

GRADE 4 ENGINEERING & PHYSICS

First edition

8 units

32 lessons + Toy Lab

A video for every lesson

FIRST EDITION

COURSE GUIDE

This course follows eight strands of engineering through one school year: energy and machines, bridges, buildings, electricity, public utilities, boats and ships, flight, and robots and coding. Each unit is built around real moments from history: John Smeaton testing model waterwheels, Benjamin Baker's human cantilever at the Forth Bridge, Brunelleschi raising the dome of Florence without a wooden frame, Edison's team testing thousands of filaments, Joseph Bazalgette's sewers under London, the locks of the Erie Canal, the Wright brothers' wind tunnel, and Joseph-Marie Jacquard's punched cards.

Every lesson follows the same path. First comes **the story**. Then **how they figured it out**: what stood in the way, what they tried, what failed, what they measured and what they changed. Then **the physics** underneath, explained for a fourth grader, and **the engineering**: how the idea becomes a safe, useful thing. Last, the student repeats the discovery in miniature with cardboard, craft sticks, pennies, batteries, water and a box fan, recording each fair test in an engineer's notebook and improving the design in a second round. An optional ninth unit, the **Toy Lab**, studies the physics and design of four favorite toys for a bonus month after the fair or over the summer.

God made an orderly world that can be measured and understood, and He made people in His image to be makers. Engineering, rightly done, is a way of loving our neighbors: a bridge that stays up, clean water at the tap, light in a dark room. The old Latin saying *Fabricando fit faber*, "by making, one becomes a maker," is the whole method of this course.

Most videos come from museums and trusted teaching channels: the Smithsonian National Air and Space Museum, the Institution of Civil Engineers, NASA, Practical Engineering, Science Buddies, Branch Education, Science Max, SciShow Kids, the Scratch Team and a few others chosen lesson by lesson. Every video was checked in preview

for content and accuracy. Some channels end with an invitation to subscribe or a short message about the channel; you can stop the video when the teaching ends. A few videos are a little advanced for fourth grade; the lesson notes say where to pause, explain or skip. Watch together when you can.

Start with Lesson 1.1 →

WHO IT IS FOR

Written for students in grade 4 (about ages 9–10) who read independently and can measure in centimeters, add, subtract, multiply and find a simple average. A parent or teacher reads along, helps with the builds and handles any hot glue or sharp tools. No kits are required: every build uses household or inexpensive craft-store materials. Optional kits are listed in most units for families who want them.

HOW TO USE THIS COURSE

1. **The weekly rhythm.** The year has 32 lessons, one a week. Session 1 (about 45 minutes) is the warm-up, the video, the teaching and the picture study. Session 2 (about 45 minutes) is the build and the engineer's notebook. In the last week of each unit, add a third session for the unit review and the portfolio build.
2. **Story, then physics, then engineering.** The core ideas are written to be read aloud or read by the student. The paragraphs marked *The story* and *How they figured it out* tell what happened; *The physics* explains why it works; *The engineering* explains how people turn the idea into a real, safe thing. After each paragraph, ask the student to tell it back in his or her own words.
3. **Picture study.** Each lesson has one historic photograph, engraving, drawing or painting. Look at it quietly for two minutes. Then put it away and have the student tell everything he or she remembers. Bring it back and work through the “look for” items and questions, which point to the physics and engineering in the picture.
4. **The engineer's notebook.** Use a graph-paper composition book for the whole year. For every build, write a prediction first, then record measurements in a table, then write what happened and what you would change. Date every page. Honest records matter more than perfect results: “a just weight is his delight” (Proverbs 11:1).

5. **Fair tests and improvement.** Most builds change only one thing at a time and test each version three times or more. Every build ends with an “improve it” round. A design that fails and is then improved has taught more than one that worked the first time.
6. **Optional kits.** Some units list kits such as KiwiCo crates, the CrunchLabs Build Box, KEVA planks, Snap Circuits or a BBC micro:bit. They are extras for families who enjoy them. Every lesson can be completed without them.
7. **Unit review and portfolio.** Each unit ends with a short review (50 points, with a few “predict what happens” questions) and a portfolio build that pulls the unit together, such as a load-tested truss bridge, a shake-table tower, a lit and switched model room or a tested glider. Keep the portfolio pages and photographs in a folder for the year.
8. **Safety.** Read the safety box before each build. Electricity in this course comes only from AA, C, D or 9-volt batteries, never from the outlets in the wall. An adult handles hot glue guns, craft knives and anything hot. Wear safety glasses for anything that flies, snaps or is under tension, and have an adult present for every water build.
9. **The family engineering fair.** In the last week, set out the best build from each unit with its notebook pages and let the student explain them to family and guests. Explaining your work to someone else is part of being an engineer.
10. **The Toy Lab (optional Unit 9).** After the fair, over the summer, or in any week that needs something fun, the four Toy Lab lessons study the Super Soaker, the returning boomerang, the pogo stick and the loop-the-loop toy car track, with the same story, physics, engineering and build pattern as the rest of the year.

SCOPE AND SEQUENCE

UNIT 1 • WEEKS 1–4

Energy and Machines

Potential and kinetic energy on the first roller coaster; a rubber-band car inspired by Leonardo's spring cart; John Smeaton's waterwheel and windmill tests; and a chain-reaction machine built with the engineering design process.

1.1 Potential and Kinetic Energy: The Switchback Railway

1.2 Stored Energy on Wheels: Leonardo's Spring Cart and a Rubber-Band Car

1.3 Waterwheels and Windmills: John Smeaton's Model Tests

1.4 A Chain-Reaction Machine: Rube Goldberg and the Design Process

UNIT 3 • WEEKS 9–12

Buildings

Wood, stone, brick, concrete and steel, with Monier's reinforced concrete; Roman concrete and the Pantheon dome; Brunelleschi's dome in Florence; and earthquakes and a shake table.

3.1 Wood, Stone, Brick, Concrete and Steel: Monier's Flowerpots

3.2 Roman Concrete and the Pantheon Dome

3.3 Brunelleschi's Dome in Florence

3.4 Earthquakes and a Shake Table

UNIT 2 • WEEKS 5–8

Bridges

Compression, tension and the Howe, Pratt and Warren trusses; a craft-stick truss load test; the great cantilevers of the Forth Bridge; and Telford's Menai Suspension Bridge and its chains.

2.1 Why Triangles? The Howe, Pratt and Warren Trusses

2.2 Truss Against Beam: Wendel Bollman and a Craft-Stick Load Test

2.3 The Forth Bridge: Giant Cantilevers

2.4 Hanging from Chains: Telford's Menai Suspension Bridge

UNIT 4 • WEEKS 13–16

Electricity

Volta's pile and a lemon battery; Joseph Henry's electromagnets and the electric motor; Edison's light bulb and conductors and insulators; and switches and circuit diagrams.

4.1 Volta's Pile and a Lemon Battery

4.2 Joseph Henry's Electromagnets and the Electric Motor

4.3 Edison's Light Bulb: Testing Thousands of Filaments

4.4 Switches and Circuit Diagrams

UNIT 5 • WEEKS 17–20

Public Utilities

The electric grid and Stanley’s transformers; water towers and water pressure; Hoover Dam; and Joseph Bazalgette’s London sewers.

- 5.1 The Electric Grid: William Stanley’s Transformers
- 5.2 Water Towers and Water Pressure
- 5.3 Hoover Dam: Taming a River
- 5.4 Joseph Bazalgette and London’s Sewers

UNIT 7 • WEEKS 25–28

Flight

Cayley and the four forces of flight; Lilienthal, the wing and angle of attack; the Wright brothers’ wind tunnel; and propellers and Sikorsky’s helicopter.

- 7.1 The Four Forces: Sir George Cayley
- 7.2 The Wing and Angle of Attack: Otto Lilienthal
- 7.3 The Wright Brothers’ Wind Tunnel
- 7.4 Propellers and Helicopters: Spinning Wings

UNIT 6 • WEEKS 21–24

Boats and Ships

Archimedes’ principle measured with foil boats; hull design, stability and the Plimsoll line; Fulton’s *Clermont* and a paddle-wheel boat; and canals and locks on the Erie Canal.

- 6.1 Archimedes’ Principle Measured
- 6.2 Hull Design and Stability: Samuel Plimsoll’s Line
- 6.3 Robert Fulton’s *Clermont*: Steam on the River
- 6.4 Canals and Locks: The Erie Canal

UNIT 8 • WEEKS 29–32

Robots and Coding

The Jacquard loom and punch cards; algorithms and block coding with Grace Hopper’s first bug; sensors and feedback from Ctesibius to robots; and a syringe-hydraulic robot arm with the family engineering fair.

- 8.1 The Jacquard Loom and Punch Cards
- 8.2 Algorithms and Block Coding: Grace Hopper and the First Bug
- 8.3 Sensors and Feedback: From Ctesibius’s Water Clock to Robots
- 8.4 A Syringe-Hydraulic Robot Arm and the Family Engineering Fair

UNIT 9 • WEEKS 33–36

Toy Lab: The Physics of Play

Optional Toy Lab: air pressure in the Super Soaker, spin and lift in the returning boomerang, springs and energy in the pogo stick, and energy and the loop-the-loop in toy car tracks.

9.1 The Super Soaker: Lonnie Johnson and Air Pressure

9.2 The Returning Boomerang: Spin and Lift

9.3 The Pogo Stick: Springs and Energy

9.4 Loop-the-Loop Tracks: Energy and the Loop

WEEKLY PACING CALENDAR

WEEK	PLAN
1	• Session 1: Lesson 1.1 Potential and Kinetic Energy: The Switchback Railway: 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 Stored Energy on Wheels: Leonardo's Spring Cart and a Rubber-Band Car: warm-up, video, teaching and picture study • Session 2: Lesson 1.2 build project and engineer's notebook
3	• Session 1: Lesson 1.3 Waterwheels and Windmills: John Smeaton's Model Tests: warm-up, video, teaching and picture study • Session 2: Lesson 1.3 build project and engineer's notebook
4	• Session 1: Lesson 1.4 A Chain-Reaction Machine: Rube Goldberg and the Design Process: 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 Why Triangles? The Howe, Pratt and Warren Trusses: 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 Truss Against Beam: Wendel Bollman and a Craft-Stick Load Test: warm-up, video, teaching and picture study - Session 2: Lesson 2.2 build project and engineer's notebook
7	- Session 1: Lesson 2.3 The Forth Bridge: Giant Cantilevers: warm-up, video, teaching and picture study - Session 2: Lesson 2.3 build project and engineer's notebook
8	- Session 1: Lesson 2.4 Hanging from Chains: Telford's Menai Suspension Bridge: 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 Wood, Stone, Brick, Concrete and Steel: Monier's Flowerpots: warm-up, video, teaching and picture study - Session 2: Lesson 3.1 build project and engineer's notebook
10	- Session 1: Lesson 3.2 Roman Concrete and the Pantheon Dome: warm-up, video, teaching and picture study - Session 2: Lesson 3.2 build project and engineer's notebook
11	- Session 1: Lesson 3.3 Brunelleschi's Dome in Florence: warm-up, video, teaching and picture study - Session 2: Lesson 3.3 build project and engineer's notebook
12	- Session 1: Lesson 3.4 Earthquakes and a Shake Table: 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 Volta's Pile and a Lemon Battery: 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 Joseph Henry's Electromagnets and the Electric Motor: warm-up, video, teaching and picture study • Session 2: Lesson 4.2 build project and engineer's notebook
15	• Session 1: Lesson 4.3 Edison's Light Bulb: Testing Thousands of Filaments: warm-up, video, teaching and picture study • Session 2: Lesson 4.3 build project and engineer's notebook
16	• Session 1: Lesson 4.4 Switches and Circuit Diagrams: 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 The Electric Grid: William Stanley's Transformers: 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 Towers and Water Pressure: warm-up, video, teaching and picture study • Session 2: Lesson 5.2 build project and engineer's notebook
19	• Session 1: Lesson 5.3 Hoover Dam: Taming a River: warm-up, video, teaching and picture study • Session 2: Lesson 5.3 build project and engineer's notebook
20	• Session 1: Lesson 5.4 Joseph Bazalgette and London's Sewers: 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 Archimedes' Principle Measured: warm-up, video, teaching and picture study • Session 2: Lesson 6.1 build project and engineer's notebook
22	• Session 1: Lesson 6.2 Hull Design and Stability: Samuel Plimsoll's Line: 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 Robert Fulton's Clermont: Steam on the River: warm-up, video, teaching and picture study • Session 2: Lesson 6.3 build project and engineer's notebook
24	• Session 1: Lesson 6.4 Canals and Locks: The Erie Canal: 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 The Four Forces: Sir George Cayley: warm-up, video, teaching and picture study • Session 2: Lesson 7.1 build project and engineer's notebook
26	• Session 1: Lesson 7.2 The Wing and Angle of Attack: Otto Lilienthal: warm-up, video, teaching and picture study • Session 2: Lesson 7.2 build project and engineer's notebook
27	• Session 1: Lesson 7.3 The Wright Brothers' Wind Tunnel: warm-up, video, teaching and picture study • Session 2: Lesson 7.3 build project and engineer's notebook
28	• Session 1: Lesson 7.4 Propellers and Helicopters: Spinning Wings: 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 The Jacquard Loom and Punch Cards: warm-up, video, teaching and picture study • Session 2: Lesson 8.1 build project and engineer's notebook
30	• Session 1: Lesson 8.2 Algorithms and Block Coding: Grace Hopper and the First Bug: warm-up, video, teaching and picture study • Session 2: Lesson 8.2 build project and engineer's notebook
31	• Session 1: Lesson 8.3 Sensors and Feedback: From Ctesibius's Water Clock to Robots: 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 A Syringe-Hydraulic Robot Arm and the Family Engineering Fair: warm-up, video, teaching and picture study • Session 2: Lesson 8.4 build project and engineer's notebook • Session 3: Unit 8 review and portfolio project <i>Last week. Hold a family engineering fair: set out the best build from each unit with its notebook pages, and let the student show guests how one of them works.</i>
33	• Session 1: Lesson 9.1 The Super Soaker: Lonnie Johnson and Air Pressure: 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 Returning Boomerang: Spin and Lift: warm-up, video, teaching and picture study • Session 2: Lesson 9.2 build project and engineer's notebook
35	• Session 1: Lesson 9.3 The Pogo Stick: Springs and Energy: warm-up, video, teaching and picture study • Session 2: Lesson 9.3 build project and engineer's notebook
36	• Session 1: Lesson 9.4 Loop-the-Loop Tracks: Energy and the Loop: 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)

One for the whole year: predictions, data tables, labeled sketches and “what I would change.”

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

Measuring is the heart of every build.

Smartphone or stopwatch

For timing coasters, cars, paper helicopters and water tests.

Cardboard, card stock, cereal boxes, paper, masking tape, packing tape and white glue

The main building materials all year.

Craft sticks (about 150), straws (about 150), wooden skewers, string and rubber bands

For trusses, cantilevers, towers, wings and cars.

About 200 pennies, paper cups and paper clips

Standard weights for load tests and boats (a U.S. penny made since 1983 weighs 2.5 grams).

Plaster of Paris (a small box) and newspaper for papier-mâché

For the reinforced-beam and dome tests in Unit 3.

AA and D batteries with holders, alligator clip leads, small bulbs in holders, red LEDs, an iron nail, thin insulated or magnet wire and a compass

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

Lemons, copper coins and galvanized nails

For the lemon battery in Lesson 4.1.

Aluminum foil, plastic food containers, milk or juice cartons, clear plastic tubing and a funnel

For the water-tower, boat, paddle-wheel and canal-lock builds.

A box fan

The “wind” for the lift tester and wind tunnel in Unit 7.

Two kitchen thermometers

For the dam-cooling test in Lesson 5.3.

6–8 plastic syringes (10–20 mL, no needles)

For the hydraulic robot arm in Lesson 8.4 and the Toy Lab.

Free software: Scratch (scratch.mit.edu) and the Microsoft MakeCode micro:bit simulator (makecode.microbit.org)

For the coding lessons in Unit 8. A computer or tablet with an internet connection is needed.

Safety glasses

For load tests, rubber-band builds, syringes and anything else that can snap, squirt or fly.

Optional: one kit, such as a KiwiCo crate, Snap Circuits, KEVA planks or a BBC micro:bit

Never required. See the kits listed in each unit.

GRADING

Grades come mostly from the builds and the engineer's notebook, because engineering is learned by doing and recording. A build that fails but is honestly recorded and then improved earns full credit.

PART	%
Builds (effort, fair testing and the improve round)	40
Engineer's notebook (predictions, data tables, sketches, conclusions)	20
Unit reviews	15
Portfolio builds	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, record honestly and try an improvement?
- A notebook page earns full marks when it has a date, a labeled sketch, a data table with units, and a sentence about what to change.
- Unit reviews may be done orally for a student who writes slowly; the parent writes down the answers.
- The optional Toy Lab may be graded the same way or simply enjoyed; it does not need to count toward the year's grade.
- Keep each unit's portfolio pages and photographs in one folder. They make a fine record of the year and the centerpiece of the family engineering fair.

A NOTE TO PARENTS

You do not need to be an engineer to teach this course. Read the story aloud together, watch the video, and then be the student's assistant at the build: hold the ruler, write down the numbers, and ask "What do you think will happen?" and "Why do you think that happened?" Those two questions are most of what a good engineering teacher does.

Expect things to fail. Bridges will sag, beams will crack, lemons will refuse to light an LED, and gliders will dive. Smeaton, Edison and the Wright brothers all failed many times before they succeeded, and this course is built to show that failure, carefully studied, is how engineers learn. Praise careful testing and honest records more than a winning result. *Fabricando fit faber*: by making, one becomes a maker.

A few lessons mention hard moments in history, such as the Tay Bridge, the 1906 San Francisco earthquake, the loss of overloaded ships and Otto Lilienthal's last glide. They are told gently and briefly, with the focus on what engineers learned and changed so that others would be safe.

UNIT 1

ENERGY AND MACHINES

Every machine runs on energy. A roller coaster climbs a tall hill and then rolls the rest of the way on the energy it stored at the top. A wound-up rubber band pushes a car across the floor. Falling water turns a millwheel, and the wind turns the sails of a windmill. In this unit you will learn the difference between stored energy (potential energy) and the energy of motion (kinetic energy), and you will follow that energy as it changes from one form to another.

You will meet LaMarcus Thompson and his Switchback Railway, Leonardo da Vinci and his spring-powered cart, John Smeaton and his careful waterwheel experiments, and Rube Goldberg, the engineer who drew the silliest machines in the world. Along the way you will learn the engineering design process: ask, research, imagine, plan, build, test and improve. Then you will build a rubber-band car, a paper-cup waterwheel and a chain-reaction machine of your own, testing each one fairly and making it better.

PREREQUISITES

- Can measure length with a ruler or tape measure in centimeters
- Can use a stopwatch or a phone timer
- Can make a simple table and find the middle (or average) of three numbers with help

MASTERY CHECKLIST

- ☐ I can explain the difference between potential energy and kinetic energy and give an example of each.
- ☐ I can follow energy as it changes form in a roller coaster, a rubber-band car, a waterwheel and a chain-reaction machine.
- ☐ I can name the steps of the engineering design process: ask, research, imagine, plan, build, test and improve.
- ☐ I can run a fair test by changing only one thing and measuring the result three times.
- ☐ I can explain why a real machine always loses some energy to friction, sound and heat.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Tinker Crate:** Ages 9–16. A monthly box with a build and a short explanation of the science behind it; several crates (rubber-band cars, catapults, hydraulic machines) fit this unit and Unit 8.
- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. A toy to build each month with a video lesson from Mark Rober about the physics inside it. A good extra for Lessons 1.1, 1.2 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 Potential and Kinetic Energy: The Switchback Railway 2 sessions of 45 minutes

1.2 Stored Energy on Wheels: Leonardo's Spring Cart and a Rubber-Band Car

2 sessions of 45 minutes

1.3 Waterwheels and Windmills: John Smeaton's Model Tests 2 sessions of 45 minutes

1.4 A Chain-Reaction Machine: Rube Goldberg and the Design Process

2 sessions of 45 minutes

UNIT 1 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

What is the difference between potential energy and kinetic energy? Give one example of each.

2. **5 pts**

Why must every hill on a roller coaster be lower than the first hill?

3. **5 pts**

Predict: you start a marble on your coaster at 30 centimeters and then at 60 centimeters. Which start will push the cup farther, and why?

4. (5 pts)

Where is the energy stored in a rubber-band car? What does it change into?

5. (5 pts)

What powered Leonardo da Vinci's self-propelled cart, and how did people finally learn how it worked?

6. (5 pts)

What is a fair test? Use the rubber-band car as an example.

7. (5 pts)

John Smeaton tested model waterwheels. Which kind did more work with the same water, overshot or undershot? Why?

8. (5 pts)

Name the seven steps of the engineering design process in order.

9. (5 pts)

Predict: a chain-reaction machine has one step that fails 4 times out of 10 and four steps that almost never fail. What should the builder fix first, and why?

10. (5 pts)

Choose one machine from this unit (coaster, rubber-band car, waterwheel, windmill or chain-reaction machine) and trace its energy from start to finish.

ANSWER KEY

1. Potential energy is stored energy (a coaster car at the top of a hill, a wound rubber band, water held behind a dam). Kinetic energy is the energy of motion (a rolling car, a falling ball, flowing water).
2. Some energy is turned into heat and sound by friction as the car rolls, so the car never has enough energy to climb back as high as where it started.
3. The 60-centimeter start, because a higher marble has more potential energy, which becomes more kinetic energy at the bottom.
4. In the twisted or stretched rubber band, as elastic potential energy. It changes into the kinetic energy of the moving car (and some is lost to friction, heat and sound).
5. Wound-up coiled springs. Researchers studied his drawing piece by piece and, in 2004, built a working model from it.
6. A test where only one thing is changed and everything else is kept the same. For example, change only the number of winds, while using the same car, floor and start line, and do three trials of each.
7. Overshot, about twice as much. The weight of the water in the top buckets pulls the wheel down the whole way it falls, while in an undershot wheel much of the energy is lost in splashing.
8. Ask, research, imagine, plan, build, test, improve.
9. The step that fails 4 times out of 10. It is the weakest link; the whole machine can only work as often as its weakest step lets it.
10. Answers vary. Example: water held up high has potential energy; it falls into the buckets and turns the wheel (kinetic energy); the turning axle winds the string and lifts the load, storing potential energy again; some energy is lost to splashing and friction.

PORTFOLIO PIECE: THE ENERGY MACHINE FAIR TEST

Choose your best build from this unit: the marble coaster, the rubber-band car, the waterwheel or the chain-reaction machine. Improve it once more, then run a fair test of one change with at least three trials each. Make a poster or two notebook pages with a labeled drawing that shows where the energy is stored and where it moves, your data table and bar graph, and a paragraph about what you changed and what you learned. Show it to your family and explain it aloud.

LOOK FOR	WHAT IT MEANS
Energy explained	The drawing correctly labels potential energy, kinetic energy and where energy is lost to friction.
Fair test	Only one thing was changed, with at least three trials for each version.
Data	A neat table with units and a bar graph that matches it.
Improvement	One clear improvement was made and its result was measured and honestly reported.
Explanation	The student explains the build aloud using the words potential, kinetic, friction and fair test.

1.1 POTENTIAL AND KINETIC ENERGY: THE SWITCHBACK RAILWAY

OBJECTIVES

- Explain potential energy (stored energy) and kinetic energy (the energy of motion).
- Tell how LaMarcus Thompson's Switchback Railway used gravity to move riders.
- Build a marble roller coaster and measure how the height of the first hill changes how far the marble pushes a cup.

Warm-up. Hold a ball at the height of your knee and drop it. Then drop it from the height of your shoulder. Which bounce was higher? Now lift the ball slowly from the floor to the top of your head. Where does the ball have the most “ready to go” energy? Talk about it for one minute.

WATCH

Why Roller Coasters Are Awesome!

SciShow Kids · 3:49

<https://www.youtube.com/watch?v=VcRFh-dCxWE>

WHEN TO WATCH

After the story. Listen for where the coaster gets its energy and why the first hill is the tallest.

KEY TERMS

energy

The ability to make something move or change.

kinetic energy

The energy of something that is moving. The faster it moves, the more kinetic energy it has.

potential energy

Stored energy, waiting to be used. A coaster car at the top of a hill has a lot of it.

gravity

The pull that draws things toward the earth.

friction

A force that slows things down when two surfaces rub together. It turns some motion into heat.

CORE IDEAS

The story. In the 1870s LaMarcus Thompson visited an old mining railroad in Pennsylvania, the Mauch Chunk Switchback Railway. Mules pulled coal cars up a mountain, and then the cars rolled back down by gravity alone. By then the coal was carried another way, and visitors paid to ride the cars down the mountain just for fun. Thompson had an idea. In June 1884 he opened his own “Gravity Pleasure Switchback Railway” at Coney Island in New York. Riders climbed the stairs of a wooden tower, sat in a car and rolled down a gently sloping track about 600 feet long to a second tower. Workers then pushed the car up to the top of the second tower, and it rolled back to the start. A ride cost a nickel, and people lined up for hours. It went only about six miles an hour, but it was the first roller coaster built for fun in America.

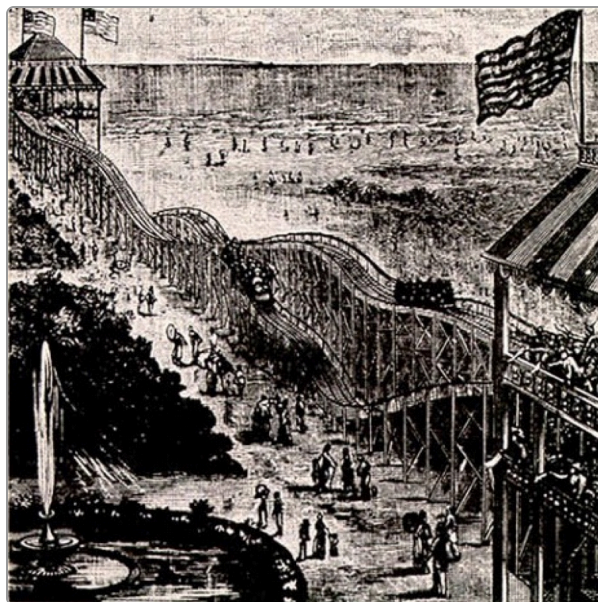
How they figured it out. Thompson and the builders who came after him learned by building and testing. The car always needed a high starting point, because a car cannot roll uphill higher than where it started. Builders found that each hill had to be a little lower than the one before it, or the car would stop partway up and roll back. Later engineers added a chain to pull cars up the first hill, so riders did not have to climb stairs and no one had to push. Every roller coaster since then has used the same idea: lift the car once, as high as you can, and let gravity do the rest.

The physics. When the car is lifted to the top of a hill, it gains **potential energy**, energy stored by its height. The higher it goes, the more it stores. As it rolls down, gravity pulls it faster and faster, and the stored energy changes into **kinetic energy**, the energy of motion. At the bottom it is moving fastest. As it climbs the next hill, the kinetic energy changes back into potential energy, and the car slows down. Energy is never used up or made from nothing; it only changes form. But every time the wheels rub the track and push through the air, **friction** turns a little of the energy into heat and sound. That is why every hill must be lower than the first.

The engineering. Coaster engineers today use the same rules Thompson learned. They calculate how tall the first hill must be for the car to make it over every hill and

around every loop, and then add a little extra for safety. They design brakes to take away kinetic energy safely at the end of the ride, and they test new coasters many times with sandbags or water-filled dummies before any person rides. God made the world so that energy always follows the same rules, which is why an engineer can predict, before a single board is nailed, how fast a car will go at the bottom of a hill.

PICTURE STUDY



Thompson's Switchback Railway at Coney Island, Unknown artist, 1884 · Print · Coney Island, New York

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

This picture shows LaMarcus Thompson's Switchback Railway the year it opened. It looks very gentle next to a modern roller coaster, but every part of it was planned around potential and kinetic energy.

Look closely

- Find the two towers. Where does the car start, and where does it gain its potential energy?
- Follow the track with your finger. Does it slope down the whole way?
- Find the riders. Which way are they facing? (On the first switchback, riders sat sideways.)
- Look for the stairs or platforms where people climbed up.

Talk about it

1. Where on the track does the car have the most potential energy? The most kinetic energy?
2. Why did workers have to push the car up to the top of the second tower?
3. If you were Thompson, what would you change to make the ride faster but still safe?

Safety first. Wear safety glasses if marbles might fly off the track, and keep marbles away from small children, who could choke on them.

BUILD

Marble Coaster: How High Is the First Hill?

You will build a marble roller coaster from paper or foam pipe insulation and run a fair test: does starting the marble higher give it more energy at the bottom? You will measure that energy by how far the marble pushes a paper cup.

You will need

- A piece of foam pipe insulation about 2 meters long, cut in half lengthwise by an adult (or card stock folded into a U-shaped track and taped end to end)
- Masking tape
- A marble
- A small paper cup with a doorway cut in the rim, laid on its side
- A chair, a stack of books, a ruler and a tape measure
- Engineer's notebook

Steps

1. **Ask.** Write the question at the top of a notebook page: "Does a higher start give the marble more energy?" Write your prediction.
2. **Build.** Tape one end of the track to the back of a chair so it slopes down to the floor and runs flat along the floor for about 50 centimeters. Lay the cup on its side at the end of the track, with the marble's doorway facing the track, so the marble rolls into it and pushes it along the floor.
3. Mark three starting heights on the track with tape: 20, 40 and 60 centimeters above the floor. Measure each one carefully with a ruler.
4. **Test.** Let the marble go from 20 centimeters (let go, do not push). Measure how far the cup slides. Put the cup back on its mark. Do three trials and record each one.
5. Repeat for 40 and 60 centimeters. Change only the height. Keep the same marble, track, cup and floor.
6. Find the middle result (or the average) for each height and make a bar graph.

7. **Add a hill.** Lift the middle of the flat part of the track over a book to make a second hill. Find the lowest starting height that still gets the marble over the hill. Is the start higher or lower than the top of the hill? Why?
8. **Improve.** Add a loop or a curve. Test it five times and record how many times the marble makes it. Change one thing (start height, size of the loop, tape on the curves) and test five more times.

Tips

- Let the marble go with your fingers, never with a push. A push adds energy and spoils the fair test.
- Smooth the tape seams so the marble does not bump and lose energy at each joint.
- If the cup slides too far to measure, put a book inside it to make it heavier, and use the same book every time.

Check your work

- ☐ I can point to where my marble has the most potential energy and the most kinetic energy.
- ☐ My graph shows how start height changed how far the cup moved.
- ☐ I can explain why the second hill must be lower than the start.

ENGINEER'S NOTEBOOK

1. Draw your marble coaster. Label the start, the place with the most potential energy, the place with the most kinetic energy, and the hill.
2. Make a table: start height, trial 1, trial 2, trial 3, middle result. Then draw the bar graph.
3. Write two sentences: "I predicted ... The test showed ..."

From history. LaMarcus Thompson went on to build dozens of gravity rides and scenic railways across America and Europe and received many patents. Later coaster builders added the chain lift and wheels underneath the track that lock the car on, so it cannot lift off at the top of a hill. Those under-wheels are one of the most important safety ideas in coaster engineering.

COMMON MISTAKES

- Thinking a car at rest on top of a hill has no energy. It is full of stored, potential energy.

- Thinking a coaster can go up a hill taller than its start. Friction always takes some energy, so each hill must be lower.
- Changing two things at once, such as the height and the marble. Then you cannot tell which change mattered.

Make it a game • Hill Top Freeze. Walk around the room slowly. When a parent calls "hilltop," freeze like a coaster car at the top and say what energy you have stored. When they call "rolling," run in place and name the energy of motion. Earn a point for each correct word, then try to say why gravity and friction slow the ride.

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

The rules that energy follows never change from one day to the next. Engineers can trust them because God holds all things together.

1.2 STORED ENERGY ON WHEELS: LEONARDO'S SPRING CART AND A RUBBER-BAND CAR

OBJECTIVES

- Explain how a twisted spring or rubber band stores elastic potential energy.
- Tell the story of Leonardo da Vinci's spring-powered cart and how it was rebuilt from his drawing.
- Build a rubber-band car and run a fair test of how the number of winds changes the distance it travels.

Warm-up. Stretch a rubber band a little and let it go onto a pillow. Then stretch it farther and let it go. (Point it away from everyone.) Which one flew farther? Where was the energy before you let go?

WATCH

Rubber Band Car | 2024 Science Buddies Engineering Challenge

Science Buddies • 2:50

<https://www.youtube.com/watch?v=f22hAgv6XWQ>

WHEN TO WATCH

Before the build. Watch how the rubber band is wound around the axle, and notice the ideas for making the car go farther.

Note: The video was made for a contest that is now over; the rules at the start can be skipped. The building ideas are what matter.

KEY TERMS

elastic potential energy

Energy stored in something that is stretched, squeezed or twisted, such as a spring or rubber band.

axle

The rod that a wheel turns on, or that turns with the wheel.

spring

A piece of metal that stores energy when it is bent or wound and gives it back when it is let go.

traction

The grip of a wheel on the ground, which keeps it from slipping.

fair test

A test where you change only one thing
and keep everything else the same.

CORE IDEAS

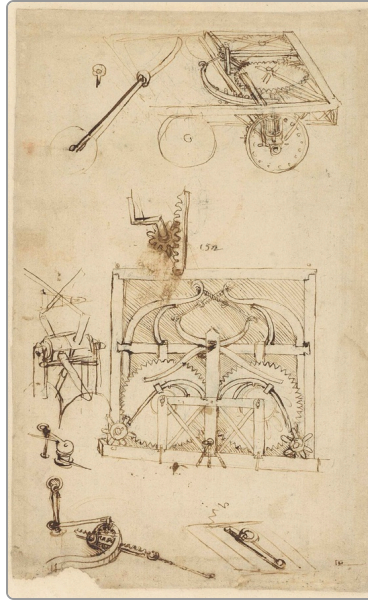
The story. Around 1478, more than four hundred years before the first automobile, Leonardo da Vinci drew a cart that could move by itself. The drawing is in a great collection of his notes now called the *Codex Atlanticus*, kept in Milan, Italy. The cart had three wheels and was driven by two large coiled springs, wound up like the spring in a clock. A brake held it still until someone let it go, and pegs on wheels inside could be set to steer it along a path. Leonardo probably meant it for a stage show or a festival, where it would roll out by itself and amaze the crowd.

How they figured it out. For hundreds of years, people who looked at the drawing could not tell how the cart was supposed to work. Some thought the springs were only decoration. In the 1990s and 2000s, researchers studied the drawing piece by piece, like detectives. They found that the springs were the motor, and that the springs did not push the wheels directly but turned gears that turned the wheels. In 2004 a team at the Museum of the History of Science in Florence built a full-size wooden model from the drawing, and it worked. Leonardo's cart rolled across the floor.

The physics. When you wind a spring or twist a rubber band, you are doing work on it, and it stores that work as **elastic potential energy**. The more you wind it (up to a point), the more energy it stores. When you let it go, the rubber band untwists and turns the **axle**, and the stored energy becomes the kinetic energy of the moving car. Some energy is lost to friction in the axle and to the wheels slipping, and the car slows to a stop when the stored energy is all used. If the wheels have poor **traction**, they spin in place and waste energy.

The engineering. Springs that store energy are everywhere: in wind-up clocks and music boxes, in the click of a ballpoint pen, in mousetraps and in the suspension of a car. Engineers choose a spring by how much energy it must store and how quickly it should give it back. A clock spring gives its energy back slowly, a little at a time, through a set of gears, so one winding runs the clock for a day or a week. Leonardo's cart did the same thing with its gears. Making a car go far is about storing energy well and wasting as little of it as possible.

PICTURE STUDY



Leonardo's Self-Propelled Cart, Leonardo da Vinci, about 1478 · Pen and ink on paper · Codex Atlanticus, Biblioteca Ambrosiana, Milan
Image: [Wikimedia Commons](#), public domain

This is a page from Leonardo's notebooks. It looked like a puzzle for five hundred years, until patient researchers worked out what each part was for and built it.

Look closely

- Find the wheels. How many are there?
- Look for round, toothed wheels. These are gears. What do you think they pass the energy to?
- Find the parts that look like coils or drums. These held the springs that stored the energy.
- Look at Leonardo's handwriting. He wrote backward, from right to left.

Talk about it

1. Why do you think a spring motor was a good choice in 1478, long before engines?
2. Why would it help to have a brake that holds the cart until the right moment?
3. Why might a drawing be hard to understand without notes that explain it?
What does that teach you about your own notebook?

Safety first. Wear safety glasses when winding rubber bands, because a band can snap or slip off. An adult does any cutting with a craft knife or makes holes with a skewer.

BUILD

A Rubber-Band Car: How Many Winds?

You will build a car from cardboard, straws, skewers and bottle caps (or old CDs) that is powered by a rubber band wound around its back axle. Then you will run a fair test to see how the number of winds changes the distance it travels, and improve the car in a second round.

You will need

- A piece of stiff cardboard about 10 by 25 centimeters for the body
- Two drinking straws and two wooden skewers (the axles turn inside the straws)
- Four plastic bottle caps or four old CDs for wheels
- Several rubber bands of the same size
- Tape, a hot glue gun (adult only) or strong glue, and a paper clip
- A tape measure, masking tape for a start line, and safety glasses

Steps

1. **Plan.** Sketch your car from the side and from the top. Label the body, axles, wheels and rubber band.
2. **Build.** Tape the two straws across the bottom of the cardboard, one near each end. Slide a skewer through each straw. An adult glues a wheel onto each end of each skewer, centered and straight.
3. Hook a rubber band over the front of the car (tape a paper clip there as a hook). Stretch it back and tie or tape the other end to the middle of the back axle so that turning the back wheels backward winds the band around the axle.
4. Mark a start line on a smooth floor. Wind the back wheels backward exactly 5 turns, set the car on the line, and let go. Measure how far it went in centimeters.
5. **Fair test.** Do 3 trials each at 5, 10 and 15 winds. Change only the number of winds. Record every trial in a table.

6. Find the middle result for each number of winds and make a bar graph. Did doubling the winds double the distance?
7. **Improve.** Watch the car carefully. Do the wheels slip? Does it curve? Does an axle rub? Pick one problem and fix it (for example, wrap a rubber band around each back wheel for traction, or straighten a wheel). Test again at 10 winds and compare.

Tips

- Wheels that wobble waste energy. Glue them on straight and centered.
- If the car jumps forward and spins its wheels, try fewer winds or add traction.
- If the rubber band is too tight to wind, use a longer band or two bands looped together.

Check your work

- ☐ I can explain where the energy is stored in my car and when it changes to motion.
- ☐ I ran a fair test and recorded three trials for each number of winds.
- ☐ I made one improvement and measured whether it helped.

ENGINEER'S NOTEBOOK

1. Draw your car from the side. Label where the energy is stored, the axle, the wheels and the place where friction slows it.
2. Make a table and a bar graph of winds and distance.
3. Write "What I would change next time" and give one reason.

From history. Clockmakers in Europe began using coiled springs instead of hanging weights in the 1400s, which let them make clocks small enough to carry. Leonardo knew this new technology and borrowed it for his cart. Wind-up toy cars that work the same way became popular in the 1800s.

COMMON MISTAKES

- Winding the wheels until the rubber band snaps. There is a limit to how much energy a band can safely store.
- Measuring from the front of the car on one test and the back on another. Measure from the same point every time.

- Thinking a heavier car always goes farther. More weight can help traction, but it also adds friction.

Make it a game · Wind-Up Charades. Act out Leonardo's spring cart without speaking: twist your body like a rubber band, hold the stored energy, then release and zoom across the floor. Your parent guesses which word you are showing: spring, axle, traction or elastic potential energy. Swap roles. First to guess three terms wins, and the loser must explain what a fair test means.

1.3 WATERWHEELS AND WINDMILLS: JOHN SMEATON'S MODEL TESTS

OBJECTIVES

- Explain how falling or moving water and moving air carry energy that a wheel can capture.
- Tell how John Smeaton used careful model experiments to find which kind of waterwheel works best.
- Build a paper-cup waterwheel and compare an overshot wheel with an undershot wheel in a fair test.

Warm-up. Hold a pinwheel (or a paper cup with slits cut in its sides) under a gently running faucet, first so the water hits the bottom blades and then so it falls onto the top. Then blow on the pinwheel. Which way spins it fastest? Where did the energy come from each time?

WATCH

How does a watermill work: from grain to flour with water power.

Sacrewell · 4:18

<https://www.youtube.com/watch?v=1L5Pt4BLEos>

WHEN TO WATCH

After the physics paragraph. This is a real overshot wheel at a working mill in England. Follow the energy from the water to the millstones.

Note: A quiet video with captions and no talking; read the captions aloud together.

KEY TERMS

waterwheel

A wheel with paddles or buckets that is turned by moving or falling water.

undershot wheel

A waterwheel where moving water pushes against paddles at the bottom.

overshot wheel

A waterwheel where water pours onto the top and its weight turns the wheel.

model

A small copy of a real thing, built to study or test it.

efficiency

How much of the energy that goes into a machine comes out as useful work.

CORE IDEAS

The story. For hundreds of years, waterwheels and windmills did the heavy work of the world. They ground grain into flour, sawed logs, pumped water and hammered iron. But millwrights built them by rules of thumb handed down from master to apprentice, and no one knew for sure which design worked best. John Smeaton, a young English instrument maker who later became the first person to call himself a “civil engineer,” decided to find out. In 1752 and 1753 he built small working models of waterwheels and windmill sails and tested them.

How they figured it out. Smeaton’s waterwheel model sat in a wooden trough. A small tank above it held water at a measured height, and a pump returned the water so he could run test after test. The wheel wound up a cord that lifted a weight, so he could measure exactly how much work the wheel did. He changed one thing at a time: where the water hit the wheel, how fast it flowed, how heavy the load was. He found that an **overshot wheel**, with water pouring into buckets at the top, did about twice as much work as an **undershot wheel** with the same amount of water falling the same height. For windmills, he mounted model sails on a long arm and swung them in a circle to make a steady “wind,” and tested how the angle of the sails changed their power. In 1759 he reported his results to the Royal Society in London and received its highest prize, the Copley Medal.

The physics. Water held up high has potential energy. When it falls, that energy can do work. In an overshot wheel, the *weight* of the water in the buckets pulls one side of the wheel down the whole way it falls, so most of its energy is captured. In an undershot wheel, the moving water only bumps the paddles at the bottom, and much of its energy is lost in splashing and swirling. Moving air has kinetic energy too. Windmill sails are set at a slant, so when the wind pushes on them, it pushes them sideways as well as backward, and they spin.

The engineering. Because of Smeaton’s tests, millwrights across Britain rebuilt their mills with overshot or breast wheels wherever they had enough height of water, and mills could do far more work. His method mattered even more than his answer: build a **model**, measure carefully, change one thing at a time, and write it all down.

Engineers still test models before building big, expensive machines. Today's hydroelectric dams and wind turbines are the great-grandchildren of the waterwheel and the windmill, turning generators instead of millstones.

PICTURE STUDY



The Windmill at Wijk bij Duurstede, Jacob van Ruisdael, about 1670 · Oil on canvas · Rijksmuseum, Amsterdam

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

Jacob van Ruisdael painted this windmill in the Netherlands, where windmills pumped water off the land and ground grain for bread. Painters loved them, and so did engineers like Smeaton.

Look closely

- Find the four sails. Are they flat to the wind or set at a slant?
- Look at the top of the mill, the cap. On many mills the whole cap turns so the sails can face the wind.
- Find the sailboat. Which way is the wind blowing? Do the sails of the boat and the mill agree?
- Look at the shape of the tower. Why might it be wider at the bottom?

Talk about it

1. Where does the energy that turns this windmill come from?
2. Why would a miller want to turn the sails to face the wind?
3. What could go wrong on a day with no wind? What would a waterwheel do better?

Safety first. Do this build outdoors, in a bathtub or over a sink, with an adult nearby, and wipe up spills so no one slips.

BUILD

Overshot or Undershot? A Paper-Cup Waterwheel

You will build a small waterwheel and use it, as Smeaton did, to lift a load on a string. Then you will pour the same amount of water from the same height onto the top (overshot) and onto the bottom (undershot) and measure which lifts the load higher.

You will need

- Two sturdy paper plates and 6–8 small paper cups (or cut-off bottoms of plastic cups)
- A pencil or wooden dowel for the axle and two cups or a shoebox to hold it up
- Tape or a hot glue gun (adult only)
- String (about 60 centimeters) and a paper clip with 5–10 pennies taped to it as a load
- A pitcher or measuring cup with exactly 500 milliliters of water each time
- A dishpan or the bathtub, a ruler and a stopwatch

Steps

1. **Plan.** Sketch your wheel: two plates with small cups glued between them around the rim, like buckets, all opening the same direction.
2. **Build.** Poke the axle through the centers of both plates and glue the cups between them. Rest the axle on two cut-down cups or in notches cut in a shoebox so the wheel turns freely above the dishpan.
3. Tape one end of the string to the axle. Hang the penny load from the other end, so the string winds up as the wheel turns.
4. **Predict.** Will pouring water on the top or on the bottom lift the load higher? Write your guess and why.
5. **Overshot test.** Hold the pitcher 15 centimeters above the top of the wheel and pour 500 milliliters steadily into the top cups. Measure how high the load rose. Do three trials.

6. **Undershot test.** Pour the same 500 milliliters from the same 15 centimeters onto the bottom cups so it pushes them sideways. Measure how high the load rose. Do three trials.
7. Record all six results in a table and compare the middle results. Which wheel captured more energy?
8. **Improve.** Change one thing to make your best wheel lift more: more cups, bigger cups, a thinner axle so the string winds more slowly, or a higher pour. Test three more times.

Tips

- Pour at the same speed each time. Count slowly to ten as you pour so every test is the same.
- If the wheel will not start, use fewer pennies. Smeaton also changed the load to find the best one.
- A thin axle turns the wheel more times for each centimeter of string, so it can lift a heavier load more slowly.

Check your work

- ☐ I can explain why an overshot wheel catches more of the water's energy.
- ☐ I kept the water amount and pour height the same for a fair test.
- ☐ I can tell how Smeaton used a model to answer a real question.

ENGINEER'S NOTEBOOK

1. Draw an overshot wheel and an undershot wheel side by side. Draw arrows to show the water and the direction the wheel turns.
2. Make a data table: wheel type, trial 1, 2, 3, middle result.
3. Write a short letter as if you were Smeaton, telling a miller which wheel to build and why.

From history. John Smeaton is best remembered for the third Eddystone Lighthouse, built on a wave-swept rock off the coast of England and finished in 1759. He shaped its granite blocks to lock together like puzzle pieces and tested limes until he found one that would set hard under water. It stood for more than 120 years, and the upper part was rebuilt on land in Plymouth, where it still stands.

COMMON MISTAKES

- Thinking the speed of the water is all that matters. In an overshot wheel, the weight of the falling water does most of the work.
- Pouring from different heights in the two tests. The height of the fall is part of the energy, so keep it the same.
- Forgetting to reset the load to the same starting point before each trial.

Make it a game • Wheel Judge. Play John Smeaton in his workshop. Your parent names a stream: fast and shallow, or deep and falling from a height. You decide aloud whether an overshot or an undershot wheel suits it and give one reason. Score a point for each sound reason. Then explain why a small model test comes before a big build.

Scripture. “He causeth the vapours to ascend from the ends of the earth; he maketh lightnings for the rain; he bringeth the wind out of his treasures.” (Psalm 135:7, KJV)

Wind and water are gifts from God’s storehouse. Millwrights and engineers learned to use them wisely to grind bread and lighten heavy work.

1.4 A CHAIN-REACTION MACHINE: RUBE GOLDBERG AND THE DESIGN PROCESS

OBJECTIVES

- Follow energy as it passes from one step to the next in a chain-reaction machine.
- Use every step of the engineering design process: ask, research, imagine, plan, build, test and improve.
- Build a chain-reaction machine of at least five steps, test how reliable it is, and improve its weakest step.

Warm-up. Set up ten dominoes (or books, or blocks) in a row and knock over the first one. Where did the energy come from? Now set up the row again with one gap that is too wide. What happens? Talk about what a gap does to a chain.

WATCH

What Is a Rube Goldberg Machine? | Amazing Experiments with Simple Machines | Science Max

Science Max - Scholastic • 4:55

<https://www.youtube.com/watch?v=ga4MZyzqyeM>

WHEN TO WATCH

Before you plan your own machine. Count the steps in each machine and name the kind of energy in each one.

KEY TERMS

chain reaction

A series of events where each one causes the next.

energy transfer

When energy passes from one object to another, like a rolling ball knocking over a domino.

engineering design process

The steps engineers use to solve problems: ask, research, imagine, plan, build, test and improve.

reliable

Working the same way every time it is used.

prototype

A first working version of an invention,
built to test and improve.

CORE IDEAS

The story. Reuben “Rube” Goldberg graduated from the University of California in 1904 with a degree in engineering and went to work drawing maps of San Francisco’s water and sewer pipes. But he loved to draw cartoons, and within a few months he left engineering to become a newspaper cartoonist. He became famous for drawing ridiculous inventions that did a simple job in the most complicated way possible. In one, a man lifts a spoon of soup to his mouth, which pulls a string, which jerks a ladle, which throws a cracker past a parrot, and so on through a dozen steps, until a napkin finally wipes his chin. Today any machine that does a simple task through a long chain of steps is called a “Rube Goldberg machine.”

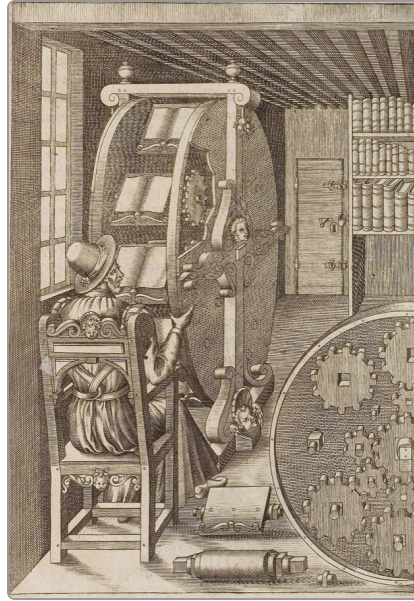
How they figured it out. Goldberg’s cartoon machines worked on paper, but real ones are hard. Since 1949, engineering students at Purdue University in Indiana have held contests to build real Rube Goldberg machines, and many schools now hold them too. Builders learn quickly that the hard part is not the idea but making every step work every time. A ball that rolls a little too slowly, a string that sags, or a domino set a little too far away will stop the whole machine. So builders test each step by itself, then two steps together, then three, fixing problems as they find them.

The physics. A chain-reaction machine is a set of **energy transfers**. A ball at the top of a ramp has potential energy. It rolls down and gains kinetic energy. It hits a domino and passes some of its energy on. The domino falls and pulls a string, which tips a cup, which drops a marble, and so on. At each step, a little energy is lost to friction, sound and heat, so many good machines add new energy along the way, using gravity again: a step tips something that was resting high up, and that object falls with fresh energy of its own.

The engineering. Rube Goldberg machines are a fun way to practice the **engineering design process**, the steps every engineer follows. *Ask* what the machine must do. *Research* how others did it. *Imagine* many ideas. *Plan* by drawing. *Build* a **prototype**. *Test* it. *Improve* it, and test again. Real factory machines are also chains of steps, and engineers work hard to make each step **reliable**, because if each step works only 9 times out of 10, a machine with many steps will fail very often. Good engineers

keep chains short and simple when the job is serious and save the long, silly chains for fun.

PICTURE STUDY



The Book Wheel, Agostino Ramelli, 1588 · Engraving · From Ramelli's book *The Various and Ingenious Machines*, Paris

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

Agostino Ramelli was an Italian military engineer who filled a whole book with drawings of clever machines. This one, a reading wheel, let a scholar turn from one heavy book to another without getting up. Like a Rube Goldberg machine, it uses many gears to do a simple job.

Look closely

- Find the large wheel and the open books on its shelves.
- Find the round inset picture in the corner. It shows the gears inside the wheel, drawn as if the cover were removed.
- Notice that the books stay level as the wheel turns, like the seats on a Ferris wheel.
- Find the scholar. Where would he push to turn the wheel?

Talk about it

1. Where does the energy to turn this wheel come from?
2. Ramelli used many gears where a simpler design might work. Why do you think he drew all of them?

3. What simple job in your house would you like a machine to do? How many steps would it need?

Safety first. Keep the machine on the floor or a low table, use soft balls or marbles and books rather than anything heavy that could fall on toes, and keep marbles away from small children.

BUILD

My Five-Step Chain-Reaction Machine

You will design and build a chain-reaction machine with at least five steps that ends by doing a simple job, such as ringing a bell, dropping a coin in a cup or knocking a toy off a table. You will test it ten times, count how often it works, and make the weakest step more reliable.

You will need

- Dominoes, blocks or books
- Marbles or small balls, toy cars
- Cardboard tubes and pieces of cardboard for ramps
- String, paper cups, tape, rubber bands, spoons, a ruler
- A small bell or a cup for the final job
- Engineer's notebook

Steps

1. **Ask.** Choose the simple job your machine will do and write it at the top of your page.
2. **Imagine.** List at least eight possible steps (a marble rolls down a tube, dominoes fall, a car rolls off a ramp, a cup tips, a string pulls a book, a seesaw ruler flips).
3. **Plan.** Draw your machine with at least five steps. Number each step and write the kind of energy at each one (potential or kinetic).
4. **Build and test each step alone.** Make sure each step works five times in a row before you join it to the next.
5. **Join the steps.** Connect them one at a time, testing after each new step.
6. **Reliability test.** Run the whole machine 10 times. Each time, record whether it finished and, if not, which step failed.
7. Make a tally chart of which steps failed. Which step is the weakest link?
8. **Improve.** Change only the weakest step and run 10 more times. Did your success count go up?

Tips

- Gaps that are too wide and ramps that are too shallow are the most common failures. Measure them and adjust a little at a time.
- Tape down anything that should not move, so bumping the table does not change your machine.
- Take a video of each run. Watching it slowly helps you see exactly where a step failed.

Check your work

- ☐ I can name the energy change at each step of my machine.
- ☐ I tested my machine 10 times and recorded which step failed.
- ☐ I improved the weakest step and measured the difference.

ENGINEER'S NOTEBOOK

1. Draw your machine plan with each step numbered and labeled “potential” or “kinetic.”
2. Make a tally chart of your 10 test runs, before and after your improvement.
3. List the seven steps of the engineering design process and write one thing you did for each.

From history. Rube Goldberg drew cartoons for more than fifty years and won the Pulitzer Prize for his cartoons in 1948. His name is now in the dictionary. Mark Rober, a former NASA engineer, and many other builders still enjoy designing chain-reaction machines today.

COMMON MISTAKES

- Building the whole machine before testing any step. Test each step by itself first.
- Fixing several steps at once. Then you cannot tell which fix helped.
- Counting only the successful runs. The failures tell you what to improve.

Make it a game • Domino Storyteller. Set up five household objects in a chain, such as a spoon, a book and a cup, and describe the energy passing from one to the next, step by step. Your parent plays the Rube Goldberg judge and asks one design-process question per step, like "What did you test?" Answer all seven to move the pretend trophy to your side.

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

Good builders plan before they build, test what they have built, and learn from what goes wrong. That is wisdom and understanding at work.

UNIT 1

ENERGY AND MACHINES

Every machine runs on energy. A roller coaster climbs a tall hill and then rolls the rest of the way on the energy it stored at the top. A wound-up rubber band pushes a car across the floor. Falling water turns a millwheel, and the wind turns the sails of a windmill. In this unit you will learn the difference between stored energy (potential energy) and the energy of motion (kinetic energy), and you will follow that energy as it changes from one form to another.

You will meet LaMarcus Thompson and his Switchback Railway, Leonardo da Vinci and his spring-powered cart, John Smeaton and his careful waterwheel experiments, and Rube Goldberg, the engineer who drew the silliest machines in the world. Along the way you will learn the engineering design process: ask, research, imagine, plan, build, test and improve. Then you will build a rubber-band car, a paper-cup waterwheel and a chain-reaction machine of your own, testing each one fairly and making it better.

PREREQUISITES

- Can measure length with a ruler or tape measure in centimeters
- Can use a stopwatch or a phone timer
- Can make a simple table and find the middle (or average) of three numbers with help

MASTERY CHECKLIST

- ☐ I can explain the difference between potential energy and kinetic energy and give an example of each.
- ☐ I can follow energy as it changes form in a roller coaster, a rubber-band car, a waterwheel and a chain-reaction machine.
- ☐ I can name the steps of the engineering design process: ask, research, imagine, plan, build, test and improve.
- ☐ I can run a fair test by changing only one thing and measuring the result three times.
- ☐ I can explain why a real machine always loses some energy to friction, sound and heat.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Tinker Crate:** Ages 9–16. A monthly box with a build and a short explanation of the science behind it; several crates (rubber-band cars, catapults, hydraulic machines) fit this unit and Unit 8.
- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. A toy to build each month with a video lesson from Mark Rober about the physics inside it. A good extra for Lessons 1.1, 1.2 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 Potential and Kinetic Energy: The Switchback Railway 2 sessions of 45 minutes

1.2 Stored Energy on Wheels: Leonardo's Spring Cart and a Rubber-Band Car

2 sessions of 45 minutes

1.3 Waterwheels and Windmills: John Smeaton's Model Tests 2 sessions of 45 minutes

1.4 A Chain-Reaction Machine: Rube Goldberg and the Design Process

2 sessions of 45 minutes

UNIT 1 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

What is the difference between potential energy and kinetic energy? Give one example of each.

2. **5 pts**

Why must every hill on a roller coaster be lower than the first hill?

3. **5 pts**

Predict: you start a marble on your coaster at 30 centimeters and then at 60 centimeters. Which start will push the cup farther, and why?

4. **5 pts**

Where is the energy stored in a rubber-band car? What does it change into?

5. **5 pts**

What powered Leonardo da Vinci's self-propelled cart, and how did people finally learn how it worked?

6. **5 pts**

What is a fair test? Use the rubber-band car as an example.

7. **5 pts**

John Smeaton tested model waterwheels. Which kind did more work with the same water, overshot or undershot? Why?

8. **5 pts**

Name the seven steps of the engineering design process in order.

9. **5 pts**

Predict: a chain-reaction machine has one step that fails 4 times out of 10 and four steps that almost never fail. What should the builder fix first, and why?

10. **5 pts**

Choose one machine from this unit (coaster, rubber-band car, waterwheel, windmill or chain-reaction machine) and trace its energy from start to finish.

ANSWER KEY

1. Potential energy is stored energy (a coaster car at the top of a hill, a wound rubber band, water held behind a dam). Kinetic energy is the energy of motion (a rolling car, a falling ball, flowing water).
2. Some energy is turned into heat and sound by friction as the car rolls, so the car never has enough energy to climb back as high as where it started.
3. The 60-centimeter start, because a higher marble has more potential energy, which becomes more kinetic energy at the bottom.
4. In the twisted or stretched rubber band, as elastic potential energy. It changes into the kinetic energy of the moving car (and some is lost to friction, heat and sound).
5. Wound-up coiled springs. Researchers studied his drawing piece by piece and, in 2004, built a working model from it.
6. A test where only one thing is changed and everything else is kept the same. For example, change only the number of winds, while using the same car, floor and start line, and do three trials of each.
7. Overshot, about twice as much. The weight of the water in the top buckets pulls the wheel down the whole way it falls, while in an undershot wheel much of the energy is lost in splashing.
8. Ask, research, imagine, plan, build, test, improve.
9. The step that fails 4 times out of 10. It is the weakest link; the whole machine can only work as often as its weakest step lets it.
10. Answers vary. Example: water held up high has potential energy; it falls into the buckets and turns the wheel (kinetic energy); the turning axle winds the string and lifts the load, storing potential energy again; some energy is lost to splashing and friction.

PORTFOLIO PIECE: THE ENERGY MACHINE FAIR TEST

Choose your best build from this unit: the marble coaster, the rubber-band car, the waterwheel or the chain-reaction machine. Improve it once more, then run a fair test of one change with at least three trials each. Make a poster or two notebook pages with a labeled drawing that shows where the energy is stored and where it moves, your data table and bar graph, and a paragraph about what you changed and what you learned. Show it to your family and explain it aloud.

LOOK FOR	WHAT IT MEANS
Energy explained	The drawing correctly labels potential energy, kinetic energy and where energy is lost to friction.
Fair test	Only one thing was changed, with at least three trials for each version.
Data	A neat table with units and a bar graph that matches it.
Improvement	One clear improvement was made and its result was measured and honestly reported.
Explanation	The student explains the build aloud using the words potential, kinetic, friction and fair test.

UNIT 2

BRIDGES

A bridge carries people safely over a river, a valley or a busy road, and every part of it is being pushed or pulled. In this unit you will learn how engineers arrange those pushes and pulls so that a bridge stays strong without being too heavy. You will start with the truss, a frame made of triangles, and meet three famous truss patterns named after their inventors: the Howe, the Pratt and the Warren. You will build trusses of your own and load-test them with pennies.

Then you will visit two of the great bridges of the 1800s. In Scotland, the Forth Bridge stretched giant steel arms, called cantilevers, out over deep water. In Wales, Thomas Telford hung the Menai Bridge from iron chains high enough for tall ships to sail beneath it. You will build a cantilever and a suspension bridge, measure how they carry their loads, and learn why engineers test, test and test again before anyone crosses.

PREREQUISITES

- Knows the engineering design process and how to run a fair test (Unit 1)
- Can measure in centimeters and record results in a table
- Knows that a force is a push or a pull

MASTERY CHECKLIST

- ☐ I can explain compression and tension and show which parts of a bridge are pushed and which are pulled.
- ☐ I can explain why triangles make a truss rigid and recognize Howe, Pratt and Warren trusses.
- ☐ I can explain how a cantilever bridge balances its arms, using the Forth Bridge as an example.
- ☐ I can trace the load in a suspension bridge from the deck to the cables, towers and anchorages.
- ☐ I can build a bridge, load-test it fairly, record the results and improve it.

OPTIONAL KITS FOR THIS UNIT

- **LEGO Technic:** Ages vary by set. Beams, pins and connectors make it easy to build Howe, Pratt and Warren trusses and see how the diagonals stiffen a frame. Fits Lessons 2.1 and 2.2.
- **K'NEX building sets:** Ages vary by set. Rods and connectors make it easy to build truss, cantilever and suspension bridges side by side. Fits Lessons 2.1–2.4.

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

LESSONS IN THIS UNIT

2.1 Why Triangles? The Howe, Pratt and Warren Trusses

2 sessions of 45 minutes

2.2 Truss Against Beam: Wendel Bollman and a Craft-Stick Load Test

2 sessions of 45 minutes

2.3 The Forth Bridge: Giant Cantilevers

2 sessions of 45 minutes

2.4 Hanging from Chains: Telford's Menai Suspension Bridge

2 sessions of 45 minutes

UNIT 2 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

What is the difference between compression and tension? Give an example of each from a bridge.

2. **5 pts**

Why are trusses made of triangles instead of squares?

3. **5 pts**

William Howe used both wood and iron in his truss. Which parts were iron, and why?

4. **5 pts**

Predict: you build a flat beam and a truss from the same 24 craft sticks. Which will probably hold more, and why?

5. **5 pts**

A model bridge weighs 50 grams and holds 2,500 grams. What is its efficiency?

6. **5 pts**

What is a cantilever? What does a counterweight do?

7. **5 pts**

Why did Benjamin Baker measure the wind for years before the Forth Bridge was built?

8. **5 pts**

Trace the load in a suspension bridge from a car on the deck to the ground.

9. **5 pts**

Predict: on your string bridge, you pull the cable almost straight with very little sag. Will the anchorage rubber bands stretch more or less than with a big sag? Why?

10. **5 pts**

Name one thing Thomas Telford did to be sure the Menai Bridge would be safe, and one thing engineers learned from it afterward.

ANSWER KEY

1. Compression is a squeezing or pushing force; tension is a pulling or stretching force. Examples: a bridge tower or the top chord of a truss is in compression; a suspension cable, a suspender or the bottom chord of a truss is in tension.
2. A triangle cannot change shape unless one of its sides changes length, so it is rigid. A square can lean over into a diamond without any side changing length.
3. The vertical rods were iron because they were in tension, and iron is good at being pulled. Their nuts could also be tightened if the wood shrank. The wood was used where it was pushed.
4. The truss. It moves the material to the top and bottom, far apart, and connects them with triangles, so it is much stiffer than a flat beam that only bends.
5. $2,500 \div 50 = 50$. It holds 50 times its own weight.
6. A cantilever is an arm held at only one end that sticks out over empty space. A counterweight balances the load on the other side so the cantilever does not tip over.
7. The Tay Bridge had fallen in a storm because its designer did not allow enough for the wind. Baker wanted real measurements so the Forth Bridge would be strong beyond doubt.
8. Deck → suspenders (tension) → main cables or chains (tension) → over the towers (compression) down to the foundations; the cable ends are held by the anchorages.
9. More. A nearly straight cable must pull much harder to hold up the same load; more sag lets the cable pull more gently.
10. He tested the iron bars (and every bar for the bridge) before using them. Afterward, engineers learned that a light, narrow deck can be moved and damaged by wind, so suspension bridges need stiff decks.

PORTFOLIO PIECE: A LOAD-TESTED TRUSS BRIDGE

Design, build and test a craft-stick truss bridge that spans 30 centimeters, using no more than 60 sticks. Choose a Howe, Pratt or Warren pattern (or invent your own) and draw it full size first, marking the members you expect to be pushed and pulled. Weigh it, load-test it until it fails, and calculate its efficiency. Then write a one-page engineer's report with your drawing, your data, a photograph of the failure, and what you would change next time.

LOOK FOR	WHAT IT MEANS
Plan	A full-size drawing names the truss pattern and marks pushed and pulled members.
Craftsmanship	The two sides match, the joints overlap and are well glued, and the bridge is braced.
Fair test and data	The bridge was weighed, the load was added gently at the middle, and the load and efficiency were recorded honestly.
Failure explained	The report shows where the bridge failed and explains why, using the words compression, tension or joint.
Improvement	A sensible change is suggested (or built and tested) based on how the bridge failed.

2.1 WHY TRIANGLES? THE HOWE, PRATT AND WARREN TRUSSES

OBJECTIVES

- Explain compression and tension, and why a triangle keeps its shape when a square does not.
- Recognize Howe, Pratt and Warren trusses and tell how William Howe's design helped railroads cross rivers.
- Build straw trusses and test how much load each one holds compared with a frame without diagonals.

Warm-up. Make a square from four straws joined at the corners with tape or pipe cleaners. Push gently on one corner. What happens? Now make a triangle from three straws and push on it. Which shape changed? Add one straw across the square from corner to corner and push again.

WATCH

Bridge Design Tutorial - Pratt vs Howe Truss

Scientific Monkey • 5:51

<https://www.youtube.com/watch?v=oL-39NZJmhl>

WHEN TO WATCH

After the physics paragraph. In the video, blue members are pushed (compression) and red members are pulled (tension). Pause and predict which color each diagonal will turn before the load is added.

Note: A Georgia Tech engineering professor uses a bridge-building app to compare the two trusses. The app is not needed for this lesson.

KEY TERMS

compression

A squeezing force that pushes on something and tries to make it shorter.

tension

A pulling force that stretches something and tries to make it longer.

truss

A frame of straight pieces joined in triangles, used to hold up a bridge or a roof.

member

One straight piece of a truss.

rigid

Stiff; keeping its shape when pushed.

CORE IDEAS

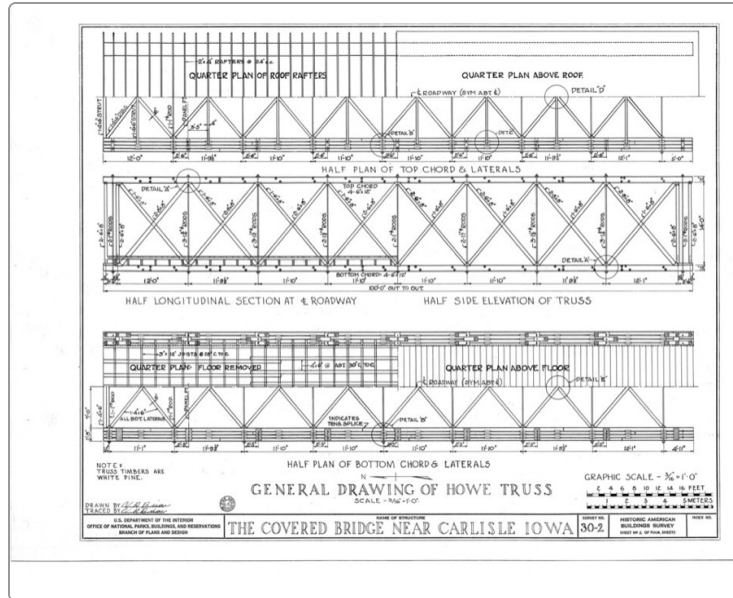
The story. In the 1830s and 1840s, railroads were spreading across America, and trains needed bridges over hundreds of rivers. Trains are far heavier than wagons, and many old wooden bridges sagged or shook under them. William Howe was a builder from Massachusetts who had worked on barns and church roofs. In 1840 he patented a new kind of truss bridge. It used heavy timbers for the slanting pieces and the long top and bottom, but for the upright pieces it used iron rods with nuts on the ends. The very next year, a Howe truss bridge carried the Western Railroad across the wide Connecticut River at Springfield.

How they figured it out. Howe noticed that some pieces of a truss are always pulled and others are always pushed. Wood is very good at being pushed, but its joints tend to pull apart. Iron rods are very good at being pulled. So he used each material where it worked best. Even better, the nuts on the iron rods could be tightened, so if the wood shrank as it dried, a worker with a wrench could snug the whole bridge back up. A few years later Thomas Pratt and his father, Caleb, turned the idea around: in the Pratt truss of 1844, the upright pieces are pushed and the slanting pieces are pulled. In 1848 James Warren and Willoughby Monzani in England patented a truss made of a simple zigzag of equal triangles.

The physics. Every part of a bridge is in **compression** (being squeezed) or **tension** (being pulled). When a load pushes down on a bridge, the top is squeezed and the bottom is stretched, just like a ruler bending between two books. A square frame cannot stay square when it is pushed sideways; it leans over into a diamond, even though none of its sides changes length. A **triangle** cannot change its shape at all unless one side gets longer or shorter. That makes a triangle **rigid**. A **truss** is a row of triangles, so the whole frame stays stiff.

The engineering. A truss puts material only where it is needed, so it can be much lighter than a solid beam that carries the same load. In a **Howe truss**, the diagonals slant toward the ends of the bridge and are pushed; the verticals are pulled. In a **Pratt truss**, the diagonals slant toward the middle and are pulled; the verticals are pushed. In a **Warren truss**, there may be no verticals at all, and the diagonals take turns being pushed and pulled. Engineers still choose among these patterns today depending on the materials and the span. Look for them on railroad bridges, roofs, cranes and the towers that carry power lines.

PICTURE STUDY



Drawing of a Howe Truss Covered Bridge, Historic American Buildings Survey, Measured drawing of a bridge built in the 1800s · Measured drawing · Library of Congress, Prints and Photographs Division

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

Government survey teams measure and draw old bridges and buildings so that their design is never lost. This sheet shows the Howe truss inside a wooden covered bridge in Iowa. The roof and walls kept rain off the truss so the wood would not rot.

Look closely

- Find the long top and bottom pieces (the chords). Which one is squeezed when a wagon crosses?
- Find the slanting timbers. Which way do they lean, toward the ends or toward the middle?
- Find the thin vertical lines. These are the iron rods. Are they pushed or pulled?
- Look for small drawings of the joints. Why would an engineer draw those so carefully?

Talk about it

1. Why do you think Howe used iron for the vertical rods instead of wood?
2. Count the triangles. What would happen if you took out every slanting timber?

3. Why did builders put a roof over a wooden bridge?

Safety first. An adult cuts straws or skewers with scissors or a craft knife. Wear safety glasses during the load test in case a straw snaps or pennies spill.

BUILD

Straw Truss Load Test: Square, Howe, Pratt and Warren

You will build four flat bridge sides from straws, all the same length: one with only squares, and one each in the Howe, Pratt and Warren patterns. You will load each one with pennies and find out how much the triangles help.

You will need

- About 40 plastic or paper drinking straws
- Masking tape, straight pins or pipe cleaners for the joints
- Two stacks of books the same height, set 25 centimeters apart
- A small paper cup with a string handle, and about 100 pennies
- A ruler and engineer's notebook

Steps

1. **Plan.** On graph paper, draw four bridge sides, each 30 centimeters long and 6 centimeters tall, divided into 4 sections: squares only, Howe, Pratt and Warren. Count the straws each one needs.
2. **Build.** Make each side flat on the table, joining straws at the corners with small pieces of tape or straight pins. Use the same kind of joint on every bridge.
3. Make each flat side stand up by taping a second matching side to it with short straw spacers along the top and bottom, so you have four narrow box bridges.
4. **Predict.** Rank the four bridges from strongest to weakest and write why.
5. **Test.** Lay the first bridge across the gap. Hang the cup from the middle of the bottom. Add pennies one at a time until the bridge bends down 2 centimeters or breaks. Record the number of pennies.
6. Test every bridge the same way: same gap, same cup, cup hung in the same place.
7. Record your results in a table and make a bar graph. Was your prediction right?

8. **Improve.** Watch where your best bridge failed. Strengthen only that spot (double a straw or add a pin) and test it again.

Tips

- Pinch each straw end flat before taping. Flat ends make stronger joints.
- Add pennies gently. Dropping them adds a sudden push that is not fair to the bridge.
- Most straw bridges fail when a pushed straw kinks. Look for the kink.

Check your work

- ☐ I can explain why triangles make a truss stiff.
- ☐ I can point to a member in tension and one in compression on my bridge.
- ☐ My table and graph show how the four patterns compared.

ENGINEER'S NOTEBOOK

1. Draw a Howe, a Pratt and a Warren truss. Color the pushed members blue and the pulled members red.
2. Make a table: bridge type, number of straws, pennies held, where it failed.
3. Write one sentence about why the square bridge did so poorly.

From history. Howe's brother-in-law, Amasa Stone, bought the rights to the Howe truss and built many railroad bridges with it. Thousands of covered bridges in America and Canada use the Howe truss, and many are still standing and carrying cars today.

COMMON MISTAKES

- Thinking a square frame is just as strong as a triangle. A square can lean over without any side changing length.
- Mixing up compression and tension. Compression squeezes; tension pulls.
- Hanging the load in a different place on each bridge, which spoils the fair test.

Make it a game • Wobble or Hold. Make a square and a triangle from four and three straws or pencils and a bit of tape. Push on each corner. Say which one keeps its shape, and name the straws in compression and in tension. Your parent then names Howe, Pratt or Warren, and you sketch it from memory in thirty seconds.

2.2 TRUSS AGAINST BEAM: WENDEL BOLLMAN AND A CRAFT-STICK LOAD TEST

OBJECTIVES

- Tell how Wendel Bollman, a self-taught builder, designed iron truss bridges for the Baltimore and Ohio Railroad.
- Explain why a truss can be stronger than a beam made from the same amount of material.
- Build a craft-stick truss and a craft-stick beam from the same number of sticks, load-test both fairly, and improve the truss.

Warm-up. Lay a single craft stick (or a ruler) across a gap between two books and press down on the middle with one finger. Now stack three sticks together and press again. Then turn the stack on its edge and press. Which way was stiffest? Why do you think that is?

WATCH

Harvard Model Bridge Testing! Trusses and Beams

Paul Kassabian • 13:16

<https://www.youtube.com/watch?v=oqUNMGr0lo8>

WHEN TO WATCH

After the story. Watch the first 6 minutes in Session 1. Before each bridge is loaded, predict where it will break.

Note: A structural engineer shows university students loading the long model bridges they built. The rest can be watched in Session 2 before testing your own bridge.

BACKUP VIDEO

Easy Popsicle Stick Bridge

Physics Burns (Raymond Burns) • 4:43

https://www.youtube.com/watch?v=s3HZievv_3Y

Before the build, for step-by-step building tips.

KEY TERMS

beam

A solid bar that carries a load across a gap by bending.

span

The distance a bridge crosses between its supports.

load test

A test where weight is added to a structure to see how much it can hold.

joint

A place where members meet and are fastened together.

efficiency

For a model bridge, how many times its own weight it can hold.

CORE IDEAS

The story. Wendel Bollman was born in Baltimore in 1814 and left school young. He became a carpenter and went to work for the Baltimore and Ohio Railroad, one of the first railroads in America. In those days most railroad bridges were made of wood, and wood could rot or catch fire from the sparks of a steam engine. Bollman taught himself the mathematics of bridges and designed a truss made almost entirely of iron. He patented it in 1852, and it became the first iron bridge design used again and again on an American railroad. One of his bridges, built in 1869 near an old cotton mill in Savage, Maryland, still stands today. It is the last Bollman truss in the world.

How they figured it out. Bollman's truss used long iron rods running from the top of each end post down to the bottom of the bridge, like the strings of a harp. Each rod was in tension and carried part of the load straight back to the end towers. Because Bollman knew which pieces would be pulled and which would be pushed, he could make the pulled ones thin and light and the pushed ones thick and hollow. Railroad engineers tested the iron and the finished bridges with heavy locomotives before trusting them with passengers.

The physics. A **beam** carries a load by bending. Its top gets squeezed and its bottom gets stretched, while the middle of the beam does little work at all. A **truss** takes that same material and moves it to the top and the bottom, far apart, and then connects them with triangles. The farther apart the top and bottom are, the stiffer the bridge.

That is why a ruler on its edge is much stiffer than a ruler lying flat. A truss made from the same sticks as a beam can often carry many times more load.

The engineering. Engineers compare bridges by **efficiency**: how much load a bridge carries for its own weight. A light bridge that carries a heavy load is a good design, because it saves material and money. In model bridges, the weak spot is usually a **joint**, not a stick, so builders take great care with glue and overlap. Real bridges are load-tested too. Before a new bridge opens, engineers often drive heavy, loaded trucks onto it and measure exactly how much it bends, to be sure it matches their calculations. Honest testing protects every family that will drive across.

PICTURE STUDY



The Bollman Truss Bridge at Savage, Maryland, Historic American Engineering Record, Photograph of a bridge built in 1869 · Photograph · Library of Congress, Prints and Photographs Division

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

This is the last Bollman truss bridge in the world. It once carried trains over the Little Patuxent River and now carries people on a walking trail. Look for the long, thin iron rods that Bollman used in tension.

Look closely

- Find the tall posts at each end of the bridge.
- Find the long thin rods that slant down from the top of the end posts. Are they pushed or pulled?
- Find the thicker upright posts in the middle. Why might those be thicker than the rods?
- Find the old mill tower behind the bridge. What does it tell you about how long this bridge has stood?

Talk about it

1. Why would iron be a better choice than wood for a railroad bridge in 1869?
2. How does this bridge use triangles?
3. Why is it important to save one old bridge like this for people to study?

Safety first. An adult runs the glue gun (use a low-temperature gun) and cuts any sticks. Wear safety glasses during the load test, because craft sticks can snap and fly.

BUILD

Truss Against Beam: A Craft-Stick Load Test

You will use the same number of craft sticks to build two bridges: a flat beam made of sticks glued in layers, and a Warren truss. You will load-test both, compare them by efficiency, and then improve your truss.

You will need

- About 60 craft sticks
- White glue (allow a night to dry) or a low-temperature glue gun with an adult
- Two stacks of books or two chairs to make a 25-centimeter gap
- A small bucket or bag with a string handle, pennies or sand, and a kitchen scale
- A pencil or short dowel to hang the bucket from
- Graph paper, ruler and engineer's notebook

Steps

1. **Plan.** Decide how many sticks each bridge may use (for example, 24). Draw a Warren truss side about 35 centimeters long at full size on graph paper.
2. **Build the beam.** Glue 24 sticks into a long, flat laminated beam, overlapping the ends like bricks in a wall so there is no weak joint in the middle.
3. **Build the truss.** Lay sticks on your drawing and glue two matching truss sides. Join them at the top and bottom with short cross-sticks. Use the same total of 24 sticks.
4. Let both dry fully. Weigh each bridge and record its mass in grams.
5. **Predict.** Which bridge will hold more? How many times more?
6. **Test.** Lay each bridge across the gap. Hang the bucket from the pencil at the middle. Add pennies or sand a little at a time until the bridge breaks or sags 3 centimeters. Weigh the bucket and load. Record where it failed.
7. Calculate efficiency for each bridge: $\text{load held} \div \text{bridge mass}$. Record both in a table.

8. **Improve.** Look at where your truss failed. Strengthen only that spot, using no more than 4 extra sticks, and test again. Did the efficiency go up or down?

Tips

- Overlap sticks at every joint. Most model bridges break at a joint.
- Keep the two sides of the truss exactly the same. If one side is weaker, the bridge twists.
- Photograph each bridge just before and just after it fails.

Check your work

- ☐ I can explain why a truss can hold more than a beam made of the same sticks.
- ☐ I load-tested both bridges the same way and calculated their efficiency.
- ☐ I can tell where my truss failed and what I changed.

ENGINEER'S NOTEBOOK

1. Draw both bridges. Mark where each one failed with an arrow.
2. Make a table: bridge, sticks used, mass (g), load held (g), efficiency.
3. Write a short report as if you were Bollman telling the railroad why your truss is a good design.

From history. Bollman later started his own iron bridge company in Baltimore. The bridge at Savage was saved and restored by people who valued its history, and in 1966 it was named a National Historic Landmark. Engineers still visit it to see how bridges were built before steel.

COMMON MISTAKES

- Testing before the glue has fully dried. Then the glue fails, not the design.
- Comparing only the load held. A heavier bridge should hold more; efficiency is the fair comparison.
- Dropping weight suddenly onto the bridge. Add it gently.

Make it a game · Bollman's Bridge Quiz. Be the teacher. Explain to your parent why a truss can carry more than a plain beam of the same material, and how Wendel Bollman designed iron bridges for the railroad. Your parent sneaks in one wrong fact, such as a joint being the long gap. Catch it and score a point. Switch, then repeat.

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

A load test is only useful if the numbers are honest. Record what really happened, even when your bridge breaks early.

2.3 THE FORTH BRIDGE: GIANT CANTILEVERS

OBJECTIVES

- Explain what a cantilever is and how a counterweight keeps it from tipping.
- Tell how John Fowler and Benjamin Baker designed the Forth Bridge to be strong beyond doubt.
- Build a cantilever and measure how far it can reach with different counterweights.

Warm-up. Slide a ruler over the edge of a table a little at a time until it tips. How far out did it go? Now hold the end on the table down with a book and slide it out again. How far can it go now? What did the book do?

WATCH

Forth Crossings - Forth Bridge

Institution of Civil Engineers • 4:54

https://www.youtube.com/watch?v=_IAfoP-b7No

WHEN TO WATCH

After the story. Look for the old photograph of the human cantilever and the bridge being built out from its towers.

KEY TERMS

cantilever

An arm or beam held at only one end that sticks out over empty space.

counterweight

A weight on one side that balances a load on the other side.

pier

A strong support that holds up a bridge, often standing in the water.

suspended span

A shorter section of bridge that hangs between the tips of two cantilevers.

rivet

A metal pin, put in red-hot and hammered flat, that holds steel plates together.

CORE IDEAS

The story. The Firth of Forth is a wide, deep arm of the sea in Scotland, and the railway needed to cross it. In 1879 another long railway bridge in Scotland, over the nearby Firth of Tay, fell in a storm while a train was crossing, and many people were lost. After that, people were afraid of big railway bridges. The engineers John Fowler and Benjamin Baker were given the job of designing a bridge over the Forth that no one would ever doubt. Work began in 1883, and at the busiest time more than 4,000 workers were building it. It opened on March 4, 1890, and it still carries trains every day.

How they figured it out. The inquiry into the Tay Bridge found that its designer had not allowed enough for the force of the wind. Baker did not want to guess. He set up wind gauges on an island in the middle of the Forth and measured the real wind for years. Then he designed the bridge to stand winds far stronger than any storm was likely to bring. To help the public understand the design, he arranged a famous living model: two men sat on chairs with their arms out, holding sticks braced against the chairs, and a third man sat on a board hung between their hands, with bricks at the far ends as counterweights.

The physics. A **cantilever** is an arm held at only one end, like a diving board or your arm held straight out. A load on the tip of a cantilever tries to tip the whole thing over. To stop it, engineers either fix the near end firmly or balance it with a **counterweight**, just as the book held your ruler down. The Forth Bridge has three great towers standing on **piers**. From each tower, two huge steel arms reach out in opposite directions, balancing each other like a seesaw. Between the tips of the arms hang two shorter **suspended spans**. In the arms, the giant tubes underneath are pushed (compression) and the lighter lattice girders on top are pulled (tension).

The engineering. A cantilever bridge can be built without any support underneath the middle. Workers start at a tower and build outward, piece by piece, over the water, and each new piece is held by the part already built. That is why cantilevers were chosen for deep water where no temporary supports could be set up. The Forth Bridge used about 54,000 tons of steel and about six and a half million **rivets**. Its two main spans, each about 1,710 feet, were the longest in the world when it opened. Its steel must be painted to keep away rust, and people in Britain still say a never-ending job is “like painting the Forth Bridge.”

PICTURE STUDY



The Fife Cantilever Under Construction, Unknown photographer, about 1888 · Photograph · Rijksmuseum, Amsterdam

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

This photograph was taken while the bridge was being built. The arms of the cantilever stretch out over the water from the tower, and the span that will join them to the next tower has not yet been hung.

Look closely

- Find the tower in the middle. How many arms reach out from it?
- Find the great curved tubes along the bottom of the arms. Are they pushed or pulled?
- Look at the ends of the arms. They are holding themselves up with nothing underneath. What keeps them from falling?
- Look for tiny cranes or workers to help you see how big the bridge is.

Talk about it

1. Why do you think the arms on both sides of the tower were built out at the same time?
2. Why would a cantilever be a good choice over very deep water?
3. How does this picture match Baker's living model with the men on chairs?

Safety first. Keep counterweights low and centered, and keep toes out from under any arm that might tip. Do the human cantilever only with adults, seated low to the ground.

BUILD

How Far Can It Reach? A Cantilever and Counterweight Test

You will build a cardboard cantilever arm, hang a penny load at its tip, and measure how far it can reach out past the table edge before it tips, using different counterweights. Then you will join two cantilevers with a suspended span, like the Forth Bridge.

You will need

- Two strips of stiff corrugated cardboard, each about 8 by 50 centimeters (or two yardsticks)
- A small paper cup with 10 pennies for the load
- Counterweights: a can of soup, a paperback book and a hardcover book (weigh each on a kitchen scale)
- A third shorter strip of cardboard about 20 centimeters long
- Tape, a ruler and engineer's notebook
- For the human cantilever: two sturdy chairs, two broomsticks and a strong towel

Steps

1. Weigh each counterweight and the cup of pennies. Record the masses in grams.
2. Tape the cup to the tip of one cardboard arm. Lay the arm on the table with no counterweight. Slide it out over the edge until it just begins to tip. Measure how far past the edge it reached.
3. **Predict.** How much farther will it reach with each counterweight on the back end?
4. **Test.** Put the lightest counterweight on the very back end of the arm and slide it out again until it begins to tip. Measure. Repeat three times.
5. Repeat with the medium and heaviest counterweights. Change only the counterweight. Record everything and make a bar graph.
6. **Build a Forth Bridge.** Set two tables (or two stacks of books) apart. Make a cantilever on each, reaching toward each other, with counterweights on the

back ends. Hang the short strip between the tips as the suspended span, taped lightly at each end.

7. Add pennies to the middle of the suspended span one at a time. Record how many it held before an arm tipped or the span fell.
8. **Improve.** Change one thing (more counterweight, shorter arms, or a stiffer arm made of two strips) and test again. Did it hold more?

Tips

- Push the counterweight to the very back end of the arm every time. Its position matters as much as its weight.
- Slide the arm slowly so you can see the exact moment it starts to tip.
- If the arm bends a lot before it tips, double it up. A floppy arm is a weak cantilever.

Check your work

- ☐ I can explain what a counterweight does for a cantilever.
- ☐ My graph shows how heavier counterweights let the arm reach farther.
- ☐ I can point to the cantilevers and the suspended span on my model and on the Forth Bridge.

ENGINEER'S NOTEBOOK

1. Draw the Forth Bridge with its three towers, six arms and two suspended spans. Color pushed parts blue and pulled parts red.
2. Make a table and bar graph: counterweight, reach in centimeters.
3. Draw Baker's human cantilever with the men on chairs and label the cantilevers, the counterweights and the suspended span.

From history. In 2015 the Forth Bridge was named a World Heritage Site. Two newer road bridges now stand beside it: a suspension bridge opened in 1964 and a cable-stayed bridge opened in 2017. Standing on the shore, you can see three kinds of bridge from three centuries side by side.

COMMON MISTAKES

- Thinking the tips of a cantilever must be held up from below. They are held by the arm itself and balanced by the other side.

- Moving the counterweight closer to the edge. A counterweight works best far back from the edge.
- Forgetting that a heavier load at the tip needs a heavier or farther-back counterweight.

Make it a game · Seesaw Reach. Lay a ruler or book over the edge of a table and slide it out until it just tips, using small toys as counterweights on the inside end. Predict before each slide how far it will reach. Then say what a cantilever is and what the Forth Bridge's counterweights do. Closest prediction wins the round.

2.4 HANGING FROM CHAINS: TELFORD'S MENAI SUSPENSION BRIDGE

OBJECTIVES

- Trace how a suspension bridge carries a load from the deck to the cables, towers and anchorages.
- Tell how Thomas Telford tested iron and lifted the chains of the Menai Bridge.
- Build a string suspension bridge and measure how the sag of the cable changes the pull in it.

Warm-up. With a partner, hold a piece of string between you, pulled almost straight. Hang a small bag of pennies from the middle. What happens to the string? Now let the string sag more. Is it easier or harder to hold? Talk about why.

WATCH

4. Suspension Bridges

Engineering Models · 7:02

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

WHEN TO WATCH

After the physics paragraph. Pause when the hammock is tightened and predict whether the pull on the rope will go up or down.

Note: From the University of Waterloo's engineering models series. The bridge shown at 6:25 is really a cable-stayed bridge, as the video's own description explains.

KEY TERMS

suspension bridge

A bridge whose deck hangs from cables or chains draped over tall towers.

suspender

A vertical rope or rod that hangs the deck from the main cable.

anchorage

A massive block, set deep in the ground, that holds the ends of the main cables.

sag

How far the middle of a cable hangs down below its ends.

deck

The flat part of a bridge where people and vehicles travel.

CORE IDEAS

The story. Anglesey is an island off the coast of Wales, separated from the mainland by a narrow, swirling strait called the Menai. Travelers and farmers driving cattle had to cross it by ferry, which was slow and sometimes dangerous. The great Scottish engineer Thomas Telford was asked to build a bridge. But the Royal Navy insisted that tall sailing ships must still be able to pass underneath, so the deck had to be about 100 feet above high water, with no supports in the middle of the channel. No arch or beam of the time could do it. Telford chose to hang the bridge from iron chains. It opened on January 30, 1826, with a main span of about 580 feet, the longest in the world at that time.

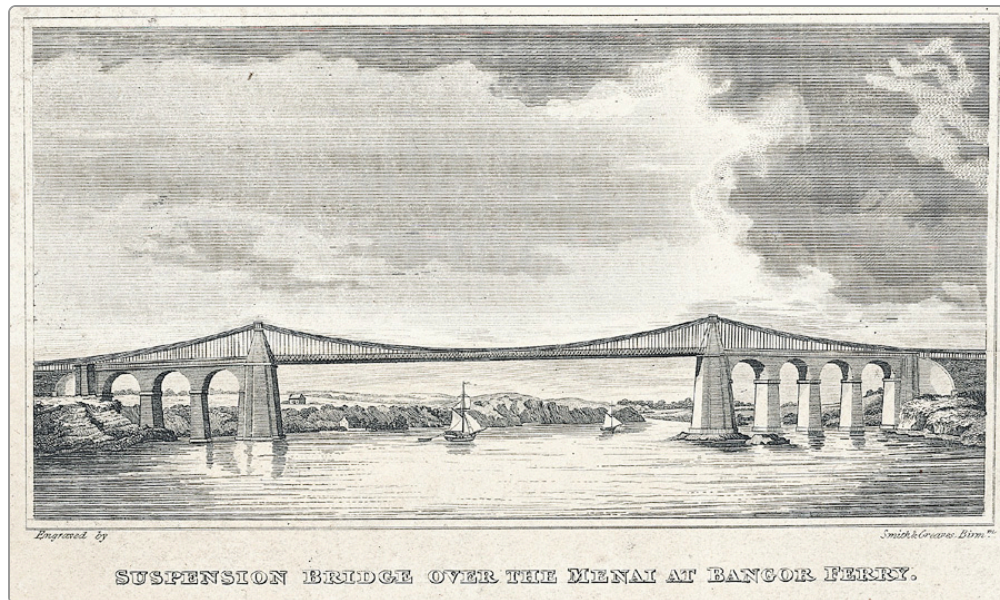
How they figured it out. No one had ever hung so heavy a bridge from iron chains, so Telford tested before he built. He had iron bars pulled in a testing machine until they stretched and broke, to learn how strong the iron really was, and he had every bar for the bridge tested before it was used. The 16 chains were made of iron links, each about 9 feet long, joined by pins. To lift the chains into place, workers floated each one out on a raft, fastened it to a rope hanging from the top of a tower, and pulled it up with large winches turned by teams of men. Crowds watched, and when the first chain was raised in April 1825, workers walked across it.

The physics. In a suspension bridge, the **deck** hangs from vertical **suspenders**. The suspenders hang from the main cables or chains, which are in tension. The cables pass over the tops of the towers and pull down on them, so the towers are in compression and carry the load down to the ground. The ends of the cables are held by **anchorages** buried in rock. The amount a cable **sags** matters a great deal. A cable pulled almost straight has to pull with an enormous force to hold up even a small weight in the middle. A cable that sags more pulls with less force. That is why your string was hard to hold when it was nearly straight.

The engineering. Engineers choose the sag carefully. More sag means less pull in the cable, but it also means taller towers. Telford's first deck was light and narrow, and storms made it sway and twist. It was damaged in strong winds and had to be strengthened, and engineers learned that suspension bridges need stiff decks. In the

1930s the old iron chains were replaced with stronger steel ones. Later suspension bridges, like the Brooklyn Bridge and the Golden Gate Bridge, used cables spun from thousands of steel wires instead of chains. The Menai Bridge still carries cars today, nearly two hundred years after it opened.

PICTURE STUDY



The Suspension Bridge over the Menai, Unknown artist, 1800s · Print · Published in Britain in the 1800s
Image: [Wikimedia Commons](#), public domain

Artists loved to draw Telford's bridge, because nothing like it had been seen before. Notice how high it is and how thin the chains look against the sky.

Look closely

- Find the two tall towers. What are they made of?
- Find the curved chains. Where do they go at each end?
- Find the deck. How is it joined to the chains?
- Look for ships. How tall are their masts compared with the bridge?

Talk about it

1. Why did the bridge have to be so high above the water?
2. Which parts of the bridge are pulled, and which are pushed?
3. Why do you think the narrow, light deck was moved around by strong winds?

Safety first. Wear safety glasses during the load test, because a stretched string can snap. Keep the towers steady with books so they cannot fall.

BUILD

A String Suspension Bridge: Sag and Pull

You will build a suspension bridge between two towers made of cereal boxes or stacks of books, with a card-stock deck hanging from string cables. Then you will run a fair test of sag, using a rubber band as a simple force meter to see how hard the cable pulls.

You will need

- Two cereal boxes or tall stacks of books for towers, about 30 centimeters tall, set 40 centimeters apart
- Strong string or thin cord (about 3 meters)
- A strip of card stock about 8 by 50 centimeters for the deck, and short pieces of string for suspenders
- Two heavy books or cans for the anchorages
- A thin rubber band, a paper clip, a ruler and about 50 pennies
- Tape and engineer's notebook

Steps

1. **Plan.** Draw your bridge from the side. Label the towers, main cable, suspenders, deck and anchorages.
2. **Build.** Run one long string over the tops of both towers, letting it hang down in a curve between them. Tie each end of the string to a rubber band, and loop each rubber band around a heavy book far behind each tower (the anchorages). The rubber band will stretch more when the cable pulls harder.
3. Hang the deck from the cable with 5 short suspender strings, each taped to the deck and tied to the cable.
4. **Fair test.** Adjust the cable so it sags 5 centimeters below the tower tops in the middle. Put 20 pennies on the deck. Measure how long one of the anchor rubber bands has stretched.
5. Change only the sag: test at 10 centimeters and at 15 centimeters, with the same 20 pennies. Measure the rubber band each time. Do each test twice.
6. Record your results in a table. Which sag pulled hardest on the anchorage?

7. **Load test.** Choose the sag you think is best. Add pennies one at a time until the deck sags badly or a string slips. Record how many it held.
8. **Improve.** Make one change (more suspenders, a stiffer deck of two card strips, or a second cable on the other side) and test again.

Tips

- Use the same rubber band in every test, and measure it from the same marks.
- Spread the pennies evenly along the deck so the load is the same each time.
- If the towers lean in when you add pennies, the anchorages are too light or too close.

Check your work

- ☐ I can trace a load from the deck to the anchorages and name each part.
- ☐ My data shows whether more sag made the cable pull harder or more gently.
- ☐ I can explain why Telford tested his iron before building.

ENGINEER'S NOTEBOOK

1. Draw a suspension bridge and label deck, suspenders, main cable, tower and anchorage. Draw red arrows for tension and blue arrows for compression.
2. Make a table: sag, rubber-band stretch (trial 1 and 2).
3. Write two sentences comparing a cantilever bridge and a suspension bridge.

From history. Telford was the son of a shepherd and started work as a stonemason. He built more than a thousand miles of roads, many canals and over a thousand bridges, and he became the first president of the Institution of Civil Engineers. A few miles from his bridge, Robert Stephenson later built the Britannia Bridge, which carried trains through giant iron tubes.

COMMON MISTAKES

- Thinking the towers hold up the deck directly. The cables hold the deck; the towers hold up the cables.
- Forgetting the anchorages. Without them, the cables would pull the towers over.
- Thinking a tighter, straighter cable is always stronger. A straighter cable must pull much harder.

Make it a game • Load Path Trace. Draw a quick suspension bridge on paper. Your parent places a toy car on the deck. Trace the load with your finger from deck to suspenders, cables, towers and anchorages, saying each name aloud. Do it in under twenty seconds without a mistake. Then explain what Thomas Telford tested before lifting the Menai chains.

Scripture. “He stretcheth out the north over the empty place, and hangeth the earth upon nothing.” (Job 26:7, KJV)

A suspension bridge seems to hang in the air, but it is held by chains, towers and rock. God holds the whole earth with no chains at all.

UNIT 2

BRIDGES

A bridge carries people safely over a river, a valley or a busy road, and every part of it is being pushed or pulled. In this unit you will learn how engineers arrange those pushes and pulls so that a bridge stays strong without being too heavy. You will start with the truss, a frame made of triangles, and meet three famous truss patterns named after their inventors: the Howe, the Pratt and the Warren. You will build trusses of your own and load-test them with pennies.

Then you will visit two of the great bridges of the 1800s. In Scotland, the Forth Bridge stretched giant steel arms, called cantilevers, out over deep water. In Wales, Thomas Telford hung the Menai Bridge from iron chains high enough for tall ships to sail beneath it. You will build a cantilever and a suspension bridge, measure how they carry their loads, and learn why engineers test, test and test again before anyone crosses.

PREREQUISITES

- Knows the engineering design process and how to run a fair test (Unit 1)
- Can measure in centimeters and record results in a table
- Knows that a force is a push or a pull

MASTERY CHECKLIST

- ☐ I can explain compression and tension and show which parts of a bridge are pushed and which are pulled.
- ☐ I can explain why triangles make a truss rigid and recognize Howe, Pratt and Warren trusses.
- ☐ I can explain how a cantilever bridge balances its arms, using the Forth Bridge as an example.
- ☐ I can trace the load in a suspension bridge from the deck to the cables, towers and anchorages.
- ☐ I can build a bridge, load-test it fairly, record the results and improve it.

OPTIONAL KITS FOR THIS UNIT

- **LEGO Technic:** Ages vary by set. Beams, pins and connectors make it easy to build Howe, Pratt and Warren trusses and see how the diagonals stiffen a frame. Fits Lessons 2.1 and 2.2.
- **K'NEX building sets:** Ages vary by set. Rods and connectors make it easy to build truss, cantilever and suspension bridges side by side. Fits Lessons 2.1–2.4.

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

LESSONS IN THIS UNIT

2.1 Why Triangles? The Howe, Pratt and Warren Trusses

2 sessions of 45 minutes

2.2 Truss Against Beam: Wendel Bollman and a Craft-Stick Load Test

2 sessions of 45 minutes

2.3 The Forth Bridge: Giant Cantilevers

2 sessions of 45 minutes

2.4 Hanging from Chains: Telford's Menai Suspension Bridge

2 sessions of 45 minutes

UNIT 2 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

What is the difference between compression and tension? Give an example of each from a bridge.

2. **5 pts**

Why are trusses made of triangles instead of squares?

3. **5 pts**

William Howe used both wood and iron in his truss. Which parts were iron, and why?

4. (5 pts)

Predict: you build a flat beam and a truss from the same 24 craft sticks. Which will probably hold more, and why?

5. (5 pts)

A model bridge weighs 50 grams and holds 2,500 grams. What is its efficiency?

6. (5 pts)

What is a cantilever? What does a counterweight do?

7. (5 pts)

Why did Benjamin Baker measure the wind for years before the Forth Bridge was built?

8. (5 pts)

Trace the load in a suspension bridge from a car on the deck to the ground.

9. (5 pts)

Predict: on your string bridge, you pull the cable almost straight with very little sag. Will the anchorage rubber bands stretch more or less than with a big sag? Why?

10. (5 pts)

Name one thing Thomas Telford did to be sure the Menai Bridge would be safe, and one thing engineers learned from it afterward.

ANSWER KEY

1. Compression is a squeezing or pushing force; tension is a pulling or stretching force. Examples: a bridge tower or the top chord of a truss is in compression; a suspension cable, a suspender or the bottom chord of a truss is in tension.
2. A triangle cannot change shape unless one of its sides changes length, so it is rigid. A square can lean over into a diamond without any side changing length.
3. The vertical rods were iron because they were in tension, and iron is good at being pulled. Their nuts could also be tightened if the wood shrank. The wood was used where it was pushed.
4. The truss. It moves the material to the top and bottom, far apart, and connects them with triangles, so it is much stiffer than a flat beam that only bends.
5. $2,500 \div 50 = 50$. It holds 50 times its own weight.
6. A cantilever is an arm held at only one end that sticks out over empty space. A counterweight balances the load on the other side so the cantilever does not tip over.
7. The Tay Bridge had fallen in a storm because its designer did not allow enough for the wind. Baker wanted real measurements so the Forth Bridge would be strong beyond doubt.
8. Deck → suspenders (tension) → main cables or chains (tension) → over the towers (compression) down to the foundations; the cable ends are held by the anchorages.
9. More. A nearly straight cable must pull much harder to hold up the same load; more sag lets the cable pull more gently.
10. He tested the iron bars (and every bar for the bridge) before using them. Afterward, engineers learned that a light, narrow deck can be moved and damaged by wind, so suspension bridges need stiff decks.

PORTFOLIO PIECE: A LOAD-TESTED TRUSS BRIDGE

Design, build and test a craft-stick truss bridge that spans 30 centimeters, using no more than 60 sticks. Choose a Howe, Pratt or Warren pattern (or invent your own) and draw it full size first, marking the members you expect to be pushed and pulled. Weigh it, load-test it until it fails, and calculate its efficiency. Then write a one-page engineer's report with your drawing, your data, a photograph of the failure, and what you would change next time.

LOOK FOR	WHAT IT MEANS
Plan	A full-size drawing names the truss pattern and marks pushed and pulled members.
Craftsmanship	The two sides match, the joints overlap and are well glued, and the bridge is braced.
Fair test and data	The bridge was weighed, the load was added gently at the middle, and the load and efficiency were recorded honestly.
Failure explained	The report shows where the bridge failed and explains why, using the words compression, tension or joint.
Improvement	A sensible change is suggested (or built and tested) based on how the bridge failed.

UNIT 3

BUILDINGS

Every building is a choice of materials. Wood, stone, brick, concrete and steel each have their own strengths and weaknesses, and a good builder uses each one where it works best. In this unit you will test materials yourself and learn how a French gardener named Joseph Monier made concrete much stronger by hiding iron inside it. Then you will study two of the greatest domes ever built: the Pantheon in Rome, made of Roman concrete almost nineteen hundred years ago, and Filippo Brunelleschi's brick dome in Florence, built without any wooden frame to hold it up.

Last, you will learn why some buildings stand through earthquakes and others do not, and you will build a shake table to test your own towers. Through the whole unit you will see the same two forces from Unit 2, compression and tension, deciding what stands and what falls. "Through wisdom is an house builded" (Proverbs 24:3), and part of that wisdom is knowing your materials.

PREREQUISITES

- Knows compression and tension and why triangles make frames rigid (Unit 2)
- Can run a fair test with three trials and record results in a table
- Can measure in centimeters and weigh things on a kitchen scale

MASTERY CHECKLIST

- ☐ I can describe the strengths and weaknesses of wood, stone, brick, concrete and steel.
- ☐ I can explain why concrete is strong in compression but weak in tension, and how steel reinforcement helps.
- ☐ I can explain how the Pantheon's dome was made lighter toward the top and why that helps it stand.
- ☐ I can tell how Brunelleschi built the Florence dome without a wooden frame and how its chains keep it from spreading.
- ☐ I can build a shake table and test what helps a tower survive shaking.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** Ages 3 and up. Identical small wooden planks with no glue or connectors, good for building arches, domes and towers and testing them on the shake table in Lesson 3.4.
- **Thames & Kosmos engineering kits:** Ages 8 and up. Their structural engineering sets build towers, domes and bridges with explanations of the forces; good extras for Lessons 3.2–3.4.

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

LESSONS IN THIS UNIT

3.1 Wood, Stone, Brick, Concrete and Steel: Monier's Flowerpots

2 sessions of 45 minutes

3.2 Roman Concrete and the Pantheon Dome

2 sessions of 45 minutes

3.3 Brunelleschi's Dome in Florence

2 sessions of 45 minutes

3.4 Earthquakes and a Shake Table

2 sessions of 45 minutes

UNIT 3 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

Name one strength and one weakness of each: wood, stone, concrete, steel.

2. **5 pts**

What did Joseph Monier do to make his concrete flowerpots stronger?

3. **5 pts**

Predict: a concrete beam sags under a load. Where will it crack first, and where should the steel go?

4. (5 pts)

Give two ways the Romans made the Pantheon's dome lighter near the top.

5. (5 pts)

A dome pushes down. What other way does it push at its base?

6. (5 pts)

What is centering, and why did Brunelleschi not use it?

7. (5 pts)

How did Brunelleschi's chains of stone, iron and wood help his dome?

8. (5 pts)

What did engineers learn from the buildings that stood and fell in the 1906 San Francisco earthquake?

9. (5 pts)

Predict: you test two straw towers on your shake table. One has a heavy weight on top; the other has the same weight on the bottom floor. Which will survive the bigger shake, and why?

10. (5 pts)

Name three things engineers do to help buildings survive earthquakes.

ANSWER KEY

1. Wood: light and easy to cut / can rot or burn. Stone: very strong when squeezed and long-lasting / heavy and weak when pulled. Concrete: strong in compression and can be poured into any shape / weak and brittle in tension. Steel: strong both pushed and pulled / rusts and costs more. Other reasonable answers accepted.
2. He put an iron wire mesh inside the concrete, making reinforced concrete. The iron carries the pulling (tension) that concrete is weak at.
3. It will crack first at the bottom, which is stretched (tension). The steel should go near the bottom.
4. Any two: lighter aggregate higher up, ending with pumice; a thinner shell at the top; coffer cut into the inside; leaving out the top entirely as the oculus.
5. Outward. The base tends to spread and the lower rings are stretched (hoop tension).
6. Centering is a temporary wooden frame that holds up an arch or dome while it is built. The Florence dome was too big: there was not enough timber, and such a frame might have collapsed under its own weight. He made the dome support itself as it rose.
7. They wrapped around the dome like the hoops of a barrel, holding the base together in tension so it would not spread and crack. That let the brick carry only compression.
8. Plain brick walls without steel often fell, while steel-framed buildings bent and held; buildings on soft, filled ground shook harder than those on rock.
9. The one with the weight on the bottom. Weight high up makes the top lag and sway more, so the tower tips or breaks sooner.
10. Any three: diagonal bracing; tying floors, walls and foundations together; using steel or reinforced concrete that bends before it breaks; base isolation bearings; swinging weights (dampers) near the top; wide bases; testing on shake tables.

PORTFOLIO PIECE: THE SHAKE-TABLE TOWER

Design and build a tower at least 40 centimeters tall from straws, craft sticks or KEVA-style planks that carries a weight of at least 100 grams on its top floor. Test it on your shake table, find its weakest point, improve it, and test it again. Make a poster or two notebook pages with your labeled drawing, your test data before and after the improvement, and a paragraph explaining which materials and shapes you chose and why, using the words compression, tension and bracing.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the tower's materials, base, bracing and the position of the weight.
Craftsmanship	The tower is straight, its joints are firm, and it meets the height and weight rules.
Fair test and data	Shakes were measured, three trials were done for each version, and results were recorded honestly.
Improvement	The tower was changed in one clear way after the first test, and the change was measured.
Explanation	The student explains the choices aloud using compression, tension, bracing and sway.

3.1 WOOD, STONE, BRICK, CONCRETE AND STEEL: MONIER’S FLOWERPOTS

OBJECTIVES

- Describe the strengths and weaknesses of wood, stone, brick, concrete and steel.
- Explain why concrete is strong when squeezed but weak when pulled, and how Joseph Monier made it stronger with iron mesh.
- Make small plaster beams with and without reinforcement and load-test them fairly.

Warm-up. Gather five small things made of different materials: a wooden pencil, a stone or pebble, a piece of chalk, a metal spoon and a plastic straw. Try (gently) to squeeze, bend and pull each one. Which ones bend? Which ones snap? Which ones do nothing at all? Sort them into “good at being squeezed” and “good at being pulled.”

WATCH

Why Concrete Needs Reinforcement

Practical Engineering • 8:11

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

WHEN TO WATCH

After the physics paragraph. Before each concrete test, predict whether it will crack, and where.

Note: Grady Hillhouse, a civil engineer, breaks concrete samples in a hydraulic press. The words are sometimes advanced; pause and explain “tension” and “compression” as they come up.

KEY TERMS

material

What something is made of, such as wood, stone, brick, concrete or steel.

concrete

A man-made stone made by mixing cement, sand, gravel and water. It hardens as it dries.

mortar

A paste that hardens to hold bricks or stones together.

reinforced concrete

Concrete with steel bars or mesh inside it, so it is strong when pulled as well as when squeezed.

brittle

Breaking suddenly with a snap instead of bending first, like chalk or glass.

CORE IDEAS

The story. Joseph Monier was a gardener in Paris in the 1860s. He grew orange trees and other plants in large pots and tubs, but clay pots cracked and wooden tubs rotted. He tried making pots from concrete, but they were heavy and they cracked too. So he tried something new: he made a basket of iron wire mesh and spread the concrete over it and through it, so the iron was hidden inside. His new pots were thinner, lighter and much stronger. In 1867 he received a patent for them. He went on to patent reinforced concrete pipes, water tanks, beams and even a small bridge. A gardener had helped invent one of the most important building materials in the world.

How they figured it out. Monier found his answer by trying and testing, not by calculation. Later engineers in Germany and France bought his patents and asked why it worked. They tested concrete beams with and without iron and found that plain concrete beams cracked across the bottom, where they were stretched, while beams with iron near the bottom held many times more. They also learned that concrete and iron (and later steel) grow and shrink by about the same amount when they get hot and cold, so they stay stuck together. By the early 1900s, engineers had worked out how to calculate exactly how much steel a beam needed.

The physics. Every **material** has its own strengths. **Stone, brick and concrete** are very strong in compression: you can stack an enormous weight on them. But they are weak in tension and **brittle**: when they are stretched, they crack suddenly. **Wood** is fairly strong both ways along its grain, light and easy to cut, but it can rot, burn and be eaten by insects. **Steel** is strong in both compression and tension and bends before it breaks, but it rusts and is costly. When a beam bends, its bottom is

stretched. So concrete beams crack at the bottom first, and that is exactly where engineers put the steel.

The engineering. Builders have always chosen materials for the job. The Bible tells of builders who “had brick for stone, and slime had they for mortar.” After the Great Fire of London in 1666, the city was rebuilt in brick and stone instead of wood so a fire could not spread so easily. Today, **reinforced concrete** is the most used building material on earth: foundations, floors, bridges, dams and tall buildings all use it. Engineers choose concrete for strength in compression, steel for tension, wood for light houses, and brick or stone for walls that will last for centuries.

PICTURE STUDY



The Tower of Babel, Pieter Bruegel the Elder, 1563 · Oil on panel · Kunsthistorisches Museum, Vienna

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

Bruegel painted the tower from Genesis 11 as if it were being built in his own time, with real tools and real materials. He showed hundreds of tiny builders at work. Engineers love this painting because it is full of building methods, and because it reminds us that a proud builder can spoil his work.

Look closely

- Find stone blocks being cut and lifted. Where are the stonecutters working?
- Find places where the tower is made of red brick and places where it is faced with pale stone.
- Find the cranes and the great treadwheels that men walk inside to lift heavy loads.
- Look at the arches in every level. Arches carry their load in compression. Why are they a good shape for stone and brick?

Talk about it

1. Why would stone and brick be good materials for the bottom of a very tall tower?
2. Some of the lower levels are already crumbling while the top is still being built. What might the builders have done wrong?

3. What does this story teach about building with wisdom instead of boasting?

Safety first. Plaster of Paris gets warm as it sets; mix it with an adult, do not put hands in it for long, and never pour leftover plaster down a drain. Wear safety glasses when breaking beams.

BUILD

Plaster Beams: Plain or Reinforced?

You will cast small beams of plaster of Paris (a stand-in for concrete). Some will be plain, some will have reinforcement near the bottom, and some will have reinforcement near the top. Then you will load-test them to see where reinforcement helps most.

You will need

- Plaster of Paris (a small box from a craft store) and water
- A long, narrow mold: a cardboard box cut into 6 channels about 3 centimeters wide, 3 centimeters deep and 20 centimeters long, lined with plastic wrap
- Reinforcement: pieces of wire mesh, straightened paper clips or strips of window screen
- A disposable cup and stick for mixing
- Two books set 15 centimeters apart, a small cup with a string handle, and pennies or sand
- A kitchen scale, ruler and safety glasses

Steps

1. **Plan.** Label your 6 mold channels: 2 plain, 2 with reinforcement near the bottom, 2 with reinforcement near the top.
2. **Cast.** With an adult, mix the plaster as the box says. Pour 1 centimeter into each channel. For the “bottom” beams, lay the reinforcement in now. Pour in the rest. For the “top” beams, press the reinforcement in just under the top surface. Smooth each beam.
3. Let the beams set and dry for at least a day. Mark which side is the bottom.
4. **Predict.** Which beams will hold the most? Why?
5. **Test.** Lay a beam across the gap with its marked bottom down. Hang the cup from the middle with a loop of string. Add pennies or sand slowly until the beam cracks. Weigh the cup and load. Note where the crack started.
6. Test all six beams the same way. Record each load and where it cracked.

7. Make a bar graph comparing the average for plain, bottom-reinforced and top-reinforced beams.
8. **Improve.** Look closely at the reinforced beams after they cracked. Did the plaster crack but the beam still hang together? Cast one more beam with a change you think will help (more mesh, or mesh closer to the bottom) and test it.

Tips

- Make all the beams from one batch of plaster so they are as alike as possible.
- Add the load slowly and gently. A sudden drop breaks a beam early.
- Plaster beams are brittle and will snap with little warning. That is exactly what plain concrete does.

Check your work

- ☐ I can explain why a plain plaster or concrete beam cracks at the bottom first.
- ☐ My data shows where reinforcement helped most.
- ☐ I can name one strength and one weakness of wood, stone, brick, concrete and steel.

ENGINEER'S NOTEBOOK

1. Draw a beam bending under a load. Label the top “squeezed” and the bottom “stretched,” and draw where the steel should go.
2. Make a table of your six beams: type, load held, where it cracked.
3. Make a chart of five materials with one strength and one weakness for each.

From history. Around the same time as Monier, a Frenchman named François Hennebique developed a system of reinforced concrete beams, columns and floors joined into one piece, and his company built thousands of buildings in the 1890s and 1900s. In America, Ernest Ransome patented twisted steel bars in 1884; the twist helps the concrete grip the steel, and the bumpy bars used today grew from that idea.

COMMON MISTAKES

- Thinking concrete is strong in every way. It is strong when squeezed but weak and brittle when pulled.

- Putting the reinforcement in the middle or on top of a beam. In a beam that sags, the bottom is stretched, so the steel goes near the bottom.
- Testing beams that are not fully dry. Wet plaster is weaker.

Make it a game · Strong When Squeezed. Play two truths and a tall tale about wood, stone, brick, concrete and steel. Tell your parent three facts, one of them false, like "concrete is strong when pulled." They spot the tall tale. Include one fact about Joseph Monier and his iron mesh. Switch roles and try to fool each other twice.

Scripture. “And they said one to another, Go to, let us make brick, and burn them thoroughly. And they had brick for stone, and slime had they for mortar.” (Genesis 11:3, KJV)

This is one of the oldest records of building materials: baked brick instead of stone, and tar for mortar. The builders were skilled, but they built to make a name for themselves, and God scattered them. Good engineering serves others.

3.2 ROMAN CONCRETE AND THE PANTHEON DOME

OBJECTIVES

- Describe the Pantheon and explain why its concrete dome has stood for nearly nineteen hundred years.
- Explain how a dome carries its weight in compression and why making the top lighter helps.
- Build paper domes that use the same amount of material in different ways, and load-test them fairly.

Warm-up. Hold an egg (or half an empty eggshell, washed) in the palm of your hand and wrap your fingers around it. Squeeze gently and evenly from all sides. (Do this over the sink.) It is very hard to break this way. Now tap it on the edge of a bowl. Why is the curved shape so strong one way and so weak the other?

WATCH

The Largest Concrete Dome Ever Built

Science Channel • 2:57

<https://www.youtube.com/watch?v=NZo1otljfl4>

WHEN TO WATCH

After the story. Watch how the dome gets thinner toward the top, and listen for what the Romans mixed into the concrete up high.

KEY TERMS

dome

A curved roof shaped like half of a ball, which is like an arch turned all the way around in a circle.

coffer

A sunken square panel in a ceiling, used to make it lighter and more beautiful.

oculus

A round opening at the very top of a dome, Latin for “eye.”

aggregate

The stones, gravel or broken brick mixed into concrete.

pumice

A light, bubbly volcanic stone that can even float on water.

CORE IDEAS

The story. The Pantheon in Rome was built under the Roman emperor Hadrian and finished around the year 125. Its round hall is covered by a dome 142 feet across, and the floor is exactly as far below the top as the dome is wide, so a giant ball would fit perfectly inside. In the middle of the dome is a round opening about 27 feet wide, the **oculus**, which is open to the sky and lets in the only light. In the year 609 it became a church, and because it was used and cared for, it was never torn down. It is still the largest dome in the world made of concrete without any steel inside.

How they figured it out. The Romans did not have engineering formulas, but they had long experience with arches and vaults, and they had a wonderful concrete. They mixed lime with a volcanic ash from near the town of Pozzuoli, which made concrete that hardened even under water. For the Pantheon they were clever about weight. Near the bottom of the dome they used heavy **aggregate** of broken stone and brick, and higher up they switched to lighter and lighter stone, until near the top they used light, bubbly **pumice**. They made the dome thick at the bottom, about 21 feet, and thin at the top, about 4 feet. They cut 140 sunken panels called **coffers** into the inside, which removed more weight. And at the very top, they left out the heaviest middle part entirely, making the oculus.

The physics. A **dome** is like an arch spun around in a circle. Its weight presses down and outward through the curved shell, keeping the concrete squeezed together in compression, which is what concrete is good at. But a dome also pushes outward at its base, like a person leaning on a wall, and near the bottom the outer rings are stretched. That is why the Pantheon's dome is thickest at the bottom and why its outer wall has heavy rings of concrete stepped around the base, pressing in. Making the top lighter means less weight pushing down and out on the bottom, so the whole dome is safer.

The engineering. Roman concrete has lasted far longer than many modern buildings. In 2023, scientists at the Massachusetts Institute of Technology found small white lumps of lime in Roman concrete. When water seeps into a tiny crack, the lime can dissolve and harden again, filling the crack. Engineers today study

Roman concrete to make modern concrete last longer. They also still use the Pantheon's ideas: shell roofs that are thin and curved, lightweight aggregate where weight matters, and openings that remove weight where it is not needed.

PICTURE STUDY



View of the Pantheon, Giovanni Battista Piranesi, 1761 · Etching · Metropolitan Museum of Art, New York

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

Piranesi was an Italian artist who spent his whole career drawing the ruins and buildings of ancient Rome. His etchings were so careful that architects used them to study Roman building.

Look closely

- Find the porch with its tall columns and triangular roof.
- Find the dome behind it. Is it tall and pointed or low and rounded?
- Look for the rings or steps around the bottom of the dome. Why might these heavy rings be there?
- Find the small people in the square. How do they help you see how big the building is?

Talk about it

1. Why might the builders have made the dome low and wide instead of tall and pointed?
2. The dome's outside looks plain, but the inside has 140 coffers. Why would coffers help the dome stand?
3. Why do you think this building has lasted when so many other Roman buildings fell?

Safety first. Use a low-temperature glue gun or white glue with an adult. Keep raw eggs over the sink, and wash hands after handling eggshells.

BUILD

Thick at the Bottom: A Paper-Dome Load Test

You will make three papier-mâché domes over a bowl, each with the same total number of paper strips. One will be the same thickness all over, one will be thick at the top and thin at the bottom, and one will be thick at the bottom and thin at the top, like the Pantheon. Then you will load-test them.

You will need

- A small round bowl to use as a mold, covered with plastic wrap
- Newspaper strips about 2 centimeters wide, and white glue thinned with a little water
- A ruler, a kitchen scale and a small flat piece of cardboard
- Pennies, or a cup you can fill with sand
- Engineer's notebook

Steps

1. **Plan.** Count out 60 strips for each dome. Decide how you will place them: Dome A, the same thickness everywhere; Dome B, extra strips near the top; Dome C, extra strips in rings near the bottom and fewer near the top.
2. **Build.** Lay glued strips over the upside-down bowl to make Dome A, using all 60. Let it dry, pop it off, and trim the edge level with scissors. Make Domes B and C the same way. Leave a small hole at the top of Dome C if you like, as an oculus.
3. When all three are dry, weigh each one and record its mass.
4. **Predict.** Which dome will hold the most? Why?
5. **Test.** Set a dome on the table, rim down. Lay the cardboard on top and add pennies (or sand in a cup) a little at a time until the dome dents or cracks. Record the load and where it failed.
6. Test all three the same way and make a bar graph.
7. **Improve.** Make one more dome with your best idea, still using 60 strips, and test it. Did it beat the others?

Tips

- Smooth out every strip so there are no bubbles. Bubbles make weak spots.
- Trim each rim flat. A wobbly rim puts all the load on one spot.
- If your domes hold more pennies than you have, put a cup on the cardboard and fill it with sand, then weigh the sand.

Check your work

- ☐ I can explain why a dome is strong when it is pressed evenly from above.
- ☐ I can explain why the Romans made the Pantheon's dome lighter at the top.
- ☐ My graph compares my three domes fairly.

ENGINEER'S NOTEBOOK

1. Draw a cut-in-half view of the Pantheon. Label the dome, the oculus, the coffers and the thick bottom rings.
2. Make a table: dome, mass, load held, where it failed.
3. Write a short letter as a Roman builder explaining to a new worker why we use pumice near the top.

From history. The Pantheon's bronze doors and its great dome inspired many later builders. Brunelleschi studied it before building the dome in Florence, and Thomas Jefferson modeled the Rotunda at the University of Virginia on it. Rain falls through the oculus, and the marble floor is gently sloped with small drain holes to carry the water away.

COMMON MISTAKES

- Thinking the oculus makes the dome weaker. Leaving out the top removes weight where it is least needed.
- Thinking a dome only pushes down. It also pushes outward at its base.
- Using more paper on one dome than another. Then it is not a fair test.

Make it a game • Pantheon Press Test. Stand in a ring shape with your parent and imagine a dome pressing down and inward. Take turns naming a Pantheon word in sixty seconds: oculus, coffer, aggregate, pumice, dome. Each used correctly with its meaning earns a point. Finish by explaining why Roman builders made the top of the dome lighter than the bottom.

3.3 BRUNELLESCHI'S DOME IN FLORENCE

OBJECTIVES

- Tell how Filippo Brunelleschi built the dome of Florence Cathedral without a wooden frame.
- Explain why a dome spreads outward at its base and how chains or rings stop it.
- Build a model dome of cardboard ribs and measure how much a tension ring reduces spreading.

Warm-up. Stand a few books upright in a circle, leaning in so their tops touch. Press down gently on the top. Which way do the bottoms slide? Now wrap a rubber band or string around the bottoms and press again. What changed?

WATCH

How Was the World's Biggest Dome Built? - Florence Cathedral

Manuel Bravo · 12:49

<https://www.youtube.com/watch?v=QD3fJphus-o>

WHEN TO WATCH

After the story. Watch the first 7 minutes in Session 1 and the rest before the build. Look for the herringbone bricks and the stairs between the two shells.

Note: A clear, calm video filmed in Florence and inside the dome itself. It is longer than most; it can be split across both sessions.

KEY TERMS

centering

A temporary wooden frame that holds up an arch or dome while it is being built.

hoop tension

The pull around the base of a dome, caused by the dome pushing outward.

herringbone

A zigzag pattern of bricks, some laid upright, that locks each new ring of brick in place.

rib

A curved beam running up the corner of a dome from the base to the top.

hoist

A machine for lifting heavy loads.

CORE IDEAS

The story. For more than a hundred years, the great cathedral of Florence, Italy, had a huge octagon-shaped hole where its dome was supposed to be. The opening was about 140 feet across, too wide for anyone to know how to cover. In 1418 the city held a contest. Filippo Brunelleschi, a goldsmith and clockmaker who had studied the ancient buildings of Rome, won with a plan that seemed impossible: he would build the dome without any wooden frame to hold it up while it was being built. Work began in 1420, and the dome was finished in 1436. It is still the largest brick dome in the world.

How they figured it out. Normally an arch or dome is built over a wooden frame called **centering**, which holds the bricks up until the top is closed. But there were not enough tall trees in Tuscany to build centering that big, and it might have collapsed under its own weight. Brunelleschi made the dome hold itself up as it grew. He laid some bricks in a **herringbone** pattern, standing upright every so often, so that each new ring was locked by the ring below. He built two shells, a thick inner one and a thinner outer one, joined by **ribs**, which made the dome strong but lighter. He hid great rings of sandstone beams, joined with iron, and one ring of chestnut wood inside the walls to hold the base together. To lift about four million bricks and huge blocks of stone, he invented an ox-powered **hoist** with a gear that could reverse, so the oxen never had to turn around.

The physics. As you saw with the books, a dome pushes outward at its base as well as down. That outward push stretches the lower part of the dome around its circle, a pull called **hoop tension**. Brick and stone are weak in tension, so a dome left alone tends to crack and spread at the bottom. Brunelleschi's rings of stone, iron and wood worked like the hoops on a wooden barrel. They held the base together in tension so that the brick only had to carry compression, which brick is good at. The pointed shape of the dome also helped, because a pointed dome pushes outward less than a round one.

The engineering. Brunelleschi had to invent his tools, his methods and even his machines as he went, and he had to keep the workers safe high above the floor. He arranged for food and water to be brought up so workers did not have to climb down

at midday. Engineers still study his dome with modern instruments. Cracks have appeared over the centuries, and sensors now measure them carefully so that the dome can be protected. Today, steel tension rings hold the bases of many large domes and round roofs, just as Brunelleschi's chains have done for nearly six hundred years.

PICTURE STUDY



The Cathedral of Florence from the Palazzo Vecchio, Detroit Publishing Company, about 1890–1900 · Photochrom print · Library of Congress, Prints and Photographs Division

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

A photochrom is an old photograph that was carefully colored by hand-made printing plates. This one looks across the rooftops of Florence to Brunelleschi's dome, still the tallest thing in the city.

Look closely

- Find the eight white ribs that run up the corners of the dome.
- Find the small tower on the very top, the lantern. Its weight presses down and helps lock the ribs together.
- Compare the size of the dome with the houses around it.
- Look at the shape of the dome. Is it round like the Pantheon or more pointed?

Talk about it

1. Why do you think the dome has eight sides instead of being perfectly round?
2. Where would the dome push outward the most? Where did Brunelleschi put his chains?
3. How do you think workers got four million bricks up to the top?

Safety first. An adult cuts the cardboard with a craft knife. Keep fingers clear when pressing down on the model.

BUILD

Keep It from Spreading: A Rib Dome and a Tension Ring

You will build an eight-rib dome from strips of card, press down on its top with a measured load, and measure how far its base spreads outward. Then you will add a string “chain” around the base and test again.

You will need

- Eight strips of thin cardboard (a cereal box works), each about 2 by 30 centimeters
- A small paper cup (for the lantern) and tape
- A large sheet of paper with an octagon drawn on it, each side about 8 centimeters
- String and a ruler
- Pennies for the load, a small flat piece of cardboard
- Engineer’s notebook

Steps

1. **Build.** Bend each strip into a gentle curve. Tape the top ends of all eight strips to the bottom of the upside-down paper cup so they spread out like the ribs of an umbrella. Stand the dome on the paper so each rib foot sits on one corner of the octagon. Mark each foot’s starting place.
2. **Predict.** When you load the top, which way will the feet move?
3. **Test without a ring.** Put the flat cardboard on the lantern and add 20 pennies. Measure how far each foot slid outward from its mark. Add the eight numbers together for the total spread. Do three trials, resetting the feet each time.
4. **Add a tension ring.** Tie a string around all eight feet, snug but not tight, about 1 centimeter above the paper.
5. **Test with a ring.** Repeat the same three trials with 20 pennies. Record the total spread.
6. Compare the averages. How much did the ring help?

7. **Improve.** Add a second string ring halfway up the ribs, or cross-strips between the ribs like Brunelleschi's shells. Find out how many pennies the dome can hold before it collapses, with your best design.

Tips

- Use a smooth paper base so the feet can slide; that makes the spreading easy to see.
- Make all eight ribs the same length and curve so the load is shared.
- Measure each foot from the outside edge of its mark every time.

Check your work

- ☐ I can explain why a dome spreads at its base.
- ☐ My data shows how much the tension ring reduced spreading.
- ☐ I can tell two ways Brunelleschi built his dome without centering.

ENGINEER'S NOTEBOOK

1. Draw the Florence dome cut in half to show the inner shell, outer shell, the stairs between them, and the chains around the base.
2. Make a table: test, trial 1, trial 2, trial 3, average spread.
3. Draw Brunelleschi's ox hoist and write how its reversing gear helped.

From history. A famous old story says that during the contest Brunelleschi challenged the other builders to stand an egg on its end. When no one could, he tapped the egg gently on the table to flatten its bottom and stood it up. When they objected that they could have done that, he answered that they would also say they could build the dome once they had seen his plan. Whether or not it happened, Brunelleschi kept many of his methods secret, and builders still debate exactly how he did it.

COMMON MISTAKES

- Thinking a dome only pushes straight down. It pushes outward at the base too.
- Pulling the tension ring so tight that it bends the ribs before the test. It should be snug, not tight.
- Thinking a bigger dome needs a thicker shell everywhere. Brunelleschi made his lighter by using two shells.

Make it a game • Hold the Ring. Be Brunelleschi. With a parent, sit in a circle holding hands and lean outward slightly to show a dome spreading. Then explain what the chains or rings do to stop it. Take turns drawing a rib dome in thirty seconds, labeling hoop tension and herringbone bricks. The best labeled drawing gets three pretend florins.

3.4 EARTHQUAKES AND A SHAKE TABLE

OBJECTIVES

- Explain how shaking ground moves a building and why some buildings fall while others stand.
- Tell what engineers learned from the San Francisco earthquake of 1906.
- Build a shake table and test how bracing, a wide base and a heavy or light top change how a tower survives.

Warm-up. Stand a tall, thin book and a short, wide box on a tray. Slide the tray quickly back and forth. Which one falls first? Now put a heavy can on top of the box and try again. Then hold a ruler upright by its bottom end and wiggle your hand slowly and then quickly. When does the top swing the most?

WATCH

Why do buildings fall in earthquakes? - Vicki V. May

TED-Ed • 4:51

https://www.youtube.com/watch?v=H4VQul_SmCg

WHEN TO WATCH

After the physics paragraph. Listen for why tall and short buildings sway differently, and for the ways engineers help buildings survive.

Note: An engineering professor explains with a cartoon city; a giant cartoon creature shakes a building to show how buildings sway.

BACKUP VIDEO

Earthquake Building Design - Educator Moment (Daily Virtual Learning)

Children's Museum Houston • 2:58

<https://www.youtube.com/watch?v=TvGo11JGdks>

Before the build, to see block towers tested on a museum's shake table.

KEY TERMS

earthquake

A sudden shaking of the ground caused by great blocks of rock slipping deep in the earth.

bracing

Extra diagonal pieces that make a frame stiff, turning rectangles into triangles.

base isolation

Setting a building on flexible pads or bearings so the ground can move under it without shaking it as hard.

shake table

A platform that shakes back and forth so engineers can test models of buildings.

sway

To swing back and forth.

CORE IDEAS

The story. Early in the morning of April 18, 1906, a great earthquake shook San Francisco, California. Many brick buildings cracked and fell. Broken gas pipes and stoves started fires, and broken water pipes left firefighters with little water, so the fires burned for three days and destroyed much of the city. Many people were lost. But some buildings stood. Many of the new tall buildings with steel frames were still standing when the shaking stopped, even when fire later burned out their insides. The Ferry Building on the waterfront, with its steel-framed clock tower, survived and is still in use today.

How they figured it out. After the earthquake, scientists and engineers walked the city and wrote down which buildings stood and which fell, what they were made of and what kind of ground they stood on. They found that plain brick walls without steel often crumbled, while steel frames bent and held. Buildings on soft, filled-in land near the bay shook much harder than buildings on solid rock. A state commission studied the earthquake carefully and published a long report with maps and photographs. Over the next decades, engineers in California and Japan built the first **shake tables** and tested model buildings on them, and building rules were written so that new buildings would be stronger.

The physics. In an earthquake, the ground moves suddenly back and forth. The bottom of a building moves with the ground, but the top lags behind, because of its weight, and the building bends and **sways**. Every building has its own natural speed of swaying. A tall building sways slowly; a short building sways quickly. If the ground happens to shake at the same speed as the building's own sway, each shake adds to the last, and the swaying grows larger and larger, like pushing a swing at just the right moment. Heavy weight high up makes swaying worse. A wide base makes a building harder to tip.

The engineering. Engineers today design buildings to bend without breaking. They add **bracing** to turn rectangles into triangles, they tie floors, walls and foundations firmly together, and they use steel and reinforced concrete that bend before they snap. Some buildings sit on rubber and steel bearings, called **base isolation**, so the ground can move under them while the building above moves much less. Some very tall towers have giant weights near the top that swing against the building's sway to calm it. Every new idea is tested on shake tables first, and some of today's shake tables are big enough to hold a full-size house.

PICTURE STUDY



The Ferry Building after the 1906 Earthquake, Unknown photographer, 1906 · Photograph · National Archives and Records Administration

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

This photograph was taken soon after the earthquake. Much of the city around it was damaged or burned, but the Ferry Building and its clock tower stood.

Look closely

- Find the clock tower. Is it standing straight?
- Look at the long building below it. Can you see cracks or damage anywhere?
- Look at the street and the ground in front. What clues tell you something has happened?
- Find the windows and arches. Arches in a strong frame helped this building hold together.

Talk about it

1. Why might a tall tower with a steel frame survive when a plain brick wall did not?
2. The building stands near the water on filled ground. Why would engineers worry about soft ground?
3. If you were an engineer in 1906, what would you write down about this building?

Safety first. Keep the shake table on the floor or a low table, and keep faces back from falling towers. Wear safety glasses if your towers use craft sticks or pencils.

BUILD

A Rubber-Band Shake Table and Tower Test

You will build a simple shake table from two pieces of cardboard, rubber bands and a few marbles or balls. Then you will build towers from straws or craft sticks and test what helps them survive: bracing, a wider base, or a lighter top.

You will need

- Two pieces of stiff cardboard or two baking sheets of the same size
- 4 rubber bands and 4–6 marbles or small balls (or 4 tennis balls cut in half)
- Straws or craft sticks, tape and modeling clay
- A small weight for the top of the tower (a few pennies or a lump of clay, weighed)
- A ruler and a stopwatch
- Engineer's notebook

Steps

1. **Build the shake table.** Lay the marbles between the two cardboard sheets so the top sheet can roll. Join the two sheets at each side with a rubber band so the top springs back to the middle. Pull the top sheet 3 centimeters to one side and let go: that is one “earthquake.” Practice until you can pull it the same distance every time.
2. **Build a test tower.** Make a straw or stick tower about 30 centimeters tall with a square base about 8 centimeters wide and three floors, with no diagonal bracing. Press its feet into small lumps of clay on the table top.
3. **Test.** Put the weight on top. Give the table one 3-centimeter shake, then a 4-centimeter shake, then a 5-centimeter shake, and so on until the tower falls. Record the largest shake it survived.
4. **Fair tests.** Change only one thing at a time and test again: (a) add diagonal bracing on every side; (b) make the base 12 centimeters wide; (c) move the weight from the top to the bottom floor. Test each version three times.
5. Record all your results in a table and make a bar graph.

6. **Improve.** Combine the two changes that helped most into one tower and test it. Can it survive the biggest shake you can make?

Tips

- Mark 3, 4, 5 and 6 centimeters on the bottom sheet with a marker so each shake is measured.
- Use the same weight on top every time unless the weight is the thing you are testing.
- Watch the top of the tower. Does it lag behind the bottom? That is the sway.

Check your work

- ☐ I can explain why weight high up makes a building sway more.
- ☐ My graph shows which change helped my tower most.
- ☐ I can name three things engineers do to help buildings survive earthquakes.

ENGINEER'S NOTEBOOK

1. Draw your shake table and label the parts.
2. Make a table: tower version, biggest shake survived (three trials), average.
3. Draw a building with bracing and base isolation, and write one sentence about how each helps.

From history. In 1908 the State Earthquake Investigation Commission, led by the geologist Andrew Lawson, published its report on the 1906 earthquake, and it is still studied. Today the largest outdoor shake table in the United States, at the University of California San Diego, can shake a full-size building several stories tall.

COMMON MISTAKES

- Thinking the stiffest, heaviest building is always safest. Weight high up makes swaying worse, and buildings must bend a little without breaking.
- Shaking the table harder for one tower than another. Measure every shake.
- Changing the bracing and the base at the same time. Then you cannot tell which helped.

Make it a game • Shake and Stand. Build a small tower of blocks or cans on a tray. Your parent shakes the tray gently while you predict which tower will stand. Try a wide base, then a narrow one, then add card bracing. Say aloud what sway and bracing do. Tell one thing engineers learned from the 1906 San Francisco earthquake.

UNIT 3

BUILDINGS

Every building is a choice of materials. Wood, stone, brick, concrete and steel each have their own strengths and weaknesses, and a good builder uses each one where it works best. In this unit you will test materials yourself and learn how a French gardener named Joseph Monier made concrete much stronger by hiding iron inside it. Then you will study two of the greatest domes ever built: the Pantheon in Rome, made of Roman concrete almost nineteen hundred years ago, and Filippo Brunelleschi's brick dome in Florence, built without any wooden frame to hold it up.

Last, you will learn why some buildings stand through earthquakes and others do not, and you will build a shake table to test your own towers. Through the whole unit you will see the same two forces from Unit 2, compression and tension, deciding what stands and what falls. "Through wisdom is an house builded" (Proverbs 24:3), and part of that wisdom is knowing your materials.

PREREQUISITES

- Knows compression and tension and why triangles make frames rigid (Unit 2)
- Can run a fair test with three trials and record results in a table
- Can measure in centimeters and weigh things on a kitchen scale

MASTERY CHECKLIST

- ☐ I can describe the strengths and weaknesses of wood, stone, brick, concrete and steel.
- ☐ I can explain why concrete is strong in compression but weak in tension, and how steel reinforcement helps.
- ☐ I can explain how the Pantheon's dome was made lighter toward the top and why that helps it stand.
- ☐ I can tell how Brunelleschi built the Florence dome without a wooden frame and how its chains keep it from spreading.
- ☐ I can build a shake table and test what helps a tower survive shaking.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** Ages 3 and up. Identical small wooden planks with no glue or connectors, good for building arches, domes and towers and testing them on the shake table in Lesson 3.4.
- **Thames & Kosmos engineering kits:** Ages 8 and up. Their structural engineering sets build towers, domes and bridges with explanations of the forces; good extras for Lessons 3.2–3.4.

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

LESSONS IN THIS UNIT

3.1 Wood, Stone, Brick, Concrete and Steel: Monier's Flowerpots

2 sessions of 45 minutes

3.2 Roman Concrete and the Pantheon Dome

2 sessions of 45 minutes

3.3 Brunelleschi's Dome in Florence

2 sessions of 45 minutes

3.4 Earthquakes and a Shake Table

2 sessions of 45 minutes

UNIT 3 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

Name one strength and one weakness of each: wood, stone, concrete, steel.

2. **5 pts**

What did Joseph Monier do to make his concrete flowerpots stronger?

3. **5 pts**

Predict: a concrete beam sags under a load. Where will it crack first, and where should the steel go?

4. (5 pts)

Give two ways the Romans made the Pantheon's dome lighter near the top.

5. (5 pts)

A dome pushes down. What other way does it push at its base?

6. (5 pts)

What is centering, and why did Brunelleschi not use it?

7. (5 pts)

How did Brunelleschi's chains of stone, iron and wood help his dome?

8. (5 pts)

What did engineers learn from the buildings that stood and fell in the 1906 San Francisco earthquake?

9. (5 pts)

Predict: you test two straw towers on your shake table. One has a heavy weight on top; the other has the same weight on the bottom floor. Which will survive the bigger shake, and why?

10. (5 pts)

Name three things engineers do to help buildings survive earthquakes.

ANSWER KEY

1. Wood: light and easy to cut / can rot or burn. Stone: very strong when squeezed and long-lasting / heavy and weak when pulled. Concrete: strong in compression and can be poured into any shape / weak and brittle in tension. Steel: strong both pushed and pulled / rusts and costs more. Other reasonable answers accepted.
2. He put an iron wire mesh inside the concrete, making reinforced concrete. The iron carries the pulling (tension) that concrete is weak at.
3. It will crack first at the bottom, which is stretched (tension). The steel should go near the bottom.
4. Any two: lighter aggregate higher up, ending with pumice; a thinner shell at the top; coffer cut into the inside; leaving out the top entirely as the oculus.
5. Outward. The base tends to spread and the lower rings are stretched (hoop tension).
6. Centering is a temporary wooden frame that holds up an arch or dome while it is built. The Florence dome was too big: there was not enough timber, and such a frame might have collapsed under its own weight. He made the dome support itself as it rose.
7. They wrapped around the dome like the hoops of a barrel, holding the base together in tension so it would not spread and crack. That let the brick carry only compression.
8. Plain brick walls without steel often fell, while steel-framed buildings bent and held; buildings on soft, filled ground shook harder than those on rock.
9. The one with the weight on the bottom. Weight high up makes the top lag and sway more, so the tower tips or breaks sooner.
10. Any three: diagonal bracing; tying floors, walls and foundations together; using steel or reinforced concrete that bends before it breaks; base isolation bearings; swinging weights (dampers) near the top; wide bases; testing on shake tables.

PORTFOLIO PIECE: THE SHAKE-TABLE TOWER

Design and build a tower at least 40 centimeters tall from straws, craft sticks or KEVA-style planks that carries a weight of at least 100 grams on its top floor. Test it on your shake table, find its weakest point, improve it, and test it again. Make a poster or two notebook pages with your labeled drawing, your test data before and after the improvement, and a paragraph explaining which materials and shapes you chose and why, using the words compression, tension and bracing.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the tower's materials, base, bracing and the position of the weight.
Craftsmanship	The tower is straight, its joints are firm, and it meets the height and weight rules.
Fair test and data	Shakes were measured, three trials were done for each version, and results were recorded honestly.
Improvement	The tower was changed in one clear way after the first test, and the change was measured.
Explanation	The student explains the choices aloud using compression, tension, bracing and sway.

UNIT 4

ELECTRICITY

Two hundred years ago, electricity was a puzzle for scientists and a curiosity for crowds. Then, in a single lifetime, people learned to store it in batteries, turn it into magnetism, make it spin motors and make it glow in a glass bulb. In this unit you will follow that story. You will meet Alessandro Volta and his pile of metal discs, Joseph Henry and his giant electromagnets, Thomas Edison and his team testing thousands of filaments, and the engineers who invented the switches and drawings we still use today.

You will build a lemon battery, an electromagnet whose strength you can measure, a tester like the ones Edison's team used, and circuits with switches that you plan first on paper with a circuit diagram. All of the electricity in this unit comes from batteries. Electricity from the outlets in the wall is far more powerful and very dangerous, so we never use it for experiments.

PREREQUISITES

- Can measure, count and record results in a table
- Knows that energy changes form (Unit 1)
- Has seen a battery, a flashlight bulb or an LED

MASTERY CHECKLIST

- ☐ I can explain how Volta's pile made a steady flow of electricity and build a lemon battery that lights an LED.
- ☐ I can build an electromagnet and show how more turns of wire make it stronger.
- ☐ I can explain how an electric motor uses magnets to turn.
- ☐ I can tell how Edison's team tested filaments, and sort materials into conductors and insulators.
- ☐ I can draw a circuit diagram with standard symbols and build circuits with switches in series and in parallel.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco):** Ages 8 and up. Parts snap onto a base with no soldering, and each part is marked with its circuit symbol, which makes Lesson 4.4 especially clear. Fits Lessons 4.2–4.4.
- **KiwiCo Tinker Crate:** Ages 9–16. Several crates include battery-powered motors, switches and circuits with clear instructions; good extras 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

4.1	Volta's Pile and a Lemon Battery	2 sessions of 45 minutes
4.2	Joseph Henry's Electromagnets and the Electric Motor	2 sessions of 45 minutes
4.3	Edison's Light Bulb: Testing Thousands of Filaments	2 sessions of 45 minutes
4.4	Switches and Circuit Diagrams	2 sessions of 45 minutes

UNIT 4 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. 5 pts

What did Volta's pile have in it, and why was it so important?

2. 5 pts

Predict: one lemon cell gives about 0.9 volts and a red LED needs about 1.8 volts. How many lemons in a row will you need? Explain.

3. 5 pts

How did Joseph Henry make his electromagnets so much stronger than Sturgeon's?

4. (5 pts)

Predict: your electromagnet lifts 4 paper clips with 10 turns. About how many might it lift with 40 turns? Why?

5. (5 pts)

How does an electric motor use magnets to keep spinning?

6. (5 pts)

What is the difference between a conductor and an insulator? Give two examples of each.

7. (5 pts)

Why did Edison's bulbs need a vacuum inside?

8. (5 pts)

What does a switch do in a circuit? Why was the quick-break switch safer?

9. (5 pts)

Two switches are in series with a lamp. Switch A is closed and switch B is open. Is the lamp on or off? What if they were in parallel?

10. (5 pts)

Draw a circuit diagram of one battery, one lamp and one switch in a loop, using standard symbols.

ANSWER KEY

1. Stacked discs of two different metals (such as zinc and copper or silver) with cloth or cardboard soaked in salt water between them. It was the first battery and gave a steady flowing current, so scientists could do many new experiments.
2. At least two, connected in series (nail to copper), because cells in series add their volts: $0.9 + 0.9 = 1.8$. Three is safer.
3. He insulated the wire (with silk) so he could wind many turns, layer on layer, around the iron without the loops touching. More turns made a stronger magnet.
4. More, perhaps 10 or more (answers vary). More turns of wire make a stronger magnetic field.
5. A coil on the shaft becomes an electromagnet and is pulled toward the opposite pole of a permanent magnet; the commutator flips the current at just the right moment so the coil is pushed onward, and it keeps turning.
6. A conductor lets current flow easily (copper, aluminum foil, a coin, salt water). An insulator does not (plastic, rubber, glass, dry wood, paper).
7. The hot filament would burn up quickly in air. With the air pumped out, there is almost no oxygen, so it can glow without burning.
8. It opens or closes a gap, turning the current off or on. The quick-break switch snapped the contacts apart quickly so a spark (arc) could not burn the metal or start a fire.
9. In series: off, because both must be closed. In parallel: on, because current can flow through the closed switch A.
10. A closed loop with the cell symbol (long and short lines), the lamp symbol (circle with a cross), and the switch symbol (a line with a hinged gap), joined by straight lines.

PORTFOLIO PIECE: A LIT AND SWITCHED MODEL ROOM

Build a shoebox room with at least two lights powered by batteries and controlled by switches you made. Use one pair of switches in series or in parallel for a reason you can explain (for example, a hallway light that can be turned on from either door). Draw the circuit diagram first, then build it, test every switch setting, and record the results in a table. Add a page explaining your circuit with the words circuit, switch, series, parallel, conductor and insulator.

LOOK FOR	WHAT IT MEANS
Circuit diagram	A neat diagram with standard symbols matches the circuit that was built.
It works	Every light and switch works as the diagram says, and wires are tidy and secure.
Testing	A table records every switch setting, with predictions and results.
Safety	Only batteries are used, nothing gets hot, and the student can explain why the outlets in the wall are never used.
Explanation	The student explains the circuit aloud using the unit’s key words.

4.1 VOLTA'S PILE AND A LEMON BATTERY

OBJECTIVES

- Tell how Alessandro Volta built the first battery in 1800.
- Explain that a battery makes electricity from two different metals and a liquid between them.
- Build a lemon battery, test how many lemons it takes to light an LED, and compare different pairs of metals.

Warm-up. Look at a flashlight battery. Find the + end and the – end. What do you think is inside? Now look at a coin and a steel nail. They are different metals. Make a guess: could two different metals and a lemon make electricity?

WATCH

How to Make Lemon Batteries!

Branch Education • 4:56

<https://www.youtube.com/watch?v=EA751OyNLOk>

WHEN TO WATCH

Before the build. Watch how the lemons are joined one to the next, and count how many it takes to light the LED.

KEY TERMS

battery

A device that stores chemical energy and gives it out as electricity.

cell

One unit of a battery: two different metals with a liquid or paste between them.

electric current

A flow of electric charge through a wire.

volt

The unit for measuring how hard a battery pushes the current, named after Volta.

LED

Light-emitting diode: a tiny light that needs very little current and works only one way around.

CORE IDEAS

The story. In the 1780s an Italian doctor named Luigi Galvani noticed that the legs of a frog he was studying twitched when they were touched by two different metals at once. He thought the electricity came from the animal itself and called it “animal electricity.” His friend Alessandro Volta, a professor of physics in Pavia, was not so sure. He suspected that the electricity came from the two different metals, and that the frog was only acting like a very sensitive detector.

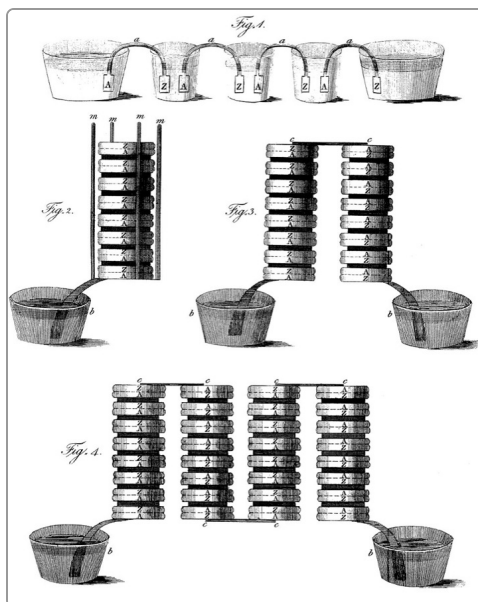
How they figured it out. Volta tested his idea for years. He touched pairs of different metals to his own tongue and felt a tingle and a sour taste. He found that some pairs gave a stronger effect than others. Then he made a stack: a disc of zinc, a disc of copper or silver, and a piece of cardboard or cloth soaked in salt water, then zinc, copper, wet cloth again, over and over. In 1800 he wrote to the Royal Society in London describing his “pile.” It gave a steady, flowing current of electricity, the first time anyone had made one. The more layers he stacked, the stronger the push. Scientists all over Europe built piles and began to discover what electricity could do.

The physics. A cell is made of two different metals with a liquid between them. A chemical change happens where each metal touches the liquid, and one metal ends up with extra negative charge. When a wire connects the two metals outside the cell, charge flows through the wire from one to the other. That flow is an **electric current**. Stacking cells one after another, which is called connecting them in series, adds their pushes together. The push is measured in **volts**, named after Volta. One lemon cell makes a little less than one volt, but a red **LED** needs almost two, so you need two or three lemons in a row.

The engineering. A lemon battery gives only a tiny current, and it soon runs down as the metal is used up. Engineers have worked for two centuries to make batteries that are small, safe and long-lasting. A flashlight battery uses a paste instead of a liquid so it cannot spill, and it gives about 1.5 volts. A 9-volt battery is really six small cells stacked inside, just like Volta’s pile. Today’s rechargeable lithium batteries in

phones store a great deal of energy in a small space, which is why they must never be punctured, crushed or heated.

PICTURE STUDY



Volta's Drawings of His Battery, Alessandro Volta, 1800 · Engraving · Philosophical Transactions of the Royal Society, London

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

These drawings come from the letter Volta sent to the Royal Society in London in 1800. Figure 1 shows a “crown of cups”: cups of salt water joined by bent strips of two metals. The other figures show his piles: tall stacks of metal discs with wet cloth between them.

Look closely

- Find the row of cups at the top. Each cup and its two metals is one cell.
- Find the letters Z and A on the metal strips. Z is zinc; A is *argent*, French for silver.
- Find the tall stacks of discs. Can you see the repeating pattern of layers?
- Find where two stacks are joined at the top. Why would joining them make a stronger battery?

Talk about it

1. What would happen to the push of the battery if Volta added more cups or made the stacks taller?
2. Why must the pattern always go in the same order?
3. How is the row of cups like your row of lemons?

Safety first. Use only lemons, coins, nails and small wires; never connect anything to an outlet in the wall. Do not eat or drink anything that has had metal in it. An adult makes the cuts in the lemons.

BUILD

How Many Lemons? A Lemon Battery Test

You will build a lemon battery, find out how many lemon cells in a row it takes to light an LED, and then run a fair test of different metal pairs to find the best one, as Volta did.

You will need

- 4 lemons (roll each firmly on the table first to make it juicy)
- 4 copper coins or strips of copper (pennies made before 1982 are mostly copper; newer ones work too because they are coated in copper)
- 4 galvanized (zinc-coated) nails, plus a plain steel nail and a strip of aluminum foil to test
- 5 alligator clip leads
- 1 red LED
- Optional: a simple multimeter set to DC volts

Steps

1. **Build one cell.** An adult cuts a small slit in a lemon. Push a copper coin into the slit and a galvanized nail into the lemon about 3 centimeters away. They must not touch.
2. If you have a multimeter, touch its red lead to the copper and its black lead to the nail. Record the volts.
3. **Predict.** How many lemons will it take to light the LED? Write your guess.
4. **Build a battery.** Make more cells. Join the nail of the first lemon to the copper of the second with a clip lead, then the nail of the second to the copper of the third, and so on. Connect the free copper to the long leg of the LED and the free nail to the short leg.
5. Test with 1, 2, 3 and 4 lemons in a row. Record whether the LED lights and how bright (none, faint, clear). Look in a dark room.
6. **Fair test of metals.** Using one lemon and a multimeter (or the number of lemons needed to light the LED), test three pairs: copper with zinc nail, copper with steel nail, copper with foil. Change only the metal pair.

7. Record all your results in a table. Which pair gave the strongest push?
8. **Improve.** Try one change to make your battery stronger: cut each lemon in half to make twice as many cells, use a potato, or use salt water in cups. Test it the same way.

Tips

- If the LED does not light, turn it around. LEDs work only one way.
- Make sure the copper and the nail do not touch inside the lemon.
- Check that every clip goes from a nail to the next copper, never nail to nail.

Check your work

- ☐ I can explain why one lemon is not enough to light an LED.
- ☐ I tested different metal pairs fairly and recorded the results.
- ☐ I can tell how Volta's pile was built.

ENGINEER'S NOTEBOOK

1. Draw your lemon battery and label the copper, the zinc nail, the lemon juice, the clip leads and the LED. Draw arrows to show the path of the current.
2. Make a table: number of lemons, volts (if measured), LED (yes or no).
3. Draw Volta's pile and label its repeating layers.

From history. Volta was a devout Catholic who wrote a statement of his faith near the end of his life. In 1881, long after he died, scientists chose the name “volt” for the unit of electric push in his honor. Volta's original equipment can still be seen in a museum in his hometown of Como, Italy.

COMMON MISTAKES

- Thinking the electricity is stored in the lemon. It comes from the two different metals; the lemon juice only lets the chemical change happen.
- Connecting the lemons nail to nail or copper to copper. Each nail must connect to the next copper.
- Putting the LED in backward and deciding the battery does not work.

Make it a game • Volta's Pile Race. Set a timer for sixty seconds. Name everything you remember about Volta's first battery: the two metals, the liquid, the year, and what a cell and a volt are. Each fact earns a point. Then draw a lemon battery with labels and beat your own score on a second try.

4.2 JOSEPH HENRY'S ELECTROMAGNETS AND THE ELECTRIC MOTOR

OBJECTIVES

- Explain that an electric current makes a magnetic field, and that a coil of wire around iron makes an electromagnet.
- Tell how Joseph Henry made electromagnets far stronger by winding many turns of insulated wire.
- Build an electromagnet, test how the number of turns changes its strength, and explain how a motor uses electromagnets to spin.

Warm-up. Lay a compass flat on the table and let the needle settle. Lay a wire across the top of the compass, lined up with the needle. Touch the two ends of the wire to the two ends of a D-cell battery for just a second. Watch the needle. What happened? (Let go quickly; the wire gets warm.)

WATCH

How does an Electromagnet Work?

Science Buddies • 2:56

<https://www.youtube.com/watch?v=cxELqN7wjS0>

WHEN TO WATCH

After the physics paragraph, before the build. Watch how adding a coil and an iron core makes the magnet stronger.

BACKUP VIDEO

How does an Electric Motor work? (DC Motor)

The Engineering Mindset • 4:49

https://www.youtube.com/watch?v=1AaUK6pT_cE

After the engineering paragraph, to see the coils, magnets and commutator inside a small motor like the one in your kit.

KEY TERMS

magnetic field

The space around a magnet or a current-carrying wire where magnetic forces can be felt.

electromagnet

A magnet made by sending current through a coil of wire, usually wrapped around iron. It can be turned on and off.

coil

Wire wound around and around in loops.

insulated wire

Wire covered with a coating that electricity cannot pass through, so the loops do not touch each other electrically.

motor

A machine that turns electrical energy into spinning motion.

CORE IDEAS

The story. In 1820 a Danish professor, Hans Christian Ørsted, noticed that a compass needle moved when a current flowed through a nearby wire, just as yours did. Electricity could make magnetism! In 1825 an Englishman, William Sturgeon, wound bare wire loosely around a horseshoe-shaped piece of iron and made the first electromagnet. It could lift several pounds. In Albany, New York, a young teacher named Joseph Henry heard about it and wanted to do better.

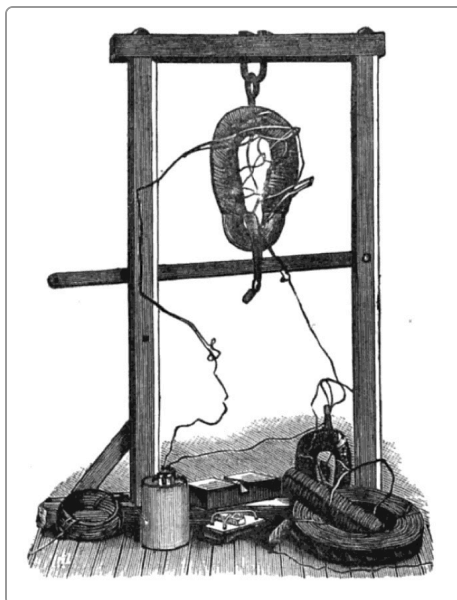
How they figured it out. Henry saw the problem: Sturgeon's bare wire could only be wound in one loose layer, or the loops would touch and the current would take a shortcut. So Henry wrapped his wire in silk thread to **insulate** it. Now he could wind hundreds of turns, layer upon layer, tightly around the iron. He tested magnet after magnet, changing the number of coils, the length of wire and the battery, and recording how much each could lift. In 1831 he built an electromagnet for Yale College that lifted more than a ton. The same year he built a small machine with a rocking electromagnet that moved back and forth by itself, one of the first electric motors.

The physics. Every electric current makes a **magnetic field** around the wire. One straight wire makes a weak field. Wind the wire into a **coil**, and the fields of all the

loops add together. Put a piece of iron inside the coil, and the iron becomes strongly magnetized too, making the field many times stronger. More turns of wire and more current make a stronger **electromagnet**. When the current stops, most of the magnetism goes away. That on-and-off control is what makes electromagnets so useful.

The engineering. A **motor** uses electromagnets and permanent magnets that push and pull on each other. In a small hobby motor, a coil on a shaft sits between two magnets. The coil becomes an electromagnet and is pulled around toward the opposite pole. Just as it arrives, a little switch on the shaft called a commutator flips the direction of the current, so the coil is pushed onward again, around and around. In 1837 a Vermont blacksmith, Thomas Davenport, received the first American patent for an electric motor. Today motors run fans, washing machines, elevators, trains and electric cars, and electromagnets lift scrap iron, ring doorbells and run speakers.

PICTURE STUDY



Joseph Henry's Electromagnet, Unknown, Electromagnet built about 1831 · Engraving · Smithsonian Institution

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

This electromagnet was made by Joseph Henry. It looks like a simple horseshoe of iron wrapped in wire, but it could lift far more than a person could.

Look closely

- Find the horseshoe magnet hanging from the frame. Can you see how much wire is wound around it?
- Find the wires that lead down to the battery on the floor.
- Find the bar across the frame below the magnet. What might hang from it?
- Find the extra coils of wire lying on the floor.

Talk about it

1. Why did Henry wrap so many turns of wire around the iron?
2. Why did the wire need to be covered with silk or some other insulation?
3. What would happen to the load if the battery were disconnected?

Safety first. Use only a D-cell or AA battery. Connect the battery only while testing, a few seconds at a time; a coil connected straight to a battery gets hot quickly and drains the battery. Never use wall power. An adult helps strip wire ends with sandpaper or a stripper.

BUILD

More Turns, More Paper Clips: An Electromagnet Test

You will wind insulated wire around an iron nail to make an electromagnet and test how the number of turns changes how many paper clips it can lift. Then you will look at (or build) a simple motor.

You will need

- A large iron or steel nail (about 8 centimeters long)
- About 2 meters of thin insulated wire or magnet wire, with the ends stripped by an adult
- A D-cell battery in a battery holder, and two alligator clip leads
- A box of small steel paper clips
- A compass
- Optional: a small hobby motor (1.5–3 volts) to connect to the battery and watch

Steps

1. **Predict.** Write how many paper clips you think the nail will lift with 10, 20, 30 and 40 turns of wire.
2. **Build.** Leave about 20 centimeters of loose wire at one end. Wind exactly 10 turns neatly around the nail, all in the same direction.
3. **Test.** Connect the wire ends to the battery with the clip leads. Touch the point of the nail to the pile of paper clips and lift. Count how many clips it picks up. Disconnect the battery. Do three trials.
4. Wind 10 more turns in the same direction (20 in all) and test three times. Repeat for 30 and 40 turns. Change only the number of turns.
5. Make a table and a line graph: turns (across) and paper clips lifted (up).
6. Hold the compass near each end of your electromagnet with the battery connected. Which end is north? Switch the battery around. What happens?
7. **Improve.** Try one other change and test it: two batteries in a row, or a thicker nail. Did it lift more?

8. **Motor.** If you have a hobby motor, connect it to the battery and watch it spin. Reverse the wires. Which way does it spin now? Explain why using the word electromagnet.

Tips

- Wind all the turns the same direction. Turns that go back the other way cancel out.
- Use the same pile of paper clips each time and dip the nail the same way.
- If the battery gets warm, disconnect it and let it rest between tests.

Check your work

- ☐ I can explain why a coil around iron makes a stronger magnet.
- ☐ My graph shows how the number of turns changed the strength.
- ☐ I can explain how a motor uses electromagnets to spin.

ENGINEER'S NOTEBOOK

1. Draw your electromagnet, battery and clip leads, and label each part. Mark the north and south ends.
2. Make a table and a line graph of turns and paper clips.
3. Draw a simple motor: a coil between two magnets. Draw arrows to show which way it turns.

From history. Joseph Henry later taught at Princeton and in 1846 became the first leader (Secretary) of the Smithsonian Institution in Washington, D.C. He was a devout Presbyterian who saw science as the study of the works of God. The unit of a coil's electrical "inertia," the henry, is named after him.

COMMON MISTAKES

- Thinking the nail is a magnet by itself. It is magnetized only while current flows (a little magnetism may stay behind).
- Leaving the battery connected for a long time. The wire gets hot and the battery runs down.
- Winding some turns one way and some the other. Their magnetic fields cancel.

Make it a game • Coil Detective. Your parent hides a clue sentence about electromagnets, such as "I get stronger with more turns of insulated wire." Guess the term from clues like magnetic field, coil, motor or current. Then play Joseph Henry and tell how many turns of wire you would try next and why. Score a point for every correct explanation.

4.3 EDISON'S LIGHT BULB: TESTING THOUSANDS OF FILAMENTS

OBJECTIVES

- Tell how Thomas Edison's team at Menlo Park found a filament that would glow for many hours.
- Explain why a thin filament glows when current passes through it, and why the bulb needs a vacuum.
- Build a conductor tester and test many materials, sorting them into conductors and insulators.

Warm-up. Rub your hands together hard and fast for ten seconds. What do you feel? Now think: when a current is pushed through a very thin wire, the wire “rubs” against it. What might happen to the wire?

WATCH

The Incandescent Lamp

Edison Tech Center • 6:15

<https://www.youtube.com/watch?v=aPaelFjpoQ8>

WHEN TO WATCH

After the story. Look for the carbon filaments and the bamboo filament, and for the names of the other inventors.

Note: A light-bulb collector shows old and new bulbs. The end describes later kinds of lamps; you may stop when the history ends.

BACKUP VIDEO

Light bulb filament

engineerguy • 3:38

<https://www.youtube.com/watch?v=DIGqBb3iZPo>

After the engineering paragraph, to see how long and thin a modern tungsten filament really is.

KEY TERMS

filament

The very thin thread inside a light bulb that glows when current flows through it.

insulator

A material that does not let current flow through it, such as plastic, rubber, glass or dry wood.

vacuum

A space with almost all of the air pumped out.

conductor

A material that lets electric current flow through it easily, such as copper or other metals.

resistance

How much a material holds back the flow of current. Resistance turns some electrical energy into heat.

CORE IDEAS

The story. In 1876 Thomas Edison built a laboratory at Menlo Park, New Jersey, and filled it with tools, chemicals and a team of skilled workers. He called it his “invention factory.” Many inventors before him, such as Joseph Swan in England, had made lamps that glowed for a little while, but none lasted long enough or cost little enough for every home. In October 1879 Edison’s team tested a bulb with a **filament** made of cotton thread that had been baked into carbon. It glowed for about thirteen hours. On New Year’s Eve 1879, crowds came by train to Menlo Park to see the lab and the street outside lit by electric lamps.

How they figured it out. Edison’s method was to test, measure and write everything down. The team tried thread, paper, fishing line, cork, wood shavings and many metals. They tested platinum, but it was rare and costly. They found that carbon worked best, if it could be kept from burning. So they worked as hard on the pump as on the filament, building better pumps that removed almost all the air from the bulb. After the cotton thread, they tested carbonized cardboard, and then sent people around the world to collect plant fibers. They tested more than six thousand plants and found that a certain kind of bamboo from Japan made filaments that lasted more than a thousand hours. Lewis Latimer, a draftsman who worked for another lamp company and later for Edison, improved the way carbon filaments were made so they were stronger and cheaper.

The physics. Some materials are **conductors**: current flows through them easily. Metals such as copper are excellent conductors, which is why wires are made of copper. Others are **insulators**: current hardly flows through them at all. Between the two are materials with high **resistance**, which let current through but hold it back. When current is pushed through a very thin thread with high resistance, the electrical energy turns into heat, and the thread gets so hot it glows white. In air, a hot carbon thread would burn up in a moment. In a **vacuum**, there is almost no oxygen, so it can glow without burning.

The engineering. Edison knew a bulb alone was not enough. His team designed a whole system: generators, underground wires, meters to measure how much each home used, fuses for safety, sockets, and switches. In 1882 his Pearl Street Station in New York City began sending electricity to homes and offices. Later engineers replaced carbon with tungsten, a metal that can glow even hotter, and filled bulbs with gases that slow down wear. Today most lamps use LEDs, which give the same light with far less electricity and much less heat. But the method of Menlo Park, careful testing and honest records, is still how engineers work.

PICTURE STUDY



Workers Outside the Menlo Park Laboratory, Unknown photographer, about 1880 · Photograph · Thomas Edison National Historical Park
Image: [Wikimedia Commons](#), public domain

This plain wooden building was the most famous laboratory in the world. Edison did not invent alone; the men in this photograph built, tested and recorded the experiments that led to the light bulb.

Look closely

- Find the long laboratory building. Count the windows. Why would an inventor want so many?
- Look at the people. How many are there? What kinds of jobs might each one have done?
- Look for clues of the work done there, such as tools, wires, poles or lamps.
- Look at the surroundings. Was Menlo Park a big city or a quiet country place?

Talk about it

1. Why do you think a team could test thousands of filaments faster than one person?
2. Why would it matter that every test was written down?
3. What would you want to invent if you had a laboratory like this?

Safety first. Use only one AA or D-cell battery and an LED or small bulb. Never try to make a glowing filament from steel wool, pencil lead or wire, because it gets hot enough to burn. Never put anything into an outlet in the wall.

BUILD

Test Like Menlo Park: Conductors and Insulators

Edison's team tested thousands of materials. You will build a simple tester and test at least fifteen materials, predicting first and recording every result. Then you will test pencil lines to see how thickness changes resistance.

You will need

- Two AA batteries in a holder, a red LED (or a small flashlight bulb in a holder), and three alligator clip leads
- At least 15 test materials: a coin, aluminum foil, a paper clip, a key, a rubber band, a plastic spoon, a craft stick, a glass jar, a leaf, a piece of string, a pencil lead (graphite), salt water in a cup, sugar water in a cup, paper, a crayon
- A soft (No. 2 or softer) pencil and paper
- Engineer's notebook

Steps

1. **Build the tester.** Connect the battery holder, the LED and one clip lead in a loop, leaving two free clip ends as “test probes.” Touch the probes together: the LED should light. If not, turn the LED around.
2. **Predict.** Make a table with three columns: material, prediction (conductor or insulator), result. Fill in all your predictions first.
3. **Test.** Touch both probes to each material, about 2 centimeters apart. Record whether the LED lights brightly, dimly or not at all.
4. For the salt water and sugar water, dip both probes into the cup without letting them touch. Compare.
5. Count how many predictions were right. Were any surprising?
6. **Fair test.** With the pencil, draw three lines 10 centimeters long on paper: one thin and light, one medium, one thick and heavy (go over it many times). Touch the probes to the two ends of each line. Which glows brightest? Then test the thick line at 2, 5 and 10 centimeters apart.

7. **Improve.** Design a better tester: use a small bulb and an LED side by side, or add a switch. Test it on five materials and compare.

Tips

- Press the probes firmly against each material and clean off any paint or tape where you touch.
- Graphite is a conductor with high resistance; the LED may glow only dimly.
- Water from the tap conducts a little; salt makes it conduct much more. That is why electricity and water must never mix at home.

Check your work

- ☐ I can name three conductors and three insulators.
- ☐ I recorded a prediction and a result for every material.
- ☐ I can explain why Edison needed a vacuum inside his bulb.

ENGINEER'S NOTEBOOK

1. Draw a light bulb and label the filament, the glass, the vacuum inside and the wires.
2. Copy your table of predictions and results and circle every surprise.
3. Write a short page as a Menlo Park worker describing one day of testing filaments.

From history. Lewis Latimer taught himself drafting and drew the patent drawings for Alexander Graham Bell's telephone. He later joined Edison's engineers and wrote one of the first books about electric lighting in 1890. Edison and Joseph Swan eventually joined their companies in Britain rather than argue over who invented the lamp first.

COMMON MISTAKES

- Thinking Edison invented the very first electric light. Others made glowing lamps before him; his team made one that lasted, and a whole system to power it.
- Thinking all metals are insulators because they feel cold. Metals are the best conductors.
- Testing a material with the probes touching each other. The current must go through the material.

Make it a game • Filament Hunt. Gather six household objects. Predict which are conductors and which are insulators, then say how Edison's team at Menlo Park might have tested a filament. Draw a bulb and label filament, vacuum and current. Your parent asks why a bulb needs a vacuum, and you answer in one sentence. Score a point per correct prediction.

4.4 SWITCHES AND CIRCUIT DIAGRAMS

OBJECTIVES

- Explain open and closed circuits and what a switch does.
- Read and draw circuit diagrams with standard symbols.
- Build circuits with two switches in series and in parallel, record which switch settings light the bulb, and use them to solve a real problem.

Warm-up. Walk through your house and count every switch you can find without touching any wall wiring: light switches, a flashlight, a lamp, a toy, a fan, a remote control. For each, guess what the switch is doing inside: opening a gap or closing it?

WATCH

The Power of Circuits! | Technology for Kids | SciShow Kids

SciShow Kids · 4:42

<https://www.youtube.com/watch?v=HOFp8bHTN30>

WHEN TO WATCH

At the start of Session 1. Listen for what “closed” and “open” mean in a circuit.

Note: The video’s own description notes that some animations show the current flowing the wrong way; engineers usually draw current from + to –, so this does not matter for this lesson.

KEY TERMS

circuit

A complete loop through which electric current can flow from a battery and back.

switch

A device that opens or closes a gap in a circuit to turn the current off or on.

circuit diagram

A drawing of a circuit using simple standard symbols instead of pictures.

series

Connected one after another in a single path.

parallel

Connected side by side, so there is more than one path for the current.

CORE IDEAS

The story. When Edison's electric lights first came into homes in the 1880s, people turned them on and off with a key or knob right at the lamp. Switches on the wall came soon after. The first wall switches had a problem: when the contacts were pulled apart slowly, the electricity jumped across the small gap as a spark, called an arc, which burned the metal and could start a fire. In 1884 an English engineer named John Henry Holmes, in Newcastle, invented the “quick-break” switch. A spring inside snapped the contacts apart very fast, no matter how slowly you moved the handle, so the spark had no time to do damage. That “click” you hear when you flip a light switch comes from the same idea.

How they figured it out. As electric systems grew, engineers needed a way to plan and share circuits without drawing every battery and lamp as a little picture. They agreed on simple symbols: two lines of different lengths for a cell, a circle with a cross for a lamp, a line with a hinged gap for a switch. With a **circuit diagram**, an engineer in one city could draw a plan and a worker in another city could build it exactly. Engineers also learned that the way switches are joined decides how they work together, and they began to use this to build machines that make decisions.

The physics. Current flows only in a complete loop, a closed **circuit**. A **switch** is simply a gap that you can close or open. When it is closed, the loop is complete and current flows. When it is open, the loop is broken and everything stops. If two switches are in **series**, one after the other, the current must pass through both, so the light comes on only when switch A *and* switch B are closed. If two switches are in **parallel**, side by side, the current can take either path, so the light comes on when switch A *or* switch B is closed.

The engineering. Engineers use these two patterns everywhere. A washing machine runs only if the door is shut *and* the start button is pressed: switches in series. A doorbell rings if the front button *or* the back button is pressed: switches in parallel. Safety switches are often put in series, so a machine stops if any one of them is opened. Computers are built from millions of tiny electronic switches joined in “and” and “or” patterns. Every one of those circuits starts as a diagram, carefully drawn and checked before anything is built.

PICTURE STUDY



Thomas A. Edison's System of Electric Illumination, Unknown artist, about 1880 · Print · Library of Congress, Prints and Photographs Division

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

This page from an illustrated newspaper explained Edison's new lighting system to readers who had never seen electric light. It shows that a lamp needs a whole circuit: a generator, wires, switches and fittings, all working together.

Look closely

- Find the generator that made the electricity.
- Find the lamps. How many can you count?
- Look for wires, fittings or switches that connect the lamps.
- Find a picture of people at work. What are they doing?

Talk about it

1. Trace with your finger a path the current might take from the generator to a lamp and back.
2. Why did the readers of this newspaper need pictures to understand electric light?
3. How would a circuit diagram make this page simpler?

Safety first. Use only AA or D batteries and small bulbs or LEDs. Never take apart a wall switch or anything that plugs into the wall. If a wire or battery gets hot, disconnect it.

BUILD

And or Or? Paper-Clip Switches in Series and Parallel

You will make two simple switches from paper clips and brass fasteners, draw circuit diagrams first, and then build a series circuit and a parallel circuit. You will test every switch setting, record the results in a table, and then design a circuit to solve a real problem.

You will need

- A battery holder with 2 AA batteries
- A small bulb in a holder or a red LED
- 4–6 alligator clip leads
- Two pieces of cardboard about 5 by 8 centimeters, four brass paper fasteners and two metal paper clips (for two switches)
- Pencil, ruler and engineer's notebook

Steps

1. **Make two switches.** Push two brass fasteners through each piece of cardboard about 3 centimeters apart. Hook a paper clip around one fastener so it can swing to touch the other. Touching = closed; not touching = open.
2. **Learn the symbols.** Copy the symbols for a cell, a battery, a lamp, a switch and a wire into your notebook.
3. **Draw first.** Draw a circuit diagram with the battery, the lamp and both switches in series. Then draw one with the two switches in parallel.
4. **Predict.** For each circuit, make a table with four rows: A open, B open; A closed, B open; A open, B closed; A closed, B closed. Predict lamp on or off for each.
5. **Build and test the series circuit.** Follow your diagram exactly. Test all four settings and record the results.
6. **Build and test the parallel circuit.** Test all four settings and record the results.
7. Compare your results with your predictions. Write the rule for each: series = “and”, parallel = “or”.

8. Improve: solve a problem. Design a circuit for a “safe box” light that turns on only when the lid is open and a secret switch is on, or a doorbell with buttons at two doors. Draw the diagram first, then build and test it.

Tips

- Put your finger on the diagram and trace the loop before you build it. If your finger cannot get back to the battery, the circuit is open.
- Make sure the paper clip touches bare metal on both fasteners.
- Label your switches A and B with tape so your table matches your circuit.

Check your work

- ☐ I can draw a circuit diagram with standard symbols.
- ☐ I can predict and test when a lamp lights with two switches in series and in parallel.
- ☐ I can name a real machine that uses switches in series and one that uses switches in parallel.

ENGINEER'S NOTEBOOK

1. Draw both circuit diagrams neatly with a ruler and label switch A, switch B, the battery and the lamp.
2. Copy your two test tables and circle any setting you predicted wrong.
3. Draw the diagram for your problem-solving circuit and explain it in two sentences.

From history. Light switches went through many changes: push-button switches with one button for on and another for off were common in the early 1900s, and the familiar up-and-down toggle switch came later. Inside every one is the same idea John Henry Holmes used in 1884: open the gap quickly and cleanly.

COMMON MISTAKES

- Thinking the current gets used up before it returns to the battery. The current flows all the way around the loop.
- Drawing a picture of the parts instead of using symbols. Symbols make diagrams quick and clear.
- Leaving a gap in the loop by accident. Check every clip.

Make it a game • Circuit Draw-Off. Your parent calls out a circuit situation: a switch is open, a lamp in series, two lamps in parallel. Draw the circuit diagram on paper with standard symbols as fast as you can, then say whether current flows. Each correct drawing earns a point. Race for five rounds and try to beat your previous best.

Scripture. “Neither do men light a candle, and put it under a bushel, but on a candlestick; and it giveth light unto all that are in the house.” (Matthew 5:15, KJV)

A light is made to be seen and to help others. A well-built circuit that lights a room is a small way of serving everyone in the house.

UNIT 4

ELECTRICITY

Two hundred years ago, electricity was a puzzle for scientists and a curiosity for crowds. Then, in a single lifetime, people learned to store it in batteries, turn it into magnetism, make it spin motors and make it glow in a glass bulb. In this unit you will follow that story. You will meet Alessandro Volta and his pile of metal discs, Joseph Henry and his giant electromagnets, Thomas Edison and his team testing thousands of filaments, and the engineers who invented the switches and drawings we still use today.

You will build a lemon battery, an electromagnet whose strength you can measure, a tester like the ones Edison's team used, and circuits with switches that you plan first on paper with a circuit diagram. All of the electricity in this unit comes from batteries. Electricity from the outlets in the wall is far more powerful and very dangerous, so we never use it for experiments.

PREREQUISITES

- Can measure, count and record results in a table
- Knows that energy changes form (Unit 1)
- Has seen a battery, a flashlight bulb or an LED

MASTERY CHECKLIST

- ☐ I can explain how Volta's pile made a steady flow of electricity and build a lemon battery that lights an LED.
- ☐ I can build an electromagnet and show how more turns of wire make it stronger.
- ☐ I can explain how an electric motor uses magnets to turn.
- ☐ I can tell how Edison's team tested filaments, and sort materials into conductors and insulators.
- ☐ I can draw a circuit diagram with standard symbols and build circuits with switches in series and in parallel.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco):** Ages 8 and up. Parts snap onto a base with no soldering, and each part is marked with its circuit symbol, which makes Lesson 4.4 especially clear. Fits Lessons 4.2–4.4.
- **KiwiCo Tinker Crate:** Ages 9–16. Several crates include battery-powered motors, switches and circuits with clear instructions; good extras 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

4.1	Volta's Pile and a Lemon Battery	2 sessions of 45 minutes
4.2	Joseph Henry's Electromagnets and the Electric Motor	2 sessions of 45 minutes
4.3	Edison's Light Bulb: Testing Thousands of Filaments	2 sessions of 45 minutes
4.4	Switches and Circuit Diagrams	2 sessions of 45 minutes

UNIT 4 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**
What did Volta's pile have in it, and why was it so important?
2. **5 pts**
Predict: one lemon cell gives about 0.9 volts and a red LED needs about 1.8 volts. How many lemons in a row will you need? Explain.
3. **5 pts**
How did Joseph Henry make his electromagnets so much stronger than Sturgeon's?

4. (5 pts)

Predict: your electromagnet lifts 4 paper clips with 10 turns. About how many might it lift with 40 turns? Why?

5. (5 pts)

How does an electric motor use magnets to keep spinning?

6. (5 pts)

What is the difference between a conductor and an insulator? Give two examples of each.

7. (5 pts)

Why did Edison's bulbs need a vacuum inside?

8. (5 pts)

What does a switch do in a circuit? Why was the quick-break switch safer?

9. (5 pts)

Two switches are in series with a lamp. Switch A is closed and switch B is open. Is the lamp on or off? What if they were in parallel?

10. (5 pts)

Draw a circuit diagram of one battery, one lamp and one switch in a loop, using standard symbols.

ANSWER KEY

1. Stacked discs of two different metals (such as zinc and copper or silver) with cloth or cardboard soaked in salt water between them. It was the first battery and gave a steady flowing current, so scientists could do many new experiments.
2. At least two, connected in series (nail to copper), because cells in series add their volts: $0.9 + 0.9 = 1.8$. Three is safer.
3. He insulated the wire (with silk) so he could wind many turns, layer on layer, around the iron without the loops touching. More turns made a stronger magnet.
4. More, perhaps 10 or more (answers vary). More turns of wire make a stronger magnetic field.
5. A coil on the shaft becomes an electromagnet and is pulled toward the opposite pole of a permanent magnet; the commutator flips the current at just the right moment so the coil is pushed onward, and it keeps turning.
6. A conductor lets current flow easily (copper, aluminum foil, a coin, salt water). An insulator does not (plastic, rubber, glass, dry wood, paper).
7. The hot filament would burn up quickly in air. With the air pumped out, there is almost no oxygen, so it can glow without burning.
8. It opens or closes a gap, turning the current off or on. The quick-break switch snapped the contacts apart quickly so a spark (arc) could not burn the metal or start a fire.
9. In series: off, because both must be closed. In parallel: on, because current can flow through the closed switch A.
10. A closed loop with the cell symbol (long and short lines), the lamp symbol (circle with a cross), and the switch symbol (a line with a hinged gap), joined by straight lines.

PORTFOLIO PIECE: A LIT AND SWITCHED MODEL ROOM

Build a shoebox room with at least two lights powered by batteries and controlled by switches you made. Use one pair of switches in series or in parallel for a reason you can explain (for example, a hallway light that can be turned on from either door). Draw the circuit diagram first, then build it, test every switch setting, and record the results in a table. Add a page explaining your circuit with the words circuit, switch, series, parallel, conductor and insulator.

LOOK FOR	WHAT IT MEANS
Circuit diagram	A neat diagram with standard symbols matches the circuit that was built.
It works	Every light and switch works as the diagram says, and wires are tidy and secure.
Testing	A table records every switch setting, with predictions and results.
Safety	Only batteries are used, nothing gets hot, and the student can explain why the outlets in the wall are never used.
Explanation	The student explains the circuit aloud using the unit’s key words.

UNIT 5

PUBLIC UTILITIES

When you flip a switch or turn on a tap, you are using some of the greatest machines ever built. Behind every light is a power plant, a web of wires and transformers called the grid, and the lineworkers who keep it running. Behind every faucet is a water tower or a pumping station pushing clean water through miles of pipes, and behind every drain is a sewer carrying dirty water safely away. These are the public utilities, and engineers design them to work every hour of every day for everyone.

In this unit you will see William Stanley light a whole street with the first transformers, find out why water towers stand so tall, follow the building of Hoover Dam, and walk beneath London with Joseph Bazalgette, whose sewers made a great city healthy again. You will build a model grid, a water-pressure test, a dam-cooling experiment and model sewers, and you will learn how engineers serve their neighbors through work that most people never see.

PREREQUISITES

- Can build a battery circuit and draw a circuit diagram (Unit 4)
- Knows that water held up high has potential energy (Unit 1)
- Can measure, time and record results in a table

MASTERY CHECKLIST

- ☐ I can trace electricity from a power plant through transformers and lines to a house, and explain why houses are wired in parallel.
- ☐ I can explain why a water tower is tall and how the height of water makes pressure.
- ☐ I can explain why Hoover Dam is thick at the bottom and how its builders cooled the concrete.
- ☐ I can tell how Joseph Bazalgette's sewers made London healthy and why sewers need the right shape and slope.
- ☐ I can name safety rules for power lines, substations, manholes and digging.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco):** Ages 8 and up. Useful for building the model grid in Lesson 5.1, with several lamps wired in parallel like houses on a street.

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 The Electric Grid: William Stanley's Transformers	2 sessions of 45 minutes
5.2 Water Towers and Water Pressure	2 sessions of 45 minutes
5.3 Hoover Dam: Taming a River	2 sessions of 45 minutes
5.4 Joseph Bazalgette and London's Sewers	2 sessions of 45 minutes

UNIT 5 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

- 5 pts**
Put these in order from the power plant to your house: substation, pole transformer, generator, transmission lines, step-up transformer.
- 5 pts**
Why is electricity sent across the country at very high voltage?
- 5 pts**
Predict: on a street wired in series, one house turns off its lamp. What happens to the others? Why are real houses wired in parallel?
- 5 pts**
What did William Stanley do in Great Barrington in 1886?

5. (5 pts)

Predict: you raise your funnel “water tower” from 30 to 90 centimeters. What happens to the fountain? Why?

6. (5 pts)

Give two reasons a town builds a water tower.

7. (5 pts)

Why is Hoover Dam much thicker at the bottom than at the top?

8. (5 pts)

Why did Hoover Dam’s builders pour the concrete in blocks with cooling pipes?

9. (5 pts)

Why did Bazalgette build egg-shaped sewers with the narrow end down?

10. (5 pts)

Name three safety rules about utilities.

ANSWER KEY

1. Generator → step-up transformer → transmission lines → substation → pole transformer (→ house).
2. High voltage lets the same energy travel with less current, so much less energy is wasted as heat in the wires.
3. In series, all the lamps go out because the loop is broken. Houses are wired in parallel so each gets full voltage and can switch its own lights without affecting the others.
4. He sent alternating current at high voltage to Main Street and used transformers to lower it for lamps, lighting the shops and offices: the first town lit this way.
5. It shoots higher, because a taller column of water makes more pressure.
6. Any two: gravity pushes the water to houses with steady pressure; it stores water so pumps can run steadily; it supplies extra water when many people use it at once or for firefighting; it smooths out pump surges.
7. Water pressure grows with depth, so the water pushes hardest at the bottom of the dam.
8. Concrete heats up as it hardens. Poured in one piece, the dam would have taken more than a hundred years to cool and would have cracked. Blocks with cold water in pipes cooled quickly.
9. When only a little water flows, it collects in the narrow bottom and stays deep and fast enough to carry solids along, so the sewer cleans itself. The wide top holds big storm flows.
10. Any three: never touch or go near power lines or fallen wires; stay away from substations and transformers; never fly kites or drones near power lines; never open or enter manholes or storm drains; call 811 before anyone digs; use only batteries for experiments.

PORTFOLIO PIECE: MY TOWN’S UTILITY MAP

Make a large map or model of a small town that shows how it gets electricity and water and how its sewage is carried away. Include a power plant, transformers, transmission and distribution lines, a substation, a water tower on high ground, water mains, sewers that slope downhill, and a treatment plant. Add one working part from this unit, such as your model street of lamps or your water-tower fountain, and a page explaining how each system works and three safety rules for children.

LOOK FOR	WHAT IT MEANS
Complete systems	Power, water and sewer systems are all shown, each with its main parts labeled.
Correct science	Transformers, the water tower’s height and the sewers’ slope are placed and explained correctly.
Working part	One working model is included, tested and explained.
Safety	At least three correct utility safety rules are written clearly.
Explanation	The student can walk a visitor through the map, explaining how each utility serves the town.

5.1 THE ELECTRIC GRID: WILLIAM STANLEY'S TRANSFORMERS

OBJECTIVES

- Name the main parts of the electric grid: power plant, generator, transformers, transmission lines, substations and distribution lines.
- Tell how William Stanley used transformers to light a town in 1886, and explain why electricity is sent at high voltage.
- Build a model street of lamp “houses” and compare series and parallel wiring with a fair test.

Warm-up. Look out a window or take a short walk with an adult. Find power poles or lines. Count the wires on one pole. Look for a gray metal can on a pole or a green box on the ground. Those are transformers. Draw what you see. (Look only; never touch or climb.)

WATCH

Electrical Grid 101 : All you need to know ! (With Quiz)

Engineering World · 3:47

<https://www.youtube.com/watch?v=nbPmsBmo03Y>

WHEN TO WATCH

After the story. Follow the electricity from the generating plant to the house, and stop to answer the quiz at the end.

BACKUP VIDEO

How Transformers Work

Northwest Lineman College · 2:05

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

After the physics paragraph, to see how the transformer on a pole steps the voltage down for houses.

KEY TERMS

generator

A machine that turns spinning motion into electricity, using magnets and coils of wire.

transmission line

A high-voltage line on tall towers that carries electricity a long way from the power plant.

grid

The whole connected network of power plants, lines and transformers that brings electricity to everyone.

transformer

A device that raises or lowers the voltage of alternating current, using two coils of wire around an iron core.

substation

A fenced yard of transformers and switches where high voltage is lowered for the lines in town.

alternating current

Electric current that switches direction back and forth many times every second (AC).

CORE IDEAS

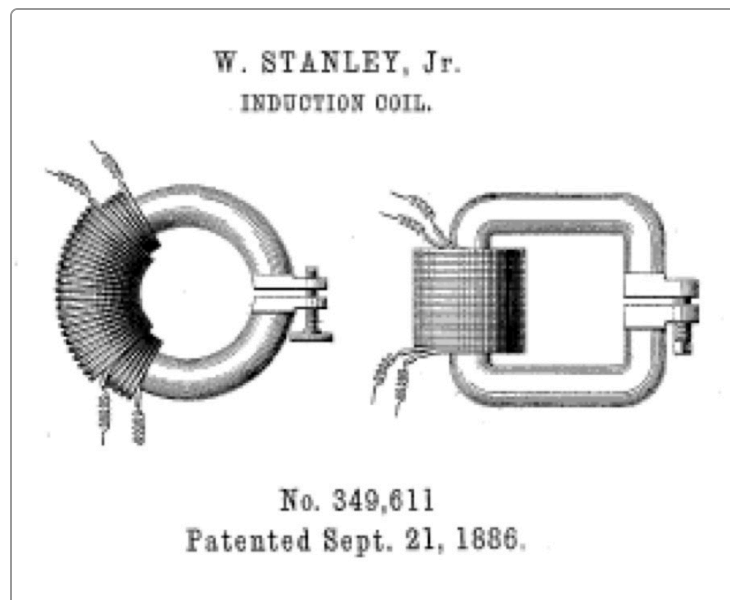
The story. Edison's first power stations sent direct current a short way through thick copper wires, so a station could only serve homes within about a mile. To light a whole country that way would take thousands of stations. A young engineer named William Stanley, working for George Westinghouse, believed there was a better way. In the winter of 1886 he set up a small generator in an old rubber mill in Great Barrington, Massachusetts. He sent **alternating current** at high voltage along wires strung through the trees to Main Street, and there, in the basements of the shops, his **transformers** lowered the voltage to a safe level for lamps. On March 20, 1886, the shops and offices of Main Street glowed with electric light.

How they figured it out. European inventors had built early transformers, but they were not practical for a town. Stanley built his own, wound coils on cores made of thin iron plates, and tested them in his laboratory, changing the windings until they worked well and stayed cool. He tested the whole system on a small scale first: a generator, a line about four thousand feet long, and transformers serving a few dozen lamps. When it worked, Westinghouse bought the rights and began building AC systems across the country. Within ten years, AC generators at Niagara Falls were sending power more than twenty miles to the city of Buffalo.

The physics. A **generator** spins coils of wire past magnets, which pushes current through the wire. Electricity loses some energy as heat as it travels along a wire, and the bigger the current, the more it loses. A **transformer** can raise the voltage and lower the current at the same time, so the same amount of energy travels with much less loss. Near the power plant, transformers step the voltage way up for the long **transmission lines**. At a **substation** it is stepped down for the lines through town, and a transformer on a pole or in a green box steps it down again for your house. Inside your home, every lamp and outlet is wired in parallel, so each one gets the full voltage and can be switched on or off by itself.

The engineering. The **grid** must make exactly as much electricity as people are using at every moment, so operators watch it day and night. Power plants use many energy sources, such as falling water, coal, natural gas, nuclear fuel, wind and sunlight, and engineers weigh what each costs, how reliable it is and what it needs. Lineworkers climb poles and repair lines in storms so others can have light and heat; it is skilled and dangerous work. Everyone else must stay far away from power lines: never fly a kite or drone near them, never touch a fallen line, and always call 811 before anyone digs.

PICTURE STUDY



Stanley's Transformer, William Stanley, 1886 · Patent drawing · United States Patent Office

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

This drawing shows the kind of transformer William Stanley built for Great Barrington. The same idea is inside every transformer on every power pole today.

Look closely

- Find the iron core. Can you see that it is made of many thin plates?
- Find the two coils of wire. Do they look the same, or does one have more turns?
- Find where the wires come in and go out.
- Look for labels or letters an engineer would use to explain the parts.

Talk about it

1. Why would a transformer with more turns on one coil than the other change the voltage?
2. Why was it important for the transformer to stay cool?
3. How did this small machine make it possible to send electricity far from the power plant?

Safety first. Use only batteries for this build. Never touch, climb or go near power lines, poles with equipment, transformers or substations, and never touch a fallen wire; tell an adult and call for help. Electricity from the wall is far too dangerous for experiments.

BUILD

A Model Street: Wiring Houses in Series and in Parallel

You will make a model street of three or four paper “houses,” each with a small bulb or LED inside, powered by a battery “power plant.” You will wire them two ways, in series and in parallel, and compare how bright the lamps are and what happens when one house turns its lamp off.

You will need

- A battery holder with 2 AA batteries (the power plant)
- 3 or 4 small bulbs in holders (or LEDs, each with a resistor of about 100 ohms)
- 8–10 alligator clip leads
- Small boxes or folded card for houses, and a long strip of cardboard for the street
- Engineer’s notebook

Steps

1. **Draw first.** Draw a circuit diagram of the battery with three lamps in series (one loop) and another with three lamps in parallel (each lamp on its own branch).
2. **Predict.** In which wiring will the lamps be brighter? What will happen to the others if one lamp is unscrewed?
3. **Series street.** Build the series circuit with each lamp inside a house. Rate each lamp’s brightness from 0 (off) to 3 (bright). Unscrew one lamp. Record what happens.
4. **Parallel street.** Rebuild it in parallel. Rate the brightness and unscrew one lamp again. Record what happens.
5. **Fair test.** Test 1, 2, 3 and then 4 houses in series and then in parallel. Change only the number of houses. Rate the brightness each time and make a table.
6. Write a rule: which way of wiring gives every house full brightness and lets each house switch its own lamp?

7. **Improve.** Add a paper-clip switch (from Lesson 4.4) to each house on your parallel street, and a “main switch” at the power plant. Test that each house can turn its own light on and off, and that the main switch turns off the whole street.

Tips

- Look at the lamps in a dim room so you can judge brightness better.
- If nothing lights, check every clip, and turn LEDs around.
- Parallel circuits drain the batteries faster because each house uses its own current. Disconnect when you are not testing.

Check your work

- ☐ I can explain why houses are wired in parallel.
- ☐ I can trace electricity from the power plant to my house and name each part.
- ☐ I can name three safety rules for power lines.

ENGINEER’S NOTEBOOK

1. Draw the grid as a picture map: power plant, step-up transformer, transmission towers, substation, distribution lines, pole transformer and house. Label each part.
2. Make a table of your fair test: number of houses, series brightness, parallel brightness.
3. Write a thank-you note to a lineworker telling what you learned about the work.

From history. William Stanley later started his own electric company in Pittsfield, Massachusetts. A historical marker on Main Street in Great Barrington tells the story of the first town lit by alternating current through transformers, and the same kind of AC system now powers nearly every home in the world.

COMMON MISTAKES

- Thinking electricity comes from the outlet. The outlet is only the end of a long path from a power plant.
- Thinking high voltage is used because it is “stronger.” It is used because it wastes less energy over long distances.
- Thinking a bird on a wire means wires are safe to touch. Never touch any power line.

Make it a game • Power Line Relay. Line up five objects for the grid: power plant, generator, transformer, substation and house. Mix them up. Your parent times you putting them in order and saying what each does. Try for under thirty seconds. Then explain in one sentence why William Stanley sent electricity at high voltage before stepping it down.

Scripture. “And God said, Let there be light: and there was light.” (Genesis 1:3, KJV)

God made light with a word. People must work hard with generators, wires and transformers to bring a little light into dark rooms, and that work is a way of serving our neighbors.

5.2 WATER TOWERS AND WATER PRESSURE

OBJECTIVES

- Explain how the height of water creates pressure.
- Tell why cities built tall water towers and standpipes, using the Chicago Water Tower as an example.
- Build a gravity water system and measure how the height of the “tower” changes the pressure at the tap.

Warm-up. Fill a plastic bottle with water and hold it over a sink. With an adult, poke three small holes one above the other with a pushpin. Which stream shoots out farthest? Why do you think the water at the bottom pushes hardest?

WATCH

How Water Towers Work

Practical Engineering · 10:59

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

WHEN TO WATCH

After the physics paragraph. Pause when the drawing shows the tank above the houses and explain why the water flows into them.

BACKUP VIDEO

How it Works: Water Tower

City of Bloomington, Minnesota · 2:20

<https://www.youtube.com/watch?v=ZI8WOzqHl7w>

A short tour of a real city water tower and the people who run it.

KEY TERMS

water pressure

How hard water pushes on everything it touches.

water tower

A tall tank that stores water high above a town, so gravity pushes it through the pipes.

pump

A machine that pushes water, often up into a tower or through pipes.

standpipe

A tall pipe or tank, open at the top, connected to a water system to keep the pressure steady.

water main

A large underground pipe that carries water under the streets.

CORE IDEAS

The story. In the 1860s Chicago was growing fast, and its water was pumped from Lake Michigan by great steam pumps. But a steam pump pushes in strokes, and each stroke sent a surge through the pipes that could shake and crack them. The engineer Ellis Chesbrough planned a new waterworks, and beside it the city built a tall stone tower around an iron **standpipe** about 138 feet high. The pumps pushed water up the standpipe, and the column of water inside smoothed out the surges and kept the pressure steady. The Chicago Water Tower was finished in 1869. Two years later, in the Great Chicago Fire of 1871, most of the city around it burned, but the stone tower survived. It still stands on Michigan Avenue.

How they figured it out. Engineers had long known that water seeks its own level: water in connected pipes rises to the same height everywhere. If a tank is higher than every house, water will flow into every house by gravity alone. So towns began building elevated tanks on the highest hill in town or on tall steel legs. Engineers measured how much water a town used each hour of the day and found that people use the most water in the morning and evening. A tower stores water during the quiet hours, so the pumps can run steadily, and then gives out extra water when everyone needs it at once, or when firefighters need a great deal in a hurry.

The physics. Water is heavy. A column of water presses down on everything below it, and the taller the column, the harder it presses. That push is **water pressure**. Every foot of height adds the same amount of pressure, so a tank twice as high gives twice the pressure at the bottom. That is why the lowest hole in your bottle squirted farthest. A **water tower** does not need to be full of a huge amount of water to give strong pressure; what matters most is how high the water stands above the tap.

The engineering. City engineers choose a tower's height so the pressure is strong enough to reach the top floors of houses and to fight fires, but not so strong that it bursts pipes. **Pumps** fill the tower, usually at night when electricity costs less. **Water mains** run under the streets in loops, so if one pipe breaks, water can reach houses another way. Very tall buildings have their own pumps and rooftop tanks. Water towers are painted, inspected and cleaned regularly. Clean water at the right pressure, day and night, is one of the quiet gifts that engineers and water operators give their neighbors.

PICTURE STUDY



The Townsend Water Tower, Historic American Engineering Record, Photograph of a tower built in the early 1900s · Photograph · Library of Congress, Prints and Photographs Division

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

This photograph shows the water tower of the small town of Townsend, Delaware. Towers like this stood in thousands of American towns. They work on the same idea as Chicago's great standpipe: water held high above the houses.

Look closely

- Find the tank at the top. Why is it so high?
- Find the four legs. Can you see the diagonal braces between them? What shape do they make?
- Find the pipe running down the middle. Which way does the water go in it?
- Compare the height of the tank with the roofs of the houses.

Talk about it

1. Why must the water in the tank be higher than the houses?
2. Why do the legs need diagonal braces? (Think back to triangles in Unit 2.)
3. What would happen to the pressure in the houses if the tank were nearly empty?

Safety first. Do this build outdoors, in a bathtub or over a sink with an adult. Never go near storm drains, manholes or water towers; they are dangerous places to explore.

BUILD

How High Is the Tower? A Gravity Water System Test

You will build a model water system: a funnel or bottle “tower” connected by a long tube to a “tap” at the bottom. Then you will raise the tower to different heights and measure how high the water squirts from the tap, which shows the pressure.

You will need

- A funnel or a plastic bottle with its bottom cut off (by an adult)
- About 1.5 meters of clear plastic tubing that fits the funnel
- A drinking straw or a ballpoint-pen tube for the nozzle, taped into the end of the tubing
- A pitcher of water, a ruler or tape measure, and tape
- A step stool, a chair and a stack of books to hold the tower at different heights
- A dishpan or the bathtub

Steps

1. **Build.** Push the funnel into one end of the tubing and tape the nozzle into the other. Pinch the tube near the nozzle so no water escapes.
2. **Predict.** If you raise the funnel twice as high, will the water squirt twice as high? Write your guess.
3. **Test.** Hold the nozzle pointing straight up, 10 centimeters above the bottom of the dishpan. Have a partner hold the funnel so its bottom is 30 centimeters above the nozzle. Fill the funnel, keep it full, and release the pinch. Measure how high the fountain rises above the nozzle.
4. Repeat with the funnel 60, 90 and 120 centimeters above the nozzle. Keep the funnel full each time. Change only the height. Do each height twice.
5. Record your results and make a line graph: tower height (across) and fountain height (up).
6. **Fair test 2.** Keep the height at 60 centimeters, but compare a nearly empty funnel with a full one. Does the amount of water or the height of the water

matter more?

7. **Improve.** Add a second “house” tap using a T-connector or a second tube from a bottle. Open both at once. Does the pressure drop? How could a town keep strong pressure when everyone uses water at once?

Tips

- The fountain never quite reaches the height of the tower, because the water rubs on the tube. Real pipes lose some pressure the same way.
- Keep the tube free of kinks and air bubbles.
- Have one person watch the fountain against a ruler held behind it at eye level.

Check your work

- ☐ I can explain why the height of the water makes pressure.
- ☐ My graph shows how tower height changed the fountain height.
- ☐ I can explain why a town builds its water tower on high ground.

ENGINEER'S NOTEBOOK

1. Draw a water tower on a hill with pipes running to three houses at different heights. Mark which house gets the strongest pressure.
2. Make a table and line graph of tower height and fountain height.
3. Draw the Chicago Water Tower and label the standpipe.

From history. Ellis Chesbrough, who planned Chicago's waterworks, also built a tunnel two miles out under Lake Michigan in 1867 so the city could draw cleaner water far from shore. Workers dug from the shore and from a crib built two miles out in the lake, and the two tunnels met almost perfectly, a triumph of careful surveying.

COMMON MISTAKES

- Thinking a wider tank gives more pressure. The height of the water matters, not how wide the tank is.
- Thinking water towers are only for storage. They also keep pressure steady and give extra water in emergencies.
- Thinking the water in a tower is pushed up by the tower. Pumps lift it; the tower lets gravity push it back down.

Make it a game • Tower Height Duel. Poke a hole in the side of a plastic bottle near the bottom and another higher up, then, over a sink, fill it and watch the streams. Predict which squirts farther and why. Explain what water pressure is and why cities built water towers. Your parent scores each correct explanation. Beat your last score next time.

Scripture. “As cold waters to a thirsty soul, so is good news from a far country.” (Proverbs 25:25, KJV)

Cold water is such a simple gift that we forget how many engineers and workers it takes to bring it to us. Be thankful for it.

5.3 HOOVER DAM: TAMING A RIVER

OBJECTIVES

- Tell the story of building Hoover Dam and the problems its engineers solved.
- Explain why a dam is thicker at the bottom and how an arch dam pushes against the canyon walls.
- Run a fair test of how cooling pipes help a warm “concrete” block cool faster, as Hoover Dam’s builders did.

Warm-up. Put your palms together and push as hard as you can. Now bend your fingers and press only your fingertips together in an arch. Then have someone press on the curve of your arch from outside. Which way does the push go, into your wrists or out sideways?

WATCH

Hoover Dam | All the Secrets of the Engineering Wonder

Sabin Civil Engineering • 9:47

<https://www.youtube.com/watch?v=hopBzK6BOwo>

WHEN TO WATCH

After the story. Watch for the arch shape, the tunnels that moved the river and the pipes buried in the concrete.

Note: A clear 3D animation. Pause on the gravity-arch drawings and ask where the water pushes.

KEY TERMS

dam

A wall built across a river to hold back water.

reservoir

The lake that forms behind a dam.

arch-gravity dam

A dam that holds back water both by its great weight and by its curved shape, which pushes the load into the canyon walls.

diversion tunnel

A tunnel that carries a river around the place where a dam is being built.

turbine

A wheel with blades that spins when water or steam rushes through it, turning a generator.

CORE IDEAS

The story. The Colorado River flooded farms in spring and dried to a trickle in late summer. In 1931 the United States began building a great dam in Black Canyon, on the border of Nevada and Arizona, to control the floods, store water for farms and cities, and make electricity. Thousands of men came to work in the desert heat. They finished in 1936, two years ahead of schedule. The dam is 726 feet tall, as tall as a 60-story building, and the **reservoir** behind it is one of the largest lakes made by people in the country. The work was dangerous; many workers were injured, and some were lost.

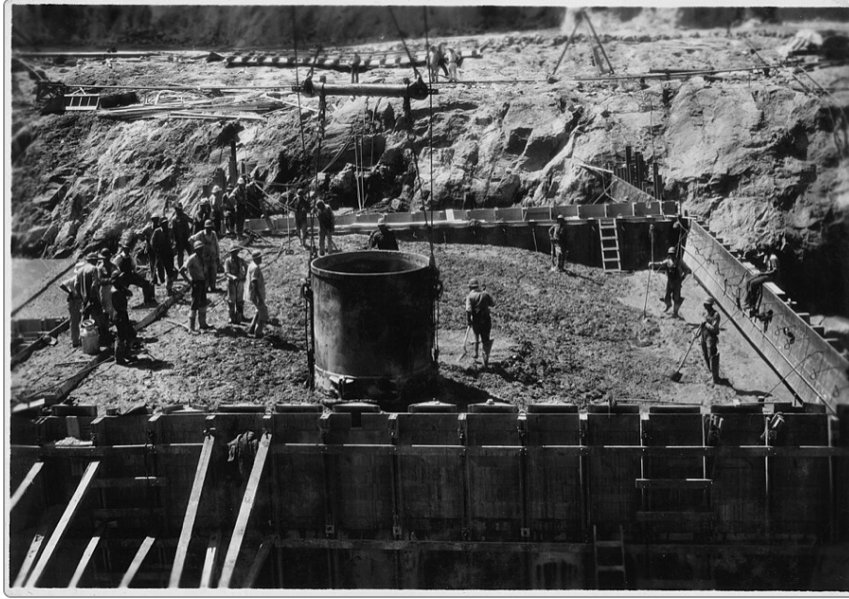
How they figured it out. First the river had to be moved. Workers blasted four huge **diversion tunnels**, each about 56 feet across, through the canyon walls, then built temporary dams to send the whole river through them. “High scalers” hung from ropes on the canyon walls to knock loose rock away. Then came the concrete. Concrete gets hot as it hardens, and engineers calculated that a dam this big, poured in one piece, would take more than a hundred years to cool, cracking as it shrank. So they poured it in separate blocks, like giant building blocks, and buried more than 580 miles of steel pipes in the concrete. Cold river water, then chilled water from a refrigeration plant, flowed through the pipes and carried the heat away. When the blocks had cooled, the pipes were filled with grout.

The physics. Water pressure grows with depth, as you saw with the holes in the bottle. At the bottom of the reservoir, the water pushes far harder than at the top. That is why Hoover Dam is about 660 feet thick at its base but only about 45 feet thick at the top. The dam is also curved like an arch, bowed toward the water. When the water pushes on the curve, the arch squeezes the push sideways into the solid rock of the canyon walls. Hoover is an **arch-gravity dam**: its weight and its shape both hold the water back.

The engineering. Water from the reservoir flows down through huge pipes to the power plant at the base of the dam. There it spins **turbines** that turn generators, making electricity for millions of people in three states, with no fuel to burn. Dams

are a trade-off. They store water, stop floods and make power, but they cover land and change the river below them. Engineers inspect Hoover Dam constantly and measure tiny movements in the concrete. It was built to last, and almost ninety years later it still does its work every day.

PICTURE STUDY



Placing Concrete at Hoover Dam, U.S. Bureau of Reclamation, 1930s · Photograph · National Archives and Records Administration

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

This government photograph was taken while Hoover Dam was being built. The dam rose one block at a time, and huge buckets of concrete swung down from cables stretched across the canyon.

Look closely

- Find the giant bucket. Each one carried eight cubic yards of concrete, enough to fill a small room.
- Find the workers. How big are they next to the bucket?
- Look at the edges of the blocks. Can you see that the dam is made of separate columns?
- Look for pipes, hoses or wooden forms.

Talk about it

1. Why did the engineers pour the dam in separate blocks instead of all at once?
2. How do you think the bucket was moved across the canyon?
3. What safety dangers can you see for the workers?

Safety first. An adult handles the hot tap water. Use water only as warm as a comfortable bath, never boiling. Wipe up spills.

BUILD

Cooling the Concrete: A Fair Test of Cooling Pipes

Fresh concrete gets warm as it hardens. You will use two cups of warm water (or warm sand) as “concrete blocks.” One will have a coil of tubing through it with cold water running through, like the pipes in Hoover Dam. You will measure which cools faster.

You will need

- Two identical plastic cups or jars
- Warm tap water (or sand warmed in the sun), the same amount in each cup
- About 1 meter of clear plastic tubing (or several bendable straws taped end to end)
- A funnel and a pitcher of ice water, and a bowl to catch the water
- Two kitchen thermometers (or one, read quickly in each cup)
- A stopwatch and engineer’s notebook

Steps

1. **Warm-up test.** Poke holes in a tall bottle at three heights (bottom, middle, top), fill it over the sink and measure how far each stream shoots. Record the distances. This shows why a dam is thick at the bottom.
2. **Build.** Coil the tubing inside cup B so both ends hang over the edge. Put the funnel in one end. Cup A gets no tubing.
3. Fill both cups with the same amount of warm water. Put a thermometer in each and record the starting temperature.
4. **Predict.** Which cup will be cooler after 10 minutes? By how much?
5. **Test.** Slowly pour ice water through the funnel so it runs through the coil in cup B and out into the bowl. Keep it flowing. Record both temperatures every 2 minutes for 10 minutes.
6. Make a line graph with two lines: time (across) and temperature (up), one line for each cup.

7. **Improve.** Change one thing about the cooling pipe (a longer coil, faster flow, colder water) and repeat the test. Which change helped most?

Tips

- Start both cups at the same temperature, within a degree or two.
- Keep the cups away from a sunny window or a fan so the only difference is the pipe.
- Stir each cup gently with the thermometer before reading it.

Check your work

- ☐ I can explain why Hoover Dam is thicker at the bottom than at the top.
- ☐ My graph shows how much the cooling pipe helped.
- ☐ I can explain why the builders needed to cool the concrete.

ENGINEER'S NOTEBOOK

1. Draw a side view of Hoover Dam with the reservoir behind it. Draw arrows for the water pressure, longer arrows at the bottom.
2. Draw the dam from above and show how the arch pushes the load into the canyon walls.
3. Make a table and a two-line graph of your cooling test.

From history. The superintendent of construction, Frank Crowe, had built many dams in the West and was famous for planning every step. The dam was first called Boulder Dam and was officially named Hoover Dam in 1947 after President Herbert Hoover, who had helped arrange the agreement among the states that share the Colorado River.

COMMON MISTAKES

- Thinking a dam curves out toward the river below. Hoover Dam bows toward the water it holds back.
- Thinking water pressure depends on how big the lake is. It depends on how deep the water is.
- Starting the two cups at different temperatures, which spoils the fair test.

Make it a game • Dam Builders' Quiz. Pretend you are a Hoover Dam chief engineer.

Your parent plays a worried reporter and asks questions like "Why is the dam thicker at the bottom?" and "What does a diversion tunnel do?" Answer in full sentences. Add one problem the engineers solved, like cooling the concrete. Three good answers in a row win the round.

5.4 JOSEPH BAZALGETTE AND LONDON'S SEWERS

OBJECTIVES

- Tell how Joseph Bazalgette planned and built the London sewers after the Great Stink of 1858.
- Explain why sewers need a steady slope and why Bazalgette used egg-shaped pipes.
- Build model sewer channels of different shapes and test which carries “waste” away best with a small flow of water.

Warm-up. Pour a little water with a pinch of sand into a flat baking pan tilted slightly. Watch where the sand stops. Now pour the same water and sand down a folded piece of card shaped like a V. Which carries the sand farther?

WATCH

How Sewers Work (feat. Fake Poop).

Practical Engineering · 12:27

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

WHEN TO WATCH

After the story. Look for Bazalgette's plaque near the start, and watch the clear-pipe model test closely before your own build.

Note: A civil engineer explains sewer slopes with a clear-pipe model and pretend waste. The subject is handled plainly and without crude humor, though the title uses a common word.

KEY TERMS

sewer

An underground pipe or tunnel that carries away dirty water from homes and streets.

intercepting sewer

A large sewer that collects the flow from many smaller sewers and carries it away.

slope

How steeply a pipe or channel slants downhill.

pumping station

A building with pumps that lift sewage or water up to a higher level so it can keep flowing.

self-cleaning

Flowing fast enough to carry solids
along so they do not settle and clog the
pipe.

CORE IDEAS

The story. In the 1850s London was the largest city in the world, and nearly all its waste flowed straight into the River Thames, the same river many people drew their drinking water from. Terrible outbreaks of cholera swept the city, and many people became sick. In the hot summer of 1858 the river smelled so bad that it was called “the Great Stink,” and the curtains of the Houses of Parliament were soaked in lime to cover the smell. At last the government gave Joseph Bazalgette, chief engineer of the Metropolitan Board of Works, the money and power to fix it. Work began in 1859, and the main system was opened in 1865.

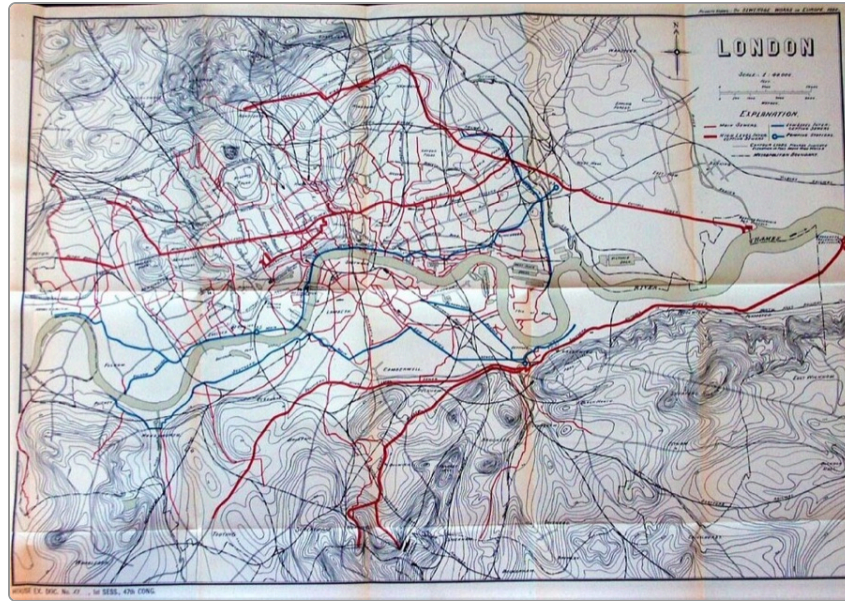
How they figured it out. Bazalgette’s plan was to catch the waste before it reached the river. He built great **intercepting sewers** running east along both sides of the Thames, collecting the flow from the old sewers and carrying it many miles downstream, away from the city. He built about 82 miles of main sewers and 1,100 miles of street sewers, using about 318 million bricks. He tested every batch of cement and refused any that was weak. He measured how many people lived in each district and how much it rained, and then he made his sewers much larger than the numbers required, because he expected London to grow. Where the land was too flat, he built steam **pumping stations** to lift the sewage so it could flow downhill again.

The physics. A sewer works by gravity, so every pipe must have a steady downhill **slope**. If the slope is too gentle, the water moves slowly, and solids settle and clog the pipe. If the flow is fast enough, it carries the solids along and the sewer is **self-cleaning**. The problem is that the amount of water changes: a great deal in a storm, very little on a dry night. Bazalgette used egg-shaped sewers, with the narrow end at the bottom. When only a little water flows, it gathers in the narrow bottom, where it stays deep enough and fast enough to keep moving. When a lot flows, the wide top gives it room.

The engineering. Bazalgette’s sewers ended the cholera outbreaks caused by dirty water, and the river slowly became clean again. He also built the Victoria, Albert and

Chelsea Embankments along the Thames, with sewers, an underground railway and gas pipes inside them and wide roads and gardens on top. More than 150 years later, his sewers still serve London, and engineers have now built a new “super sewer” tunnel deep under the river to carry the overflow from a much larger city. Engineers say his decision to build bigger than needed is the reason his system has lasted so long. Clean water and safe sewers save more lives than almost any other invention.

PICTURE STUDY



Map of London's Main Drainage, Rudolph Hering, 1881 · Engineering drawing · From Hering's report on European sewer systems for the U.S. National Board of Health

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

In 1880 an American engineer named Rudolph Hering traveled to Europe to study the best sewer systems so that American cities could learn from them. This map from his report shows the main sewers of London, with Bazalgette's great intercepting sewers running along both sides of the Thames.

Look closely

- Find the River Thames winding through the middle of the map.
- Find the long colored lines that run east, roughly along the river. These are the intercepting sewers.
- Follow them east to where they end, far downstream of the city.
- Look for smaller lines joining the big ones. Those are sewers from the streets.

Talk about it

1. Why did Bazalgette carry the waste so far east, away from the city?
2. Why do sewers on both sides of the river need their own intercepting sewers?
3. Where on this map would you build a pumping station, and why?

Safety first. Wash hands after the build. Never open, climb into or play near manholes or storm drains; they can fill with water quickly and contain harmful gases.

BUILD

Flat, V or Egg? A Model Sewer Test

You will build three model sewer channels of the same length and slope but different shapes: a flat-bottomed box channel, a V-shaped channel and an egg-shaped channel. You will send the same small flow of water carrying sand down each one and measure how much sand is left behind.

You will need

- Three strips of card stock or file folders, each about 60 centimeters long (tape two together if needed)
- A paper towel tube or a cut plastic bottle to help bend the egg shape
- Tape, a ruler and a stack of books to set the slope
- A measuring cup and a teaspoon of sand (or dry rice) for each test
- A dishpan to catch the water, and a spoon
- Engineer's notebook

Steps

1. **Build.** Make three channels from card: (A) a flat bottom 4 centimeters wide with low sides; (B) a V folded down the middle; (C) an egg shape, round and narrow at the bottom and wider at the top, formed by bending card around a tube. Tape the sides so each holds its shape. Use packing tape to make them water-resistant.
2. **Set the slope.** Rest the top end of each channel on books so it is 3 centimeters higher than the bottom end. Measure carefully; the slope must be the same for all three.
3. **Predict.** Which shape will carry the sand away best with only a little water?
4. **Test with a dry-weather flow.** Put one teaspoon of sand 5 centimeters from the top. Slowly pour 100 milliliters of water at the top over 10 seconds. Scoop up the sand left in the channel, let it dry or just compare piles, and rate it: none, a little, half, most.
5. Test each channel three times the same way, cleaning it between tests.

6. **Storm test.** Repeat with 500 milliliters poured quickly. Do the shapes still differ?
7. Record all results in a table. Which shape was the most self-cleaning in dry weather?
8. **Improve.** Try your best shape at a gentler slope (1.5 centimeters). Is it still self-cleaning? Find the gentlest slope that still carries all the sand.

Tips

- Pour from the same height and at the same speed every time.
- Smooth seams make a big difference; bumps catch sand, just as rough joints catch solids in real sewers.
- Rice is easier to see and count than sand if you prefer.

Check your work

- ☐ I can explain why a sewer needs a steady slope.
- ☐ I can explain why Bazalgette's egg-shaped sewers worked well when the flow was small.
- ☐ I tested three shapes fairly and recorded the results.

ENGINEER'S NOTEBOOK

1. Draw cross sections of your three channels with a small amount of water in each. Shade the water and show how deep it is.
2. Make a table: channel shape, dry-weather result (three trials), storm result.
3. Draw a map of the Thames with Bazalgette's intercepting sewers running along both sides and out to the east.

From history. Bazalgette was knighted in 1875 for his work. His pumping station at Crossness, with its huge beam engines and beautiful painted ironwork, has been restored by volunteers and can be visited today. A monument to him on the Victoria Embankment, above one of his sewers, carries a Latin motto meaning "He put the river in chains."

COMMON MISTAKES

- Thinking a steeper sewer is always better. Too steep wears out pipes, and engineers must also keep sewers from getting too deep underground.

- Thinking the sewers cleaned the water. Bazalgette's first system carried waste away from the city; treatment plants were added later.
- Using different slopes for different channels, which spoils the fair test.

Make it a game · The Great Stink Story. Build a story chain with your parent about London in 1858. Each person adds one sentence in turn: the smell, the Thames, Joseph Bazalgette's plan, the slope of the sewer, the egg-shaped pipes. Each sentence must include a correct fact. If someone adds a wrong fact, the other calls "flush it" and corrects it.

UNIT 5

PUBLIC UTILITIES

When you flip a switch or turn on a tap, you are using some of the greatest machines ever built. Behind every light is a power plant, a web of wires and transformers called the grid, and the lineworkers who keep it running. Behind every faucet is a water tower or a pumping station pushing clean water through miles of pipes, and behind every drain is a sewer carrying dirty water safely away. These are the public utilities, and engineers design them to work every hour of every day for everyone.

In this unit you will see William Stanley light a whole street with the first transformers, find out why water towers stand so tall, follow the building of Hoover Dam, and walk beneath London with Joseph Bazalgette, whose sewers made a great city healthy again. You will build a model grid, a water-pressure test, a dam-cooling experiment and model sewers, and you will learn how engineers serve their neighbors through work that most people never see.

PREREQUISITES

- Can build a battery circuit and draw a circuit diagram (Unit 4)
- Knows that water held up high has potential energy (Unit 1)
- Can measure, time and record results in a table

MASTERY CHECKLIST

- ☐ I can trace electricity from a power plant through transformers and lines to a house, and explain why houses are wired in parallel.
- ☐ I can explain why a water tower is tall and how the height of water makes pressure.
- ☐ I can explain why Hoover Dam is thick at the bottom and how its builders cooled the concrete.
- ☐ I can tell how Joseph Bazalgette's sewers made London healthy and why sewers need the right shape and slope.
- ☐ I can name safety rules for power lines, substations, manholes and digging.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco):** Ages 8 and up. Useful for building the model grid in Lesson 5.1, with several lamps wired in parallel like houses on a street.

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 The Electric Grid: William Stanley's Transformers	2 sessions of 45 minutes
5.2 Water Towers and Water Pressure	2 sessions of 45 minutes
5.3 Hoover Dam: Taming a River	2 sessions of 45 minutes
5.4 Joseph Bazalgette and London's Sewers	2 sessions of 45 minutes

UNIT 5 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

Put these in order from the power plant to your house: substation, pole transformer, generator, transmission lines, step-up transformer.

2. **5 pts**

Why is electricity sent across the country at very high voltage?

3. **5 pts**

Predict: on a street wired in series, one house turns off its lamp. What happens to the others? Why are real houses wired in parallel?

4. **5 pts**

What did William Stanley do in Great Barrington in 1886?

5. (5 pts)

Predict: you raise your funnel “water tower” from 30 to 90 centimeters. What happens to the fountain? Why?

6. (5 pts)

Give two reasons a town builds a water tower.

7. (5 pts)

Why is Hoover Dam much thicker at the bottom than at the top?

8. (5 pts)

Why did Hoover Dam’s builders pour the concrete in blocks with cooling pipes?

9. (5 pts)

Why did Bazalgette build egg-shaped sewers with the narrow end down?

10. (5 pts)

Name three safety rules about utilities.

ANSWER KEY

1. Generator → step-up transformer → transmission lines → substation → pole transformer (→ house).
2. High voltage lets the same energy travel with less current, so much less energy is wasted as heat in the wires.
3. In series, all the lamps go out because the loop is broken. Houses are wired in parallel so each gets full voltage and can switch its own lights without affecting the others.
4. He sent alternating current at high voltage to Main Street and used transformers to lower it for lamps, lighting the shops and offices: the first town lit this way.
5. It shoots higher, because a taller column of water makes more pressure.
6. Any two: gravity pushes the water to houses with steady pressure; it stores water so pumps can run steadily; it supplies extra water when many people use it at once or for firefighting; it smooths out pump surges.
7. Water pressure grows with depth, so the water pushes hardest at the bottom of the dam.
8. Concrete heats up as it hardens. Poured in one piece, the dam would have taken more than a hundred years to cool and would have cracked. Blocks with cold water in pipes cooled quickly.
9. When only a little water flows, it collects in the narrow bottom and stays deep and fast enough to carry solids along, so the sewer cleans itself. The wide top holds big storm flows.
10. Any three: never touch or go near power lines or fallen wires; stay away from substations and transformers; never fly kites or drones near power lines; never open or enter manholes or storm drains; call 811 before anyone digs; use only batteries for experiments.

PORTFOLIO PIECE: MY TOWN’S UTILITY MAP

Make a large map or model of a small town that shows how it gets electricity and water and how its sewage is carried away. Include a power plant, transformers, transmission and distribution lines, a substation, a water tower on high ground, water mains, sewers that slope downhill, and a treatment plant. Add one working part from this unit, such as your model street of lamps or your water-tower fountain, and a page explaining how each system works and three safety rules for children.

LOOK FOR	WHAT IT MEANS
Complete systems	Power, water and sewer systems are all shown, each with its main parts labeled.
Correct science	Transformers, the water tower’s height and the sewers’ slope are placed and explained correctly.
Working part	One working model is included, tested and explained.
Safety	At least three correct utility safety rules are written clearly.
Explanation	The student can walk a visitor through the map, explaining how each utility serves the town.

UNIT 6

BOATS AND SHIPS

Why does a steel ship weighing thousands of tons float, when a steel nail sinks? In this unit you will answer that question the way Archimedes did, by measuring. You will learn his principle of buoyancy and use it to predict how many pennies a foil boat can carry before you test it. Then you will meet Samuel Plimsoll, who fought to stop owners from overloading their ships, and you will learn what keeps a boat upright and how engineers mark a safe load.

In the second half of the unit, you will ride with Robert Fulton on the *Clermont*, the steamboat that changed travel on American rivers, and climb the Erie Canal's "Flight of Five" locks at Lockport, where boats were lifted up a cliff by water alone. You will build and test foil boats, a stability tester, a paddle-wheel boat and a working model lock. "They that go down to the sea in ships, that do business in great waters; these see the works of the LORD" (Psalm 107:23-24).

PREREQUISITES

- Can measure length, volume (milliliters) and mass (grams)
- Knows that water pressure grows with depth (Unit 5)
- Can run a fair test and record results

MASTERY CHECKLIST

- ☐ I can state Archimedes' principle and use it to predict how much a boat can carry.
- ☐ I can explain what makes a boat stable and why an overloaded ship is dangerous.
- ☐ I can tell how Robert Fulton's *Cle* worked and why it mattered.
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- ☐ I can explain step by step how a canal lock lifts a boat.
- ☐ I can build and fairly test a boat and improve its design.

LESSONS IN THIS UNIT

6.1 Archimedes' Principle Measured

2 sessions of 45 minutes

6.2 Hull Design and Stability: Samuel Plimsoll's Line

2 sessions of 45 minutes

6.3 Robert Fulton's Clermont: Steam on the River

2 sessions of 45 minutes

6.4 Canals and Locks: The Erie Canal

2 sessions of 45 minutes

UNIT 6 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. 5 pts

State Archimedes' principle in your own words.

2. 5 pts

A foil boat is 10 cm long, 8 cm wide and 3 cm tall. What is its volume? About how many grams can it hold before water reaches its rim (ignore the boat's own mass)?

3. 5 pts

Why does a steel ship float when a steel nail sinks?

4. 5 pts

Predict: you move a heavy lump of clay from the top of your model boat's mast to the bottom of its hull. Will the boat be easier or harder to tip? Why?

5. 5 pts

What is the Plimsoll line, and why did Samuel Plimsoll fight for it?

6. 5 pts

What is freeboard, and why does an overloaded ship lack it?

7. 5 pts

How does a paddle wheel move a boat forward? Name the law of motion.

8. 5 pts

Why was the *Clermont's* 1807 trip so important?

9. **5 pts**

List in order the steps to lift a boat up through a lock.

10. **5 pts**

Give two reasons the Erie Canal was important.

ANSWER KEY

1. An object in water is pushed upward by a force equal to the weight of the water it pushes aside (displaces).
2. $10 \times 8 \times 3 = 240 \text{ cm}^3$, so about 240 grams, because 1 cm^3 of water weighs 1 gram.
3. The ship's hollow hull pushes aside a large volume of water whose weight equals the ship's weight. The small solid nail cannot push aside enough water for its weight.
4. Harder to tip. Weight placed low (ballast) helps the boat come back upright; weight high up makes it roll farther.
5. A mark on a ship's side showing how deep it may safely be loaded. He fought for it because owners were overloading ships and many ships and sailors were being lost.
6. Freeboard is the height of the ship's side above the water. An overloaded ship sits so low that little side is left above the water, so waves can wash aboard.
7. The paddles push water backward, and the water pushes the boat forward: Newton's third law (every action has an equal and opposite reaction).
8. It steamed about 150 miles up the Hudson, against the current and without wind, in 32 hours, and ran reliably and profitably, opening the way for steamboats on rivers all over America.
9. Lower the lock water to the lower level; open the lower gates; the boat enters; close the lower gates; let water in from above until the levels match; open the upper gates; the boat leaves.
10. Any two: it cut shipping costs from about \$100 to about \$10 a ton; it made New York City the greatest port in America; it opened the West to settlement and trade; it trained America's first civil engineers.

PORTFOLIO PIECE: A CARGO BOAT WITH A LOAD LINE

Design and build a cargo boat from foil, card covered in tape, or a plastic container that can carry at least 40 pennies safely. Measure its volume and predict its capacity with Archimedes' principle. Find and mark its load line so it keeps 2 centimeters of freeboard, and test it for stability with a mast pull and the wave test. Record everything, improve the design once, and present the boat with a page explaining your prediction, your results and the meaning of your load line.

LOOK FOR	WHAT IT MEANS
Prediction	The volume was measured and the capacity was predicted correctly with Archimedes' principle.
Load line	A clear load line is marked, with the freeboard and the number of pennies at that line recorded.
Stability testing	Mast-pull and wave tests were done fairly and recorded.
Improvement	One clear change was made after testing, and its result was measured.
Explanation	The student explains buoyancy, stability and the load line in his or her own words.

6.1 ARCHIMEDES' PRINCIPLE MEASURED

OBJECTIVES

- Tell the story of Archimedes and the king's crown, and state Archimedes' principle.
- Explain that a floating boat pushes aside its own weight in water.
- Predict how many pennies a foil boat can carry from its volume, then test the prediction and measure the water it pushes aside.

Warm-up. Fill a bowl to the very top with water and set it in a baking pan. Slowly push an empty plastic cup, open end up, down into the water. What do you feel pushing back? What happens to the water in the bowl? Save the water that spills into the pan.

WATCH

How Much Weight Can Boats Float? | Science Project

Science Buddies • 2:59

https://www.youtube.com/watch?v=s7bopU_N_fQ

WHEN TO WATCH

Before the build. Watch how the volume of the boat is used to predict how many pennies it can hold.

KEY TERMS

buoyancy

The upward push of water (or air) on anything placed in it.

displace

To push aside. A boat displaces water when it sits in it.

Archimedes' principle

The upward push on an object in water equals the weight of the water it pushes aside.

volume

How much space something takes up, measured in cubic centimeters or milliliters.

density

How heavy something is for its size.
Things denser than water sink; things
less dense float.

CORE IDEAS

The story. Archimedes lived in the Greek city of Syracuse, on the island of Sicily, more than two hundred years before Christ. He was the greatest mathematician and engineer of his day. The Roman writer Vitruvius tells a famous story about him. King Hiero had given a goldsmith pure gold to make a crown, but he suspected the goldsmith had kept some gold and mixed in cheaper silver. He asked Archimedes to find out without damaging the crown. Archimedes was puzzled until, stepping into a full bath, he saw the water spill over the side. He realized that an object pushes aside water equal to its own volume, so he could compare the crown with a lump of pure gold of the same weight.

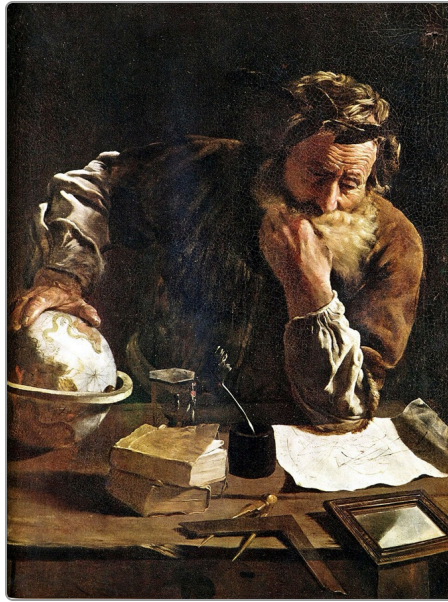
How they figured it out. Archimedes did not stop at one clever trick. He studied floating carefully and wrote a book called *On Floating Bodies*. In it he explained that anything placed in water is pushed upward by a force equal to the weight of the water it pushes aside. A floating object sinks until it has pushed aside exactly its own weight in water, and then it stops sinking. Archimedes reasoned this out with careful geometry and checked it against what he saw. The same idea is used by every shipbuilder today.

The physics. When a boat sits in water, it **displaces**, or pushes aside, some water. The water pushes back up with a force called **buoyancy**. **Archimedes' principle** says that push equals the weight of the water displaced. One milliliter of water weighs one gram, so a boat that weighs 100 grams floats when it has pushed aside 100 milliliters of water. A lump of steel sinks because it cannot push aside enough water for its weight. Shape the same steel into a wide, hollow hull, and it can push aside a great deal of water, enough to float. That is why a steel ship floats.

The engineering. Naval architects, the engineers who design ships, use Archimedes' principle to calculate how deep a ship will sit in the water and how much cargo it can carry. The more **volume** a hull has below the deck, the more water it can push aside, and the more it can carry. But a ship must never be loaded until it sinks to its

deck; it needs extra height above the water to stay safe in waves. That extra height is called freeboard, and you will learn about it in the next lesson.

PICTURE STUDY



Archimedes Thoughtful, Domenico Fetti, 1620 · Oil on canvas · Gemäldegalerie Alte Meister, Dresden

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

Domenico Fetti painted Archimedes as a scholar thinking hard about a problem. No one knows what Archimedes really looked like, but the painter showed what mattered most about him: careful thinking and measuring.

Look closely

- Find the drawing tools on the table. What would Archimedes use them for?
- Look at the drawings or diagrams in his book.
- Look at his face and his hand. What do they tell you about what he is doing?
- Find the light in the picture. Where does it fall most brightly?

Talk about it

1. Why do you think the painter showed Archimedes thinking instead of jumping out of his bath?
2. What problem from this lesson might he be thinking about?
3. How is careful thinking part of an engineer's work, as well as building?

Safety first. Work over a tray or in the bathtub with an adult nearby, and wipe up spills so no one slips.

BUILD

Predict, Then Float: Foil Boats and Displaced Water

You will build a box-shaped foil boat, measure its volume, and use Archimedes' principle to predict how many pennies it can carry. Then you will test it and measure the water it pushes aside.

You will need

- Aluminum foil (squares about 20 by 20 centimeters)
- A ruler, a calculator and a kitchen scale
- About 150 pennies (each U.S. penny made since 1983 weighs 2.5 grams)
- A large bowl, a baking pan to catch overflow, and a measuring cup
- A tub or sink of water, and a towel

Steps

1. **Build.** Fold a square of foil into a box-shaped boat with flat sides, about 8 by 8 centimeters at the bottom and 3 centimeters tall.
2. **Measure.** Measure the length, width and height in centimeters. Multiply them to find the volume in cubic centimeters. Because 1 cubic centimeter of water weighs 1 gram, this is the most mass (in grams) the boat could hold before water reaches the rim.
3. **Predict.** Subtract the boat's own mass. Divide what is left by 2.5 to predict how many pennies it will hold. Write your prediction.
4. **Test.** Float the boat in the tub and add pennies one at a time, spreading them out evenly, until it sinks. Record the number that sank it and subtract one. Do the test twice.
5. Compare your result with your prediction. Was it close? Why might it be a little lower?
6. **Measure the displaced water.** Fill the large bowl to the very brim and stand it in the empty pan. Gently float your boat with 20 pennies in it. Pour the water that spilled into the pan into a measuring cup. Weigh the boat and pennies together. Compare the milliliters of water with the grams of boat and pennies.

7. **Improve.** Using the same size square of foil, design a boat that holds more pennies. Make it wider and shallower, or taller and narrower. Measure its volume, predict, test, and compare.

Tips

- Spread the pennies evenly. Piling them on one side tips the boat and sinks it early.
- Fold the corners carefully so there are no leaks.
- Fill the bowl until the water bulges slightly at the rim before floating the boat in it.

Check your work

- ☐ I can state Archimedes' principle in my own words.
- ☐ I predicted my boat's capacity from its volume and tested it.
- ☐ I showed that a floating boat pushes aside about its own weight in water.

ENGINEER'S NOTEBOOK

1. Draw your boat floating, with an arrow down for its weight and an arrow up for buoyancy. Label each.
2. Make a table: boat design, volume (cm^3), predicted pennies, actual pennies.
3. Write the displaced-water result: mass of boat and pennies (g), water spilled (mL). Are they nearly the same?

From history. Archimedes is also said to have designed the *Syracusia*, one of the largest ships of the ancient world, built for King Hiero, and to have used a system of pulleys to help move it. The Archimedes screw, a spiral inside a tube that lifts water when turned, is still named after him and is still used today.

COMMON MISTAKES

- Thinking heavy things always sink. Shape matters: a heavy hull that pushes aside enough water floats.
- Forgetting to subtract the boat's own mass before predicting the pennies.
- Thinking a floating boat pushes aside its own volume of water. A floating boat pushes aside its own weight of water; a sunken object pushes aside its own volume.

Make it a game • Sink or Float?. Find ten small household objects. Predict aloud whether each floats, then test in a basin. Explain with one sentence each using buoyancy, displace or density. Then retell Archimedes and the king's crown in under a minute to your parent, who sneaks in one wrong detail for you to catch.

Scripture. “They that go down to the sea in ships, that do business in great waters; These see the works of the LORD, and his wonders in the deep.” (Psalm 107:23-24, KJV)
Sailors trust their lives to the same law of buoyancy every day. It never changes, because God made the waters and the laws they follow.

6.2 HULL DESIGN AND STABILITY: SAMUEL PLIMSOLL'S LINE

OBJECTIVES

- Explain what keeps a boat upright, and why a low, heavy load makes a boat more stable.
- Tell how Samuel Plimsoll worked to stop the overloading of ships, and what the load line on a ship means.
- Test hull shapes and ballast for stability, and mark a safe load line on a model boat.

Warm-up. Float an empty plastic food container in the sink. Push down on one edge and let go. It rocks and comes back. Now tape a tall pencil upright in the middle with a lump of clay on top and try again. Then move the clay to the bottom. What changed?

WATCH

THE PLIMSOLL LINE

[Lloyd's Register Foundation Heritage Centre](https://www.youtube.com/watch?v=vuve8DU84Co) · 5:10

<https://www.youtube.com/watch?v=vuve8DU84Co>

WHEN TO WATCH

After the story. Find the load line marks on the drawings and listen for why ships may load more in summer than in winter.

Note: From a maritime history archive. Old engravings of storms and wrecks appear briefly without detail of people.

KEY TERMS

hull

The main body of a boat or ship, the part that sits in the water.

ballast

Heavy material placed low in a boat to make it more stable.

stability

A boat's ability to come back upright after it is tipped by wind or waves.

freeboard

The height of a ship's side above the water, from the waterline to the deck.

load line

A mark on a ship's side showing how low it may safely sit in the water when loaded; also called the Plimsoll line.

CORE IDEAS

The story. In the 1860s and 1870s, many British cargo ships were lost at sea, and many sailors were lost with them. Some ship owners crammed their ships so full of coal and grain that the decks were barely above the water. Some even sent out old, rotten ships, because they were insured for more than they were worth. Samuel Plimsoll, a coal merchant who became a member of Parliament, was shocked when he learned of it. He wrote a book called *Our Seamen* and spoke out year after year. In 1876 a new law required British cargo ships to have a mark painted on their sides showing how deep they could safely be loaded. Sailors called him “the sailor’s friend,” and the mark is still called the Plimsoll line.

How they figured it out. Plimsoll and his supporters gathered records of lost ships and showed how many had been overloaded. But where exactly should the line go? At first, owners were allowed to paint the mark wherever they liked, and some painted it on the funnel. Engineers at Lloyd’s Register and the Board of Trade studied ships’ shapes, sizes and voyages and worked out rules for how much freeboard each kind of ship needed. By 1890 the government decided where the line must be placed. Later the marks included different lines for summer, winter and fresh water, because a ship floats a little higher in salty sea water than in fresh water, and winter storms need more freeboard.

The physics. A boat is **stable** when it rights itself after it tips. When a wide **hull** tips, more of it pushes down into the water on the low side, and the extra buoyancy there pushes that side back up. Weight placed low in the boat, called **ballast**, helps pull it upright. Weight placed high up does the opposite; it makes the boat roll farther and can tip it over. An overloaded ship sits so low that it has little **freeboard**. Waves wash over its deck, water gets in, and it may roll over or sink.

The engineering. Naval architects design every ship to stay stable when it is empty, half full and fully loaded, in calm water and in storms. They choose a hull shape that is wide enough, place heavy engines and cargo low, and add ballast tanks that can be filled with sea water. Before a new ship sails, they do an inclining test: they move

known weights across the deck and measure exactly how far the ship leans. Every large ship today has a **load line** mark, and inspectors check it in port. Plimsoll's line is a reminder that engineering rules exist to protect real people.

PICTURE STUDY



The Sailing Ship Samuel Plimsoll, Unknown artist, 1887 · Watercolor painting · State Library collection, Australia

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

This ship was named in honor of Samuel Plimsoll. It carried passengers and cargo between Britain and Australia, a long voyage through some of the stormiest seas in the world. Sailors and owners liked to have paintings made of their ships.

Look closely

- Find the hull. How much of it sits above the water? That height is the freeboard.
- Count the masts and the rows of sails. Why would tall masts and heavy sails make stability important?
- Look at the waves. Which way is the ship leaning?
- Find the flag. Which way is the wind blowing?

Talk about it

1. Why do you think a ship was named after Samuel Plimsoll?
2. Where would a ship like this carry its heaviest cargo, and why?
3. What would happen to this ship in these waves if it were loaded until the deck was almost at the water?

Safety first. Work over a tray or tub with an adult nearby. Keep pennies and clay away from small children.

BUILD

Stability and the Load Line: A Hull Test

You will compare a wide hull and a narrow hull with the same load, test how ballast placed low or high changes stability, and paint your own load line on a model boat.

You will need

- Two plastic food containers of different shapes, one wide and shallow and one narrow and deep (or two foil hulls you fold)
- A pencil or dowel for a mast, modeling clay, and about 40 pennies
- A permanent marker and a ruler
- A tub of water and a small cup for making waves
- Engineer's notebook

Steps

1. **Waterline.** Float the wide container empty. Mark where the water reaches on the outside with the marker. Add 10 pennies, spread evenly, and mark again. Repeat with 20 and 30 pennies. Measure the freeboard (from each mark to the top edge) each time.
2. **Load line.** Decide on a safe freeboard of 2 centimeters. Draw a load line on the side at that point and write how many pennies brought the boat down to it.
3. **Predict.** Which hull, wide or narrow, will be harder to tip with the same 20 pennies?
4. **Tilt test.** Stick the mast upright in the middle of each hull with clay. Put in 20 pennies. Hook a paper clip over the top of the mast and pull it sideways gently with a rubber band, measuring how far the band stretches before the boat tips water over its side. Do three trials for each hull.
5. **Ballast test.** In the narrow hull, put a 30-gram lump of clay at the top of the mast and test again. Then move the clay to the bottom of the hull and test again. Record your results.

6. **Wave test.** Load each hull to its load line. Make small waves by dipping the cup at the far end of the tub ten times. Does water slosh in? Then overload one hull below its line and test again.
7. **Improve.** Design a hull from foil that holds 30 pennies and passes the wave test while still at least 2 centimeters above the water. Test and record.

Tips

- Pull the mast very slowly and watch the boat carefully, so you can see the exact moment it tips too far.
- Make the waves the same size every time: the same cup, dipped the same way.
- Put pennies flat on the bottom of the hull, not stacked high.

Check your work

- ☐ I can explain why weight placed low makes a boat more stable.
- ☐ I can explain what a load line is and why Plimsoll fought for it.
- ☐ My tests compared hull shapes and ballast fairly.

ENGINEER'S NOTEBOOK

1. Draw a ship's side with a load line mark and label the waterline, the freeboard and the deck.
2. Make a table of your tilt test: hull, ballast position, rubber-band stretch.
3. Write a short letter as Samuel Plimsoll explaining to a ship owner why the line matters.

From history. In 1930 many nations signed the first International Load Line Convention, so ships of every country now carry load line marks. Next to the Plimsoll mark there are letters such as S for summer, W for winter and F for fresh water. A statue of Samuel Plimsoll stands in the Victoria Embankment Gardens in London.

COMMON MISTAKES

- Thinking a heavier load always makes a ship safer and steadier. Low weight helps; too much weight removes freeboard and sinks it.
- Putting heavy things high on a boat, which makes it easier to tip.
- Thinking the load line is the same in every sea. Ships float higher in salt water and need more freeboard in winter.

Make it a game • Load Line Balance. Use a plastic container as a boat. Load pennies or buttons low and then high, predicting which stays upright longer. Say aloud what ballast, stability and freeboard mean. Then draw a ship's side and mark where Samuel Plimsoll's load line goes. Your parent checks it for a point.

6.3 ROBERT FULTON'S CLERMONT: STEAM ON THE RIVER

OBJECTIVES

- Tell the story of Robert Fulton's steamboat and its first voyage up the Hudson River in 1807.
- Explain how a paddle wheel pushes water backward so the boat moves forward (Newton's third law).
- Build a rubber-band paddle-wheel boat and run a fair test of paddle size or number.

Warm-up. Sit on a rolling chair (or stand on a skateboard on carpet, with an adult) and throw a soft, heavy pillow forward. Which way do you roll? Now pull through water in a tub with your cupped hand. Which way does the water go, and which way does your hand get pushed?

WATCH

17th August 1807: The North River Steamboat was launched between New York and Albany.

[HistoryPod](#) · 2:37

https://www.youtube.com/watch?v=2C7_E4LarLg

WHEN TO WATCH

After the story. Look at the old drawings of the engine and paddle wheels.

BACKUP VIDEO

Invention of the Steamboat

[NBC News Learn](#) · 2:01

<https://www.youtube.com/watch?v=2QXq5D37YEw>

After the engineering paragraph, to hear how the steamboat changed travel and trade.

KEY TERMS

steam engine

An engine that uses the push of steam from boiling water to move a piston.

paddle wheel

A large wheel with flat boards that pushes against the water as it turns.

thrust

The forward push that moves a boat, an airplane or a rocket.

Newton's third law

For every action there is an equal and opposite reaction. Push water back, and the water pushes the boat forward.

upstream

Against the flow of a river, toward where it comes from.

CORE IDEAS

The story. Robert Fulton grew up in Pennsylvania and first earned his living as a painter of portraits. In England and France he became fascinated with canals and machines and decided to become an engineer. With his partner Robert Livingston, he built a steamboat in New York with an engine made by Boulton and Watt in England. On August 17, 1807, the boat left New York City and steamed up the Hudson River to Albany, about 150 miles, in 32 hours, against the current. A sailing sloop usually took about four days, and it could not move at all without wind. People on the riverbanks were astonished. The boat was officially called the *North River Steamboat*, but history remembers it as the *Clermont*.

How they figured it out. Fulton was not the first to build a steamboat. John Fitch had run one on the Delaware River in 1790, but it lost money and failed. Fulton studied why. He calculated how much power was needed to push a boat of a certain size through the water, and he chose a long, narrow hull to cut through the water easily. Instead of oars or paddles that moved like a canoe's, he used two large paddle wheels, one on each side, turned by the engine. In 1803 he had tested a steamboat on the Seine River in Paris; its hull broke under the weight of the engine, and he rebuilt it stronger. He learned from each failure until the *Clermont* ran on a regular schedule and made money.

The physics. A **steam engine** burns wood or coal to boil water. The steam pushes a piston back and forth, and rods and cranks turn that motion into the spinning of the **paddle wheels**. As each paddle dips into the water, it pushes water backward. By **Newton's third law**, the water pushes the paddle, and the boat, forward. That forward push is called **thrust**. To go **upstream**, the thrust must be greater than the push of the current plus the drag of the water on the hull.

The engineering. Within a few years, steamboats carried passengers and freight on rivers all over America, especially the Mississippi and Ohio. Trips that had taken weeks took days, and goods could travel upriver as easily as down. Engineers kept improving the design: stronger boilers with safety valves, lighter and more powerful engines, and later the screw propeller, which works better at sea than a paddle wheel. Paddle wheels are still used on some river boats today because they work well in shallow water.

PICTURE STUDY



A Replica of the Clermont, Unknown photographer, 1909 · Photograph · Hudson River, New York
Image: [Wikimedia Commons](#), public domain

For the hundredth anniversary of Fulton's voyage in 1909, New York built a full-size copy of the *Clermont* and sailed it on the Hudson River. This photograph shows what Fulton's boat looked like on the water.

Look closely

- Find the paddle wheel. Where is it on the boat?
- Find the smokestack. What does it tell you about how the engine worked?
- Look at the shape of the hull. Is it long and narrow or short and wide?
- Find the masts. Why might a steamboat still carry sails?

Talk about it

1. Which way does the paddle wheel push the water to move the boat forward?
2. Why would a long, narrow hull help the boat go faster?
3. Why was going upstream without wind such a big change for people on the river?

Safety first. An adult cuts the plastic or carton with scissors or a craft knife. Work in a tub or sink with an adult nearby, and wear safety glasses when winding rubber bands.

BUILD

A Paddle-Wheel Boat: How Many Paddles?

You will build a boat from a milk carton or foam tray with a rubber-band-powered paddle wheel at the back. Then you will test paddle wheels with 2, 4 and 6 paddles to find which pushes the boat farthest.

You will need

- A half-gallon milk or juice carton cut in half lengthwise (or a foam tray) for the hull
- Two pencils or wooden skewers taped along the sides, sticking out past the back
- A strong rubber band
- Stiff plastic (from a lid or a second carton) cut into paddles about 4 by 6 centimeters
- Tape, scissors, a tape measure and a stopwatch
- A bathtub or long tub of water

Steps

1. **Build the hull.** Tape the two pencils along the sides of the carton so they stick out about 8 centimeters past the back.
2. **Build paddle wheels.** Make three paddle wheels: slot two paddle pieces together for a 2-paddle wheel (a flat blade), two crossed for a 4-paddle wheel, and three crossed for a 6-paddle wheel. Make all the paddles the same size.
3. Stretch the rubber band between the ends of the pencils and slide the 2-paddle wheel into the middle of the band.
4. **Predict.** Which wheel will push the boat farthest?
5. **Test.** Wind the wheel backward exactly 15 turns. Set the boat at one end of the tub and let go. Measure how far it goes (or time how long it takes to travel 50 centimeters). Do three trials.
6. Test the 4-paddle and 6-paddle wheels the same way, with 15 turns each time. Change only the number of paddles.
7. Record your results in a table and make a bar graph.

8. **Improve.** Change one more thing on your best design (paddle size, the number of winds, or a more pointed bow) and test again.

Tips

- If the wheel hits the back of the boat, make the pencils longer or the paddles shorter.
- Wind the wheel so the bottom paddles push water backward. If the boat goes backward, wind it the other way.
- Keep the paddles mostly underwater on the bottom of their turn but not dragging the whole wheel deep.

Check your work

- ☐ I can explain how a paddle wheel pushes a boat forward using Newton's third law.
- ☐ I tested 2, 4 and 6 paddles fairly and graphed the results.
- ☐ I can tell why Fulton's steamboat changed travel on American rivers.

ENGINEER'S NOTEBOOK

1. Draw your boat from the side with arrows showing the paddle pushing water back and the water pushing the boat forward.
2. Make a table and bar graph: number of paddles, distance (three trials), average.
3. Draw a map of the Hudson River from New York to Albany and mark Fulton's trip, 150 miles in 32 hours.

From history. Fulton also built the first steam ferryboats between New York City and Brooklyn, with a hull at each end so they never had to turn around. He died in 1815. The name *Clermont* came from Livingston's home on the Hudson, Clermont, where the boat stopped on its first voyage.

COMMON MISTAKES

- Thinking the paddle wheel pushes against the air. It pushes against the water.
- Thinking Fulton invented the steamboat. Others built steamboats first; Fulton built the first one that ran reliably and made money.
- Winding the rubber band a different number of turns for each test.

Make it a game • Push It Backward. Act out Newton's third law. Sit on a rolling chair or stand on a smooth floor and gently push against a wall to see yourself move, with your parent watching. Explain how a paddle wheel pushes water backward so the boat moves forward. Then tell the story of the Clermont in under a minute.

Scripture. “Behold also the ships, which though they be so great, and are driven of fierce winds, yet are they turned about with a very small helm, whithersoever the governor listeth.” (James 3:4, KJV)

A great ship is steered by a small rudder. James uses it to teach that small things, like our words, can steer our whole lives.

6.4 CANALS AND LOCKS: THE ERIE CANAL

OBJECTIVES

- Tell how the Erie Canal was planned and built, and why it mattered.
- Explain step by step how a lock lifts or lowers a boat using only water and gravity.
- Build a working model lock and measure how much water it takes to lift a boat.

Warm-up. Put a small toy boat in the bottom of an empty dishpan. Slowly pour water into the pan. What happens to the boat? Now imagine the dishpan is a room with doors at each end. How could you use it to lift a boat from a low river to a higher one?

WATCH

The Surprising Efficiency of Canal Locks

Practical Engineering • 10:37

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

WHEN TO WATCH

After the physics paragraph. Watch the clear model lock closely; you will build one like it.

Note: The later part about water-saving basins is more advanced; it is fine to stop after the model lock is explained.

KEY TERMS

canal

A man-made waterway for boats.

lock

A chamber with gates at each end where the water level can be raised or lowered to move a boat up or down.

gate

A large door at each end of a lock that holds back water.

lift

How far a lock raises or lowers a boat.

hydraulic cement

Cement that hardens even under water.

CORE IDEAS

The story. In the early 1800s it cost more to haul a ton of goods thirty miles over rough roads than to ship it across the Atlantic Ocean. New York's governor, DeWitt Clinton, championed a bold plan: a canal 363 miles long from Albany on the Hudson River to Buffalo on Lake Erie, through forests, swamps and hills. Many people laughed and called it "Clinton's Ditch." Digging began on July 4, 1817. When the canal opened on October 26, 1825, the cost of shipping a ton of goods from Buffalo to New York City fell from about \$100 to about \$10. New York City became the greatest port in America.

How they figured it out. America had almost no trained engineers. The chief engineers, Benjamin Wright and James Geddes, were land surveyors who taught themselves canal engineering as they went, and many of the young men who worked with them became the country's first civil engineers. They surveyed every mile with simple levels. They needed mortar that would harden under water, and imported cement was costly. Canvass White, another self-taught engineer, found limestone in New York that made good **hydraulic cement**. The hardest place was at Lockport, where the canal had to climb a steep rock cliff about 60 feet high. Nathan Roberts designed a staircase of five double **locks**, one set for boats going up and one for boats going down, cut from the rock: the famous "Flight of Five."

The physics. A **lock** is a chamber with watertight **gates** at each end. To lift a boat, the lower gates open, the boat floats in, and the gates close behind it. Then valves let water flow in from the higher canal. Water always flows downhill until the levels are the same, so the chamber fills until its water matches the upper level, lifting the boat as it fills. Then the upper gates open and the boat floats out. To go down, the steps are reversed. No pumps are needed; gravity and the water from the higher part of the canal do all the work. The Erie Canal had 83 locks, which together lifted boats about 568 feet.

The engineering. Every time a lock is used, a chamber full of water flows from the higher level to the lower one. Canal engineers must bring in enough water at the canal's high points, from rivers and reservoirs, to keep the canal full. They also design the gates to be strong enough to hold back a deep wall of water, and they angle double gates into a V that points upstream, so the water pressure pushes them tightly closed. Mules or horses on towpaths pulled the first canal boats. The Erie

Canal was later enlarged twice, and it still carries boats today. The same lock ideas are used on the great canals of the world, from the Panama Canal to the St. Lawrence Seaway.

PICTURE STUDY



Lockport, Erie Canal, William Henry Bartlett, about 1838 · Engraving, hand-colored · From *American Scenery*, published in London

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

William Bartlett traveled across America drawing its scenery. At Lockport he drew one of the engineering wonders of the age: the double staircase of locks that lifted canal boats up the cliff.

Look closely

- Find the two rows of locks side by side. Why are there two?
- Find the steps between the locks. How many can you count?
- Find a canal boat. Is it going up or down?
- Look for the gates at the ends of each lock.

Talk about it

1. Explain how a boat would climb from the bottom of this staircase to the top.
2. Where does the water to fill the locks come from?
3. Why do you think a town grew up around these locks?

Safety first. Work in the bathtub or outside with an adult nearby. Never play near real canals, locks or dams; the water moves fast and the walls are steep.

BUILD

A Working Model Lock

You will build a model canal with a high level, a lock chamber and a low level from cartons or plastic containers. You will float a small boat up through the lock and measure how much water each trip uses.

You will need

- Three clean half-gallon milk or juice cartons, or three long plastic food containers
- Card stock or plastic for sliding gates, and waterproof tape (packing tape or duct tape)
- A small boat (a bottle cap or a cork)
- A measuring cup, a pitcher of water and a ruler
- Books to set the canal levels at different heights
- A dishpan or bathtub to work in

Steps

1. **Plan.** Draw your model from the side: an upper canal, the lock in the middle and a lower canal, each a little lower than the one before.
2. **Build.** Cut each carton in half lengthwise to make long troughs. Cut a doorway in the ends where troughs meet. Make sliding gates from card covered in tape that fit snugly in slots made of tape on each side of the doorways.
3. Set the three troughs on books so the upper canal is highest and the lower canal lowest, with the lock in between. Tape the joints so they do not leak.
4. **Fill.** With both gates closed, fill the upper canal deep and the lower canal shallow. Put the boat in the lower canal.
5. **Lift the boat.** Lower the water in the lock to match the lower canal (scoop it out), open the lower gate, float the boat in, and close the gate. Open the upper gate a crack to let water flow in. Watch the boat rise. When the levels match, open the gate fully and float the boat into the upper canal.

6. **Measure.** Measure the lift in centimeters and the length and width of the lock chamber. Measure how much water flowed in (refill the upper canal to its mark from a measuring cup). Record it.
7. **Fair test.** Raise the upper canal on one more book to make a bigger lift. Repeat and measure the water used. How does the water used change when the lift doubles?
8. **Improve.** Fix any leaking gate. Then try a staircase: add a second lock chamber, like Lockport, and lift your boat through both.

Tips

- A little leaking is normal; real lock gates leak a little too.
- Open the gate slowly so the water does not rush in and tip the boat.
- Mark the water levels on the outside of each trough with a marker.

Check your work

- ☐ I can explain every step of lifting a boat through a lock.
- ☐ I measured the water a lock uses and how it changes with the lift.
- ☐ I can tell why the Erie Canal mattered to America.

ENGINEER'S NOTEBOOK

1. Draw four pictures in a row showing a boat going up through a lock, with the gates and water levels labeled.
2. Make a table: lift (cm), chamber size, water used (mL).
3. Draw the Flight of Five at Lockport as a staircase of locks and explain why there were two sets.

From history. To celebrate the canal's opening, Governor Clinton traveled by boat from Buffalo to New York City and poured a keg of Lake Erie water into the Atlantic Ocean, which people called the "Wedding of the Waters." The canal's success led other states to build canals and then railroads, opening the West to settlement and trade.

COMMON MISTAKES

- Thinking pumps lift the boats in a lock. Gravity fills the lock from the higher water.
- Opening both gates at once, which lets the upper canal drain into the lower one.

- Forgetting that every trip through a lock uses a chamber full of water that must be replaced from somewhere.

Make it a game • Lock Through. Use three cups on a table at three heights as canal levels. Your parent plays a boat captain, a small toy, and you are the lock keeper. Say the steps aloud: close the gate, let water in or out, open the other gate. Do it without mistakes. Add one fact about why the Erie Canal mattered.

UNIT 6

BOATS AND SHIPS

Why does a steel ship weighing thousands of tons float, when a steel nail sinks? In this unit you will answer that question the way Archimedes did, by measuring. You will learn his principle of buoyancy and use it to predict how many pennies a foil boat can carry before you test it. Then you will meet Samuel Plimsoll, who fought to stop owners from overloading their ships, and you will learn what keeps a boat upright and how engineers mark a safe load.

In the second half of the unit, you will ride with Robert Fulton on the *Clermont*, the steamboat that changed travel on American rivers, and climb the Erie Canal’s “Flight of Five” locks at Lockport, where boats were lifted up a cliff by water alone. You will build and test foil boats, a stability tester, a paddle-wheel boat and a working model lock. “They that go down to the sea in ships, that do business in great waters; these see the works of the LORD” (Psalm 107:23-24).

PREREQUISITES

- Can measure length, volume (milliliters) and mass (grams)
- Knows that water pressure grows with depth (Unit 5)
- Can run a fair test and record results

MASTERY CHECKLIST

- ☐ I can state Archimedes’ principle and use it to predict how much a boat can carry.
- ☐ I can explain what makes a boat stable and why an overloaded ship is dangerous.
- ☐ I can tell how Robert Fulton’s *Cle
rm
on
t* worked and why it mattered.
- ☐ I can explain step by step how a canal lock lifts a boat.
- ☐ I can build and fairly test a boat and improve its design.

LESSONS IN THIS UNIT

6.1 Archimedes’ Principle Measured

2 sessions of 45 minutes

6.2 Hull Design and Stability: Samuel Plimsoll's Line

2 sessions of 45 minutes

6.3 Robert Fulton's Clermont: Steam on the River

2 sessions of 45 minutes

6.4 Canals and Locks: The Erie Canal

2 sessions of 45 minutes

UNIT 6 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. 5 pts

State Archimedes' principle in your own words.

2. 5 pts

A foil boat is 10 cm long, 8 cm wide and 3 cm tall. What is its volume? About how many grams can it hold before water reaches its rim (ignore the boat's own mass)?

3. 5 pts

Why does a steel ship float when a steel nail sinks?

4. 5 pts

Predict: you move a heavy lump of clay from the top of your model boat's mast to the bottom of its hull. Will the boat be easier or harder to tip? Why?

5. 5 pts

What is the Plimsoll line, and why did Samuel Plimsoll fight for it?

6. 5 pts

What is freeboard, and why does an overloaded ship lack it?

7. 5 pts

How does a paddle wheel move a boat forward? Name the law of motion.

8. 5 pts

Why was the *Clermont's* 1807 trip so important?

9. 5 pts

List in order the steps to lift a boat up through a lock.

10. 5 pts

Give two reasons the Erie Canal was important.

ANSWER KEY

1. An object in water is pushed upward by a force equal to the weight of the water it pushes aside (displaces).
2. $10 \times 8 \times 3 = 240 \text{ cm}^3$, so about 240 grams, because 1 cm^3 of water weighs 1 gram.
3. The ship's hollow hull pushes aside a large volume of water whose weight equals the ship's weight. The small solid nail cannot push aside enough water for its weight.
4. Harder to tip. Weight placed low (ballast) helps the boat come back upright; weight high up makes it roll farther.
5. A mark on a ship's side showing how deep it may safely be loaded. He fought for it because owners were overloading ships and many ships and sailors were being lost.
6. Freeboard is the height of the ship's side above the water. An overloaded ship sits so low that little side is left above the water, so waves can wash aboard.
7. The paddles push water backward, and the water pushes the boat forward: Newton's third law (every action has an equal and opposite reaction).
8. It steamed about 150 miles up the Hudson, against the current and without wind, in 32 hours, and ran reliably and profitably, opening the way for steamboats on rivers all over America.
9. Lower the lock water to the lower level; open the lower gates; the boat enters; close the lower gates; let water in from above until the levels match; open the upper gates; the boat leaves.
10. Any two: it cut shipping costs from about \$100 to about \$10 a ton; it made New York City the greatest port in America; it opened the West to settlement and trade; it trained America's first civil engineers.

PORTFOLIO PIECE: A CARGO BOAT WITH A LOAD LINE

Design and build a cargo boat from foil, card covered in tape, or a plastic container that can carry at least 40 pennies safely. Measure its volume and predict its capacity with Archimedes' principle. Find and mark its load line so it keeps 2 centimeters of freeboard, and test it for stability with a mast pull and the wave test. Record everything, improve the design once, and present the boat with a page explaining your prediction, your results and the meaning of your load line.

LOOK FOR	WHAT IT MEANS
Prediction	The volume was measured and the capacity was predicted correctly with Archimedes' principle.
Load line	A clear load line is marked, with the freeboard and the number of pennies at that line recorded.
Stability testing	Mast-pull and wave tests were done fairly and recorded.
Improvement	One clear change was made after testing, and its result was measured.
Explanation	The student explains buoyancy, stability and the load line in his or her own words.

FLIGHT

For thousands of years people watched birds and wished they could fly. Then, in a little more than a hundred years, careful thinkers and builders learned how. In this unit you will follow them. Sir George Cayley worked out the four forces of flight. Otto Lilienthal measured wings and made more than two thousand glides from his own hill. Wilbur and Orville Wright found that the old tables of numbers were wrong, built a wind tunnel, and tested wing after wing until they knew exactly what would work. Igor Sikorsky built the first practical helicopter.

You will test paper airplanes, measure how the angle of a wing changes its lift, build a wind tunnel of your own and compare wing shapes, and design paper helicopters. Every build follows the Wrights' method: change one thing, measure, write it down, and improve. "Doth the hawk fly by thy wisdom?" (Job 39:26). People learned to fly by studying the wisdom God built into the air and the birds.

PREREQUISITES

- Knows Newton's third law from the paddle-wheel boat (Unit 6)
- Can use a protractor or a printed angle guide, a ruler and a stopwatch
- Can run a fair test and make a bar or line graph

MASTERY CHECKLIST

- ☐ I can name and draw the four forces of flight: lift, weight, thrust and drag.
- ☐ I can explain how a wing makes lift by turning air downward, and what angle of attack and a stall are.
- ☐ I can tell how the Wright brothers used a wind tunnel to find better wing shapes.
- ☐ I can explain how a propeller and a helicopter rotor are spinning wings.
- ☐ I can test a flying model fairly, record the data and improve it.

OPTIONAL KITS FOR THIS UNIT

- **Guillow's balsa gliders:** Simple, inexpensive balsa-wood gliders, good for ages 8 and up with help. Slide the wing forward or back and add clay to the nose to test balance and glide distance in Lessons 7.1–7.3.
- **KiwiCo Tinker Crate:** Ages 9–16. Some crates build gliders, launchers or spinning flyers with an explanation of the physics; a good extra for this unit.

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

LESSONS IN THIS UNIT

7.1	The Four Forces: Sir George Cayley	2 sessions of 45 minutes
7.2	The Wing and Angle of Attack: Otto Lilienthal	2 sessions of 45 minutes
7.3	The Wright Brothers' Wind Tunnel	2 sessions of 45 minutes
7.4	Propellers and Helicopters: Spinning Wings	2 sessions of 45 minutes

UNIT 7 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**
Name the four forces of flight and tell which way each one acts.
2. **5 pts**
How does a wing make lift?
3. **5 pts**
Predict: your paper airplane swoops up and stalls. Should you add weight to the nose or take it away? Why?
4. **5 pts**
What is the angle of attack? What happens if it gets too steep?

5. (5 pts)

What did Otto Lilienthal discover about curved wings, and how did he share it?

6. (5 pts)

Why did the Wright brothers build a wind tunnel?

7. (5 pts)

Predict: two wings have the same area. One is long and narrow; one is short and wide. Which will make more lift with less drag?

8. (5 pts)

Give the date, time in the air and distance of the Wrights' first powered flight.

9. (5 pts)

Why is a propeller called a spinning wing?

10. (5 pts)

Why does a helicopter like Sikorsky's VS-300 need a tail rotor?

ANSWER KEY

1. Lift (up), weight (down), thrust (forward), drag (backward).
2. It turns the air flowing past it downward, so the air pushes the wing up (Newton's third law); the air pressure above the wing is also lower than below it.
3. Add a little weight to the nose. That moves the balance point forward, so the nose does not pitch up too far.
4. The angle between the wing and the oncoming air. If it is too steep (about 15 degrees for most wings), the air breaks away from the top of the wing, lift suddenly drops, and the wing stalls.
5. Curved (cambered) wings lift more than flat ones. He measured lift at many angles and published his tables and his book so others could use them.
6. Their gliders lifted much less than the published tables predicted, so they built a wind tunnel to measure lift and drag for themselves on about two hundred wing shapes.
7. The long, narrow wing (high aspect ratio), as the Wrights found in their wind tunnel.
8. December 17, 1903, at Kitty Hawk: 12 seconds and 120 feet, with Orville at the controls.
9. Each blade is shaped and angled like a wing. As it spins, it turns air backward, and the air pushes it forward, making thrust, just as a wing turns air down to make lift.
10. Spinning the main rotor twists the body the opposite way (torque). The tail rotor pushes sideways to stop the body from spinning.

PORTFOLIO PIECE: A TESTED GLIDER

Design and build a glider from paper, card stock or foam plates that flies at least 5 meters from a gentle hand launch. Test it at least three ways, changing one variable each time, such as nose weight, wing shape or wing angle, with five flights for each version. Record every flight in a data table, make a graph, and write a short engineer's report explaining the four forces on your glider, what you changed and what you learned, like the Wrights' notebooks.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the wings, tail, balance point and the four forces.
Fair testing	Only one variable was changed at a time, with five flights for each version.
Data	A neat table with units and a graph that matches it.
Improvement	The final glider flies better than the first, and the report explains why.
Explanation	The student explains lift, angle of attack and balance in his or her own words.

7.1 THE FOUR FORCES: SIR GEORGE CAYLEY

OBJECTIVES

- Name the four forces of flight and show which way each one acts.
- Tell how Sir George Cayley worked out the forces of flight and designed the first gliders that carried a person.
- Build a paper airplane and run a fair test of how weight at the nose changes how far it flies.

Warm-up. Drop a flat sheet of paper and a crumpled ball of paper from the same height at the same time. Which lands first? Now throw the flat sheet forward gently, held level. What is holding it up? Name as many pushes and pulls on it as you can.

WATCH

Four Forces of Flight with Paper Airplanes - Science Never Stops

U.S. Space & Rocket Center • 9:27

https://www.youtube.com/watch?v=m5y9QX_bjB4

WHEN TO WATCH

Before the build. Fold your airplane along with the video.

Note: The presenter mentions Bernoulli's principle. It is true that air pressure is lower above a wing, but the air over the top does not have to "catch up" with the air underneath; read the physics paragraph for the correct picture.

KEY TERMS

lift

The upward force made by a wing moving through the air.

weight

The downward pull of gravity on the aircraft.

thrust

The forward push that moves an aircraft, from a throw, a propeller or an engine.

drag

The backward push of the air that slows an aircraft down.

glider

An aircraft with wings but no engine.

center of gravity

The balance point of an object, where all its weight seems to act.

CORE IDEAS

The story. For centuries, people who tried to fly strapped on feathered wings and flapped, and they always failed. Sir George Cayley, an English landowner born in 1773, decided to think the problem through instead. In 1799, when he was 26, he engraved a small silver disc. On one side he drew a flying machine with a fixed wing, a tail and paddles for pushing; on the other he drew arrows showing the forces on a wing. It was the first drawing of an airplane as we know it: a fixed wing to hold it up, and a separate way to push it forward.

How they figured it out. Cayley tested ideas instead of guessing. He mounted small wings on the end of a long arm and whirled them around to measure how much they lifted at different angles. He flew model gliders, and in 1804 he built a model with a kite-shaped wing and a tail that glided well. He wrote it all down in a famous paper in 1809 and 1810 called “On Aerial Navigation.” Then, in 1853, when he was almost 80, he built a full-size glider and sent his coachman across a small valley on his estate. The coachman landed safely and, the story goes, asked to quit, saying he had been hired to drive, not to fly.

The physics. Four forces act on everything that flies. **Weight** pulls down. **Lift**, made by the wings, pushes up. **Thrust** pushes forward. **Drag**, the push of the air, holds it back. A wing makes lift by turning the air that flows past it downward. By Newton’s third law, when the wing pushes air down, the air pushes the wing up. At the same time, the air pressure above a curved, tilted wing is lower than the pressure below it, and that difference also pushes up. These are two ways of describing the same thing. When lift equals weight and thrust equals drag, a plane flies steadily.

The engineering. Cayley saw that a flying machine needs three things: wings for lift, a way to make thrust, and a way to control it. A glider makes its own thrust by gliding slightly downhill, trading height for speed. For a plane to fly smoothly, its **center of gravity** must be in the right place, usually a little ahead of the middle of the wing. Too far back and it swoops and stalls; too far forward and it dives. That is why a paper clip on the nose of a paper airplane can make it fly better, or worse. Aircraft

engineers today still calculate the balance point of every airplane before it flies, and pilots check it before every flight.

PICTURE STUDY



Cayley's Glider Sketch of 1804, Sir George Cayley, 1804 · Drawing from his notebook · Cayley's notebook, England

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

This is Cayley's own sketch of the model glider he built in 1804. It looks like a kite on a stick, but it has every part of a modern airplane except the engine: a fixed wing for lift, a body, and a tail for balance and steering.

Look closely

- Find the large kite-shaped wing near the front.
- Find the tail at the back. What shape is it?
- Find the long stick that joins them. What does it do?
- Look for the small weight under the front. Why might Cayley have added weight there?

Talk about it

1. Draw arrows on a sketch of this glider for lift, weight, thrust and drag. Where does the thrust come from?
2. Why does a glider need a tail?
3. How is this glider different from the flapping wings people tried before Cayley?

Safety first. Throw airplanes only in an open space, away from faces, and never toward people. Wear safety glasses if you use a rubber-band launcher.

BUILD

Nose Weight and the Paper Airplane: A Fair Test

You will fold one good paper airplane and test how adding paper clips to its nose changes how far it flies. You will use the same plane, the same throw and the same place for every flight, so that the only change is the weight.

You will need

- Several sheets of the same printer paper
- 4 small paper clips
- Masking tape for a launch line, and a tape measure (at least 10 meters)
- Optional: a simple launcher made from a rubber band hooked over a pencil, so every launch is the same
- Engineer's notebook

Steps

1. **Build.** Fold a dart or glider airplane, following the video or your own design. Make every crease sharp.
2. **Label the forces.** On the plane itself, draw small arrows with a pencil: lift up from the wings, weight down from the middle, thrust forward, drag backward.
3. **Predict.** Will one clip, two clips or three clips on the nose make it fly farthest? Write your guess.
4. **Test.** Stand at the launch line. Throw the plane with no clips the same way each time, level and gently. Measure where it lands. Do five flights.
5. Add 1 clip to the nose and do five flights. Then 2 clips, then 3. Change only the number of clips.
6. Record every flight, cross out any that hit a wall or person, and find the middle (median) distance for each.
7. Make a bar graph. Write which nose weight was best and why you think so.
8. **Improve.** Keep the best nose weight. Now change one other thing, such as bending the back edges of the wings up slightly (elevators) or making the wings wider, and test five more flights.

Tips

- Test indoors in a long hallway or outdoors on a calm day; wind spoils a fair test.
- Watch how each plane flies. Does it swoop up and stall, glide smoothly, or dive? Write a word for each flight.
- If your throws vary a lot, use the rubber-band launcher or have the same person throw every time.

Check your work

- ☐ I can name the four forces and draw them on an airplane.
- ☐ I ran a fair test with five flights for each nose weight.
- ☐ I can explain how nose weight changes the balance point of my plane.

ENGINEER'S NOTEBOOK

1. Draw an airplane with the four forces as arrows and label them.
2. Make a table: paper clips, five distances, median distance, and how it flew (swoop, glide, dive).
3. Draw Cayley's silver disc: the flying machine on one side and the force arrows on the other.

From history. Cayley also invented a lightweight wheel with wire spokes held in tension, like a bicycle wheel, for his flying machines, and he worked on safety ideas for railways. The Wright brothers said that Cayley had understood the principles of flight better than anyone before the end of the 1800s.

COMMON MISTAKES

- Thinking air over the top of a wing must “catch up” with the air underneath. It does not; the wing turns the air downward, and the pressure is lower above.
- Thinking a heavier plane always flies farther. The balance point matters more than the weight.
- Throwing harder for some tests than others, which spoils the fair test.

Make it a game • Four Forces Charades. Act out each force with your whole body: lift, weight, thrust and drag. Your parent guesses which one. Then fold a paper airplane and predict how nose weight changes its flight. Draw arrows on the plane showing the four forces. Add one fact about Sir George Cayley's first gliders. Best three out of five wins.

7.2 THE WING AND ANGLE OF ATTACK: OTTO LILIENTHAL

OBJECTIVES

- Explain angle of attack and how it changes lift, and what happens when a wing stalls.
- Tell how Otto Lilienthal studied birds, measured wings and made more than two thousand glides.
- Build a lift tester and measure how the angle of attack changes the lift of a wing in front of a fan.

Warm-up. Ride in a car with an adult (as a passenger, with the window down only a little and your arm held safely inside the window frame), or stand in front of a fan, and hold your flat hand in the moving air. Tilt the front edge of your hand up a little, then more, then a lot. When is the upward push strongest? What happens when you tilt it too far?

WATCH

What is angle of attack?

[flight-club](#) • 5:36

<https://www.youtube.com/watch?v=t0tCRq2JedY>

WHEN TO WATCH

After the physics paragraph. Pause on the drawing of the wing and the oncoming air, and find the angle of attack. Try the quiz at the end.

Note: A flight-school lesson made of simple drawings. The quiz questions use some pilot words; answer them together.

BACKUP VIDEO

World's First Aircraft - Lilienthal's Glider Flight

[Markus Raffel](#) • 3:09

https://www.youtube.com/watch?v=_AZjozlvYz4

After the story, to see modern copies of Lilienthal's gliders flown the way he flew them.

KEY TERMS

wing

The broad, flat or curved surface that makes lift as it moves through the air.

angle of attack

The angle between a wing and the oncoming air.

stall

When the angle of attack is too steep, the air stops flowing smoothly over the wing and lift suddenly drops.

camber

The gentle upward curve of a wing from front to back.

airfoil

The cross-section shape of a wing.

CORE IDEAS

The story. Otto Lilienthal grew up in Germany and, with his brother Gustav, spent his boyhood watching storks fly. He became an engineer and ran a factory that made small steam engines, but he never stopped thinking about flight. In 1889 he published a book called *Birdflight as the Basis of Aviation*. Then, starting in 1891, he built gliders of willow and cotton cloth, shaped like the wings of a bird, and jumped from hills, hanging below the wings and steering by swinging his legs and body. He even had a man-made hill built near Berlin so he could launch into the wind from any direction. He made more than two thousand glides, and photographs of him in the air amazed the world. In 1896 his glider stalled in a gust and fell, and he died the next day.

How they figured it out. Lilienthal did not just copy birds; he measured. He and Gustav built a whirling arm and other machines that moved wings through the air while they measured the forces on them. They found that curved wings, with **camber** like a bird's, lifted much more than flat ones. They measured the lift of their wings at every **angle of attack** and printed the results in tables so that others could use them. Lilienthal shared everything he learned, and builders all over the world, including the Wright brothers, read his book.

The physics. The **angle of attack** is the angle between the **wing** and the oncoming air. When it is zero, a flat wing slices through the air and makes almost no lift. Tilt the front edge up a little, and the wing turns more air downward, so the air pushes

back up harder: more lift. Up to a point, a bigger angle means more lift. But if the angle gets too steep, the air can no longer follow the curve of the top of the wing. It breaks away into swirls, lift suddenly drops, and drag jumps. That is a **stall**. Most wings stall at about 15 degrees.

The engineering. Wing designers choose an **airfoil** shape and size so that a plane can fly slowly enough to land safely without stalling. Pilots learn to keep the angle of attack below the stall, and many airplanes have a stall warning horn or light. Lilienthal's accident taught a hard lesson: a flying machine needs better ways to control it than shifting the pilot's body. The Wrights read about his death and decided to solve the problem of control.

PICTURE STUDY



Otto Lilienthal's Flight of May 29, 1895, Richard Neuhauss, May 29, 1895 · Photograph · Berlin, Germany

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

Richard Neuhauss was a doctor and an expert photographer who took some of the sharpest pictures of Lilienthal in flight. Photographs like this one showed the world that a person could really glide through the air.

Look closely

- Find the wing. Is it flat, or curved like a bird's?
- Find Lilienthal. How is he holding on, and where are his legs?
- Find the tail. What do you think it does?
- Look at the angle of the wing. Is the front edge tilted up?

Talk about it

1. How did Lilienthal steer his glider?
2. What would happen to this glider if Lilienthal tilted the front of the wing up too far?
3. Why were photographs so important to Lilienthal's work?

Safety first. Keep fingers, hair and loose clothes away from the fan, and never put anything into a fan's blades. An adult cuts the skewer with clippers or scissors.

BUILD

The Lift Tester: Finding the Best Angle of Attack

You will build a small curved paper wing that can slide up and down a vertical string in front of a fan. As the fan blows, the wing rises if it makes enough lift. You will change only the angle of attack and measure how high the wing climbs, and find the angle where it stalls.

You will need

- A box fan or desk fan
- Card stock for a wing about 10 centimeters wide (front to back) and 15 centimeters long, and tape
- A drinking straw cut into two 3-centimeter pieces
- About 1 meter of thread or fishing line, a heavy book to anchor it and a ruler or yardstick taped upright to a chair
- A protractor (or a printed angle guide), and a pencil
- Engineer's notebook

Steps

1. **Build the wing.** Fold the card in half from front to back, then slide the back edge forward a little so the top bulges in a gentle curve, and tape it. That curve is camber. Push two straw pieces straight down through the wing, one near the front and one near the back, so a thread can pass through both.
2. **Build the tester.** Tie the thread to a heavy book on the floor and stretch it straight up to the top of the upright yardstick, about 80 centimeters high. Thread the wing onto it through the straws so it can slide up and down. Set the fan about 50 centimeters away, blowing straight at the wing.
3. To change the angle of attack, tilt the wing on the thread using a small lump of clay or tape at the front or back of the straws, and check the angle with the protractor.
4. **Predict.** At which angle will the wing climb highest: 0, 5, 10, 15, 20 or 30 degrees?

5. **Test.** Set the angle to 0 degrees. Turn on the fan to the same speed. Measure how high the wing rises. Do three trials. Repeat for each angle. Change only the angle.
6. Make a line graph: angle of attack (across) and height (up). Mark the angle where the height drops. That is where your wing stalls.
7. **Improve.** Make a second wing of the same size but flat (no camber) and test it at your best angle. Which lifts more? Then try your curved wing at its best angle with the fan on a lower speed.

Tips

- The straws must slide freely. Rub the thread with a little soap if it sticks.
- Keep the fan the same distance and speed for every test.
- If the wing spins around the thread, add a small tail of card at the back to keep it pointing into the wind.

Check your work

- ☐ I can explain angle of attack and point to it on my wing.
- ☐ My graph shows how lift grew with angle and where it stalled.
- ☐ I can tell what Lilienthal discovered about curved wings.

ENGINEER'S NOTEBOOK

1. Draw a wing at a small angle and at a stall angle. Show smooth airflow over the first and swirling, broken airflow over the second.
2. Make a table and line graph: angle, three heights, average.
3. Draw Lilienthal in flight and label the wing, the tail and how he steered.

From history. Lilienthal sold copies of his most successful glider, the “normal soaring apparatus,” to buyers in several countries, making it the first airplane ever produced in a series. One of them is kept today at the Smithsonian National Air and Space Museum in Washington, D.C.

COMMON MISTAKES

- Thinking more angle always means more lift. Past the stall angle, lift drops.
- Thinking a stall means the engine stopped. A stall is about the wing and the airflow, not the engine.
- Changing the fan speed between tests, which spoils the fair test.

Make it a game • Wing Tilt Test. Hold a flat card out a car window or in front of a fan, or run with it. Tilt it to three angles and feel the lift. Describe what changes, then explain stall to your parent. Tell how Otto Lilienthal studied birds and made over two thousand glides. Score a point for each correct claim.

Scripture. “Doth the hawk fly by thy wisdom, and stretch her wings toward the south?” (Job 39:26, KJV)

God asks Job whether he taught the hawk to fly. Lilienthal learned from the birds God made, and the wisdom of flight was there long before anyone measured it.

7.3 THE WRIGHT BROTHERS' WIND TUNNEL

OBJECTIVES

- Tell how the Wright brothers discovered that the old lift tables were wrong and built a wind tunnel to find the truth.
- Explain how a wind tunnel lets engineers test small models safely and fairly.
- Build a box wind tunnel and compare wings of the same area but different shapes, recording the data as the Wrights did.

Warm-up. Blow across a pinwheel or a strip of paper while walking, then while standing still in front of a fan. Does it matter whether the paper moves through the air or the air moves past the paper? Why would that be useful to a scientist?

WATCH

NASA Now: Engineering Design: Wind Tunnel Testing

NASA Video • 5:36

<https://www.youtube.com/watch?v=P6sCjXISmEU>

WHEN TO WATCH

After the story. Listen for why engineers test small models instead of full-size airplanes.

Note: A NASA research engineer explains wind tunnels. The short part about Mach and Reynolds numbers is for older students and can be skipped.

BACKUP VIDEO

The Brilliant Engineering of FIRST FLIGHT !

Sabin Civil Engineering • 8:36

<https://www.youtube.com/watch?v=LigpsX1KoQE>

After the engineering paragraph, to see the 1903 Flyer's wing, propellers, engine and controls in 3D.

KEY TERMS

wind tunnel

A tube or box where a fan blows a steady stream of air past a model so engineers can measure the forces on it.

balance

A measuring device inside a wind tunnel that shows how much lift or drag a model makes.

aspect ratio

How long a wing is compared with how wide it is from front to back. A long, narrow wing has a high aspect ratio.

data

Measurements and observations, carefully recorded.

variable

The one thing you change in a fair test.

CORE IDEAS

The story. Wilbur and Orville Wright ran a bicycle shop in Dayton, Ohio. They were sons of a bishop, raised in a home full of books, and they read everything they could about flight, including Lilienthal's tables. In 1900 and 1901 they built large gliders and tested them on the windy sand dunes of Kitty Hawk, North Carolina. But the gliders lifted only about a third as much as the tables said they should. Wilbur came home so discouraged that he said people might not fly for a thousand years. Then the brothers decided to find out for themselves.

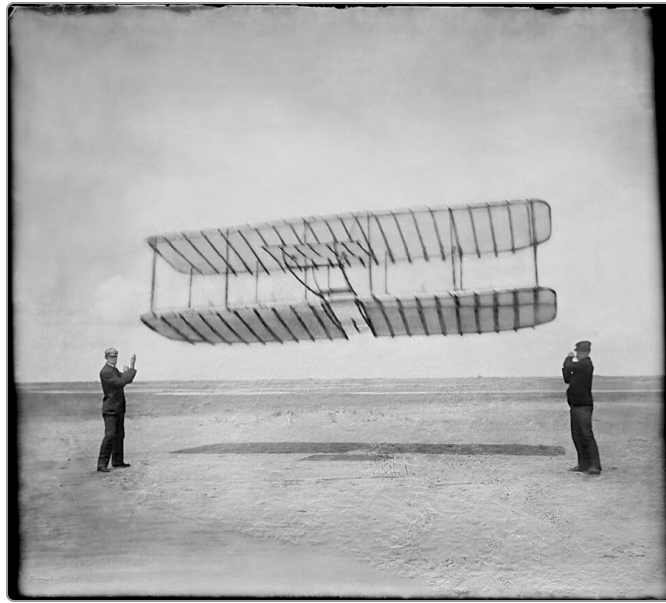
How they figured it out. In the fall of 1901, in the back of their shop, they built a **wind tunnel**: a wooden box about six feet long with a fan at one end, driven by the shop's engine. Inside, they built clever **balances** from bicycle spokes and hacksaw blades that measured how much lift and drag each small metal test wing made. Over a few weeks they tested about two hundred wing shapes: flat and curved, square and long, thick and thin, at many angles. They wrote down every number. They found that a number in the old tables, used to calculate lift, was wrong, and that long, narrow wings with a gentle curve worked best. With their new **data**, they built the 1902 glider, which flew beautifully and made hundreds of glides. On December 17, 1903, at Kitty Hawk, Orville made the first powered, controlled flight in the Wright Flyer: 12 seconds and 120 feet. By the end of the day Wilbur had flown 852 feet in 59 seconds.

The physics. A wing does not care whether it moves through still air or still air moves past it; the forces are the same. A wind tunnel uses that fact. A model sits still while a steady stream of air flows past it, so engineers can measure the forces exactly and test many shapes quickly, one **variable** at a time. The Wrights discovered that a wing with a high **aspect ratio**, long from tip to tip and narrow from front to

back, makes more lift and less drag than a short, wide wing of the same area. Birds that soar for hours, such as albatrosses, have long, narrow wings too.

The engineering. The Wrights succeeded where many others failed because they were careful engineers. They solved one problem at a time: first lift, with the wind tunnel; then control, with wing warping and a movable rudder; then power, with a light engine and propellers they designed themselves. They learned to fly gliders first, safely, before adding an engine. Every new airplane today, from small planes to airliners and spacecraft, is tested in wind tunnels before it flies, and computer models are checked against wind-tunnel data. The Wrights' six-foot box was the start of it all.

PICTURE STUDY



The 1901 Wright Glider Flown as a Kite, Wilbur or Orville Wright, 1901 · Glass-plate photograph · Library of Congress, Prints and Photographs Division

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

Before risking a flight, the Wrights flew their gliders as kites and measured the pull on the ropes. These measurements showed them that their 1901 glider made far less lift than the tables predicted. That puzzle led to the wind tunnel.

Look closely

- Find the two wings, one above the other. Why might two wings be better than one big one?
- Find the ropes. What could the brothers measure by holding them?
- Look at the curve of the wings, if you can see it.
- Find the elevator, the small surface in front of the wings.

Talk about it

1. Why was it wise to fly the glider as a kite before a person rode on it?
2. What did the Wrights do when their measurements did not match the tables?
3. How is testing a kite on the dunes like testing a model in a wind tunnel? How is it different?

Safety first. Keep fingers, hair and loose clothes away from the fan. An adult cuts the cardboard box with a craft knife.

BUILD

A Box Wind Tunnel: Long or Short Wings?

You will build a simple wind tunnel from a cardboard box and straws, and use your lift tester from Lesson 7.2 inside it to compare wings of the same area but different shapes: long and narrow, square, and short and wide. You will record your data in a table, just as the Wrights did.

You will need

- A large cardboard box about as wide as your box fan
- About 100 drinking straws, cut in half, and tape (to make a “honeycomb” that smooths the air)
- Clear plastic wrap or a sheet of clear plastic for a window
- Your lift tester from Lesson 7.2 (thread, book and upright stick)
- Card stock for three test wings, each with an area of 120 square centimeters: 24×5 cm, 12×10 cm and 8×15 cm
- A box fan, a ruler, a protractor and engineer’s notebook

Steps

1. **Build the tunnel.** An adult cuts the ends off the box to make a tunnel. Bundle the half-straws tightly side by side and tape them into a block that fills one end of the box. This honeycomb makes the air flow straight and steady. Cut a window in one side and cover it with clear plastic.
2. Set the fan so it blows through the honeycomb into the tunnel. Put the lift tester inside, with the thread running from the floor of the box to its top.
3. **Build test wings.** Make three cambered wings with the same area (120 square centimeters) but different shapes, as listed. Each has straws for the thread through its center.
4. **Predict.** Which wing will rise highest? Write your guess and why.
5. **Test.** Set each wing at your best angle from Lesson 7.2. Run the fan at the same speed. Measure how high each wing rises. Do three trials for each.
6. Record your results in a data table with columns for wing shape, length, width, area, the three heights and the average.

7. Make a bar graph. Did the long, narrow wing do better, as the Wrights found?
8. **Improve.** Pick one more variable to test with your best wing: more camber, a thicker airfoil, or a bent-up tip. Change only that one thing and test it three times.

Tips

- The long wing should run across the tunnel from side to side, with its narrow edge facing the wind.
- Make sure every wing weighs nearly the same. Weigh them on a kitchen scale and add tape to the lighter ones.
- If the wind is gusty, add more straws to the honeycomb.

Check your work

- ☐ I can explain why the Wrights built a wind tunnel.
- ☐ My data table and graph compare three wing shapes fairly.
- ☐ I can explain what aspect ratio means.

ENGINEER'S NOTEBOOK

1. Draw your wind tunnel and label the fan, honeycomb, test section, window and lift tester.
2. Copy your data table neatly, like a page from the Wrights' notebooks.
3. Draw a timeline from 1900 to 1903: the 1900 glider, the 1901 glider, the wind tunnel, the 1902 glider and the 1903 Flyer.

From history. The Wrights' 1902 glider was the first aircraft with control of roll, pitch and yaw, the three ways an airplane can turn. In 1906 they received a patent for their flying machine. The original 1903 Wright Flyer hangs today in the Smithsonian National Air and Space Museum.

COMMON MISTAKES

- Thinking the Wrights succeeded by luck. They succeeded by measuring, recording and solving one problem at a time.
- Comparing wings of different areas. A bigger wing lifts more just because it is bigger; keep the area the same.
- Testing in a gusty tunnel. Smooth air makes the measurements fair.

Make it a game • Wrong Table Mystery. Play the Wright brothers. Your parent gives you a puzzle: "The old lift tables say a wing should do this, but your model does that." Tell what you would test next and why a wind tunnel makes tests fair. Name the variable you would change and the one you keep the same.

7.4 PROPELLERS AND HELICOPTERS: SPINNING WINGS

OBJECTIVES

- Explain that a propeller and a helicopter rotor are spinning wings that push air to make thrust or lift.
- Tell how the Wright brothers designed their propellers and how Igor Sikorsky built the first practical helicopter.
- Build paper helicopters and run a fair test of how blade length changes the time they take to fall.

Warm-up. Drop a maple seed (or a strip of paper folded into a simple spinner) from as high as you can reach. Watch it spin. Now drop a flat piece of paper of the same size. Which falls more slowly? Why do you think spinning helps?

WATCH

How does a Helicopter fly?

Sabin Civil Engineering • 8:29

<https://www.youtube.com/watch?v=2tdnqZgKa0E>

WHEN TO WATCH

After the physics paragraph. Watch how the angle of each rotor blade changes and why a tail rotor is needed.

Note: A clear 3D animation. The part about the engine and the swash plate is detailed; you may watch it twice.

BACKUP VIDEO

Thrust: Propellers (How Things Fly Demonstration)

Smithsonian National Air and Space Museum • 1:07

<https://www.youtube.com/watch?v=JuKRKAi2Ctw>

Before the physics paragraph, to see a museum guide show how a propeller pushes air.

KEY TERMS

propeller

A set of twisted blades that spin to push air (or water) backward, making thrust.

torque

A twisting force. A spinning rotor twists the helicopter body the opposite way.

pitch

The angle of a propeller or rotor blade; a steeper pitch takes a bigger bite of air.

rotor

The large spinning blades on top of a helicopter that make lift.

tail rotor

A small propeller on a helicopter's tail that pushes sideways to stop the body from spinning.

CORE IDEAS

The story. When the Wright brothers needed propellers for their 1903 Flyer, they looked for tables of propeller data and found almost none. Ship propellers were designed mostly by trial and error. So they worked it out themselves. They realized that a **propeller** is really a wing that spins, and that each part of the blade moves at a different speed, so the blade had to be twisted. They carved two eight-foot propellers from layers of spruce wood, and they turned out to be far better than anyone else's at that time. Thirty-six years later, on September 14, 1939, Igor Sikorsky, a Russian-born engineer in Connecticut, lifted off in a strange machine called the VS-300: the first practical helicopter with one main rotor and a small tail rotor.

How they figured it out. Sikorsky had dreamed of helicopters since he was a boy, when his mother told him about Leonardo da Vinci's sketch of an "aerial screw." He tried to build helicopters in 1909 and 1910, and both failed: the engines were too weak. He turned to airplanes and became famous for building large ones. In 1939 he returned to his dream. The VS-300 at first was tied to the ground with ropes, and it shook, wobbled and even flew backward better than forward. Sikorsky, flying it himself in his business suit and hat, changed the rotors and controls again and again, testing each change, until it flew smoothly in every direction. By 1942 his company was building helicopters for real use.

The physics. A propeller blade is a small wing. As it spins, it meets the air at an angle of attack and turns the air backward; by Newton's third law, the air pushes the propeller forward. That is thrust. A helicopter **rotor** does the same thing, but it points up, so the air is pushed down and the helicopter is pushed up. The angle of the blades, called **pitch**, controls how much air they push. But spinning a rotor one way twists the helicopter's body the other way. That twist is **torque**. Sikorsky's small **tail rotor** pushes sideways to cancel it, so the body stays pointed where the pilot wants.

The engineering. To steer a helicopter, the pilot tilts the spinning rotor by changing the pitch of each blade as it goes around, so it pushes harder on one side than the other. Engineers must make rotor blades strong and light, balance them perfectly so they do not shake, and inspect them often. Helicopters can land on rooftops, ships and mountainsides, so they are used for rescue, medical flights and fighting forest fires. Small drones with four propellers work on the same ideas, using a computer to change the speed of each propeller many times every second.

PICTURE STUDY



Igor Sikorsky Flying the VS-300, Unknown photographer, about 1940 · Photograph · Connecticut
Image: [Wikimedia Commons](#), public domain

The VS-300 had no cabin, only an open frame of steel tubes, an engine and a seat. Sikorsky flew it himself to test each change. Look closely at how simple it is, and find the parts that make it work.

Look closely

- Find the main rotor. How many blades does it have?
- Find the small tail rotor. Which way does it point?
- Find the pilot. What is he wearing?
- Look at the frame of tubes. Why would the builders keep it so light and open?

Talk about it

1. What would happen to this helicopter if it had no tail rotor?
2. Why do you think Sikorsky tested it close to the ground first?
3. How is the main rotor like a wing, and how is it different?

Safety first. Drop paper helicopters from a safe height, such as standing on the floor or from a stair landing with an adult, never from a window, roof or railing. Keep everyone out from under the drop.

BUILD

Paper Helicopters: How Long Should the Blades Be?

You will cut and fold paper helicopters with blades of different lengths and drop them from the same height. You will time how long each takes to reach the floor and find the best blade length. Then you will improve your best design.

You will need

- Printer paper or card stock, scissors and a ruler
- Small paper clips (one for each helicopter)
- A stopwatch
- A tape measure and a safe place to drop from, about 2 meters high (an adult holding it high, or a stair landing)
- Engineer's notebook

Steps

1. **Build.** Cut a strip of paper 5 centimeters wide and 20 centimeters long. Cut down the middle from the top to make two blades 8 centimeters long. Fold one blade forward and one back. Fold the bottom part in from the sides to make a narrow body, and put a paper clip on the bottom.
2. Make three more helicopters exactly the same, except with blades 4, 6 and 10 centimeters long. (Make the strips longer as needed so the bodies are the same.)
3. **Predict.** Which blade length will fall most slowly?
4. **Test.** Hold each helicopter by its body at exactly 2 meters high, and let it go (no throw). Time how long it takes to reach the floor. Do five drops for each.
5. Record the times and find the middle (median) time for each blade length. Make a bar graph.
6. Watch which way each one spins. Does folding the blades the other way change the direction?
7. **Improve.** Take your best blade length and change one more thing: two paper clips instead of one, wider blades, or blades bent down slightly. Test five more drops. Did it fall even more slowly?

Tips

- Drop indoors where there is no breeze, or the test will not be fair.
- Start the stopwatch the instant you let go and stop it the instant it touches the floor. Let the same person time every drop.
- If a helicopter tumbles instead of spinning, check that the blades are folded evenly in opposite directions.

Check your work

- ☐ I can explain how a rotor makes lift and why a helicopter needs a tail rotor.
- ☐ I tested four blade lengths fairly with five drops each.
- ☐ I can explain why the Wrights said a propeller is a spinning wing.

ENGINEER'S NOTEBOOK

1. Draw a helicopter and label the main rotor, tail rotor, body and the direction of the air the rotor pushes.
2. Make a table and bar graph: blade length, five drop times, median time.
3. Draw a propeller blade and show how it is twisted, steeper near the middle and flatter near the tip.

From history. Igor Sikorsky's helicopters have rescued tens of thousands of people from floods, ships and mountains. He believed the helicopter's greatest work would be saving lives. He also wrote books about the Lord's Prayer and the Christian faith.

COMMON MISTAKES

- Thinking a propeller pulls an airplane like a screw in wood. It pushes air backward, and the air pushes the propeller forward.
- Forgetting torque. Without a tail rotor, a helicopter's body would spin the opposite way from its rotor.
- Throwing the paper helicopter down instead of letting it go, which spoils the test.

Make it a game • Spinning Wings. Each of you cuts out a paper helicopter. Predict whose blades will make it fall slowest, then drop both from the same height three times, timing with counting. Explain how a rotor pushes air and what torque and a tail rotor do. Tell one fact about Igor Sikorsky. Winner is the best average.

Scripture. “they shall mount up with wings as eagles; they shall run, and not be weary; and they shall walk, and not faint.” (Isaiah 40:31, KJV)

Igor Sikorsky was a devout Christian who wrote books about faith as well as about flight. He knew that the strength to keep going after failure comes from God.

FLIGHT

For thousands of years people watched birds and wished they could fly. Then, in a little more than a hundred years, careful thinkers and builders learned how. In this unit you will follow them. Sir George Cayley worked out the four forces of flight. Otto Lilienthal measured wings and made more than two thousand glides from his own hill. Wilbur and Orville Wright found that the old tables of numbers were wrong, built a wind tunnel, and tested wing after wing until they knew exactly what would work. Igor Sikorsky built the first practical helicopter.

You will test paper airplanes, measure how the angle of a wing changes its lift, build a wind tunnel of your own and compare wing shapes, and design paper helicopters. Every build follows the Wrights' method: change one thing, measure, write it down, and improve. "Doth the hawk fly by thy wisdom?" (Job 39:26). People learned to fly by studying the wisdom God built into the air and the birds.

PREREQUISITES

- Knows Newton's third law from the paddle-wheel boat (Unit 6)
- Can use a protractor or a printed angle guide, a ruler and a stopwatch
- Can run a fair test and make a bar or line graph

MASTERY CHECKLIST

- ☐ I can name and draw the four forces of flight: lift, weight, thrust and drag.
- ☐ I can explain how a wing makes lift by turning air downward, and what angle of attack and a stall are.
- ☐ I can tell how the Wright brothers used a wind tunnel to find better wing shapes.
- ☐ I can explain how a propeller and a helicopter rotor are spinning wings.
- ☐ I can test a flying model fairly, record the data and improve it.

OPTIONAL KITS FOR THIS UNIT

- **Guillow's balsa gliders:** Simple, inexpensive balsa-wood gliders, good for ages 8 and up with help. Slide the wing forward or back and add clay to the nose to test balance and glide distance in Lessons 7.1–7.3.
- **KiwiCo Tinker Crate:** Ages 9–16. Some crates build gliders, launchers or spinning flyers with an explanation of the physics; a good extra for this unit.

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

LESSONS IN THIS UNIT

7.1	The Four Forces: Sir George Cayley	2 sessions of 45 minutes
7.2	The Wing and Angle of Attack: Otto Lilienthal	2 sessions of 45 minutes
7.3	The Wright Brothers' Wind Tunnel	2 sessions of 45 minutes
7.4	Propellers and Helicopters: Spinning Wings	2 sessions of 45 minutes

UNIT 7 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**
Name the four forces of flight and tell which way each one acts.
2. **5 pts**
How does a wing make lift?
3. **5 pts**
Predict: your paper airplane swoops up and stalls. Should you add weight to the nose or take it away? Why?
4. **5 pts**
What is the angle of attack? What happens if it gets too steep?

5. (5 pts)

What did Otto Lilienthal discover about curved wings, and how did he share it?

6. (5 pts)

Why did the Wright brothers build a wind tunnel?

7. (5 pts)

Predict: two wings have the same area. One is long and narrow; one is short and wide. Which will make more lift with less drag?

8. (5 pts)

Give the date, time in the air and distance of the Wrights' first powered flight.

9. (5 pts)

Why is a propeller called a spinning wing?

10. (5 pts)

Why does a helicopter like Sikorsky's VS-300 need a tail rotor?

ANSWER KEY

1. Lift (up), weight (down), thrust (forward), drag (backward).
2. It turns the air flowing past it downward, so the air pushes the wing up (Newton's third law); the air pressure above the wing is also lower than below it.
3. Add a little weight to the nose. That moves the balance point forward, so the nose does not pitch up too far.
4. The angle between the wing and the oncoming air. If it is too steep (about 15 degrees for most wings), the air breaks away from the top of the wing, lift suddenly drops, and the wing stalls.
5. Curved (cambered) wings lift more than flat ones. He measured lift at many angles and published his tables and his book so others could use them.
6. Their gliders lifted much less than the published tables predicted, so they built a wind tunnel to measure lift and drag for themselves on about two hundred wing shapes.
7. The long, narrow wing (high aspect ratio), as the Wrights found in their wind tunnel.
8. December 17, 1903, at Kitty Hawk: 12 seconds and 120 feet, with Orville at the controls.
9. Each blade is shaped and angled like a wing. As it spins, it turns air backward, and the air pushes it forward, making thrust, just as a wing turns air down to make lift.
10. Spinning the main rotor twists the body the opposite way (torque). The tail rotor pushes sideways to stop the body from spinning.

PORTFOLIO PIECE: A TESTED GLIDER

Design and build a glider from paper, card stock or foam plates that flies at least 5 meters from a gentle hand launch. Test it at least three ways, changing one variable each time, such as nose weight, wing shape or wing angle, with five flights for each version. Record every flight in a data table, make a graph, and write a short engineer's report explaining the four forces on your glider, what you changed and what you learned, like the Wrights' notebooks.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the wings, tail, balance point and the four forces.
Fair testing	Only one variable was changed at a time, with five flights for each version.
Data	A neat table with units and a graph that matches it.
Improvement	The final glider flies better than the first, and the report explains why.
Explanation	The student explains lift, angle of attack and balance in his or her own words.

ROBOTS AND CODING

A robot is a machine that can sense the world, decide what to do, and act, all by following instructions that people have written. In this unit you will discover where those instructions came from. Two hundred years ago a French weaver, Joseph-Marie Jacquard, made a loom that followed holes punched in cards, the first machine controlled by a stored program. Grace Hopper helped teach computers to understand words. Ancient engineers like Ctesibius built machines that could check themselves and correct their own mistakes, the idea of feedback that every robot uses today.

You will weave a pattern from your own punch-card program, code a game in Scratch with loops and decisions, be the “controller” in a feedback test, and build a robot arm moved by water in syringes. The last week is the family engineering fair, where you will show the best build from each unit and explain how it works.

Fabricando fit faber: by making, one becomes a maker.

PREREQUISITES

- Can follow and write step-by-step instructions
- Knows how switches work in series and parallel (Unit 4) and water pressure (Unit 5)
- Has access to a computer or tablet with an internet connection for Scratch (free)

MASTERY CHECKLIST

- ☐ I can explain how Jacquard’s punched cards controlled a loom and how that idea led to computer programs.
- ☐ I can write an algorithm and code it in Scratch using loops and “if” decisions, and find and fix bugs.
- ☐ I can explain sense, think, act and feedback, using a float valve or a thermostat as an example.
- ☐ I can explain how a hydraulic syringe system passes a push through water, and build a robot arm that uses it.
- ☐ I can present a build at the family engineering fair and explain how I tested and improved it.

OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** A small, inexpensive programmable board with buttons, lights and sensors, coded with free Microsoft MakeCode blocks. The free online simulator works without the board. Fits Lessons 8.2 and 8.3.
- **Makeblock mBot:** A small robot car with line-following and distance sensors, programmed with Scratch-style blocks. A good next step after Lesson 8.3 for families who want a real robot.
- **KiwiCo Tinker Crate:** Ages 9–16. Some crates build hydraulic claws and arms with syringes; a good extra or alternative for Lesson 8.4.

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

8.1 The Jacquard Loom and Punch Cards

2 sessions of 45 minutes

8.2 Algorithms and Block Coding: Grace Hopper and the First Bug

2 sessions of 45 minutes

8.3 Sensors and Feedback: From Ctesibius's Water Clock to Robots

2 sessions of 45 minutes

8.4 A Syringe-Hydraulic Robot Arm and the Family Engineering Fair

2 sessions of 45 minutes

UNIT 8 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

How did Jacquard's punched cards tell the loom what to weave?

2. **5 pts**

Why is a chain of punched cards like a computer program?

3. **5 pts**

What is an algorithm? Give a short example.

4. **5 pts**

What is a loop? What is a conditional? Give one example of each from your Scratch game.

5. **5 pts**

Where does the word “bug” come from, and what does it mean to debug?

6. **5 pts**

Name the three things every robot does, and give an example of each for a line-following robot.

7. **5 pts**

How did Ctesibius’s float keep his water clock steady? Name one machine at home that works the same way.

8. **5 pts**

Predict: in your water-level test, will the level stay closer to the line with feedback or without it? Why?

9. **5 pts**

State Pascal’s law. Why does water work better than air in a syringe robot arm?

10. **5 pts**

A small syringe pushes a large syringe. Which one moves farther, and which pushes harder?

ANSWER KEY

1. Each card stood for one row. Where there was a hole, a needle passed through and its hook lifted a warp thread; where there was no hole, the thread stayed down.
2. It is a list of instructions in order that a machine follows exactly; holes and no-holes are a two-choice (binary) code, like the 1s and 0s computers use.
3. A step-by-step set of instructions for a task. Example: fill a glass: get a glass, hold it under the tap, turn on the water, wait until it is nearly full, turn off the water.
4. A loop repeats instructions (forever: move the bowl to the mouse; repeat: change y by -5). A conditional does something only if something is true (if the apple touches the bowl, change score by 1).
5. Engineers called problems bugs, and in 1947 a real moth was found in a relay of the Harvard Mark II and taped in the logbook. To debug is to find and fix mistakes in a program or machine.
6. Sense (light sensors see the line), think (the controller decides to turn left or right), act (the motors turn the wheels).
7. When the water rose, the float pushed a stopper into the inlet and slowed the flow; when it fell, the opening widened. The level stayed steady, so water dripped at a steady rate. A toilet tank's float valve works the same way (or a thermostat uses feedback).
8. With feedback, because you can see the level and correct it when it drifts; without feedback you cannot tell when you are pouring too much or too little.
9. A push on a liquid in a closed container is passed equally to every part. Water hardly squeezes, so the push passes through right away; air squeezes like a spring, so the arm is spongy and weak.
10. The small syringe's plunger moves farther; the large syringe pushes harder but moves a shorter distance. You trade distance for force.

PORTFOLIO PIECE: MY ROBOT ARM AND THE FAMILY ENGINEERING FAIR

Finish, test and improve your syringe-hydraulic robot arm until it can pick up a paper cup holding at least 10 pennies and move it to a new spot. Then hold a family engineering fair: set out the arm and your best build from each of the other units, each with its notebook pages. For each build, prepare a short talk: what it does, the science behind it, the fair test you ran, and what you improved. Present to your family or guests and invite them to try the arm.

LOOK FOR	WHAT IT MEANS
Working arm	The arm lifts and moves the cup of 10 pennies, with at least three working hydraulic joints.
Testing and improvement	Load tests and the water-or-air test are recorded, and one improvement is measured.
Fair display	At least five builds from the year are shown with neat, dated notebook pages.
Explanation	The student explains each build clearly, using correct engineering words, and answers questions.
Care and safety	Tools and materials were used safely, and the display is tidy and well labeled.

8.1 THE JACQUARD LOOM AND PUNCH CARDS

OBJECTIVES

- Tell how Joseph-Marie Jacquard used punched cards to control a loom.
- Explain that a punched card is a program: holes and no-holes are instructions a machine can follow.
- Write a punch-card program, weave a paper pattern from it, and test whether the program gives the same result every time.

Warm-up. Weave your fingers together, then try to describe in words exactly which fingers go over and which go under. Now look at a piece of woven cloth, a dish towel or a basket, very closely. Can you see threads going over and under? Write the pattern of one row as O for over and U for under.

WATCH

Paradise Mill How The Jacquard Mechanism Works

Macclesfield Museums · 4:32

https://www.youtube.com/watch?v=x_ijmjx7Xys

WHEN TO WATCH

After the story. Watch the hooks and needles closely as each card is pressed against them.

KEY TERMS

loom

A machine for weaving threads into cloth.

warp

The threads that run the long way on a loom; some are lifted for each row.

weft

The thread that is passed across, over and under the warp threads.

punched card

A stiff card with a pattern of holes that gives instructions to a machine.

program

A set of instructions that a machine follows in order.

binary

A way of writing information with only two choices, such as hole or no hole, 1 or 0.

CORE IDEAS

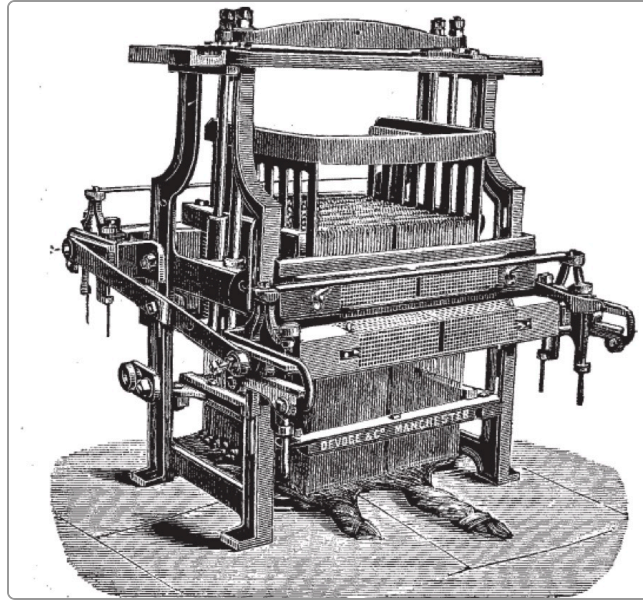
The story. In the 1700s the silk weavers of Lyon, France, made beautiful patterned cloth, but it was slow, hard work. For every row of a pattern, a child called a draw boy had to sit on top of the loom and pull up exactly the right threads by hand, row after row, thousands of times. A mistake ruined the pattern. Joseph-Marie Jacquard, the son of a weaver, wanted to make that work automatic. In 1804 he finished a loom attachment that read the pattern from a long chain of punched cards. Each card stood for one row of the pattern. By 1812 there were thousands of Jacquard looms in France.

How they figured it out. Jacquard built on the ideas of earlier inventors, including Jacques de Vaucanson, who had tried punched paper decades before. Jacquard made the idea reliable. Above the loom, a row of hooks held the **warp** threads. For each row, a **punched card** was pressed against a set of needles. Where there was a hole, a needle slid through and its hook lifted a warp thread. Where there was no hole, the needle was pushed back and the thread stayed down. Then the weaver threw the **weft** across. The cards were laced together in order, so the loom stepped through them one by one. To change the pattern, you simply changed the cards.

The physics. The Jacquard mechanism is a set of simple machines: levers, hooks and springs worked by a treadle. But its big idea is about information. Each hole position has only two possibilities: hole or no hole. That is **binary**, the same two-choice code that computers use today as 1 and 0. A chain of cards is a **program**: a list of instructions, in order, that a machine can follow exactly the same way every time.

The engineering. In the 1830s the English mathematician Charles Babbage designed a calculating machine, the Analytical Engine, that would have been controlled by punched cards like Jacquard's. His friend Ada Lovelace wrote that it would weave patterns of numbers the way the Jacquard loom wove flowers and leaves. In 1890 Herman Hollerith used punched cards and electric sensing machines to count the United States census in a fraction of the time it had taken before. Punched cards were used to program computers until the 1970s. Today Jacquard looms are run by computers, but they still lift each thread by the same rule: hole or no hole, yes or no.

PICTURE STUDY



A Jacquard Machine, From Richard Marsden's *Cotton Weaving*, 1895 · Engraving · Published in London
Image: [Wikimedia Commons](#), public domain

This drawing comes from a book written to teach young people the trade of weaving. It shows how a Jacquard machine sits above a loom and how its chain of cards feeds through it.

Look closely

- Find the chain of punched cards. How are the cards joined?
- Find the box or cylinder that presses each card against the needles.
- Look for the hooks and the cords that lead down to the warp threads.
- Find the treadle or lever that a weaver would work.

Talk about it

1. What happens to a warp thread when its needle meets a hole? When it meets solid card?
2. Why were the cards laced together in a long chain instead of kept loose?
3. How is a chain of punched cards like a computer program?

Safety first. An adult can help with the hole punch and scissors. Keep paper fasteners and small pieces away from small children.

BUILD

Weave from Your Own Punch-Card Program

You will design a pattern on graph paper, turn each row into a punched card, and then “be the loom”: follow the cards exactly to weave a paper mat. Then you will test whether someone else can weave the same pattern from your cards alone.

You will need

- Graph paper and colored pencils
- Index cards (one for each row of your pattern) and a single-hole punch
- Two colors of construction paper
- Scissors, a ruler, tape and a stapler or yarn to lace the cards together
- Engineer’s notebook

Steps

1. **Design.** On graph paper, draw an 8×8 grid. Color in squares to make a simple pattern, such as a diamond, a checkerboard or your initial. Colored = warp up (shows on top); white = warp down.
2. **Program.** Make one index card for each row. Mark 8 hole positions across the top of each card. Punch a hole wherever that row’s square is colored. Number the cards and lace them together in order.
3. **Build the “loom.”** Cut 8 long strips of one color for the warp and tape them side by side at the top to a sheet of cardboard. Cut 8 strips of the other color for the weft.
4. **Weave.** Take card 1. For each hole, lift that warp strip; for each solid spot, leave it down. Slide a weft strip under the lifted strips. Push it to the top. Repeat with card 2, card 3 and so on.
5. Compare your woven mat with your graph-paper design. Circle any square that came out wrong.
6. **Test the program.** Give only your cards (not your drawing) to a family member and have them weave a second mat. Does it match yours exactly? If not, find the “bug”: a card that was punched wrong or read wrong.

7. **Improve.** Fix any bugs. Then change just one card and predict how the pattern will change before you weave it again.

Tips

- Punch carefully; one extra hole changes a whole row.
- Read each card from left to right every time, just as a machine would.
- Count “1” for each hole and “0” for each solid spot and write the row in binary under each card.

Check your work

- ☐ I can explain how a punched card tells a loom which threads to lift.
- ☐ My cards worked as a program that someone else could follow.
- ☐ I can write one row of my pattern as binary 1s and 0s.

ENGINEER’S NOTEBOOK

1. Glue or draw your pattern next to the cards that make it, and write each card in binary.
2. Draw how a Jacquard needle meets a hole and a solid spot, and what happens to the warp thread each time.
3. Write two sentences: How is your card chain like a computer program?

From history. Charles Babbage owned a portrait of Jacquard woven in silk on a Jacquard loom, so detailed that people thought it was an engraving. It took about 24,000 punched cards to weave. Babbage showed it to visitors to explain how a machine could follow complicated instructions.

COMMON MISTAKES

- Thinking the cards hold the thread. The cards only tell the hooks which threads to lift.
- Reading the cards out of order. A program must be followed in order.
- Fixing the mat instead of the card. When a program has a bug, fix the program.

Make it a game • Punch Card Program. Draw a grid on paper. A hole means one color of thread, no hole means another. Make a simple pattern and punch it with a pencil tip, then hand it to your parent, who reads the card and draws the weave. Explain that holes and no-holes are instructions. Swap roles and see who reads fastest.

8.2 ALGORITHMS AND BLOCK CODING: GRACE HOPPER AND THE FIRST BUG

OBJECTIVES

- Explain what an algorithm is and write one for a simple task.
- Tell how Grace Hopper helped make computers easier to program and where the word “bug” comes from.
- Code a simple catch game in Scratch using loops and “if” decisions, then test and debug it.

Warm-up. Write instructions for making a peanut-butter (or butter) sandwich, then have a family member follow them exactly, doing only what the words say. (Use real food only if an adult agrees.) What went wrong? How would you fix your instructions?

WATCH

How to Make a Catch Game in Scratch | Tutorial

Scratch Team · 6:34

<https://www.youtube.com/watch?v=7NN5v2wSL4U>

WHEN TO WATCH

Session 2, at the computer. Pause after each step and build it yourself before going on.

BACKUP VIDEO

9th September 1947: First computer ‘bug’ found in the Harvard Mark II electromechanical computer

HistoryPod · 2:11

<https://www.youtube.com/watch?v=UPuTO9vg5gk>

Session 1, after the story, to see the real logbook page with the moth taped in.

KEY TERMS

algorithm

A step-by-step set of instructions for doing a task or solving a problem.

code

Instructions written in a language a computer can follow.

loop

An instruction that repeats other instructions, a certain number of times or forever.

conditional

An “if” instruction: do something only if a certain thing is true.

bug

A mistake in a program that makes it work the wrong way.

debug

To find and fix the mistakes in a program.

CORE IDEAS

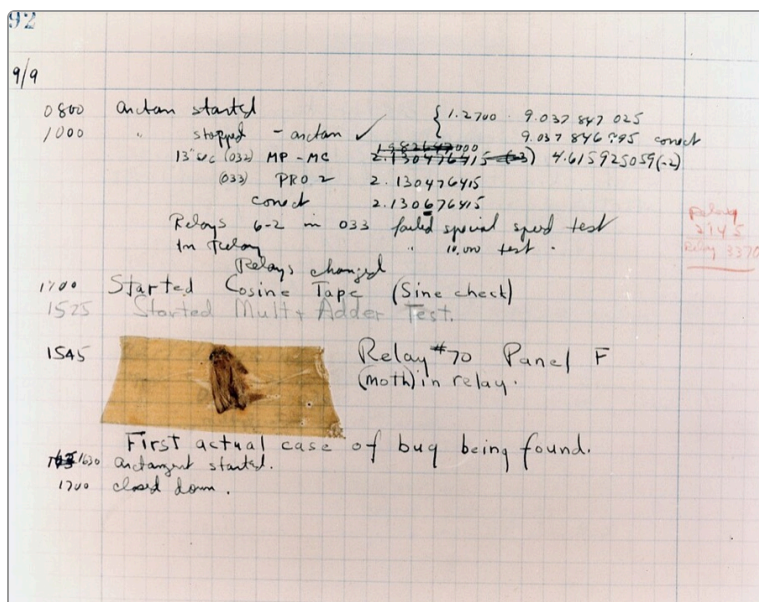
The story. Grace Hopper was a mathematics professor who joined the United States Navy in 1943. She was sent to Harvard University to program one of the first large computers, the Mark I, a machine 51 feet long, full of switches, relays and spinning shafts. Programming it meant writing long lists of number codes and punching them into paper tape. On September 9, 1947, the team working on the next machine, the Mark II, found that it was failing because a moth had been trapped in one of its relays. They taped the moth into the logbook with the note “First actual case of bug being found.” Engineers had called mistakes “bugs” for years, but Hopper loved to tell this story, and it made the words “bug” and “debugging” famous.

How they figured it out. Hopper saw that writing programs in number codes was slow and full of mistakes. She believed computers could be taught to translate instructions written in words into the codes they needed. Many experts told her a computer could only do arithmetic. She built the first “compiler” anyway in 1952, a program that translates other programs. Later she helped create COBOL, a programming language that used English words and was used by businesses for decades. She kept a clock in her office that ran backward, to remind people that “we have always done it this way” is not a good reason.

The physics. A computer does nothing on its own; it follows an **algorithm**, written as **code**. Inside, every instruction becomes millions of tiny switches turning on and off, the same “yes or no” as a Jacquard card’s hole. Good programs use a few powerful patterns. A **loop** repeats instructions, so instead of writing “move” a hundred times, you write “repeat 100: move.” A **conditional** makes a decision: “if the apple touches the bowl, add one point.” With sequences, loops and conditionals, you can build almost anything.

The engineering. Real programs are tested and debugged far more than they are written. Software engineers write a little code, test it, find the bugs, fix them and test again, just as you tested each step of your chain-reaction machine. They write clear names and short pieces of code so others can understand and check them. Block languages like Scratch let beginners use the same ideas without typing mistakes: each block snaps into place like a puzzle piece, so you can focus on the algorithm.

PICTURE STUDY



The First Computer Bug, U.S. Navy, September 9, 1947 · Logbook page with a moth taped to it · Smithsonian National Museum of American History

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

This is the actual page from the Harvard Mark II logbook. Engineers wrote down every test and every problem, minute by minute. That habit of careful records is why this page, and this moth, are in a museum today.

Look closely

- Find the moth taped to the page.
- Read the note beside it. What does it say?
- Find the times written down the left side. What do they tell you about how the engineers worked?
- Look for words like “started” or “test.”

Talk about it

1. Why would engineers write down every test in a logbook?
2. Was the moth a mistake in the program or a problem with the machine? How is that different?
3. How is this logbook like your engineer’s notebook?

Safety first. Use the computer with a parent's permission. Scratch is free at scratch.mit.edu; a parent should create any account, and you can also work offline in the Scratch app without one.

BUILD

A Catch Game in Scratch: Loops, Decisions and Debugging

You will write the algorithm for a simple catch game on paper first, then build it in Scratch: an apple falls from the top of the screen, and a bowl you move with the mouse tries to catch it. You will count your blocks, test the game, find bugs and fix them.

You will need

- A computer or tablet with Scratch (free at scratch.mit.edu, or the free Scratch app)
- Paper and pencil for the algorithm
- Engineer's notebook

Steps

1. **Algorithm first.** On paper, write the steps in plain words: (1) The bowl follows the mouse left and right forever. (2) The apple starts at the top in a random spot. (3) The apple falls down a little at a time. (4) If the apple touches the bowl, add a point and send it back to the top. (5) If it reaches the bottom, send it back to the top.
2. **Build.** Follow the video to add a bowl sprite and an apple sprite, then turn each step of your algorithm into blocks.
3. Find the **loops** (“forever,” “repeat”) and the **conditionals** (“if ... then”) in your code and label them in your notebook.
4. **Test.** Play the game five times. Write down anything that does not work the way your algorithm says.
5. **Debug.** Fix one bug at a time and test again after each fix. Record each bug and how you fixed it in a table.
6. **Count.** Count how many blocks it would take to make the apple fall 300 steps without a loop (one “change y” block for every step). Compare that with your loop.
7. **Improve.** Add one new feature, with an algorithm first: the apple falls faster as your score grows, or a second falling object takes away a point. Test and

debug it.

Tips

- Click a block to see what it does before you add it to a script.
- If something happens too fast to see, add a short “wait” block while you debug.
- Save your project often.

Check your work

- ☐ I can explain what an algorithm, a loop and a conditional are.
- ☐ I tested my game and recorded each bug and fix.
- ☐ I can tell the story of the first computer bug.

ENGINEER'S NOTEBOOK

1. Write your game's algorithm in plain words, then draw arrows to the blocks that do each step.
2. Make a debugging table: what went wrong, why, how I fixed it.
3. Write a short algorithm (6–8 steps) for a morning task, using one loop and one “if.”

From history. Grace Hopper served in the Navy for most of her life, retiring in 1986 as a rear admiral at the age of 79. She was famous for handing out pieces of wire about 11.8 inches long to show people how far electricity travels in one billionth of a second, to explain why computers have to be small to be fast.

COMMON MISTAKES

- Starting to code before planning the algorithm.
- Fixing several bugs at once, then not knowing which change worked.
- Thinking a computer understands what you meant. It does exactly what the code says.

Make it a game • Be the Robot. Write an algorithm for a simple task, such as making a sandwich or getting a toy from another room. Your parent follows your steps exactly, like a robot. When it goes wrong, call out “bug!” and fix the step. Include a loop and an “if.” Explain where Grace Hopper's word bug came from.

Scripture. “Let all things be done decently and in order.” (1 Corinthians 14:40, KJV)

Paul wrote this about worship, but it is good advice for an algorithm too. A program works only when every step is clear and in the right order.

8.3 SENSORS AND FEEDBACK: FROM CTESIBIUS'S WATER CLOCK TO ROBOTS

OBJECTIVES

- Explain sense, think, act, and how feedback lets a machine correct itself.
- Tell how Ctesibius used a float to keep his water clock running at a steady speed.
- Be the controller in a water-level test, comparing control with feedback and without it.

Warm-up. Hold a pencil balanced upright on your fingertip. Watch it and move your hand to keep it from falling. Now try with your eyes closed. What was your “sensor”? What did your brain “decide”? What did your hand “do”?

WATCH

The clepsydra of Ctesibius

Marty Jopson · 2:00

<https://www.youtube.com/watch?v=G9t3ddvBkYU>

WHEN TO WATCH

After the story. Watch the float rise and see how it controls the water.

Note: A short clip by a science presenter who rebuilt the ancient clock. Watch it twice.

BACKUP VIDEO

Line Follower: A Zippy Robot That Senses Where to Go | Science Project

Science Buddies · 1:38

<https://www.youtube.com/watch?v=S6Z8rJB30M4>

After the engineering paragraph, to see a small robot sense a line and correct itself again and again.

KEY TERMS

sensor

A part that measures something about the world, such as light, distance, temperature or water level.

controller

The part that decides what to do based on what the sensor measures; in a robot, usually a computer.

actuator

The part that acts, such as a motor, a valve or a light.

feedback

Using a measurement of what is happening to adjust what a machine does next.

float valve

A valve opened and closed by a floating ball or cup, which keeps water at a set level.

CORE IDEAS

The story. About 2,200 years ago in Alexandria, Egypt, lived Ctesibius, the son of a barber, who became one of the great inventors of the ancient world. People told time with water clocks: water dripped from one jar into another, and marks on the second jar showed the hours. But the trouble was that water drips faster when its jar is full and slower when it is nearly empty, so the clock ran fast at first and slow later. Ctesibius solved the problem with a clever idea.

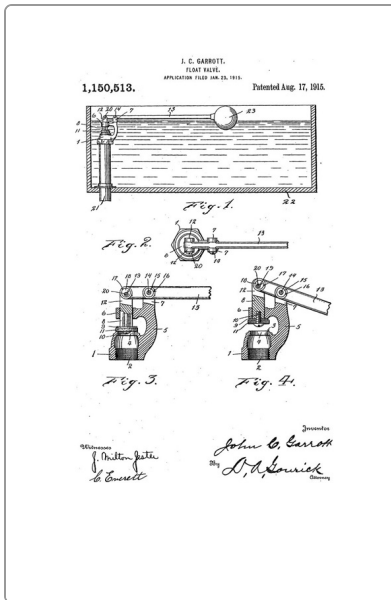
How they figured it out. Ctesibius added a small middle tank between the water supply and the clock. In it floated a cone-shaped stopper. When the water in the middle tank rose too high, the float rose and pushed the cone into the opening, slowing the water coming in. When the level dropped, the float sank, the opening widened, and more water flowed in. The level in the middle tank stayed nearly the same, so water dripped into the clock at a steady rate. The clock measured itself and corrected itself. It was one of the first machines with **feedback** control, and it is described in the writings of the Roman engineer Vitruvius.

The physics. Every robot and every automatic machine does three things over and over: it **senses**, it **thinks** and it **acts**. A **sensor** measures something. A **controller** compares the measurement with what it should be. An **actuator** makes a change. In feedback, the result of the action is measured again, and the cycle repeats. In Ctesibius's clock, the float was the sensor, controller and actuator all in one. If something goes too far one way, feedback pushes it back. That kind of correcting feedback keeps things steady.

The engineering. You probably have a Ctesibius float in your house: the **float valve** in a toilet tank, which shuts off the water when the tank is full. A thermostat

measures the temperature and turns the heat on or off. A car's cruise control measures speed and adjusts the engine. A line-following robot uses light sensors under its body to see a dark line; if the line drifts to the left, the robot turns left, again and again, many times a second. Engineers design feedback to react quickly but not too much, so the machine does not wobble back and forth. That balance is one of the most important skills in robotics.

PICTURE STUDY



A Float Valve Patent, John C. Garrett, 1915 · Patent drawing · United States Patent Office (National Archives)

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

This patent drawing from 1915 shows a float valve for a water tank, the same idea Ctesibius used more than two thousand years earlier. When the water rises, the floating ball lifts the arm and closes the valve.

Look closely

- Find the floating ball in Figure 1.
- Follow the arm from the ball to the valve. Which way does it move when the water rises?
- Find the pipe where water comes in.
- Look at Figures 3 and 4. They show the valve open and closed.

Talk about it

1. What is the sensor in this valve? What is the actuator?
2. What would happen if the ball got a hole and sank?
3. Where in your house might you find a valve like this?

Safety first. Work in the bathtub, outdoors or over a sink with an adult nearby, and wipe up spills. An adult makes the hole in the cup.

BUILD

Be the Float: A Feedback Control Test

You will be the controller in a water system. A cup with a small hole in the bottom drains steadily, and your job is to keep the water at a line by pouring in more. First you will pour on a fixed schedule without looking (no feedback), then while watching the level (feedback). You will measure how far the level strays each way.

You will need

- A clear plastic cup with a small hole near the bottom (made by an adult with a pushpin or nail)
- A marker and a ruler
- A pitcher and a small measuring cup or spoon
- A dishpan or the bathtub to catch the water
- A stopwatch and a partner
- Optional: a computer with the free Microsoft MakeCode micro:bit simulator (makecode.microbit.org)

Steps

1. **Set up.** Draw a target line halfway up the cup, then lines 1 and 2 centimeters above and below it. Fill to the target line over the dishpan and let it drain.
2. **Predict.** Will you keep the level closer to the line with your eyes open or closed?
3. **No feedback.** Fill to the target line. With your eyes closed, pour one measuring cup of water every 10 seconds as your partner calls “pour.” Every 10 seconds your partner records how far above or below the line the water is. Do this for 2 minutes.
4. **Feedback.** Now do it again with your eyes open, pouring only as much as you think you need whenever the level drops. Your partner records the level every 10 seconds for 2 minutes.
5. Make a line graph with two lines: time (across) and distance from the target line (up). Which kept the level steadier?

6. **Name the parts.** In the feedback test, what was the sensor (your eyes), the controller (your brain) and the actuator (your hand and the pitcher)?
7. **Improve.** Try to make your feedback better: pour smaller amounts more often, or start pouring before the level reaches the lower line. Test again. Did the line get steadier?
8. **Optional code.** In the MakeCode micro:bit simulator, write a “thermostat”:
forever, if the temperature is less than 20, show a sun (heater on), else show a snowflake (heater off). Drag the simulator’s temperature slider and watch your feedback program react.

Tips

- Use the same amount of water in each pour during the no-feedback test.
- Your partner should read the level at eye level for an honest reading.
- If the cup drains too fast, use a smaller hole; if too slowly, a bigger one.

Check your work

- ☐ I can explain sense, think, act.
- ☐ My graph shows how feedback kept the level steadier.
- ☐ I can explain how Ctesibius’s float kept his clock steady.

ENGINEER’S NOTEBOOK

1. Draw Ctesibius’s clock and label the sensor, controller and actuator.
2. Draw a feedback loop as a circle of arrows: sense → think → act → (measure again).
3. Find three feedback machines in your house (toilet tank, thermostat, oven, refrigerator) and write what each one senses and what it does.

From history. Ctesibius is also remembered for inventing a force pump for water and a water organ, the hydraulis, in which water pressure kept the air flowing steadily to the pipes. Much later, in 1788, James Watt used a spinning governor as feedback to keep his steam engines at a steady speed.

COMMON MISTAKES

- Thinking a robot just moves. A robot senses and decides, too.
- Overcorrecting: pouring a lot every time the level drops, which makes it bounce above and below the line.

- Thinking feedback is only for computers. A float in a tank uses feedback with no electricity at all.

Make it a game • Float Valve Human. Be the float. Your parent pours a slow stream into a bowl while you hold a spoon as a valve and adjust the flow to keep the level steady. Name the sensor, the controller and the actuator in the game. Then tell how Ctesibius used a float to keep his water clock at a steady pace.

8.4 A SYRINGE-HYDRAULIC ROBOT ARM AND THE FAMILY ENGINEERING FAIR

OBJECTIVES

- Explain Pascal's law: a push on trapped water is passed through it to every part.
- Tell how Blaise Pascal and Joseph Bramah turned that law into hydraulic machines.
- Build and test a syringe-hydraulic robot arm, and present it and your best builds at a family engineering fair.

Warm-up. Fill a syringe with water and push the plunger with your thumb while blocking the tip with your finger. Can you squeeze the water smaller? Now do the same with air. Which one squishes? Which do you think would work better for passing a push along a tube?

WATCH

Hydraulics | Forces & Motion | Physics | FuseSchool

FuseSchool - Global Education · 4:31

<https://www.youtube.com/watch?v=DdZnknku8b8>

WHEN TO WATCH

After the physics paragraph. Watch how a small push on a small piston becomes a big push on a large one.

Note: The video uses some simple numbers for pressure and area; you can pause and explain with the syringes.

KEY TERMS

hydraulics

Using a liquid in pipes or tubes to pass along a push and move things.

piston

A plug that slides inside a tube, like the plunger of a syringe.

Pascal's law

Pressure put on a liquid in a closed container is passed equally to every part of the liquid.

joint

In a robot arm, a place where it can bend or turn.

gripper

The “hand” at the end of a robot arm
that picks things up.

CORE IDEAS

The story. Blaise Pascal was a French mathematician and scientist who lived in the 1600s. As a teenager he built one of the first mechanical calculators to help his father, a tax official, with his sums. He also studied air and water pressure with careful experiments. Pascal was a devoted Christian who wrote about faith as well as science; his notes were published after his death as the *Pensées*. More than a century later, in 1795, the English inventor Joseph Bramah, a locksmith and cabinetmaker, used Pascal’s ideas to patent the hydraulic press, a machine that could press with enormous force.

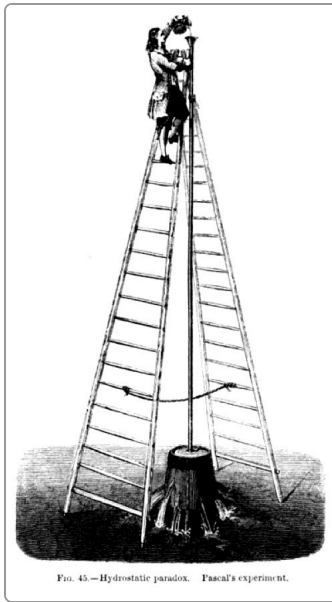
How they figured it out. Pascal found that when you push on water trapped in a closed container, the push spreads through all of it at once and presses equally on every wall. He realized this meant a small push on a small **piston** could make a big push on a large piston connected to it. Bramah built it in iron and brass. A worker pumped a small piston with a handle, and the water pushed up a large piston with many times the force, enough to press bales of cotton, test chains and anchors, and later lift the giant iron tubes of the Britannia Bridge. Bramah’s hardest problem was keeping the water from leaking around the big piston; his workman Henry Maudslay helped design a leather seal that pressed tighter as the pressure rose.

The physics. Water hardly squeezes at all, so when you push on one end of a water-filled tube, the other end pushes out right away. That is **Pascal’s law** at work, and it is how **hydraulics** passes a push along a tube. Air squeezes like a spring, so an air-filled system feels spongy and weak. If a small syringe pushes a large syringe, the large one moves a shorter distance but with more force. Energy is not created; you trade distance for force, just as a lever does.

The engineering. Hydraulics are everywhere in heavy machines: excavators and backhoes, car brakes, dump trucks, airplane landing gear and the lifts in garages. Many factory robots and some robot arms use hydraulics for strength. A robot arm has **joints** that bend or turn and a **gripper** at the end, and each joint needs its own actuator. In your arm, each syringe pair is one actuator, and you are the controller.

Real robots add sensors and a computer, sense, think and act, so that the arm can move by itself.

PICTURE STUDY



Pascal's Barrel, Unknown engraver, 1800s · Engraving · From a French physics book of the 1800s
Image: [Wikimedia Commons](#), public domain

This engraving shows a famous experiment described by Blaise Pascal. A long, thin tube is fixed into the lid of a barrel full of water. When a little more water is poured into the tube, the barrel bursts. The tall column of water presses on all the water in the barrel at once.

Look closely

- Find the man on the ladder. What is he pouring?
- Find the long, thin tube. How much water could it hold?
- Find the barrel at the bottom. What is happening to it?
- Look at where the water sprays out. Is it only at the top, or all around?

Talk about it

1. How can a small amount of water in a thin tube burst a whole barrel?
2. How is this like a small syringe pushing a large syringe?
3. Why do engineers need to know about this when they design pipes and tanks?

Safety first. An adult handles the hot glue gun and any cutting with a craft knife. Wear safety glasses, because a syringe can squirt water hard when a tube pops off. Use only water (with food coloring if you like), and keep syringes away from small children.

BUILD

A Syringe-Hydraulic Robot Arm

You will build a cardboard robot arm with three hydraulic joints, a base that turns, an arm that lifts and a gripper that closes, each worked by a pair of syringes joined by a tube of water. Then you will test how much it can lift, compare water with air, and improve it. Last, you will present it at the family engineering fair.

You will need

- 6–8 plastic syringes (10–20 milliliters, without needles, from a pharmacy or craft store) and about 2 meters of clear tubing that fits them
- Corrugated cardboard, wooden craft sticks and skewers or dowels for pivots
- A low-temperature hot glue gun (adult only), zip ties or tape
- Water with a few drops of food coloring
- Small test loads: a paper cup, pennies or cotton balls
- Safety glasses, a ruler and engineer's notebook

Steps

1. **Plan.** Sketch your arm: a base, a lifting arm on a pivot, and a two-finger gripper. Mark where each syringe pair will push.
2. **Build.** Cut the cardboard parts, join them at pivots with skewers, and let the arm move freely by hand before adding syringes.
3. **Fill.** For each pair, fill one syringe with colored water, push out the air, attach the tube, fill it, and connect an empty syringe with its plunger pushed in. Push one plunger and watch the other move.
4. Glue or tie one syringe of each pair to the arm so pushing the hand syringe moves a joint. Test each joint.
5. **Test.** Try to lift a cup with 5 pennies. Add pennies 5 at a time until the arm can no longer lift the cup. Record the most it lifted. Do three trials.
6. **Fair test: water or air?** Empty one pair and fill it with air only. Test the same joint again with the same load. Record what changes.

7. **Improve.** Find the weakest part (a bending arm, a leaking tube, a slipping gripper) and fix only that. Test again and record whether the load went up.
8. **The family engineering fair.** Set out your arm and your best build from each unit, with its notebook pages. Practice a one-minute explanation for each: what it does, what you tested, what you changed. Then present them to family and guests and answer their questions.

Tips

- Get all the air bubbles out of the tubes; bubbles make the arm spongy.
- Make pivots snug but not tight. Too loose and the arm wobbles; too tight and it sticks.
- A small syringe pushing a large one gives more force but less movement. Try it on the gripper.

Check your work

- ☐ I can explain Pascal's law and why water works better than air in my arm.
- ☐ I tested how much my arm could lift and improved it.
- ☐ I presented my builds and explained how I tested and improved them.

ENGINEER'S NOTEBOOK

1. Draw your robot arm and label the base, joints, gripper, and each syringe pair.
2. Make a table: test, load lifted (three trials), water or air, notes.
3. Write your fair talk: three sentences for each build you will show.

From history. Henry Maudslay, who helped Bramah, went on to become one of the most important machine builders in history. He made precise screw-cutting lathes and trained a generation of engineers. William Armstrong later used hydraulic power to run cranes, bridges that swing open and even the great Tower Bridge in London.

COMMON MISTAKES

- Leaving air in the tubes, which makes the arm weak and slow.
- Thinking the water is “pushed through” to the other end. The push is passed through the water almost instantly; the water itself moves only a little.
- Trying to lift too much at the end of a long arm. A long arm acts like a lever and needs more force.

Make it a game • Push Passes On. Hold a syringe-and-tube set or a squeezable water bottle and explain Pascal's law: a push on trapped water goes through it to every part. Draw a robot arm on paper with piston, joint and gripper labeled. Your parent quizzes you on each label. Add one fact about Blaise Pascal or Joseph Bramah.

Scripture. “And I have filled him with the spirit of God, in wisdom, and in understanding, and in knowledge, and in all manner of workmanship,” (Exodus 31:3, KJV)

God gave Bezalel skill to build the tabernacle. Every good gift of making comes from God, and the engineering fair is a time to thank Him for what you have learned to make.

ROBOTS AND CODING

A robot is a machine that can sense the world, decide what to do, and act, all by following instructions that people have written. In this unit you will discover where those instructions came from. Two hundred years ago a French weaver, Joseph-Marie Jacquard, made a loom that followed holes punched in cards, the first machine controlled by a stored program. Grace Hopper helped teach computers to understand words. Ancient engineers like Ctesibius built machines that could check themselves and correct their own mistakes, the idea of feedback that every robot uses today.

You will weave a pattern from your own punch-card program, code a game in Scratch with loops and decisions, be the “controller” in a feedback test, and build a robot arm moved by water in syringes. The last week is the family engineering fair, where you will show the best build from each unit and explain how it works.

Fabricando fit faber: by making, one becomes a maker.

PREREQUISITES

- Can follow and write step-by-step instructions
- Knows how switches work in series and parallel (Unit 4) and water pressure (Unit 5)
- Has access to a computer or tablet with an internet connection for Scratch (free)

MASTERY CHECKLIST

- ☐ I can explain how Jacquard’s punched cards controlled a loom and how that idea led to computer programs.
- ☐ I can write an algorithm and code it in Scratch using loops and “if” decisions, and find and fix bugs.
- ☐ I can explain sense, think, act and feedback, using a float valve or a thermostat as an example.
- ☐ I can explain how a hydraulic syringe system passes a push through water, and build a robot arm that uses it.
- ☐ I can present a build at the family engineering fair and explain how I tested and improved it.

OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** A small, inexpensive programmable board with buttons, lights and sensors, coded with free Microsoft MakeCode blocks. The free online simulator works without the board. Fits Lessons 8.2 and 8.3.
- **Makeblock mBot:** A small robot car with line-following and distance sensors, programmed with Scratch-style blocks. A good next step after Lesson 8.3 for families who want a real robot.
- **KiwiCo Tinker Crate:** Ages 9–16. Some crates build hydraulic claws and arms with syringes; a good extra or alternative for Lesson 8.4.

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

8.1 The Jacquard Loom and Punch Cards

2 sessions of 45 minutes

8.2 Algorithms and Block Coding: Grace Hopper and the First Bug

2 sessions of 45 minutes

8.3 Sensors and Feedback: From Ctesibius's Water Clock to Robots

2 sessions of 45 minutes

8.4 A Syringe-Hydraulic Robot Arm and the Family Engineering Fair

2 sessions of 45 minutes

UNIT 8 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

How did Jacquard's punched cards tell the loom what to weave?

2. **5 pts**

Why is a chain of punched cards like a computer program?

3. **5 pts**

What is an algorithm? Give a short example.

4. **5 pts**

What is a loop? What is a conditional? Give one example of each from your Scratch game.

5. **5 pts**

Where does the word “bug” come from, and what does it mean to debug?

6. **5 pts**

Name the three things every robot does, and give an example of each for a line-following robot.

7. **5 pts**

How did Ctesibius’s float keep his water clock steady? Name one machine at home that works the same way.

8. **5 pts**

Predict: in your water-level test, will the level stay closer to the line with feedback or without it? Why?

9. **5 pts**

State Pascal’s law. Why does water work better than air in a syringe robot arm?

10. **5 pts**

A small syringe pushes a large syringe. Which one moves farther, and which pushes harder?

ANSWER KEY

1. Each card stood for one row. Where there was a hole, a needle passed through and its hook lifted a warp thread; where there was no hole, the thread stayed down.
2. It is a list of instructions in order that a machine follows exactly; holes and no-holes are a two-choice (binary) code, like the 1s and 0s computers use.
3. A step-by-step set of instructions for a task. Example: fill a glass: get a glass, hold it under the tap, turn on the water, wait until it is nearly full, turn off the water.
4. A loop repeats instructions (forever: move the bowl to the mouse; repeat: change y by -5). A conditional does something only if something is true (if the apple touches the bowl, change score by 1).
5. Engineers called problems bugs, and in 1947 a real moth was found in a relay of the Harvard Mark II and taped in the logbook. To debug is to find and fix mistakes in a program or machine.
6. Sense (light sensors see the line), think (the controller decides to turn left or right), act (the motors turn the wheels).
7. When the water rose, the float pushed a stopper into the inlet and slowed the flow; when it fell, the opening widened. The level stayed steady, so water dripped at a steady rate. A toilet tank's float valve works the same way (or a thermostat uses feedback).
8. With feedback, because you can see the level and correct it when it drifts; without feedback you cannot tell when you are pouring too much or too little.
9. A push on a liquid in a closed container is passed equally to every part. Water hardly squeezes, so the push passes through right away; air squeezes like a spring, so the arm is spongy and weak.
10. The small syringe's plunger moves farther; the large syringe pushes harder but moves a shorter distance. You trade distance for force.

PORTFOLIO PIECE: MY ROBOT ARM AND THE FAMILY ENGINEERING FAIR

Finish, test and improve your syringe-hydraulic robot arm until it can pick up a paper cup holding at least 10 pennies and move it to a new spot. Then hold a family engineering fair: set out the arm and your best build from each of the other units, each with its notebook pages. For each build, prepare a short talk: what it does, the science behind it, the fair test you ran, and what you improved. Present to your family or guests and invite them to try the arm.

LOOK FOR	WHAT IT MEANS
Working arm	The arm lifts and moves the cup of 10 pennies, with at least three working hydraulic joints.
Testing and improvement	Load tests and the water-or-air test are recorded, and one improvement is measured.
Fair display	At least five builds from the year are shown with neat, dated notebook pages.
Explanation	The student explains each build clearly, using correct engineering words, and answers questions.
Care and safety	Tools and materials were used safely, and the display is tidy and well labeled.

TOY LAB: THE PHYSICS OF PLAY

Toys are some of the cleverest machines in the world. A good toy has to be fun, but it also has to work every time, survive being dropped, cost little enough to buy, and be safe in a child's hands. In this optional bonus unit you will study four toys the way an engineer would: the Super Soaker water blaster, invented by a NASA engineer; the returning boomerang; the pogo stick; and the loop-the-loop track for toy cars.

For each toy you will hear the story of who made it and how, learn the physics that makes it squirt, return, bounce or loop, and think about the engineering of materials, cost and safety. Then you will build a homemade version and test it fairly. Use this unit after the family engineering fair, over the summer, or in any week that needs something fun. “The streets of the city shall be full of boys and girls playing” (Zechariah 8:5).

PREREQUISITES

- Knows potential and kinetic energy (Unit 1) and water pressure (Unit 5)
- Knows lift, angle of attack and spinning wings (Unit 7)
- Can run a fair test and record results in a table

MASTERY CHECKLIST

- ☐ I can explain how squeezed air stores energy and pushes water out of a toy like the Super Soaker.
- ☐ I can explain why a returning boomerang curves back, using lift and spin.
- ☐ I can explain how a spring stores and gives back energy in a pogo stick, and why the rider must keep adding energy.
- ☐ I can explain why a car needs to start high enough to make it around a loop.
- ☐ I can name toy-safety rules and explain why engineers test toys before they are sold.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. Each box is a toy to build with a video lesson about the physics inside it, which fits the spirit of this unit exactly.
- **KiwiCo Tinker Crate:** Ages 9–16. Several crates build moving toys and launchers with an explanation of the science; good extras for Lessons 9.1 and 9.4.
- **Snap Circuits (Elenco):** Ages 8 and up. Many of its projects are small electronic toys (fans, alarms, flying saucers), a good follow-up for a student who wants to design an electric toy.

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 Super Soaker: Lonnie Johnson and Air Pressure	2 sessions of 45 minutes
9.2	The Returning Boomerang: Spin and Lift	2 sessions of 45 minutes
9.3	The Pogo Stick: Springs and Energy	2 sessions of 45 minutes
9.4	Loop-the-Loop Tracks: Energy and the Loop	2 sessions of 45 minutes

UNIT 9 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

How did Lonnie Johnson get the idea for the Super Soaker?

2. **5 pts**

Why does pumping air into a water toy make the water shoot out?

3. **5 pts**

Predict: you test your bottle sprayer with 3 pumps and then 12 pumps. Which goes farther, and why?

4. (5 pts)

Why is each arm of a boomerang like a wing?

5. (5 pts)

Why does a returning boomerang curve back?

6. (5 pts)

State Hooke's law. If 5 pennies squeeze a spring 2 mm, how far should 15 pennies squeeze it?

7. (5 pts)

Follow the energy in one pogo-stick bounce, from the top to the top again.

8. (5 pts)

Why must a pogo rider keep pushing down on every bounce?

9. (5 pts)

Predict: a loop is 40 cm tall. Without friction, how high must a car start? Will a real car need more or less?

10. (5 pts)

Name two ways toy engineers make toys safe.

ANSWER KEY

1. While testing a heat pump idea that used water at home in 1982, a nozzle he attached sent a powerful stream of water across the room, and he thought it would make a great water toy.
2. The pumped air is squeezed (compressed) and pushes hard on the water. When the valve opens, the air pressure drives the water out through the nozzle.
3. 12 pumps, because more air is squeezed into the bottle, making higher pressure that pushes the water out faster.
4. It has an airfoil shape (rounded leading edge, thin trailing edge, more curved on one side), so it makes lift as it moves through the air.
5. The top arm moves faster through the air and makes more lift than the bottom arm. That uneven lift would tip it, but because it is spinning, it turns sideways instead (gyroscopic effect), so it keeps curving around.
6. A spring squeezes or stretches in proportion to the force on it (twice the force, twice the squeeze). 15 pennies is three times 5, so about 6 mm.
7. Top: gravitational potential energy → falling: kinetic energy → spring squeezed: elastic potential energy → spring pushes back: kinetic energy → top: gravitational potential energy (with a little lost as heat and sound each time).
8. Every bounce loses a little energy as heat and sound, so the rider must add energy with his or her legs or the bounces get smaller and stop.
9. $1.25 \times 40 = 50$ cm. A real car will need more, because friction and air take away some of its energy.
10. Any two: testing toys by dropping, squeezing and using them many times; checking small parts with a small-parts test and adding warnings for children under 3; covering springs so they cannot pinch; making pressure tanks much stronger than needed with a release valve; using strong plastics without sharp edges; keeping magnets and button batteries sealed inside.

PORTFOLIO PIECE: DESIGN A TOY

Design, build and test your own toy that uses one of the physics ideas from this unit: air pressure, spin and lift, springs, or the energy of a loop. Make a labeled drawing, build a prototype from household materials, and test it fairly at least three times, changing one thing between versions. Then write a short “toy engineer’s report”: who the toy is for, how it works, what you tested and improved, what it would cost to make, and at least three safety rules or features.

LOOK FOR	WHAT IT MEANS
Physics	The toy clearly uses one physics idea from the unit, and the drawing explains it.
Prototype	A working prototype was built from household materials.
Fair testing	At least three versions were tested, changing one thing at a time, with results recorded.
Safety	The report names at least three safety rules or features suited to the age of the user.
Presentation	The student explains the toy, its physics and its improvements clearly to an audience.

9.1 THE SUPER SOAKER: LONNIE JOHNSON AND AIR PRESSURE

OBJECTIVES

- Tell how Lonnie Johnson, an engineer who worked on NASA spacecraft, invented the Super Soaker.
- Explain how squeezed (compressed) air stores energy and pushes water out of a nozzle.
- Build a bottle sprayer pressurized with a ball pump and test how the number of pumps changes how far the water squirts.

Warm-up. Hold a plastic syringe (no needle) with the tip blocked by your finger and push the plunger in. Feel the air push back. Let go. What happens? Now do the same with a little water in the syringe and a little air on top, pointing it into the sink. Where does the push come from?

WATCH

Changing Perspectives Through Perseverance: The Lonnie Johnson Story

National Inventors Hall of Fame - NIHF • 3:09

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

WHEN TO WATCH

After the story. Look for his boyhood robot, his NASA work and his first Super Soaker model.

KEY TERMS

pressure

How hard a gas or liquid pushes on each bit of the surface it touches.

nozzle

A narrow opening that shapes and speeds up a stream of water or air.

compressed air

Air squeezed into a smaller space, which pushes back harder.

valve

A part that lets a fluid flow one way, or opens and closes to control the flow.

prototype

A first working model of an invention,
built to test and improve.

CORE IDEAS

The story. Lonnie Johnson grew up in Mobile, Alabama, in the 1950s and 1960s, taking apart toys to see how they worked and building rockets and machines from junkyard parts. In high school he built a robot from scrap and won a state science fair. He became an engineer for the U.S. Air Force and for NASA's Jet Propulsion Laboratory, where he worked on power systems for spacecraft sent to Jupiter and Saturn. One evening in 1982, at home, he was testing an idea for a new kind of heat pump that used water. He attached a nozzle to his bathroom sink and a powerful stream of water shot across the room. His first thought was: this would make a great water toy.

How they figured it out. Johnson built a **prototype** from plastic pipe, a soda bottle and other parts from his workshop. He tested it with his young daughter, who loved it. But turning a prototype into a toy that can be sold took years. Toys must be cheap, light, strong, and safe, and they must work every time. Johnson changed the design again and again: where to put the pump, how big to make the water tank, how to make the trigger and **valves** seal. He patented his design in 1986, and after several companies turned him down, a toy company began selling it in 1990. It was soon renamed the Super Soaker and became one of the best-selling toys in the world.

The physics. Air can be squeezed; water cannot. When you pump the handle of a Super Soaker, you push extra air into a tank above the water. The air is **compressed**, and it pushes back hard on the water, like a squeezed spring. The more you pump, the higher the **pressure**. When you pull the trigger, a valve opens and the air pressure drives the water out through a narrow **nozzle**. The narrow opening makes the water speed up, so it shoots far. As water leaves, the air expands, the pressure drops, and the stream gets weaker.

The engineering. Engineers design pressurized toys to be safe: the tank is made strong enough to hold far more pressure than a child could pump, and there is usually a valve that lets out extra pressure. Water toys are made of plastics that will not crack in the sun, and every new model is tested by dropping, squeezing and pumping it thousands of times. Toy engineers also think about how a toy will be

used: water blasters are for watering plants, hitting targets and summer fun, never for spraying faces. Lonnie Johnson used the money from his invention to start a company working on new batteries and engines that turn heat into electricity, and he still invents today.

PICTURE STUDY



Lonnie Johnson, Engineer and Inventor, U.S. Navy, Office of Naval Research, 2010s · Photograph · Office of Naval Research

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

Lonnie Johnson has received more than a hundred patents. This photograph was taken by the U.S. Navy when he visited to talk with engineers and students about inventing.

Look closely

- Look at his face and hands. What do you think he is explaining?
- Look at the setting. Is this a workshop, a classroom or a meeting?
- Think about the people who might be listening. What would you ask him?
- Look for any objects or screens that might be part of his talk.

Talk about it

1. What did Lonnie Johnson's work on spacecraft have to do with a water toy?
2. Why do you think it took years to turn his prototype into a toy in stores?
3. What could you invent if you noticed something surprising, as he did?

Safety first. Do this build outdoors with an adult and wear safety glasses. Use only a sturdy plastic soda bottle made for fizzy drinks, never glass, and never more than 15 pumps. Aim only at plants or targets on the ground, never at people or animals.

BUILD

A Bottle Sprayer: How Many Pumps?

You will build a simple air-pressure water sprayer from a soda bottle, a straw and a ball pump, like a tiny Super Soaker. Then you will test how the number of pumps changes how far the water shoots.

You will need

- A clean 1-liter or 2-liter plastic soda bottle with its cap
- A bendable drinking straw and modeling clay
- A ball pump with an inflation needle
- Water, a tape measure and chalk or a rope to mark distances
- Safety glasses

Steps

1. **Build.** An adult makes two small holes in the bottle cap: one just big enough for the straw and one just big enough for the pump needle. Push the straw through so it reaches almost to the bottom of the bottle when the cap is on, with the bendy part outside as the nozzle. Seal around the straw and the needle hole with clay.
2. Fill the bottle one-third full of water and screw on the cap. Lay the bottle on its side on the ground with the nozzle pointing level across the grass, and mark the nozzle position.
3. **Predict.** How far will the water go after 3, 6, 9 and 12 pumps?
4. **Test.** Push the pump needle through its hole. Give 3 pumps, pull out the needle and cover the hole quickly with your thumb, then let the water spray. Mark where most of the water lands. Measure the distance.
5. Refill to the same one-third mark and repeat with 6, 9 and 12 pumps. Change only the number of pumps. Do each test twice.
6. Make a line graph: pumps (across) and distance (up). Does doubling the pumps double the distance?
7. **Improve.** Change one thing about the nozzle: pinch the end of the straw a little narrower, or cut it shorter. Test it at 9 pumps and compare.

Tips

- If air leaks out around the straw, add more clay and press it firmly.
- Keep the bottle in the same spot and the nozzle at the same angle for every test.
- On a hot day, pressure builds faster; do all your tests at the same time of day.

Check your work

- ☐ I can explain how pumping air into the bottle makes the water shoot out.
- ☐ My graph shows how the number of pumps changed the distance.
- ☐ I can tell the story of Lonnie Johnson's invention.

ENGINEER'S NOTEBOOK

1. Draw your bottle sprayer and label the compressed air, the water, the straw, the nozzle and the direction of the push.
2. Make a table and line graph of pumps and distance.
3. Write one safety rule for a water toy and explain why it matters.

From history. His story is told by the National Inventors Hall of Fame, which honors great American inventors. Since the first Super Soaker, toy engineers have made many water toys that use the same idea, and the compressed-air principle is also used in paint sprayers, garden sprayers and fire extinguishers.

COMMON MISTAKES

- Thinking the water is squeezed. The air is squeezed; the water is pushed out by it.
- Thinking a wider nozzle always shoots farther. A narrower nozzle makes the water move faster, though less water comes out.
- Pumping more and more to win. A toy is only good if it is safe.

Make it a game • Pump Count Challenge. With a spray bottle and a sink, predict how far the spray goes after five pumps, ten pumps and fifteen. Test each and record distances. Explain why compressed air pushes water out of a nozzle. Add one fact about Lonnie Johnson and the Super Soaker. Beat your best distance by changing just one thing.

Scripture. “And the streets of the city shall be full of boys and girls playing in the streets thereof.” (Zechariah 8:5, KJV)

God’s promise of a restored city includes children playing. Making safe, good toys is a way of serving that joy.

9.2 THE RETURNING BOOMERANG: SPIN AND LIFT

OBJECTIVES

- Explain that each arm of a boomerang is a small wing that makes lift.
- Explain why spin makes a boomerang curve around and come back.
- Build card boomerangs and test how arm length or added weight changes how close they return.

Warm-up. Hold a spinning top or a bicycle wheel (with an adult holding the axle) and try to tilt it. Does it tilt the way you push, or does it turn sideways? Now look at a boomerang picture or a three-armed card cutout. What shape are the edges of each arm?

WATCH

How Does A Boomerang Work?

[Veritasium](https://www.youtube.com/watch?v=ADJKsLEAOHo) · 2:53

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

WHEN TO WATCH

After the physics paragraph. Pause on the drawing of the arm's shape and on the arrows showing which arm makes more lift.

Note: A physicist explains with drawings and a real boomerang. You may stop at about 2:30, before a short clip of water-sport stunts that advertises another video.

BACKUP VIDEO

Tutorial: How to make a Cardboard Boomerang

[RamRez Boomerangs](https://www.youtube.com/watch?v=RhtQiaPqe6g) · 3:26

<https://www.youtube.com/watch?v=RhtQiaPqe6g>

Before the build, to see a boomerang maker draw, cut and shape a returning cardboard boomerang.

KEY TERMS

boomerang

A curved, spinning throwing toy whose arms are shaped like wings so it flies in a circle back toward the thrower.

airfoil

The cross-section shape of a wing, rounded on the leading edge and thin at the trailing edge.

spin

Turning around and around on its own center.

gyroscopic effect

When you try to tilt a spinning object, it turns sideways instead.

leading edge

The front edge of a wing, the one that meets the air first.

CORE IDEAS

The story. The returning boomerang comes from the Aboriginal people of Australia, who made boomerangs by carving them from the curved roots and branches of trees. Some heavy, straight-flying throwing sticks were used for hunting, but the light, curved returning boomerang was used for games and contests of skill, and its flight amazed European visitors who saw it in the 1800s. For a long time no one could fully explain why it came back. Boomerang throwing later became a sport, with world championships for accuracy, distance and catching.

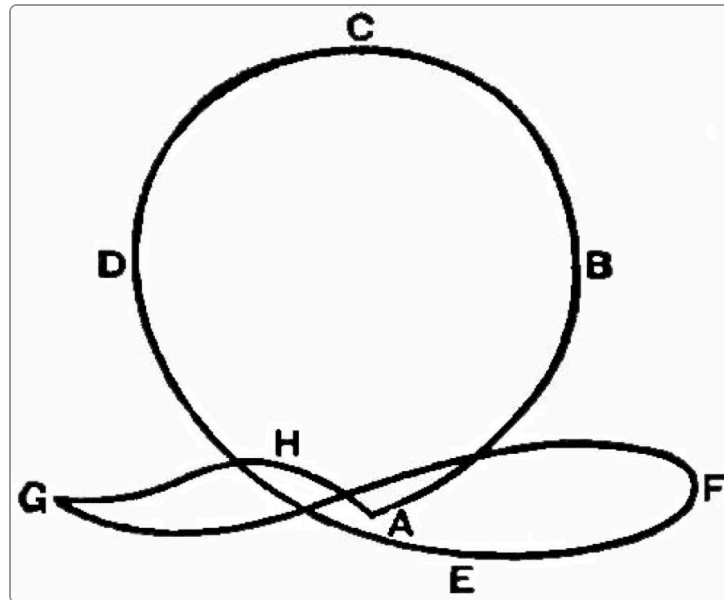
How they figured it out. Scientists at first simply could not believe that a thrown stick could turn around by itself. In the 1800s and 1900s, physicists studied boomerangs by throwing them, watching them carefully, and drawing their flight paths. In the 1970s a Dutch scientist named Felix Hess studied them for his university degree. He measured them, photographed their paths and worked out the mathematics, and his work showed exactly how lift and spin together make the boomerang circle back. Today boomerang makers use the same ideas to design boomerangs for different winds and throwing styles.

The physics. Each arm of a returning boomerang is shaped like a small wing, an **airfoil**, rounded on the leading edge and thin at the back, with one side more curved than the other. A boomerang is thrown nearly upright, with a lot of **spin**. As it spins and flies forward, the arm at the top is moving forward through the air faster than the arm at the bottom, so the top arm makes more lift. That uneven lift tries to tip the boomerang over. But a spinning object does not tip the way it is pushed; because of the **gyroscopic effect**, it turns sideways instead, just as a bicycle turns when you lean. So the boomerang keeps turning, around and around, and comes back.

The engineering. Boomerang makers choose the arm length, the angle between the arms, the airfoil shape and the weight to control how far and how fast it flies. A

heavier boomerang flies farther and handles wind better, but it is harder to catch and more dangerous. Wooden boomerangs are carved and sanded smooth; plastic ones are molded. For safety, real boomerangs are thrown only in a big, open field with no people, cars or windows nearby, and never in strong wind. Indoor boomerangs made of light card are much safer and still show all the physics.

PICTURE STUDY



How a Boomerang Flies, Encyclopaedia Britannica, 1911 · Engraving · *Encyclopaedia Britannica*, 11th edition

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

This diagram comes from a famous encyclopedia printed more than a hundred years ago. Scientists of the time drew boomerang flight paths carefully to try to understand them.

Look closely

- Find where the boomerang starts.
- Follow its path with your finger. Which way does it curve?
- Find where it ends. How close is it to the thrower?
- Look for marks, arrows or letters that explain the path.

Talk about it

1. Why does the boomerang keep curving instead of flying straight?
2. What would happen to the path if the boomerang had very little spin?
3. Why would scientists draw flight paths instead of just describing them in words?

Safety first. Throw card boomerangs only indoors in a clear room or outdoors on a calm day, with everyone behind the thrower. Never throw a wooden or plastic boomerang except in a large open field with an adult, far from people, pets, cars and windows. Catch it with two hands clapped together flat, or let it land.

BUILD

Card Boomerangs: How Long Should the Arms Be?

You will make three-armed card boomerangs with arms of different lengths, throw each one the same way, and measure how close to your starting spot it returns. Then you will try adding weight to the tips.

You will need

- Stiff card stock or cereal-box cardboard
- A ruler, a pencil, scissors (an adult helps with cutting) and tape
- Small paper clips for tip weights
- Masking tape for a throwing spot and a tape measure
- Engineer's notebook

Steps

1. **Build.** Draw a three-armed shape like a fat letter Y, with each arm 2.5 centimeters wide. Make three boomerangs: arms 7, 9 and 11 centimeters long from the center. Cut them out.
2. Bend each arm up very slightly (just a few degrees) and give each arm a slight twist so its leading edge is a little higher. Make all three the same way.
3. **Learn the throw.** Hold one arm between your thumb and finger, with the boomerang nearly upright and tilted slightly outward. Flick it forward with a snap of the wrist so it spins fast. Practice until it returns.
4. **Predict.** Which arm length will come back closest?
5. **Test.** Stand on the tape mark. Throw each boomerang five times with the same throw. Measure how far from the mark it lands each time.
6. Record the distances and find the median for each. Make a bar graph.
7. **Improve.** Take your best boomerang and tape one small paper clip to the tip of each arm. Test five more throws. Does the weight make it fly farther, return closer, or wobble?

Tips

- Spin is everything. A fast flick with a snap of the wrist matters more than throwing hard.

- If it falls flat, hold it more upright. If it climbs and drops, tilt it slightly less.
- Left-handed throwers need boomerangs with the twists and bends reversed.

Check your work

- ☐ I can explain why each arm of a boomerang is like a wing.
- ☐ I can explain how spin makes a boomerang turn back.
- ☐ I tested three arm lengths fairly and recorded the results.

ENGINEER'S NOTEBOOK

1. Draw a boomerang arm in cross-section and label the leading edge and the curved side.
2. Draw the flight path of your best boomerang from above.
3. Make a table: arm length, five landing distances, median.

From history. Boomerangs that come back have also been found in other parts of the world, and the word itself comes from a language of the Aboriginal people near Sydney. In 2008 a Japanese astronaut threw a small boomerang inside the International Space Station, and it came back even there, because its return depends on air, not on gravity.

COMMON MISTAKES

- Throwing the boomerang flat like a flying disc. A returning boomerang is thrown nearly upright.
- Throwing hard without spin. Without spin it will not curve back.
- Thinking a boomerang comes back because of the wind. It returns because of lift and spin; wind usually makes it harder.

Make it a game • Boomerang Riddles. Make a card boomerang from a cut index card. Your parent gives riddles about it: "I am a small wing on each arm" or "I keep spinning to stay steady." Answer with lift, spin, airfoil or gyroscopic effect. Then toss it indoors gently, away from people and breakables, and describe the curve.

9.3 THE POGO STICK: SPRINGS AND ENERGY

OBJECTIVES

- Explain how a spring stores energy when it is squeezed and gives it back when it is let go.
- Follow the energy changes in one bounce of a pogo stick and explain why the rider must keep adding energy.
- Test how far a spring squeezes under different loads (Hooke's law), and how high a squeezed spring launches a small load.

Warm-up. Bounce gently on your toes ten times. Where do your legs bend, and when do they push? Now bounce on a cushion or mattress (with permission). Is it easier or harder to bounce high? Talk about what the cushion does.

WATCH

[Springs](#) | [Forces & Motion](#) | [Physics](#) | [FuseSchool](#)

[FuseSchool - Global Education](#) • 5:18

<https://www.youtube.com/watch?v=ZG2XJut8TeU>

WHEN TO WATCH

After the physics paragraph. Watch the graph of force and stretch, and pause at the question about which spring stores the most energy.

Note: The last part shows a simple equation for older students; you may stop before it.

KEY TERMS

spring

A coil or bar of springy metal that squeezes or stretches under a force and springs back when the force is removed.

elastic potential energy

Energy stored in a squeezed or stretched spring.

Hooke's law

A spring squeezes or stretches in proportion to the force on it: twice the force, twice the squeeze (up to a limit).

energy loss

Energy turned into heat and sound in each bounce, which must be replaced to keep going.

elastic limit

The point past which a spring is bent out of shape and will not spring back.

CORE IDEAS

The story. Jumping sticks with springs were invented more than once. Around 1920, two German inventors, Max Pohlig and Ernst Gottschall, patented a spring-loaded jumping stick, and in the United States George Hansburg built and sold an improved one with the spring enclosed in a metal tube, where it could not pinch fingers or catch clothing. In the 1920s the pogo stick became a craze in America and Europe. Grown-ups as well as children bounced on them, and dancers even did shows on pogo sticks. More than eighty years later, in the 2000s, engineers designed new pogo sticks with powerful air springs and rubber springs that let riders bounce many feet high.

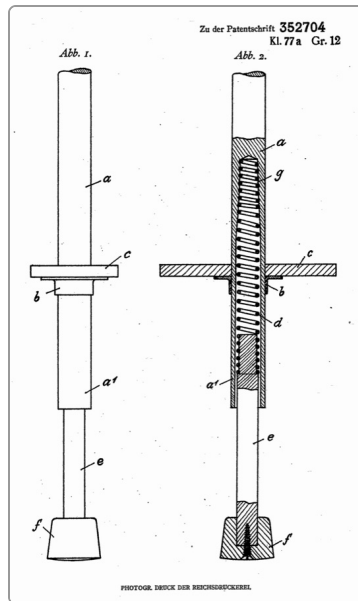
How they figured it out. The scientist who first described how springs behave was Robert Hooke, an English scientist of the 1600s who also built microscopes and helped rebuild London after the Great Fire. He hung weights on springs and wires and measured how far they stretched. He found that if you double the weight, the stretch doubles. Toy and machine engineers still use **Hooke's law** to choose springs. For a pogo stick, the spring must be stiff enough to hold up the rider without squashing flat, but soft enough to squeeze a good distance and store a lot of energy.

The physics. Follow one bounce. At the top, the rider has gravitational potential energy. Falling, the rider speeds up: kinetic energy. When the stick hits the ground, the **spring** squeezes and the rider slows down; the energy is now stored as **elastic potential energy** in the spring. Then the spring pushes back and launches the rider up again. But every bounce loses a little energy as heat in the spring and the sound of the thump. That **energy loss** is why the rider must push down with his or her legs at just the right moment on every bounce, adding energy, or the bounces get smaller and stop.

The engineering. Pogo stick engineers choose the spring's stiffness by the rider's weight, so sticks are sold for different weight ranges. The spring must never be squeezed past its **elastic limit**, or it will be bent out of shape. The handles, foot pegs and rubber tip are designed to grip well, and the spring is covered so fingers cannot be pinched. Riders should wear a helmet and ride only on flat, dry ground. The same

spring engineering is used in car suspensions, mattresses, trampolines and the running blades worn by some athletes.

PICTURE STUDY



The German Pogo Stick Patent, Max Pohlig and Ernst Gottschall, 1920s · Patent drawing · German Patent Office (Patent 352704)

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

This drawing comes from the German patent for one of the first pogo sticks. The second figure is a cutaway: it shows the inside of the tube, where the spring is hidden.

Look closely

- Find the cross-bar where the rider stands.
- Find the coiled spring in the cutaway drawing. Is it inside or outside the tube?
- Find the rubber tip at the bottom.
- Find the inner rod that slides up and squeezes the spring.

Talk about it

1. Where is the energy stored when the rider lands?
2. Why is it safer to have the spring hidden inside the tube?
3. What would happen if the spring were too soft for a heavy rider?

Safety first. Wear safety glasses, because a squeezed spring can slip and fly. Use only small springs, such as those from old ballpoint pens. Never stand in front of a spring launcher.

BUILD

The Spring Lab: Squeeze and Launch

You will use springs from ballpoint pens to test Hooke's law, measuring how far a spring squeezes under different numbers of pennies. Then you will build a tiny "pogo" launcher and measure how high a squeezed spring can launch a light load.

You will need

- Three springs from old ballpoint pens (an adult takes the pens apart), all the same if possible
- A drinking straw or a thin pencil to keep the spring upright, and a small paper cup
- About 40 pennies and a coin-sized cardboard disc
- A ruler and a tape measure taped to a wall
- Safety glasses and engineer's notebook

Steps

1. **Squeeze test.** Slide a spring over a pencil standing upright in a lump of clay. Rest the cardboard disc on top and measure the spring's height.
2. **Predict.** If 5 pennies squeeze the spring 2 millimeters, how far will 10 pennies squeeze it?
3. Stack pennies on the disc, 5 at a time, up to 30. Measure the spring's height each time and work out how much it has squeezed.
4. Make a line graph: pennies (across) and squeeze (up). Is it a straight line? That is Hooke's law.
5. **Launch test.** Stand the spring upright on the table with a small paper-cup "rider" on top. Press it down 2 millimeters, 4 millimeters and 6 millimeters (mark the pencil), and let go. Measure how high the cup jumps against the wall tape measure. Do three trials each.
6. Make a second graph: squeeze (across) and launch height (up).
7. **Improve.** Try two springs stacked end to end, or a stiffer spring. Does it store more energy and launch higher with the same squeeze?

Tips

- Press the spring straight down and let go cleanly; a sideways push sends the cup flying off course.
- Read the height at eye level and have a partner watch the very top of the jump.
- Do not squeeze the spring so far that it stays bent; that is past its elastic limit.

Check your work

- ☐ I can explain Hooke's law using my graph.
- ☐ I can follow the energy changes in one pogo bounce.
- ☐ I can explain why a pogo rider must keep pushing to keep bouncing.

ENGINEER'S NOTEBOOK

1. Draw a pogo stick in four positions of one bounce and label where the energy is in each: gravitational, kinetic, elastic, kinetic.
2. Make the two graphs from your spring lab.
3. List three other things that use springs and what each spring does.

From history. Robert Hooke first published his law in 1676 as a Latin riddle, and two years later gave the answer: “as the stretch, so the force.” He was a busy inventor who also worked with Christopher Wren to design many of the churches and the great Monument built after the Great Fire of London.

COMMON MISTAKES

- Thinking the spring makes energy. It only stores the energy that goes into it, and gives back a little less.
- Thinking any spring works for any rider. Springs must be matched to the weight they carry.
- Squeezing a spring too far, which bends it permanently.

Make it a game • Bounce Energy Map. Squeeze a spring or a sponge on the table. Then stand up and pretend to be a pogo stick: squat for stored energy, spring up for motion, slow at the top. Your parent calls each phase and you name the energy. Explain why the rider must keep adding energy. Fewest mistakes wins.

9.4 LOOP-THE-LOOP TRACKS: ENERGY AND THE LOOP

OBJECTIVES

- Explain why a car must start high enough to make it all the way around a loop.
- Tell how early loop roller coasters taught engineers to shape loops more safely, and how toy car tracks use the same physics.
- Build a loop track and find the lowest starting height that gets a car around loops of different sizes.

Warm-up. Put a little water in a small bucket. With an adult watching and everyone standing well back, swing it quickly in a big circle over your head. Does the water fall out at the top? Now (outdoors!) try it more slowly. What changes? Why does speed matter?

WATCH

LEGO Car vs Bigger Loop

Brick Technology · 11:20

<https://www.youtube.com/watch?v=w7aWcTwe9VU>

WHEN TO WATCH

After the physics paragraph. Each time the loop gets bigger, predict whether the car will make it, and watch how the builder changes speed and weight.

Note: A builder tests LEGO cars on bigger and bigger loops. It is long; you may watch half in each session.

KEY TERMS

loop

A part of a track that goes all the way around in a vertical circle, so the car travels upside down at the top.

speed

How fast something moves.

minimum height

The lowest starting point that still gives a car enough energy to go all the way around a loop.

friction

A force that slows a car down where its wheels and axles rub, turning energy into heat.

clothoid loop

A loop shaped like a teardrop, tighter at the top than at the bottom, used on modern roller coasters.

CORE IDEAS

The story. In 1895 a roller coaster called the Flip Flap Railway opened at Coney Island in New York. Its cars rolled down a steep hill and went all the way around a perfectly round loop. It worked, but the riders were thrown hard into their seats at the bottom of the loop, and many complained of sore necks. In 1901 another Coney Island ride, the Loop the Loop, used a loop that was taller than it was wide, which was gentler. In 1968 a toy company began selling small, fast die-cast toy cars on bright orange plastic tracks with loops, and children everywhere began building loops on their bedroom floors. Engineers had given those little cars thin, smooth axles so they rolled with very little friction.

How they figured it out. Early loop builders learned by building and testing, and some of their first loops were too round and too tight. Engineers later used physics to calculate exactly how fast a car must go at the top of a loop to stay pressed against the track, and how strong the push would be on the riders at the bottom. In the 1970s a German engineer, Werner Stengel, designed loops shaped like a teardrop, called **clothoid loops**. They curve gently at the bottom, where the car is fastest, and tightly at the top, where it is slowest. Nearly every looping roller coaster since then has used that shape.

The physics. To stay on the track at the top of a loop, a car must be moving fast enough. If it is too slow, gravity pulls it off the track before it finishes the circle, just as the water falls out of a slow-swinging bucket. The car gets its speed from its potential energy at the start: the higher it starts, the faster it goes. Without any friction, a car would need to start at least one and a quarter times the loop's height above the bottom of the loop. Real cars lose energy to **friction** and air, so they need to start even higher. Bigger loops need higher starts.

The engineering. Toy car engineers design low-friction wheels and axles so cars can make it around loops from a low start, and they design track pieces that clip together tightly so there are no bumps to steal energy. Roller coaster engineers calculate the speed and the push on riders at every point of a ride, test new rides with weighted

dummies many times, and add safety bars and wheels that lock the cars to the track. The same rule you discovered with your marble coaster in Lesson 1.1 is at work: energy changes form, but some is always lost, so you must start high enough.

PICTURE STUDY



The Flip Flap Railway at Coney Island, Detroit Publishing Company, 1901 · Photograph · Library of Congress, Prints and Photographs Division

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

This is the Flip Flap Railway, one of the first roller coasters with a loop. Look closely at the loop's shape. Engineers later learned that a perfectly round loop like this one was very hard on riders.

Look closely

- Find the loop. Is it perfectly round or shaped like a teardrop?
- Find the hill where the cars start. How high is it compared with the loop?
- Find the people. How big is the loop compared with them?
- Look for the wooden supports. What holds the loop up?

Talk about it

1. Why must the starting hill be higher than the top of the loop?
2. Where in the loop is the car moving fastest? Slowest?
3. Why would a teardrop-shaped loop be gentler on riders than a round one?

Safety first. Do the bucket warm-up only outdoors, with a small amount of water, a sturdy bucket and everyone standing well back. Keep toy cars and small parts away from children under 3, and wear safety glasses if cars might fly off the track.

BUILD

How High to Loop? A Loop-Track Test

You will build a loop track from a toy car track (if you have one) or from foam pipe insulation cut in half, and find the lowest starting height that gets a small toy car or a marble around the loop. Then you will change the size of the loop and test again.

You will need

- A flexible toy car track with a loop, or about 3 meters of foam pipe insulation cut in half lengthwise by an adult
- A small toy car or a marble
- Masking tape, a chair or bookshelf to hold the start, and a ruler and tape measure
- Engineer's notebook

Steps

1. **Build.** Tape the track so it runs down from a chair, across the floor, and up into a loop about 20 centimeters tall. Tape the loop firmly to a box or table leg so it holds its shape, leaving room for the track to run on past the loop.
2. **Predict.** How high must the car start to make it around the loop? Write your guess in centimeters.
3. **Test.** Start the car at 20 centimeters high (measured from the floor). Let go; do not push. Did it make the loop? Raise the start 5 centimeters at a time until it makes the loop three times in a row. Record the minimum height.
4. Compare your result with the no-friction rule ($1.25 \times$ the loop's height). How much extra height did friction cost?
5. **Fair test.** Change only the loop size: make it 30 centimeters, then 40 centimeters tall. Find the minimum starting height for each.
6. Make a table and a graph: loop height (across) and minimum start height (up).
7. **Improve.** Try one change to lower the minimum start: smooth the joints, change the loop's shape to a teardrop, or use a heavier car or marble. Test

and record.

Tips

- Always let the car go from rest; a push adds energy and spoils the test.
- Smooth, taped joints matter. A bump at a joint can steal enough energy to stop the car at the top.
- If the car flies off the track at the bottom of the loop, the curve is too sharp. Make the bottom of the loop more gradual.

Check your work

- ☐ I can explain why a car needs a high enough start to make the loop.
- ☐ My graph shows how loop size changed the minimum start height.
- ☐ I can explain why modern loops are shaped like teardrops.

ENGINEER'S NOTEBOOK

1. Draw your loop track and mark the start, the bottom of the loop (fastest) and the top of the loop (slowest).
2. Make a table and graph of loop height and minimum start height.
3. Draw a round loop and a teardrop loop side by side and explain which is gentler.

From history. Engineers still use Werner Stengel's teardrop loops, and computers now let them test a whole ride in a simulation before it is built. Toy cars and tracks are also safety-tested: small cars are checked with a small-parts test cylinder, and toys with tiny pieces carry a warning for children under three.

COMMON MISTAKES

- Thinking the car only needs to start a little higher than the top of the loop. It needs extra speed at the top to stay on the track.
- Pushing the car at the start. Let gravity do all the work.
- Thinking friction does not matter on a toy track. Even small bumps and rubbing axles add up.

Make it a game • Loop Height Guess. Build a small loop from a flexible ramp or bent cardboard strip and roll a marble from different heights. Before each try, guess whether the marble will make it all the way around. Record hits and misses. Explain the minimum height rule and the effect of friction. Closest guesser takes the point.

Scripture. “A time to weep, and a time to laugh; a time to mourn, and a time to dance;” (Ecclesiastes 3:4, KJV)

There is a time for hard work and a time for play. Even play follows the laws God made, and learning them can be a joy.

TOY LAB: THE PHYSICS OF PLAY

Toys are some of the cleverest machines in the world. A good toy has to be fun, but it also has to work every time, survive being dropped, cost little enough to buy, and be safe in a child's hands. In this optional bonus unit you will study four toys the way an engineer would: the Super Soaker water blaster, invented by a NASA engineer; the returning boomerang; the pogo stick; and the loop-the-loop track for toy cars.

For each toy you will hear the story of who made it and how, learn the physics that makes it squirt, return, bounce or loop, and think about the engineering of materials, cost and safety. Then you will build a homemade version and test it fairly. Use this unit after the family engineering fair, over the summer, or in any week that needs something fun. “The streets of the city shall be full of boys and girls playing” (Zechariah 8:5).

PREREQUISITES

- Knows potential and kinetic energy (Unit 1) and water pressure (Unit 5)
- Knows lift, angle of attack and spinning wings (Unit 7)
- Can run a fair test and record results in a table

MASTERY CHECKLIST

- ☐ I can explain how squeezed air stores energy and pushes water out of a toy like the Super Soaker.
- ☐ I can explain why a returning boomerang curves back, using lift and spin.
- ☐ I can explain how a spring stores and gives back energy in a pogo stick, and why the rider must keep adding energy.
- ☐ I can explain why a car needs to start high enough to make it around a loop.
- ☐ I can name toy-safety rules and explain why engineers test toys before they are sold.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. Each box is a toy to build with a video lesson about the physics inside it, which fits the spirit of this unit exactly.
- **KiwiCo Tinker Crate:** Ages 9–16. Several crates build moving toys and launchers with an explanation of the science; good extras for Lessons 9.1 and 9.4.
- **Snap Circuits (Elenco):** Ages 8 and up. Many of its projects are small electronic toys (fans, alarms, flying saucers), a good follow-up for a student who wants to design an electric toy.

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 Super Soaker: Lonnie Johnson and Air Pressure	2 sessions of 45 minutes
9.2	The Returning Boomerang: Spin and Lift	2 sessions of 45 minutes
9.3	The Pogo Stick: Springs and Energy	2 sessions of 45 minutes
9.4	Loop-the-Loop Tracks: Energy and the Loop	2 sessions of 45 minutes

UNIT 9 REVIEW

Answer each question in a complete sentence or two. You may draw a picture to help explain. The review is worth 50 points.

1. **5 pts**

How did Lonnie Johnson get the idea for the Super Soaker?

2. **5 pts**

Why does pumping air into a water toy make the water shoot out?

3. **5 pts**

Predict: you test your bottle sprayer with 3 pumps and then 12 pumps. Which goes farther, and why?

4. (5 pts)

Why is each arm of a boomerang like a wing?

5. (5 pts)

Why does a returning boomerang curve back?

6. (5 pts)

State Hooke's law. If 5 pennies squeeze a spring 2 mm, how far should 15 pennies squeeze it?

7. (5 pts)

Follow the energy in one pogo-stick bounce, from the top to the top again.

8. (5 pts)

Why must a pogo rider keep pushing down on every bounce?

9. (5 pts)

Predict: a loop is 40 cm tall. Without friction, how high must a car start? Will a real car need more or less?

10. (5 pts)

Name two ways toy engineers make toys safe.

ANSWER KEY

1. While testing a heat pump idea that used water at home in 1982, a nozzle he attached sent a powerful stream of water across the room, and he thought it would make a great water toy.
2. The pumped air is squeezed (compressed) and pushes hard on the water. When the valve opens, the air pressure drives the water out through the nozzle.
3. 12 pumps, because more air is squeezed into the bottle, making higher pressure that pushes the water out faster.
4. It has an airfoil shape (rounded leading edge, thin trailing edge, more curved on one side), so it makes lift as it moves through the air.
5. The top arm moves faster through the air and makes more lift than the bottom arm. That uneven lift would tip it, but because it is spinning, it turns sideways instead (gyroscopic effect), so it keeps curving around.
6. A spring squeezes or stretches in proportion to the force on it (twice the force, twice the squeeze). 15 pennies is three times 5, so about 6 mm.
7. Top: gravitational potential energy → falling: kinetic energy → spring squeezed: elastic potential energy → spring pushes back: kinetic energy → top: gravitational potential energy (with a little lost as heat and sound each time).
8. Every bounce loses a little energy as heat and sound, so the rider must add energy with his or her legs or the bounces get smaller and stop.
9. $1.25 \times 40 = 50$ cm. A real car will need more, because friction and air take away some of its energy.
10. Any two: testing toys by dropping, squeezing and using them many times; checking small parts with a small-parts test and adding warnings for children under 3; covering springs so they cannot pinch; making pressure tanks much stronger than needed with a release valve; using strong plastics without sharp edges; keeping magnets and button batteries sealed inside.

PORTFOLIO PIECE: DESIGN A TOY

Design, build and test your own toy that uses one of the physics ideas from this unit: air pressure, spin and lift, springs, or the energy of a loop. Make a labeled drawing, build a prototype from household materials, and test it fairly at least three times, changing one thing between versions. Then write a short “toy engineer’s report”: who the toy is for, how it works, what you tested and improved, what it would cost to make, and at least three safety rules or features.

LOOK FOR	WHAT IT MEANS
Physics	The toy clearly uses one physics idea from the unit, and the drawing explains it.
Prototype	A working prototype was built from household materials.
Fair testing	At least three versions were tested, changing one thing at a time, with results recorded.
Safety	The report names at least three safety rules or features suited to the age of the user.
Presentation	The student explains the toy, its physics and its improvements clearly to an audience.