator and rudder make moments about the center of gravity, and why the center of gravity must be ahead of the center of lift.
- Build a glider with movable control surfaces and test how each surface and the balance point change its flight.

Warm-up. Fold a paper airplane. Bend up the back edges of both wings slightly and throw it. Then bend both down, then one up and one down. Record what the plane does each time. You have just tested an elevator and ailerons.

WATCH

HOW RC AIRPLANES WORK (Intro to RC Electronics for Beginners)

[RCwithAdam](#) · 11:54

<https://www.youtube.com/watch?v=8-lqaNBlaDs>

WHEN TO WATCH

After the story paragraph. Draw the block diagram as he connects each part.

KEY TERMS

transmitter and receiver

The hand-held radio that sends the pilot's stick positions, and the small radio in the aircraft that receives them.

electronic speed controller (ESC)

A circuit that controls how much battery power reaches the motor, setting its speed.

servo

A small motor with a built-in position sensor that moves a control surface to a commanded angle.

aileron, elevator, rudder

Hinged surfaces on the wings (roll), horizontal tail (pitch) and vertical tail (yaw).

center of gravity (CG)

The balance point of the aircraft. For stability it must be ahead of the point where the wing's lift effectively acts.

pulse-width modulation (PWM)

A signal of short pulses whose width sets a value; servos commonly read pulses about 1 to 2 milliseconds wide, about 50 times a second.

CORE IDEAS

The story. In 1898, at an electrical exhibition in New York's Madison Square Garden, Nikola Tesla steered a small model boat around a pool by radio, and many in the audience refused to believe there was no one hiding inside. Radio control of model aircraft took longer, because radios were heavy. In the late 1930s twin brothers Walter and William Good, engineering students in Kansas, built their own lightweight radio and flew their model airplane *Guff* by remote control, winning national model contests; *Guff* is now in the Smithsonian. In 1962 a NASA engineer, Dale Reed, built balsa-wood models of a wingless "lifting body" spacecraft shape and flew them by radio control and from a towline to show it could glide and land. His model tests led NASA to build the full-size M2-F1, a step toward the Space Shuttle.

How they figured it out. The Good brothers had to make a radio receiver and a control actuator light enough for a model to carry, and reliable enough that a single noise would not crash it. They built their own vacuum-tube receiver and a simple escapement that moved the rudder one step at each signal pulse, then flew, crashed, repaired and improved for years. Reed's approach was the same as Froude's and the Wrights': build a cheap model, test it, film it, change one thing, and only then build the expensive full-size machine. He launched his models from a larger radio-controlled "mother ship" model and filmed the flights with a home movie camera. Today's RC hobby uses 2.4-gigahertz digital radios, tiny servos and lightweight lithium batteries, but the method is unchanged.

The physics. Each control surface changes the lift on part of the airplane, and that force times its distance from the center of gravity makes a moment (torque) that turns the airplane. Worked example: if the elevator makes a 0.50 N force 0.40 m behind the CG, the pitching moment is $0.50 \times 0.40 = 0.20 \text{ N}\cdot\text{m}$. **Ailerons** move in opposite directions to roll the plane; the **elevator** pitches the nose up or down; the **rudder** yaws it left or right. For stability, the CG must be ahead of the wing's neutral point; then, if a gust pitches the nose up, the tail's extra lift pushes it back down, like the feathers on an arrow. A tail-heavy airplane is unstable and very hard to

fly. Most model airplanes balance at about 25–33% of the way back from the wing's leading edge.

The engineering. An RC airplane is a small systems-engineering project: airframe (often foam board), motor and propeller, ESC, battery, receiver, servos and linkages, and the transmitter. Engineers balance weight, power, battery life and strength. Many toy drones and some RC airplanes add a flight controller with MEMS gyroscopes and accelerometers that automatically damps unwanted motion, the feedback loop you met in Lesson 7.4. Safety engineering matters: lithium-polymer batteries can catch fire if punctured, crushed, overcharged or damaged, so they are charged only with proper chargers, on a fireproof surface, with an adult present; propellers are guarded on small drones; and all flying follows the FAA rules, including passing TRUST, flying within sight and below 400 feet, and staying away from people and airports.

Try it. Your glider will have hinged control surfaces made with tape. You will set each one and observe the flight, like the Good brothers trimming *Guff*.

PICTURE STUDY



Dale Reed with His Lifting-Body Model, NASA Dryden Flight Research Center, about 1963 · Photograph · NASA, Edwards, California

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

Dale Reed's small models, flown by radio control and towline, convinced NASA to build the full-size M2-F1 behind him. Model tests are still how many aircraft begin.

Look closely

- Compare the model with the full-size aircraft. Are their shapes the same?
- Find the fins and control surfaces on the model. What do you think they controlled?
- Look at the M2-F1. Where are its wings?
- Look at Reed's expression and how he holds the model. What does that suggest about how he felt about it?

Talk about it

1. Why test a cheap model before building a full-size aircraft?
2. How could a body with no wings make lift?
3. What would you measure on a model flight to learn whether the full-size version would be safe?

Safety first. Throw gliders only where nobody can be hit. If you fly an RC airplane or drone, an adult must be present, all FAA rules apply, and lithium batteries are charged only with the correct charger, never left charging unattended, and never punctured, crushed or used if swollen. Never open a lithium battery.

BUILD

A Glider with Working Control Surfaces

You will build a foam or card-stock glider with tape-hinged ailerons, elevator and rudder, find its correct balance point, and then run a fair test of each control surface's effect on its flight, recording the results like a test pilot.

You will need

- A sheet of foam board or a foam tray, or stiff card stock; a ruler, scissors and tape (an adult cuts foam board with a craft knife)
- Paper clips or modeling clay for balance weight
- A tape measure, a stopwatch, a protractor and a large open room or calm outdoor area
- Optional: a servo and a Raspberry Pi Pico from Unit 4 to move a control surface

Steps

1. Cut a straight wing (about 40 cm span $\times$ 8 cm chord), a fuselage, a horizontal tail and a vertical fin. Cut the back 1.5 cm of the wing tips, the tail and the fin as control surfaces, hinged with tape so they bend and stay set.
2. **Balance.** Mark the wing's chord at 25% and 33% from the leading edge. Add clay to the nose until the glider balances between those marks. Weigh the glider.
3. Trim it for a straight, smooth glide by small elevator changes.
4. **CG test.** Move the balance point forward (more clay) and backward (less clay) by 1 cm and fly each three times. Describe each flight (dives, stalls, smooth).
5. **Fair test: elevator.** Set the elevator at -10° , 0° and $+10^\circ$ (measure with a protractor). Fly three times each from the same launch height and record distance and flight path.
6. **Ailerons and rudder.** Set one aileron up and the other down by 10° , then use the rudder alone at 15° . Record which way the glider rolls and turns, and how sharply.

7. Make a table: surface, setting, effect on flight. Explain each effect with forces and moments about the CG.
8. **Improve.** Design a setting that makes the glider fly a gentle full circle and land near where you launched. If you have a servo and a Pico, program the servo to move the rudder to three positions and explain how a receiver's PWM pulses would do the same.

Tips

- Make small changes. Two or three degrees of elevator can change a dive into a stall.
- Launch the same way each time: gently, level, at the same speed.
- A glider that is nose-heavy flies fast and steeply; a tail-heavy one pitches up, stalls and drops. The right balance is in between.

Check your work

- ☐ I can describe the parts of an RC system and what each does.
- ☐ I can explain how each control surface makes a moment about the center of gravity, and why the CG must be forward.
- ☐ My tests showed the effect of each control surface and the balance point, and I trimmed the glider for a planned flight.

ENGINEER'S NOTEBOOK

1. Block diagram of an RC airplane: transmitter → receiver → servos and ESC → control surfaces and motor; battery to all.
2. Top and side sketches of your glider with the CG marked and every control surface labeled.
3. Control-surface test table with your explanations.
4. Solve: a rudder makes a 0.30 N sideways force 0.35 m behind the CG. What yawing moment does it make? If the tail were twice as far back, what force would give the same moment?

From history. Walter Good later worked as a physicist at the Johns Hopkins Applied Physics Laboratory, and the brothers' *Guff* is preserved by the Smithsonian National Air and Space Museum. Dale Reed's model-first approach also led to radio-controlled research aircraft at NASA, some of them used to test unusual wing shapes and control systems too risky for a pilot on board.

COMMON MISTAKES

- Thinking the rudder is the main way to turn an airplane. Airplanes mostly turn by rolling with the ailerons; the rudder keeps the turn coordinated.
- Building a tail-heavy model. It may look fine on the ground but will be unstable in the air.
- Treating a toy drone or RC plane as too small for rules. The FAA's recreational rules apply to every drone and RC aircraft flown outdoors.

Make it a game · Fly by Radio. Parent hides one clue card for each part: transmitter, receiver, servo, ESC, motor. You ask yes-or-no questions to guess each part, no more than five per part. Then act out aileron, elevator and rudder with your hand as a plane. Explain why the center of gravity must sit ahead of the center of lift.

9.4 CAPSTONE TOY: INVENT, PROTOTYPE, TEST AND PITCH

OBJECTIVES

- Invent a toy for a specific age group that teaches or uses a physics idea from this year.
- Prototype it, play-test it with real users, and check it against toy-safety rules (small parts, sharp edges, magnets, button batteries, drop test).
- Estimate the cost per unit and pitch the toy to a panel with evidence.

Warm-up. Think of your favorite toy from when you were five. Write down three things that made it fun and one thing that annoyed you about it. Then look at a toy box (yours or a sibling's) and find one toy that is simple, cheap and still loved. What makes it last?

WATCH

Testing Toys - Safety Behind the Scenes

The Genius of Play · 4:33

<https://www.youtube.com/watch?v=VmOZ7lYmX94>

WHEN TO WATCH

Before you safety-test your prototype. List each test you see.

Note: Made by the Toy Industry Association; it shows factory and laboratory testing.

BACKUP VIDEO

How to make a cardboard prototype

Quirky · 2:02

https://www.youtube.com/watch?v=k_9Q-KDSb9o

Before you build: quick techniques for cutting, folding and laminating cardboard into a working model.

KEY TERMS

target user

The specific person the toy is designed for, including age, abilities and interests.

play test

Watching real users play with a prototype and recording what they do, enjoy and struggle with.

small-parts test

The U.S. test for toys for children under three: any part that fits completely inside a cylinder about 1¼ inches (32 mm) wide is a choking hazard and is not allowed.

use and abuse tests

Drop, twist, pull, bite and crush tests that check a toy will not break into dangerous pieces when a child plays roughly.

unit cost

The cost to make one toy: tooling cost ÷ number made + materials and labor for each.

pitch

A short, persuasive presentation of a new product to people who might make or buy it.

CORE IDEAS

The story. In 1958 Richard Knerr and Arthur “Spud” Melin, who ran a small toy company called Wham-O in California, heard that children in Australia exercised by twirling bamboo rings around their waists. They made the rings from a new, tough, light plastic called Marlex polyethylene, gave them a catchy name, the Hula Hoop, and took them to playgrounds to let children try them. In a few months they sold millions. Wham-O had already done something similar with the flying disc it named the Frisbee. Their method was simple and powerful: notice a kind of play people already love, find a cheap, safe, durable way to make it, and test it with real children.

How they figured it out. Toy inventors work through the same process as every engineer: who is the toy for, what should it do, what must it not do, and how can it be made cheaply and safely? They build quick prototypes from cardboard, clay or scrap, hand them to children, and watch. A toy that adults think is clever may bore children in a minute; a toy that looks plain may be played with for hours. Then the design is changed for manufacture: one-piece molded parts instead of glued assemblies, rounded edges, secured batteries, and materials that survive being

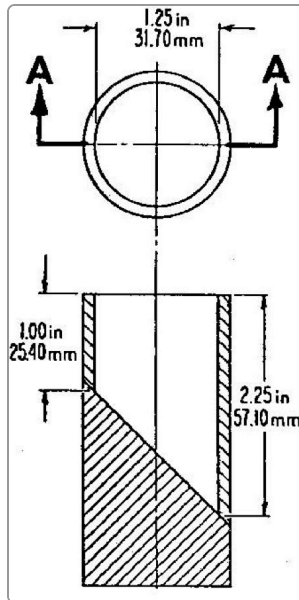
dropped, stepped on and chewed. Finally, the toy is tested by independent laboratories against safety standards before it can be sold.

The physics. Every good toy is a small physics lesson: a top shows angular momentum, a Slinky shows waves, a hoop shows circular motion, a ball shows elastic energy. Your toy should use at least one idea from this year and you should be able to calculate something about it, such as the speed at the bottom of a ramp ($v = \sqrt{2gh}$), the period of a spinning part, the force on a spring ($F = kx$) or the power of a battery motor ($P = VI$). Cost is physics and arithmetic too. Worked example: an injection mold costs \$20,000 and each toy needs \$0.80 of plastic and labor. For 10,000 toys, unit cost = $20,000 \div 10,000 + 0.80 = \$2.80$; for 100,000 toys, $20,000 \div 100,000 + 0.80 = \$1.00$. That is why toys that sell in large numbers can be cheap.

The engineering. Toy-safety rules exist because children were hurt by toys that broke, came apart or hid dangers. In the United States, toys for children under three may not have parts that fit in the small-parts test cylinder. Small, powerful magnets that can be swallowed are tightly restricted. Button and coin batteries must be inside compartments that need a tool or two separate motions to open, because a swallowed button battery can burn through a child's throat in hours. Toys must also pass tests for sharp points and edges, cords long enough to strangle, lead and other harmful chemicals, and drop and pull tests. A responsible toy designer treats these rules as the starting point, not the finish line, and asks what a curious toddler might do with the toy.

Try it. Your capstone toy will be judged on fun, physics, safety and cost. Bring data on all four to your pitch.

PICTURE STUDY



The Small-Parts Test Fixture, U.S. Consumer Product Safety Commission, modern · Dimensioned drawing · U.S. Consumer Product Safety Commission
Image: [Wikimedia Commons](#), public domain

This drawing shows the official small-parts test cylinder. Its size is based on measurements of young children's throats.

Look closely

- Find the inside diameter. How big is 1.25 inches compared with a coin you know?
- Find the two depths, 1.00 and 2.25 inches. Why do you think the bottom is slanted?
- Compare it with a toilet-paper tube, which is wider and is sometimes used as a rough home check.
- Think of five small objects at home. Which would fit completely inside?

Talk about it

1. Why is the rule for children under three, and not for older children?
2. How would you change a toy design that has a part small enough to fit?
3. Why are button batteries and magnets treated with extra rules even when they are larger than the cylinder?

Safety first. Never take apart toys with lithium batteries, button or coin cells, or a wall plug. Use only household or craft materials for your prototype, and keep small parts away from young children during play tests. An adult handles hot glue and sharp tools.

BUILD

Invent, Test and Pitch a Toy

You will design a toy for a specific child (a younger sibling, cousin or neighbor), based on a physics idea from this year. You will prototype it, play-test it, safety-check it against the rules, estimate what it would cost to make, and pitch it to a family panel.

You will need

- Cardboard, card stock, tape, glue, string, rubber bands, clay, craft sticks, marbles or other craft materials
- A toilet-paper tube (as a rough home small-parts check; parts that fit are too small for children under three)
- A tape measure, stopwatch and kitchen scale
- Your engineer's notebook; optional kit parts (Snap Circuits motor, micro:bit, CrunchLabs or KiwiCo parts)

Steps

1. **User.** Choose your target user and write a short profile: age, what he or she likes, what is hard for him or her. List requirements (what the toy must do) and constraints (safety rules for that age, cost limit, size).
2. **Ideas.** Sketch three toy ideas that use a physics idea from this year (spin, springs, ramps and energy, flight, circuits, buoyancy). Score them in a small decision matrix for fun, safety, cost and physics.
3. **Prototype.** Build the winner quickly from cardboard and craft materials. Calculate one number about how it works (a speed, a period, a force, a power).
4. **Play test.** Give it to your target user (with a parent present) for 10 minutes. Without helping, record: how long they played, what they did first, what they enjoyed, what confused or frustrated them.
5. **Safety check.** Check every part with the tube test (for children under three), feel every edge and point, check cords for length, and drop the toy five times from waist height onto a hard floor. Record anything that broke or came loose.

6. **Improve.** Change the design to fix the biggest play problem and every safety problem. Test again and record the difference.
7. **Cost.** Estimate materials per toy for a factory version and an assumed tooling cost (for example \$15,000). Calculate the unit cost for 5,000 and 50,000 toys and propose a selling price.
8. **Pitch.** Give a 3-minute pitch to a family panel: who it is for, a live demo, the physics, play-test results, safety tests passed, cost and price. Answer their questions and write down their feedback.

Tips

- Simple toys are often the best. A toy that does one thing very well beats one that does five things badly.
- Watch the user's hands and face during the play test, not just what they say.
- Write down failures honestly; they are the best evidence that you tested.

Check your work

- ☐ I designed a toy for a specific user using a physics idea from this year.
- ☐ I play-tested it, safety-checked it against the rules and improved it.
- ☐ I calculated a unit cost and gave a clear pitch with evidence.

ENGINEER'S NOTEBOOK

1. User profile, requirements and constraints, and the three idea sketches with your decision matrix.
2. Labeled drawing of the final toy with the physics calculation.
3. Play-test notes and safety-check table, before and after improvement.
4. Cost calculation and your pitch outline, with the panel's feedback.

From history. Many famous toys began as accidents or as something else: the Slinky as a ship's spring, Play-Doh as a wallpaper cleaner, and the Frisbee as pie tins tossed by college students. What turned them into toys was someone who noticed the fun and then did the hard engineering work of making them safe, cheap and durable.

COMMON MISTAKES

- Designing for yourself instead of the target user. A toy for a four-year-old must suit a four-year-old's hands and attention.

- Leaving the safety check to the end. Safety should shape the design from the first sketch.
- Forgetting tooling cost. A toy that is cheap to make one at a time may be expensive to set up for a factory, and the reverse.

Make it a game • Toy Pitch Showdown. Invent a toy that uses a physics idea from this year. You have sixty seconds to pitch it to your parent, who plays buyer and asks three questions: age group, safety and cost. Then your parent plays a toy inspector and checks it against the small-parts and drop-test rules. Win by passing the inspector.

Scripture. “A time to weep, and a time to laugh; a time to mourn, and a time to dance;” (Ecclesiastes 3:4, KJV)

God made a time for laughing as well as for working. Designing a toy that makes a child laugh, and keeping that child safe, is good work.

TOY LAB: THE PHYSICS OF PLAY

Some of the deepest physics in this whole course is hiding in the toy box. In this optional bonus unit you will study four toys the way a physicist and a product engineer would. A toy gyroscope that seems to defy gravity will teach you angular momentum, torque and precession, the same physics that steers ships and points the Hubble Space Telescope. A Slinky dropped from your hand will show, in slow motion, that a force takes time to travel through a material as a wave. A radio-controlled airplane will show how control surfaces, center of gravity and a radio link let a person fly a machine from the ground.

The last lesson is your own invention. You will invent, prototype and play-test a toy, check it against real toy-safety rules, work out what it would cost to make, and pitch it to a family panel, just as an inventor pitches to a toy company. Do this unit after the engineering fair, over the summer, or any week that needs something fun.

PREREQUISITES

- Has finished Units 1 and 7 (momentum, circular motion, energy, flight control)
- Can use $F = ma$, torque (force $\times$ distance) and a stopwatch with slow-motion video
- Can make data tables and graphs with units

MASTERY CHECKLIST

- ☐ I can explain gyroscopic precession using angular momentum and torque and calculate a precession rate.
- ☐ I can explain why the bottom of a dropped Slinky hangs still, using Hooke's law and wave travel, and measure a spring constant and a wave speed.
- ☐ I can explain how an RC airplane's control surfaces, center of gravity and radio system control its flight.
- ☐ I can invent, prototype, play-test and safety-check a toy, estimate its cost per unit and pitch it clearly.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up (Hack Pack for ages 12 and up). Each box is a toy built around one physics idea and designed to be taken apart and modified; excellent for Lessons 9.1 and 9.4.
- **KiwiCo crates:** Ages vary by line (Tinker and Eureka for ages 9–16 and up). Many crates are mechanical toys that work well as teardown and redesign projects for Lesson 9.4.
- **Snap Circuits (Elenco):** Ages 8 and up. Motors, switches and a spinning-disk launcher make it easy to prototype an electric toy for Lesson 9.4 without soldering.

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 Gyroscope and Precession	2 sessions of 60 minutes
9.2	The Slinky Drop: Waves in Slow Motion	2 sessions of 60 minutes
9.3	RC Airplanes and Toy Drones: Flying from the Ground	2 sessions of 60 minutes
9.4	Capstone Toy: Invent, Prototype, Test and Pitch	2 sessions of 60 minutes

UNIT 9 REVIEW

Answer each question. For calculations, write the formula, substitute numbers with units and box your answer. Use $g = 9.8 \text{ m/s}^2$. Use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Explain in your own words why a spinning gyroscope supported at one end precesses instead of falling.

2. **10 pts**

Calculation. A gyroscope rotor has $I = 3.0 \times 10^{-4} \text{ kg}\cdot\text{m}^2$ and spins at 250 rad/s. Its weight of 1.5 N acts 0.040 m from the pivot. Find L, the torque and the precession rate.

3. **6 pts**

What happens to the precession rate as a gyroscope slows down, and why?

4. **8 pts**

Name two engineering uses of gyroscopes and one safety rule for spinning toys.

5. **8 pts**

When you drop a hanging Slinky, why does its bottom stay still for a moment?

6. **10 pts**

Calculation. A 0.20 kg mass stretches a spring section by 0.08 m. Find k. How far would 0.50 kg stretch it?

7. **8 pts**

Calculation. A Slinky's bottom stays still for 0.28 s after release, and the stretched Slinky was 1.1 m long. Find the average speed of the collapse front and how far the center of mass fell in that time.

8. **8 pts**

List the main parts of an RC airplane's electronics and say what each does.

9. **10 pts**

Calculation and explanation. An elevator makes a 0.40 N force 0.50 m behind the CG. Find the pitching moment. Why must the CG of a model airplane be ahead of the wing's neutral point?

10. **8 pts**

Name four toy-safety checks and say why button batteries get special rules.

11. **10 pts**

Calculation. A toy mold costs \$24,000 and each toy costs \$1.20 in materials and labor. Find the unit cost for 8,000 toys and for 80,000 toys.

12. **6 pts**

Write a short paragraph: What makes a toy both good engineering and good for a child?

ANSWER KEY

1. Gravity makes a torque about the support. A torque changes angular momentum; because the rotor has a large angular momentum along its axle, the torque changes the direction of that angular momentum sideways, so the axle swings around the support (precesses) instead of tipping down.
2. $L = I\omega = 3.0 \times 10^{-4} \times 250 = 0.075 \text{ kg}\cdot\text{m}^2/\text{s}$. $\tau = 1.5 \times 0.040 = 0.060 \text{ N}\cdot\text{m}$. $\Omega = \tau \div L = 0.060 \div 0.075 = 0.80 \text{ rad/s}$.
3. It speeds up, because $\Omega = \tau \div L$ and $L = I\omega$ gets smaller as ω falls, while the torque stays the same.
4. Uses (any two): gyrocompasses; aircraft instruments and autopilots; ship stabilizers; reaction wheels for telescopes and spacecraft; MEMS gyros in phones and drones. Safety (any one): no small detachable parts for children under three; no sharp points; pull strings short enough not to be a strangling hazard.
5. The bottom coils are held in balance by tension above and gravity. Letting go changes the tension only at the top; the change travels down the Slinky as a wave of collapsing coils, and until it arrives the bottom's forces are still balanced, so it stays still.
6. $F = 0.20 \times 9.8 = 1.96 \text{ N}$; $k = 1.96 \div 0.08 = 24.5 \text{ N/m}$. For 0.50 kg: $x = (0.50 \times 9.8) \div 24.5 = 0.20 \text{ m}$.
7. $v = 1.1 \div 0.28 \approx 3.9 \text{ m/s}$. Center of mass: $\frac{1}{2}gt^2 = \frac{1}{2} \times 9.8 \times 0.28^2 \approx 0.38 \text{ m}$.
8. Transmitter (sends the pilot's commands); receiver (receives them); servos (move the control surfaces); ESC (controls motor power); motor and propeller (thrust); battery (power for all).
9. $M = 0.40 \times 0.50 = 0.20 \text{ N}\cdot\text{m}$. With the CG forward, a disturbance that pitches the nose up increases the tail's restoring force and brings the nose back down, so the airplane is stable; a tail-heavy airplane tends to keep pitching further and is unstable.
10. Any four: small-parts cylinder test (under three); sharp point and edge tests; cord length limits; drop, pull, twist and bite tests; limits on small powerful magnets; chemical tests (such as lead). Button batteries must be locked away because a swallowed one can quickly cause severe internal burns.
11. 8,000: $24,000 \div 8,000 + 1.20 = 3.00 + 1.20 = \$4.20$. 80,000: $24,000 \div 80,000 + 1.20 = 0.30 + 1.20 = \$1.50$.

12. Answers vary; a strong answer mentions that it works reliably, uses physics well, is safe for its age group, is durable and affordable, and invites real play, imagination or learning.

PORTFOLIO PIECE: A PHYSICS TOY, TESTED AND PITCHED

Present your Lesson 9.4 toy as a complete product package: a labeled drawing and working prototype; one physics calculation about how it works; play-test notes from a real child in its target age group, before and after your improvement; a safety-check table (small parts, edges and points, cords, drop test, batteries or magnets if any); a unit-cost calculation for two production quantities with a proposed price; and a short written pitch. If you prefer, you may instead build and fully test a gyroscope, Slinky or glider experiment from Lessons 9.1–9.3 and present it as a toy-company research report.

LOOK FOR	WHAT IT MEANS
Design and physics	Clear drawing and working prototype; at least one correct physics calculation with units.
Play test	Real user observed; specific notes recorded; design improved based on what was seen.
Safety	All relevant safety checks done and recorded; every problem fixed in the final design.
Cost	Unit cost calculated correctly for two quantities, with a sensible price.
Pitch	Clear, honest, evidence-based pitch that names the user, shows the toy working and answers questions.