

GRADE 5 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: forces and machines, bridges, tall buildings, electricity, public utilities, boats and ships, flight, and robots. Each unit is built around real moments from history: Leonardo da Vinci filling his notebooks, the Roeblings spinning the Brooklyn Bridge cables, Elisha Otis cutting the rope on his own elevator, Samuel Morse sending “What hath God wrought,” Joseph Bazalgette cleaning the River Thames, the warship *Vasa* tipping over on her first voyage, and Wilbur and Orville Wright testing wing shapes in a homemade wind tunnel.

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 fifth grader, and **the engineering**: how the idea becomes a safe, useful, affordable thing. Last, the student repeats the discovery in miniature with cardboard, craft sticks, pennies, batteries and a box fan, measuring and recording each test in an engineer’s notebook and making it better in a second round.

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, water that is clean, a 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, the Institution of Civil Engineers, Practical Engineering, The Engineering Mindset, Jared Owen, Science Buddies, Free School, SciShow Kids and a few others chosen lesson by lesson. Every video was watched in preview for content and accuracy. Some channels end with a short sponsor message or an invitation to subscribe; you

can stop the video when the teaching ends. Watch together when you can, and pause when the lesson's note tells you to predict what comes next.

Start with Lesson 1.1 →

WHO IT IS FOR

Written for students in grade 5 (about ages 10–11) who read independently and can measure with a ruler, multiply and divide, and work with simple fractions and decimals. 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 some units for families who want them.

HOW TO USE THIS COURSE

1. **The weekly rhythm.** The year has 32 lessons, one a week. Session 1 (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 that 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, drawing, patent or painting. Look at it quietly for two minutes. Then put it away and have the student tell everything he or she remembers. Bring it back and work through the “look for” items and questions, which point to the physics and engineering in the picture.
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 (one variable) and test each version more than once. 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, a BBC micro:bit or a Raspberry Pi. 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) and a portfolio build that pulls the unit together, such as a load-tested truss bridge, a shake-table tower, a working telegraph or a glider tested for distance. 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 and USB-powered boards, never from the outlets in the wall. An adult handles hot glue guns, craft knives and drills. Wear safety glasses for anything that flies, snaps or is under tension.
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. **Toy Lab (optional bonus unit).** Unit 9 explores the physics and design of toys: the Frisbee, the LEGO brick, the Rubik’s Cube and a careful toy teardown. Use it after the family engineering fair, over the summer, or slip a lesson in whenever a week needs something fun. It follows the same story-to-engineering pattern and has its own review and portfolio.

SCOPE AND SEQUENCE

UNIT 1 • WEEKS 1–4

Forces, Motion and the Design Process

The engineering design process, learned from Leonardo da Vinci’s notebooks; Newton’s three laws tested with balloon rockets; pulleys and mechanical advantage from Archimedes to the crane; and gears in clocks and bicycles.

1.1 The Engineering Design Process: Leonardo’s Notebooks

1.2 Newton’s Three Laws and a Balloon Rocket

1.3 Archimedes and the Pulley: Mechanical Advantage

1.4 Gears in Clocks and Bicycles

UNIT 3 • WEEKS 9–12

Tall Buildings

Dead, live and wind loads; arches, vaults and flying buttresses from the pyramids to the Gothic cathedrals; the steel frame and Otis’s safety elevator; and the Empire State Building, wind and earthquakes.

3.1 Loads and Foundations: The Washington Monument

3.2 From Pyramids to Gothic Cathedrals: Arches, Vaults and Buttresses

3.3 The Steel Frame and Otis’s Safety Elevator

3.4 The Empire State Building: Building for Wind and Earthquakes

UNIT 2 • WEEKS 5–8

Bridges

Compression, tension, shear and torsion; truss bridges and a craft-stick load test; the Roeblings and the Brooklyn Bridge; and how engineers learned from the collapse of the Tacoma Narrows Bridge.

2.1 Forces in Structures: The Forth Bridge

2.2 Truss Bridges and a Craft-Stick Load Test

2.3 The Brooklyn Bridge: The Roeblings, Caissons and Steel Wire

2.4 Tacoma Narrows: Resonance and Learning from Failure

UNIT 4 • WEEKS 13–16

Electricity and Electronics

Voltage, current and resistance; Oersted, Faraday and a homemade motor; Samuel Morse and the telegraph; and switches, LEDs and resistors.

4.1 Volta, Ohm and the Circuit: Voltage, Current and Resistance

4.2 Oersted, Faraday and a Homemade Motor

4.3 Samuel Morse and the Telegraph

4.4 Switches, LEDs and Resistors: From Edison’s Lamp to the LED

UNIT 5 • WEEKS 17–20

Public Utilities

Clean water from Roman aqueducts to the treatment plant; Bazalgette and the London sewers; generators, Edison, Tesla and Niagara Falls; and the grid, dams and the lineworker.

5.1 Clean Water: From Roman Aqueducts to the Treatment Plant

5.2 Sewers and Wastewater: Bazalgette and the Great Stink

5.3 Making Electricity: Faraday, Edison, Tesla and Niagara Falls

5.4 Dams, the Grid and the Lineworker

UNIT 7 • WEEKS 25–28

Flight

The balloonists and glider pioneers; the Wright brothers' method of kites, wind tunnel and data; the four forces and the airfoil with a glider test; and propellers, jets, rockets and drones.

7.1 The Dreamers: Montgolfier Balloons, Cayley and Lilienthal

7.2 The Wright Brothers' Method: Kites, Wind Tunnel and Data

7.3 The Four Forces and the Airfoil: A Glider Test

7.4 Propellers, Jets, Rockets and Drones

UNIT 6 • WEEKS 21–24

Boats and Ships

Archimedes' principle measured; stability and the warship *Vasa*; from sail to steam with Fulton and the screw propeller; and the *Titanic*, watertight compartments and what changed afterward.

6.1 Archimedes' Principle Measured

6.2 Stability and the Warship *Vasa*

6.3 From Sail to Steam: Fulton and the Screw Propeller

6.4 The Titanic: Watertight Compartments and What Changed

UNIT 8 • WEEKS 29–32

Robots and Invention

Sense, think, act: from the first factory robot to the Mars rovers; algorithms and coding in Scratch or MakeCode; sensors and feedback; and a capstone design challenge with a family engineering fair.

8.1 Sense, Think, Act: From Unimate to the Mars Rovers

8.2 Algorithms and Coding: Loops and Decisions in Scratch or MakeCode

8.3 Sensors and Feedback: Thermostats and Line Followers

8.4 Capstone Design Challenge and the Family Engineering Fair

UNIT 9 • WEEKS 33–36

Toy Lab: The Physics of Play

Optional bonus unit, Toy Lab: the Frisbee as a spinning wing; the LEGO brick, precision molding and clutch power; the hidden mechanism of the Rubik's Cube; and a careful toy teardown, CrunchLabs-style.

9.1 The Frisbee: A Spinning Wing

9.2 The LEGO Brick: Precision, Tolerance and Clutch Power

9.3 The Rubik's Cube: A Hidden Mechanism

9.4 Toy Teardown: How a Toy Is Engineered

WEEKLY PACING CALENDAR

WEEK	PLAN
1	• Session 1: Lesson 1.1 The Engineering Design Process: Leonardo's Notebooks: 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 Newton's Three Laws and a Balloon Rocket: warm-up, video, teaching and picture study • Session 2: Lesson 1.2 build project and engineer's notebook
3	• Session 1: Lesson 1.3 Archimedes and the Pulley: Mechanical Advantage: warm-up, video, teaching and picture study • Session 2: Lesson 1.3 build project and engineer's notebook
4	• Session 1: Lesson 1.4 Gears in Clocks and Bicycles: 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

WEEK	PLAN
5	• Session 1: Lesson 2.1 Forces in Structures: The Forth Bridge: warm-up, video, teaching and picture study • Session 2: Lesson 2.1 build project and engineer's notebook
6	• Session 1: Lesson 2.2 Truss Bridges 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 Brooklyn Bridge: The Roeblings, Caissons and Steel Wire: warm-up, video, teaching and picture study • Session 2: Lesson 2.3 build project and engineer's notebook
8	• Session 1: Lesson 2.4 Tacoma Narrows: Resonance and Learning from Failure: 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 Loads and Foundations: The Washington Monument: warm-up, video, teaching and picture study • Session 2: Lesson 3.1 build project and engineer's notebook
10	• Session 1: Lesson 3.2 From Pyramids to Gothic Cathedrals: Arches, Vaults and Buttresses: warm-up, video, teaching and picture study • Session 2: Lesson 3.2 build project and engineer's notebook
11	• Session 1: Lesson 3.3 The Steel Frame and Otis's Safety Elevator: warm-up, video, teaching and picture study • Session 2: Lesson 3.3 build project and engineer's notebook
12	• Session 1: Lesson 3.4 The Empire State Building: Building for Wind and Earthquakes: 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, Ohm and the Circuit: Voltage, Current and Resistance: 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 Oersted, Faraday and a Homemade 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 Samuel Morse and the Telegraph: 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, LEDs and Resistors: From Edison's Lamp to the LED: 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 Clean Water: From Roman Aqueducts to the Treatment Plant: warm-up, video, teaching and picture study • Session 2: Lesson 5.1 build project and engineer's notebook
18	• Session 1: Lesson 5.2 Sewers and Wastewater: Bazalgette and the Great Stink: warm-up, video, teaching and picture study • Session 2: Lesson 5.2 build project and engineer's notebook
19	• Session 1: Lesson 5.3 Making Electricity: Faraday, Edison, Tesla and Niagara Falls: warm-up, video, teaching and picture study • Session 2: Lesson 5.3 build project and engineer's notebook
20	• Session 1: Lesson 5.4 Dams, the Grid and the Lineworker: 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 Stability and the Warship Vasa: 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 From Sail to Steam: Fulton and the Screw Propeller: warm-up, video, teaching and picture study • Session 2: Lesson 6.3 build project and engineer's notebook
24	• Session 1: Lesson 6.4 The Titanic: Watertight Compartments and What Changed: 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 Dreamers: Montgolfier Balloons, Cayley and Lilienthal: 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 Wright Brothers' Method: Kites, Wind Tunnel and Data: 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 Four Forces and the Airfoil: A Glider Test: 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, Jets, Rockets and Drones: 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 Sense, Think, Act: From Unimate to the Mars Rovers: 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 Coding: Loops and Decisions in Scratch or MakeCode: 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: Thermostats and Line Followers: 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 Capstone Design Challenge 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 Frisbee: A Spinning Wing: 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 LEGO Brick: Precision, Tolerance and Clutch Power: 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 Rubik's Cube: A Hidden Mechanism: warm-up, video, teaching and picture study • Session 2: Lesson 9.3 build project and engineer's notebook
36	• Session 1: Lesson 9.4 Toy Teardown: How a Toy Is Engineered: 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 balloon rockets, pendulums, gliders and shake-table tests.

Cardboard, card stock, paper, masking tape, clear tape and white glue

The main building materials all year.

Craft sticks (about 200), straws, wooden skewers, toothpicks, string and rubber bands

For trusses, towers, pulleys and gliders.

About 200 pennies, paper cups and a small bucket or basket

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

Thread spools, a broom handle, a wire coat hanger and a small bucket

For the pulley lab in Unit 1.

D-cell and AA batteries with holders, alligator clip leads, small bulbs, red LEDs and resistors (100, 220, 470 and 1,000 ohms)

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

Magnet wire (about 22 gauge), a few strong ceramic magnets, an iron nail, a compass and fine sandpaper

For the electromagnet, motor and telegraph builds.

Aluminum foil, a plastic tub or sink, modeling clay and a measuring cup

For the boat and buoyancy builds in Unit 6.

Two clear plastic bottles, sand, gravel, coffee filters and cotton balls

For the water-filter test in Unit 5. Never drink the filtered water.

A box fan

The “wind tunnel” for wing, glider and tall-building tests.

A small hobby motor (1.5–3 volt) with a propeller

For the generator and propeller builds.

Free software: Scratch (scratch.mit.edu) or Microsoft MakeCode (makecode.microbit.org)

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

Safety glasses

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

Optional: one kit, such as a KiwiCo crate, a BBC micro:bit or a CrunchLabs Build Box

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.
- 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, gliders will dive and motors will refuse to spin. The Wright brothers crashed gliders for three summers before they flew, and the 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.

Some lessons tell of disasters, such as the Tacoma Narrows Bridge, the *Vasa* and the *Titanic*. They are told gently and briefly, with the focus on what engineers learned and changed so that others would be safe.

UNIT 1

FORCES, MOTION AND THE DESIGN PROCESS

Every engineer, from Archimedes to the people who build Mars rovers, works the same way: ask what the problem is, learn what others have learned, imagine many answers, plan one, build it, test it, and make it better. In this unit you will meet that method in the notebooks of Leonardo da Vinci, who filled thousands of pages with machines, birds, water and bridges. Then you will use it yourself all year long.

You will also learn the laws that every machine must obey. Isaac Newton's three laws of motion explain why a balloon rocket zooms along a string. Archimedes' pulleys show how a small force can lift a heavy load, if you are willing to pull farther. Gears, from the clock in a cathedral tower to the chain on your bicycle, trade speed for force and keep time. Each lesson ends with a build that you measure, record and improve.

PREREQUISITES

- Can measure length in centimeters and inches and mass in grams
- Can multiply and divide whole numbers and find an average of three numbers
- Has a graph-paper notebook ready to be the engineer's notebook for the year

MASTERY CHECKLIST

- ☐ I can name the steps of the engineering design process and show them in my own notebook.
- ☐ I can state Newton's three laws of motion and give an example of each.
- ☐ I can explain mechanical advantage and find it for a pulley system by counting the supporting ropes.
- ☐ I can find a gear ratio by counting teeth and explain how gears trade speed for force.
- ☐ I can run a fair test that changes only one thing, record the results in a table, and use them to improve a design.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. A subscription box: each month brings a toy to build that shows one physics or engineering idea, with a video lesson from Mark Rober. Fits the whole unit, especially Lessons 1.2–1.4.
- **KiwiCo Tinker Crate:** Ages 9 and up. Monthly engineering projects such as hydraulic arms, trebuchet-style launchers and gear machines, with clear instructions. A good companion to Lessons 1.3 and 1.4.
- **LEGO Technic:** Ages vary by set. Real gears, axles and beams let you build gear trains and measure gear ratios. Fits Lesson 1.4 and the unit portfolio crane.

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

LESSONS IN THIS UNIT

1.1	The Engineering Design Process: Leonardo's Notebooks	2 sessions of 45 minutes
1.2	Newton's Three Laws and a Balloon Rocket	2 sessions of 45 minutes
1.3	Archimedes and the Pulley: Mechanical Advantage	2 sessions of 45 minutes
1.4	Gears in Clocks and Bicycles	2 sessions of 45 minutes

UNIT 1 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**
List the seven steps of the engineering design process in order.
2. **5 pts**
What is the difference between criteria and constraints? Give one example of each for a bridge.
3. **5 pts**
State Newton's first law. Why do cars have seat belts?

4. (5 pts)

Predict: two identical balloon rockets are launched, but one carries 10 paper clips. Which goes farther, and which law explains it?

5. (5 pts)

Explain how a rocket flies using Newton's third law.

6. (5 pts)

A block and tackle has 4 ropes holding up the moving pulley. About how much effort is needed to lift a 200-pound engine, ignoring friction? How far must you pull the rope to lift it 2 feet?

7. (5 pts)

Why does a fixed pulley not reduce the effort? What is it good for?

8. (5 pts)

A bicycle's front sprocket has 48 teeth and the back sprocket has 16. How many times does the back wheel turn for each turn of the pedals? Is this a good gear for climbing a hill?

9. (5 pts)

Predict: a pendulum 25 centimeters long and one 100 centimeters long are released together. Which swings back and forth more times in 30 seconds?

10. (5 pts)

Name one thing Leonardo da Vinci, Archimedes or Huygens did that engineers still do today, and explain why it matters.

ANSWER KEY

1. Ask, research, imagine, plan, build, test, improve (and then repeat).
2. Criteria are what the design must do (span 30 cm, hold 100 pennies). Constraints are the limits (only 20 craft sticks, no glue, must be finished in one hour).
3. An object at rest stays at rest and an object in motion keeps moving in a straight line at the same speed unless a force acts on it. When a car stops suddenly, a passenger keeps moving forward; the seat belt supplies the force that stops the passenger safely.
4. The one without paper clips goes farther (or speeds up faster). Newton's second law: the same force gives less acceleration to a larger mass.
5. The rocket pushes hot gas out of its nozzle backward (action); the gas pushes the rocket forward with an equal and opposite force (reaction).
6. $200 \div 4 = 50$ pounds of effort. $2 \times 4 = 8$ feet of rope.
7. Only one rope holds the load, so the effort equals the load. It is useful because it changes the direction of the force, letting you pull down to lift something up.
8. $48 \div 16 = 3$ turns. No; it is a high gear for speed on flat ground. Climbing needs a smaller front sprocket or a bigger back sprocket.
9. The 25-centimeter pendulum. Shorter pendulums swing faster; length sets the timing (about twice as many swings for one-fourth the length).
10. Any good answer: Leonardo kept careful notebooks and sketches; Archimedes proved the rule for levers and tested it with real loads; Huygens published exact labeled drawings so others could build and check his clock. Records and testing let others learn from, repeat and improve the work.

PORTFOLIO PIECE: A TESTED DESK CRANE

Design and build a desk crane from cardboard, craft sticks, spools and string that can lift a cup of 100 pennies at least 30 centimeters. Use the engineering design process and at least one movable pulley, and measure its mechanical advantage with the penny method. In your notebook, include sketches of at least two ideas, a labeled plan, a data table for at least two versions, and a page explaining what you improved and why. If you can, add a gear (a spool turned by a crank and a rubber-band belt) and explain the ratio.

LOOK FOR	WHAT IT MEANS
Design process	Notebook shows criteria and constraints, two or more sketched ideas, a chosen plan with measurements, and an improve round.
It works	The crane lifts 100 pennies at least 30 centimeters without collapsing or tipping.
Measurement	Mechanical advantage is measured ($\text{load} \div \text{effort}$), compared with the number of supporting ropes, and differences are explained.
Science explanation	Uses the words load, effort, mechanical advantage and friction correctly; explains the trade between force and distance.
Craftsmanship	Neat, sturdy build and a dated, labeled notebook that someone else could follow.

1.1 THE ENGINEERING DESIGN PROCESS: LEONARDO'S NOTEBOOKS

OBJECTIVES

- Name and explain the seven steps of the engineering design process: ask, research, imagine, plan, build, test, improve.
- Describe how Leonardo da Vinci used observation, sketches and notes to learn about machines and nature.
- Build, load-test and improve Leonardo's self-supporting bridge, recording each test in an engineer's notebook.

Warm-up. Look at a simple object in your house that someone designed, such as a clothespin, a can opener or a stapler. Draw it from two sides. Under your drawing, write three questions: What problem does it solve? What would happen if one part were missing? How could it be made better?

WATCH

The Engineering Design Process

Smithsonian National Air and Space Museum • 3:46

<https://www.youtube.com/watch?v=MFGg1calQ6k>

WHEN TO WATCH

After the first core idea. Write down each step of the process as it is named.

KEY TERMS

engineering design process

The steps engineers follow to solve a problem: ask, research, imagine, plan, build, test and improve, repeating as many times as needed.

criteria

What a design must do to succeed, such as “span 30 centimeters” or “hold 100 pennies.”

constraints

The limits on a design, such as the materials, money, time or size allowed.

prototype

A first working model, built to be tested and improved.

engineer's notebook

A dated record of an engineer's sketches, ideas, measurements, results and changes.

CORE IDEAS

The story. Leonardo da Vinci was born in 1452 near the town of Vinci in Italy. As a teenager he became an apprentice in the Florence workshop of Andrea del Verrocchio, where he learned painting, sculpture and metalwork. In 1471 that workshop made the great gilded copper ball that was lifted to the very top of the dome of Florence Cathedral. To lift it, workers used the hoists and cranes that Filippo Brunelleschi had invented to build the dome. Young Leonardo studied those machines carefully and later drew them in his notebooks. For the rest of his life he carried paper with him and drew everything he wondered about: birds' wings, the flow of water, gears, pumps, canal gates, bridges and machines for flying.

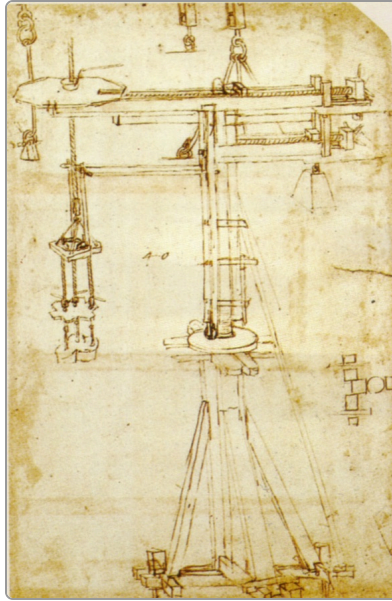
How he figured it out. Leonardo learned by looking, drawing and asking questions. He watched birds for hours and wrote down how they tilt their wings and tails to turn and land. He drew the same machine again and again from different sides, changing one part each time. More than 7,000 of his notebook pages still exist, many written in mirror-writing from right to left. Not every idea worked. His flapping flying machines could never have flown, because a person's arms and legs are far too weak to flap wings that big. Yet his habit of careful observation, many sketches and honest notes is exactly what engineers still do today.

The method. Engineers call this habit the **engineering design process**. **Ask:** What is the problem? What are the **criteria** (what it must do) and the **constraints** (the limits)? **Research:** What have others already learned? **Imagine:** Sketch many possible answers, not just one. **Plan:** Choose the best idea and draw it with measurements. **Build:** Make a **prototype**. **Test:** Measure how well it works, the same way each time. **Improve:** Change one thing and test again. The steps make a loop, not a straight line. Most good designs go around it many times.

The engineering. Leonardo sketched a bridge made only of straight poles that lock together by their own weight, with no nails, rope or glue. Each pole is held up by the poles that cross it, and each pole pushes down on the others to hold them in place. The heavier the load, the tighter the poles grip. Today engineers still keep dated

notebooks and design records, because a good record lets someone else check your work, repeat your test, or learn from your mistakes. God gave Bezalel “wisdom, and in understanding, and in knowledge, and in all manner of workmanship” to build the tabernacle, and careful, patient work is still how a maker grows in that gift.

PICTURE STUDY



Brunelleschi's Turning Crane, Leonardo da Vinci, about 1480 · Pen and ink on paper (Codex Atlanticus) ·
Biblioteca Ambrosiana, Milan

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

As a young man, Leonardo studied the machines Brunelleschi had invented to build the great dome of Florence Cathedral, and he drew them in his notebook. This page shows a crane that could lift heavy stones and then swing them sideways into place.

Look closely

- Find the long arm at the top of the crane. Which way could it turn?
- Find the ropes and the hook. Where does the load hang?
- Look for a heavy weight on the other side of the arm. Why might a crane need a counterweight?
- Find Leonardo's handwriting. Why do you think he wrote notes beside his drawings?

Talk about it

1. What problem was this machine built to solve? Use the words criteria and constraints in your answer.
2. If you were an engineer in 1480, how could you test this crane safely before lifting a real stone to the top of the dome?

3. Why is a careful drawing useful to a builder who was not there when the machine was invented?

Safety first. Do not stand on or climb on your bridge. When load-testing, keep your feet clear in case the bridge and pennies fall.

BUILD

Leonardo's Self-Supporting Bridge

You will build Leonardo's bridge from straight sticks that lock together with no glue or tape. You will use the full engineering design process: set criteria, build a prototype, test how many pennies it holds, change one thing and test again.

You will need

- 15–20 unsharpened pencils, jumbo craft sticks or wooden dowels all the same length (pencils work best)
- Two stacks of books the same height, to be the riverbanks
- A small paper cup or a sandwich bag, and about 100 pennies
- Ruler and engineer's notebook

Steps

1. **Ask.** Write the criteria in your notebook: the bridge must span the gap between two book stacks with no glue, tape or string, and hold as many pennies as possible. Write your constraints: which sticks you have and how many.
2. **Research and imagine.** Look closely at the build pattern: two sticks lie side by side, two cross sticks lie on top of them near the ends, and a third pair weaves under the cross sticks and over the middle. Sketch the pattern from the side and from above before you build.
3. **Build.** Start with a small arch of six sticks. Add sticks in pairs, always weaving over and under, so the bridge grows in an arch. Keep going until it spans a gap of at least 20 centimeters.
4. **Measure.** Record the span (the gap between the book stacks), the height of the arch at the middle, and the number of sticks used.
5. **Predict.** Write how many pennies you think it will hold. Then hang the cup from the middle of the bridge (or set the bag gently on top) and add pennies five at a time until something slips or falls. Record the number. Repeat the test two more times and find the average.

6. **Improve.** Change only one thing, such as using fewer sticks for a flatter bridge, or more sticks for a taller arch. Test it three times in the same way and record the results in the same table.
7. **Compare.** Make a bar graph of the average number of pennies for each design. Write one sentence explaining which design was strongest and why you think so.

Tips

- If the bridge keeps sliding apart, put a strip of cardboard under each end so it cannot slide on the books.
- Pencils with flat sides grip better than round dowels.
- Keep each test the same: same cup, same place, same way of adding pennies. That is what makes it a fair test.

Check your work

- ☐ I can name the seven steps of the engineering design process in order.
- ☐ I can explain why my bridge stays together with no glue.
- ☐ My notebook shows a prediction, three trials for each design, an average and a graph.

ENGINEER'S NOTEBOOK

1. Draw the engineering design process as a circle of seven labeled steps, with an arrow from “Improve” back to “Ask.”
2. Draw your self-supporting bridge from the side. Use arrows to show where the sticks push on each other.
3. Make a Leonardo page: choose one object at home and draw it from three sides with labels and three questions about how it works.

From history. Leonardo's notebooks were scattered after his death in 1519. Some pages were cut apart and glued into big albums, such as the Codex Atlanticus in Milan, which holds more than a thousand sheets. Engineers who study them today have built working models of many of his machines, and they have found that some ideas needed changes to work, just as any first design does.

COMMON MISTAKES

- Building first and planning later. Sketch and write the criteria before you touch the materials.

- Changing two things at once between tests, so you cannot tell which change made the difference.
- Testing only once. One test can be a fluke; three tests and an average are much more trustworthy.

Make it a game · Seven-Step Sprint. Write the seven design-process steps on seven scraps of paper and shuffle them. Race the clock to put them in order, then say what each step means. Your parent names a problem, such as a leaky cup, and you choose one criterion and one constraint. Beat your best time, and say how Leonardo used his notebook.

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

A wise builder thinks, plans and learns before and while he builds. The design process is one way of building with wisdom and understanding.

1.2 NEWTON'S THREE LAWS AND A BALLOON ROCKET

OBJECTIVES

- State Newton's three laws of motion and give an everyday example of each.
- Explain how Galileo's ramps and Newton's mathematics led to the laws of motion.
- Build a balloon rocket, run a fair test of one variable, and explain the results with Newton's laws.

Warm-up. Place a coin on an index card on top of a cup. Predict: what will happen to the coin if you flick the card quickly sideways? Try it three times. Then try pulling the card slowly. Write what happened and why you think it happened.

WATCH

Newton's 3 Laws of Motion for Kids: Three Physical Laws of Mechanics for Children - FreeSchool

Free School • 4:58

https://www.youtube.com/watch?v=aA_mqSzbkM0

WHEN TO WATCH

After the story, before the physics. Pause after each law and give your own example.

BACKUP VIDEO

Make a Balloon Rocket

SciShow Kids • 3:29

<https://www.youtube.com/watch?v=KMX7zgaLC0w>

Before the build, to see the balloon rocket set up.

KEY TERMS

force

A push or a pull. Forces are measured in newtons.

inertia

The way an object keeps doing what it is already doing, staying still or moving in a straight line, until a force changes it.

acceleration

Any change in speed or direction.

mass

How much matter is in an object, measured in grams or kilograms.

action and reaction

Equal and opposite forces: when one object pushes on a second, the second pushes back on the first just as hard.

CORE IDEAS

The story. Isaac Newton was born in 1643 on a farm at Woolsthorpe in England. As a boy he built water clocks, sundials and a little windmill that ground grain. He became a professor at Cambridge University. In 1687, with the help and money of his friend Edmond Halley, he published a book in Latin usually called the *Principia*. In it he stated three laws of motion and the law of gravity, and showed that the same laws explain a falling apple, a cannonball and the moon going around the earth. Newton was a believing Christian who wrote even more about the Bible than about science. He saw the order of the universe as the work of a wise Creator.

How they figured it out. Newton said that if he had seen further, it was by standing on the shoulders of giants. One giant was Galileo Galilei. Galileo rolled bronze balls down long, smooth wooden ramps and timed them. He noticed that a ball rolling down one ramp would roll up a second ramp to nearly the same height. When he made the second ramp less steep, the ball rolled farther. He reasoned that on a perfectly flat, smooth track, a ball would roll on forever. Things do not stop by themselves; friction stops them. Newton took that idea, added careful mathematics, and checked it against measurements of the planets and the moon.

The physics. **Newton's first law:** an object at rest stays at rest, and an object in motion keeps moving in a straight line at the same speed, unless a force acts on it. This is **inertia**. The coin in the warm-up stayed put because the card slid away too fast to drag it. **Newton's second law:** the bigger the force, the bigger the acceleration; the bigger the mass, the smaller the acceleration. Engineers write it as $F = m \times a$. An empty wagon speeds up much faster than one full of firewood when you pull the same way. **Newton's third law:** for every action there is an equal and

opposite reaction. When a balloon squeezes air out backward, the air pushes the balloon forward.

The engineering. Engineers use all three laws every day. Seat belts and air bags are there because of the first law: when a car stops suddenly, your body keeps moving forward until something stops it. The second law tells a truck designer how big an engine and brakes must be to speed up and stop a heavy load. The third law is how every rocket flies: it throws hot gas out of its nozzle at high speed, and the gas pushes the rocket the other way. A rocket does not need air to push against, which is why rockets work in space. “By him all things consist,” Paul writes of Christ; the laws of motion are part of the faithful order that holds creation together.

PICTURE STUDY



A Philosopher Lecturing on the Orrery, Joseph Wright of Derby, about 1766 · Oil on canvas · Derby Museum and Art Gallery, England

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

An orrery is a clockwork model of the solar system: turn a handle and gears move the planets around the sun at the right speeds. Joseph Wright painted a lecturer showing one to a family, about eighty years after Newton's *Principia* explained why the planets move as they do.

Look closely

- Find the lamp in the center. What does it stand for in the model?
- Find the rings and arms of the orrery. Which planets can you pick out?
- Look at the faces. Who looks most amazed? Who is taking notes?
- Look for the handle or gears that make the orrery turn.

Talk about it

1. Newton's first law says a moving object keeps going in a straight line unless a force acts on it. What force keeps the planets curving around the sun instead of flying off straight?
2. Why would a model like this help people understand an idea they could not see all at once in the sky?

3. The orrery uses gears to make the planets turn at different speeds. What do you think the gear inside does for the slow outer planets?

Safety first. Wear safety glasses when launching. Anyone with a latex allergy should use latex-free balloons. Never put a balloon or a piece of a popped balloon in your mouth; keep popped pieces away from small children.

BUILD

Balloon Rocket Races

You will build a balloon rocket that rides along a string, then run a fair test to see how one change affects how far it travels. You will explain your results using all three of Newton's laws.

You will need

- Long balloons (or round balloons) of the same kind
- A drinking straw, cut to 10 centimeters
- About 5 meters of smooth string or fishing line
- Tape, a tape measure, and a fabric measuring tape or a strip of paper to measure balloon size
- Paper clips (each is about 1 gram) to add mass
- Two chairs or two doorknobs to tie the string between

Steps

1. Thread the string through the straw. Tie the string tightly between two chairs about 5 meters apart, keeping it level.
2. Blow up the balloon. Measure around its widest part and write down the size. Pinch the neck closed (do not tie it) and tape the balloon to the straw.
3. Pull the balloon back to the start line, let go, and measure how far it travels. Run three trials, blowing the balloon to the same size each time, and record them.
4. **Fair test.** Choose one variable to change: either the size you blow up the balloon (for example 30, 40 and 50 centimeters around) or the mass it carries (0, 5 and 10 paper clips taped to the straw). Keep everything else the same.
5. Before testing, write a prediction for each version.
6. Run three trials for each version and record them in a table: version, trial 1, trial 2, trial 3, average distance.
7. Make a bar graph of the averages. Use Newton's second law to explain what you found.

8. **Improve.** Try to make your rocket go as far as possible. You might use a longer straw, tilt the string, or tape on a second balloon. Record your best distance and what you changed.

Tips

- A long balloon usually travels straighter than a round one.
- If the balloon spins around the string, tape it so the opening points straight back along the string.
- Smooth fishing line has less friction than cotton string.

Check your work

- ☐ I can explain how the balloon rocket shows Newton's third law.
- ☐ I can explain how adding mass changed the distance, using Newton's second law.
- ☐ My data table has three trials and an average for each version.

ENGINEER'S NOTEBOOK

1. Draw your balloon rocket with two arrows: one for the air pushed out the back (action) and one for the push on the balloon (reaction). Make the arrows the same length.
2. Draw three small cartoons, one for each law of motion, from your own life.
3. Write a sentence that begins "If I did this test again, I would change..."

From history. Galileo did not have a good clock for his ramp experiments. He timed the rolling balls by letting water run out of a large container through a thin pipe and weighing the water that collected. More water meant more time. Careful measurement with simple tools is an old engineering habit.

COMMON MISTAKES

- Thinking a moving object needs a force to keep it moving. It only needs a force to speed up, slow down or turn; friction is the force that usually slows things down.
- Thinking the rocket pushes on the air behind it. The balloon pushes on the air inside it, and that air pushes back on the balloon.
- Blowing the balloon to different sizes when the test is about mass, so two things change at once.

Make it a game • Three Laws Charades. Act out Newton's three laws without words: sit still until pushed, push a cart hard versus light, then shove a wall and drift backward. Your parent guesses the law and names an everyday example. Swap roles. Score one point per correct law and one per example. Finish by explaining what Galileo's ramps taught Newton.

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

The laws of motion work the same way in a kitchen, on the moon and in a rocket because Christ holds all things together. Science is possible because creation is faithful and orderly.

1.3 ARCHIMEDES AND THE PULLEY: MECHANICAL ADVANTAGE

OBJECTIVES

- Explain mechanical advantage and the trade between force and distance.
- Find the mechanical advantage of a pulley system by counting the supporting ropes.
- Build and test fixed, movable and compound pulleys, measuring the effort needed to lift a load.

Warm-up. Try to lift a heavy bucket or a full laundry basket straight up with one hand. Then think: how could a rope and a wheel make it easier? Draw your idea before you learn how Archimedes did it.

WATCH

Simple Machines: The Pulley

[funsciencedemos](https://www.youtube.com/watch?v=r3Ru1zZjvug) • 6:25

<https://www.youtube.com/watch?v=r3Ru1zZjvug>

WHEN TO WATCH

After the physics paragraph. Count the supporting ropes in each pulley system shown.

BACKUP VIDEO

Why Snatch Blocks are AWESOME (How Pulleys Work) - Smarter Every Day 228

[SmarterEveryDay](https://www.youtube.com/watch?v=M2w3NZzPwOM) • 16:31

<https://www.youtube.com/watch?v=M2w3NZzPwOM>

For a closer look at real working pulleys used by tree workers and riggers. Optional and longer.

KEY TERMS

simple machine

A basic device that changes the size or direction of a force: the lever, wheel and axle, pulley, inclined plane, wedge and screw.

pulley

A wheel with a groove for a rope, used to lift or move loads.

load and effort

The load is the weight being moved.
The effort is the force you use to move it.

mechanical advantage

How many times a machine multiplies your force. It equals the load divided by the effort.

work

In physics, force times the distance something is moved. A machine cannot give you more work than you put in.

CORE IDEAS

The story. Archimedes lived in the Greek city of Syracuse on the island of Sicily more than 2,200 years ago. He was a mathematician and engineer who served King Hiero. The historian Plutarch tells that Archimedes once wrote to the king that, with the right machine, any weight could be moved by a given force. The king asked him to prove it. Archimedes chose a large ship from the king's fleet, which had been hauled onto the shore by many men with great labor, and had it loaded with people and cargo. Then, sitting some distance away and pulling gently on the rope of a compound pulley, he drew the ship smoothly toward himself, as if it were sailing on the sea. He is also said to have claimed that, given a place to stand, he could move the earth with a long enough lever.

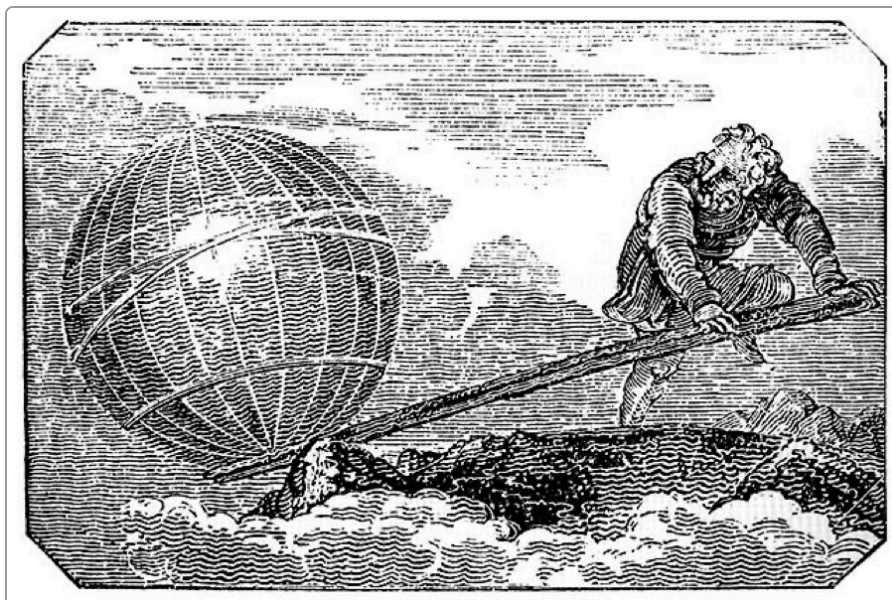
How he figured it out. Archimedes did not only build machines; he proved why they worked. He studied the lever with geometry and showed that two weights balance when each weight times its distance from the pivot is the same. A small weight far from the pivot can balance a big weight close to it. Pulleys follow the same rule in a different shape. Archimedes used reasoning and measurement together: he found a rule, then tested it with real loads.

The physics. Machines do not make energy; they trade force for distance. A **fixed pulley**, hung from a beam, only changes the direction of the pull. You pull down to lift up, but the effort is the same as the load. A **movable pulley** hangs from the rope and moves up with the load. Now two lengths of rope hold up the load, so each one carries half the weight, and you pull with half the force. But you must pull twice as much rope to lift the load the same height. Put several pulleys together in a **block and tackle**, and the **mechanical advantage** equals the number of rope segments that

hold up the moving pulley. With four supporting ropes, a 100-pound load needs only about 25 pounds of effort, but you pull 4 feet of rope for every foot the load rises. Friction in the wheels takes a little extra effort, so real machines never quite reach the ideal number.

The engineering. Pulleys are everywhere engineers lift things: cranes on building sites, elevators, the rigging that raises a ship's sails, tow trucks, flagpoles, and the block and tackle a farmer uses to lift an engine. Engineers choose the mechanical advantage they need, then pick a rope strong enough to carry the load with a large **safety factor**, often five times stronger or more than the heaviest expected load, because ropes wear and loads swing. Brunelleschi's great ox-powered hoist, which lifted the stones for the dome of Florence Cathedral, used gears and a large drum on the same principle.

PICTURE STUDY



Archimedes and the Lever, Unknown engraver, 1824 · Engraving · From *Mechanics Magazine*, London

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

This old engraving pictures Archimedes' famous boast that, with a long enough lever and a place to stand, he could move the world. It is a joke, of course, but it is also a true picture of how a lever trades distance for force.

Look closely

- Find the pivot, the point the lever turns on. Is it close to the earth or close to Archimedes?
- Compare the length of the lever on each side of the pivot.
- Look at how Archimedes is pushing. Is he pushing hard or gently?
- What would Archimedes have to do to move the earth just a tiny distance?

Talk about it

1. Why does putting the pivot close to the load make the lever more powerful?
2. If the long side of the lever is 1,000 times longer than the short side, how far must Archimedes push to move the earth one inch?
3. How is a movable pulley like a lever?

Safety first. Use only light loads (a water bottle or a bag of pennies), never a person or anything heavy enough to hurt someone if it falls. Make sure the broom handle or bar is firmly supported before you hang anything from it.

BUILD

A Pulley Lab with Penny Power

You will build three pulley systems from thread spools and string. You will measure the effort each one needs by counting the pennies it takes to lift the same load, and you will measure how much string you pull. Then you will compare your data with the rule that the mechanical advantage equals the number of supporting ropes.

You will need

- Two or three empty thread spools (or plastic spools from ribbon) and a pencil or wire through each as an axle
- A wire coat hanger cut and bent by an adult into hooks, or strong paper clips
- Strong, smooth string, about 3 meters
- A broom handle laid across the backs of two chairs
- A load: a small bottle of water in a bag (weigh it on a kitchen scale; about 250–500 grams)
- A paper cup with a string handle, and pennies (each U.S. penny made since 1983 has a mass of 2.5 grams)
- Ruler, tape and engineer's notebook

Steps

1. Weigh your load and record its mass in grams. Weigh the empty penny cup too.
2. **System 1, fixed pulley.** Hang one spool from the broom handle. Run the string over it, tie the load to one end and the penny cup to the other. Add pennies until the load just begins to rise. Record the effort in grams (cup plus pennies $\times$ 2.5 grams).
3. Lift the load 10 centimeters. Measure how far the cup moved down.
4. **System 2, movable pulley.** Tie one end of the string to the broom handle. Run it down under a spool that holds the load, then up over a fixed spool on the broom handle, and down to the penny cup. Repeat the measurements.

5. **System 3, block and tackle.** Use two spools on the broom handle and one or two on the load so that three or four ropes hold up the load. Repeat the measurements.
6. Make a table: system, number of supporting ropes, load (g), effort (g), $\text{load} \div \text{effort}$, distance load rose, distance cup fell.
7. Compare your measured mechanical advantage ($\text{load} \div \text{effort}$) with the number of supporting ropes. Explain any difference. (Hint: friction.)
8. **Improve.** Try to reduce friction, for example with smoother string or a straw sleeve over the axle, and test one system again. Did the effort go down?

Tips

- Add pennies slowly near the end. The moment the load starts to rise is the measurement you want.
- Keep the ropes straight up and down. Slanted ropes do not share the load evenly.
- Do each measurement twice and use the average.

Check your work

- ☐ I can explain why a movable pulley cuts the effort in half but doubles the rope you pull.
- ☐ I can find the ideal mechanical advantage of a pulley system by counting the supporting ropes.
- ☐ My data table compares measured and ideal mechanical advantage.

ENGINEER'S NOTEBOOK

1. Draw the three pulley systems you built. Number each supporting rope and write the ideal mechanical advantage beside each one.
2. Draw Archimedes pulling the ship with a block and tackle. Label the load, the effort and the supporting ropes.
3. Find three pulleys in real life (a flagpole, window blinds, a crane, a clothesline, a well) and sketch one.

From history. Archimedes also designed the Archimedes screw, a large screw turning inside a tube that lifts water uphill when it is turned. It is still used today to lift water and even to move grain. In another famous story he discovered how to test whether the king's crown was pure gold, which you will learn about in Unit 6.

COMMON MISTAKES

- Counting the rope you pull on as a supporting rope when it comes down from a fixed pulley. Count only the ropes that hold up the moving pulley.
- Thinking a machine gives you something for nothing. Less force always means more distance.
- Forgetting to add the weight of the movable spool and hook to the load.

Make it a game • Rope Count Duel. Draw pulley systems on index cards with two, three and four supporting ropes. Draw one at random, find the mechanical advantage by counting ropes, and say how far you must pull the rope compared with the load. Your parent checks. Win a card for each right answer. Explain the trade between force and distance.

1.4 GEARS IN CLOCKS AND BICYCLES

OBJECTIVES

- Find a gear ratio by counting teeth and explain how gears trade speed for force.
- Explain how a pendulum and escapement keep a clock running at a steady pace.
- Measure the gear ratio of a real bicycle and test how a pendulum's length changes its swing.

Warm-up. Turn a bicycle upside down (with an adult) or look closely at one. Turn the pedals one full time by hand and count how many times the back wheel turns. Write the number. Is it more or less than one? Why do you think so?

WATCH

Gears Explained - mechanical engineering

The Engineering Mindset · 8:48

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

WHEN TO WATCH

After the physics paragraph. Pause when gear ratios are explained and check the math yourself.

BACKUP VIDEO

How clocks work (in 5 easy steps) with Oliver Cooke I Curator's Corner S3 Ep3 #CuratorsCorner

The British Museum · 7:55

<https://www.youtube.com/watch?v=biDxyjwC88I>

Before the pendulum test, to see a museum curator explain the parts of a clock.

KEY TERMS

gear

A wheel with teeth that mesh with the teeth of another gear to pass on turning motion.

gear ratio

The number of teeth on the driven gear divided by the number of teeth on the driving gear. It tells how many times the driver must turn to turn the driven gear once.

sprocket

A toothed wheel that drives or is driven by a chain, as on a bicycle.

pendulum

A weight hanging from a fixed point that swings back and forth with a steady rhythm.

escapement

The part of a clock that lets the gears move forward one tooth at a time with each swing of the pendulum.

CORE IDEAS

The story of the clock. In the late 1200s and 1300s, clockmakers in Europe began building large mechanical clocks of iron for cathedrals, monasteries and town towers, often to call people to prayer at the right hours. The clock at Salisbury Cathedral in England, made around 1386, still runs today. A falling weight on a rope turned a train of gears, and a device called an **escapement** let the gears move only a little at a time. But those clocks could drift by many minutes a day. In 1656 the Dutch scientist Christiaan Huygens built the first pendulum clock. Galileo had noticed years before that a pendulum of a given length always takes the same time to swing, whether the swing is wide or narrow. Huygens used that steady swing to control the escapement, and clocks became many times more accurate almost overnight.

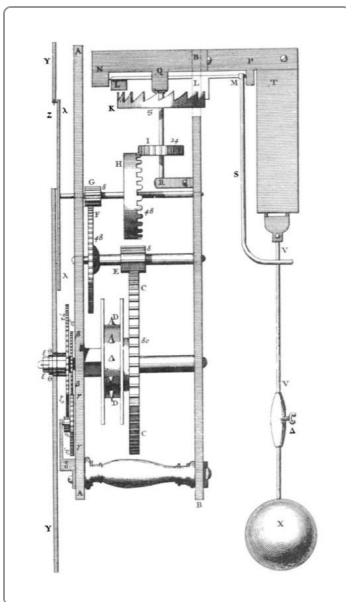
The story of the bicycle. Early bicycles had the pedals fixed right onto the front wheel, so one turn of the pedals meant exactly one turn of the wheel. To go fast, riders needed a giant front wheel, sometimes about five feet tall. These “penny-farthing” bicycles were fast, but a rider sat so high that hitting a stone could throw him headfirst over the handlebars. In 1885 John Kemp Starley of Coventry, England, sold the Rover “safety bicycle.” It had two wheels of about the same size and a chain that ran from a large front sprocket at the pedals to a small sprocket on the back wheel. The gears did the work the giant wheel used to do, and the bicycle took nearly the shape it has today.

The physics. When two gears mesh, the teeth move past each other one for one. If a 40-tooth gear drives a 10-tooth gear, each turn of the big gear turns the small gear 4 times. The small gear spins faster, but with less turning force. Turn it the other way, with the small gear driving the big one, and the big gear turns slowly but with 4 times the turning force. That is the **gear ratio**. On a bicycle, a big front sprocket and

a small back sprocket give high speed on flat ground; a small front sprocket and a big back sprocket make climbing a hill easier, though you must pedal more turns. In a clock, a 12 to 1 gear train makes the hour hand turn once while the minute hand turns twelve times.

The engineering. Engineers choose gear ratios to match the job. A car's transmission uses low gears to start moving a heavy car and high gears to cruise. A hand drill uses gears to turn a quick turn of your hand into a strong, slow turn of the bit, or the other way around. A wind-up toy, a can opener and a kitchen mixer all have gear trains inside. Gears must be strong enough not to break their teeth, cut accurately so they mesh smoothly, and oiled to reduce friction and wear.

PICTURE STUDY



Huygens's Pendulum Clock, Christiaan Huygens, 1673 · Engraving · From *Horologium Oscillatorium*, Paris

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

Christiaan Huygens published this careful drawing of his pendulum clock in 1673 so that clockmakers everywhere could build it. It shows each gear, shaft and part, labeled with letters, like a modern engineering drawing.

Look closely

- Find the pendulum. How is it connected to the gears?
- Find a large gear meshing with a small one. Which one would turn faster?
- Look for the letters beside the parts. Why would an inventor label a drawing this way?
- Find the parts that would hold the clock's weight or spring.

Talk about it

1. Why did a pendulum make clocks so much more accurate?
2. If a gear with 60 teeth drives a gear with 10 teeth, how many times does the small gear turn for each turn of the big one?
3. Why do you think Huygens published his drawing instead of keeping it secret?

Safety first. When turning a bicycle upside down, have an adult hold it steady. Keep fingers away from the chain and sprockets while the pedals are moving.

BUILD

Bicycle Gear Ratios and a Pendulum Timer

You will measure the gear ratio of a real bicycle two ways, by counting teeth and by counting wheel turns, and see whether they agree. Then you will build a pendulum and run a fair test to find how its length changes its swing, the discovery that made accurate clocks possible.

You will need

- A bicycle with gears (or a single-speed bicycle) and an adult helper
- A piece of tape or chalk to mark the wheel
- String, a metal washer or a large nut for the pendulum bob, and tape
- A doorway or table edge to hang the pendulum from
- Tape measure, stopwatch and engineer's notebook
- Optional: an egg beater or hand drill to examine another gear train

Steps

1. With an adult, turn the bicycle upside down. Put a piece of tape on the back tire so you can count turns.
2. Count the teeth on the front sprocket being used and on the back sprocket being used. Divide front teeth by back teeth. This is the predicted number of wheel turns per pedal turn.
3. Turn the pedals exactly 5 times by hand and count the wheel turns. Divide by 5. Compare with your prediction.
4. If the bicycle has gears, repeat for the easiest gear and the hardest gear. Record all results in a table.
5. **Pendulum test.** Tie the washer to the string and tape the string to a doorway so the pendulum is 25 centimeters long, measured to the middle of the washer.
6. Pull the washer a little to one side and let go. Count how many complete back-and-forth swings it makes in 30 seconds. Do three trials and average them.

7. Change only the length: test 50 centimeters and 100 centimeters the same way. Record the results. Predict first: will longer pendulums swing faster or slower?
8. Test whether the size of the swing matters: at 50 centimeters, release once from a small angle and once from a larger angle. Compare the counts.
9. **Improve.** Adjust the length until your pendulum makes exactly 30 complete swings in 60 seconds, one every two seconds. Measure that length. (A clock's "seconds pendulum" is close to 1 meter long.)

Tips

- Start the stopwatch on a count of zero, not one, as the pendulum passes the middle.
- Keep the swings small, less than about a hand's width, for the steadiest results.
- Make a line graph of length (across) and swings in 30 seconds (up).

Check your work

- ☐ I can find a gear ratio by counting teeth.
- ☐ I can explain why low gears make climbing hills easier.
- ☐ I can explain how the length of a pendulum changes its swing, using my data.

ENGINEER'S NOTEBOOK

1. Draw a bicycle drive train: front sprocket, chain and back sprocket. Write the number of teeth on each and the gear ratio.
2. Draw two meshing gears with arrows showing which way each turns. Then add a third gear and show its direction.
3. Graph your pendulum data and write one sentence about the pattern you see.

From history. Clockmaking needed such fine, accurate metalwork that clockmakers became some of the first precision engineers. Many of the people who built the earliest steam engines, textile machines and scientific instruments learned their skills cutting clock gears. John Harrison, an English carpenter and clockmaker, later built clocks accurate enough to find a ship's longitude at sea.

COMMON MISTAKES

- Dividing the wrong way. For a bicycle, front teeth $\div$ back teeth tells how many times the wheel turns for each pedal turn.
- Thinking a heavier pendulum bob swings faster. Its length, not its weight, sets the timing.
- Counting each swing to one side as a complete swing. A complete swing goes over and back.

Make it a game · Teeth and Ticks. Count the teeth on two imaginary gears your parent invents, such as 40 and 10, and call the gear ratio. Say whether the output is faster or stronger. Do five quick rounds. Then make a pendulum from string and a key, count swings in ten seconds, and explain what an escapement does in a clock.

UNIT 1

FORCES, MOTION AND THE DESIGN PROCESS

Every engineer, from Archimedes to the people who build Mars rovers, works the same way: ask what the problem is, learn what others have learned, imagine many answers, plan one, build it, test it, and make it better. In this unit you will meet that method in the notebooks of Leonardo da Vinci, who filled thousands of pages with machines, birds, water and bridges. Then you will use it yourself all year long.

You will also learn the laws that every machine must obey. Isaac Newton's three laws of motion explain why a balloon rocket zooms along a string. Archimedes' pulleys show how a small force can lift a heavy load, if you are willing to pull farther. Gears, from the clock in a cathedral tower to the chain on your bicycle, trade speed for force and keep time. Each lesson ends with a build that you measure, record and improve.

PREREQUISITES

- Can measure length in centimeters and inches and mass in grams
- Can multiply and divide whole numbers and find an average of three numbers
- Has a graph-paper notebook ready to be the engineer's notebook for the year

MASTERY CHECKLIST

- ☐ I can name the steps of the engineering design process and show them in my own notebook.
- ☐ I can state Newton's three laws of motion and give an example of each.
- ☐ I can explain mechanical advantage and find it for a pulley system by counting the supporting ropes.
- ☐ I can find a gear ratio by counting teeth and explain how gears trade speed for force.
- ☐ I can run a fair test that changes only one thing, record the results in a table, and use them to improve a design.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. A subscription box: each month brings a toy to build that shows one physics or engineering idea, with a video lesson from Mark Rober. Fits the whole unit, especially Lessons 1.2–1.4.
- **KiwiCo Tinker Crate:** Ages 9 and up. Monthly engineering projects such as hydraulic arms, trebuchet-style launchers and gear machines, with clear instructions. A good companion to Lessons 1.3 and 1.4.
- **LEGO Technic:** Ages vary by set. Real gears, axles and beams let you build gear trains and measure gear ratios. Fits Lesson 1.4 and the unit portfolio crane.

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

LESSONS IN THIS UNIT

1.1	The Engineering Design Process: Leonardo's Notebooks	2 sessions of 45 minutes
1.2	Newton's Three Laws and a Balloon Rocket	2 sessions of 45 minutes
1.3	Archimedes and the Pulley: Mechanical Advantage	2 sessions of 45 minutes
1.4	Gears in Clocks and Bicycles	2 sessions of 45 minutes

UNIT 1 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**
List the seven steps of the engineering design process in order.
2. **5 pts**
What is the difference between criteria and constraints? Give one example of each for a bridge.
3. **5 pts**
State Newton's first law. Why do cars have seat belts?

4. (5 pts)

Predict: two identical balloon rockets are launched, but one carries 10 paper clips. Which goes farther, and which law explains it?

5. (5 pts)

Explain how a rocket flies using Newton's third law.

6. (5 pts)

A block and tackle has 4 ropes holding up the moving pulley. About how much effort is needed to lift a 200-pound engine, ignoring friction? How far must you pull the rope to lift it 2 feet?

7. (5 pts)

Why does a fixed pulley not reduce the effort? What is it good for?

8. (5 pts)

A bicycle's front sprocket has 48 teeth and the back sprocket has 16. How many times does the back wheel turn for each turn of the pedals? Is this a good gear for climbing a hill?

9. (5 pts)

Predict: a pendulum 25 centimeters long and one 100 centimeters long are released together. Which swings back and forth more times in 30 seconds?

10. (5 pts)

Name one thing Leonardo da Vinci, Archimedes or Huygens did that engineers still do today, and explain why it matters.

ANSWER KEY

1. Ask, research, imagine, plan, build, test, improve (and then repeat).
2. Criteria are what the design must do (span 30 cm, hold 100 pennies). Constraints are the limits (only 20 craft sticks, no glue, must be finished in one hour).
3. An object at rest stays at rest and an object in motion keeps moving in a straight line at the same speed unless a force acts on it. When a car stops suddenly, a passenger keeps moving forward; the seat belt supplies the force that stops the passenger safely.
4. The one without paper clips goes farther (or speeds up faster). Newton's second law: the same force gives less acceleration to a larger mass.
5. The rocket pushes hot gas out of its nozzle backward (action); the gas pushes the rocket forward with an equal and opposite force (reaction).
6. $200 \div 4 = 50$ pounds of effort. $2 \times 4 = 8$ feet of rope.
7. Only one rope holds the load, so the effort equals the load. It is useful because it changes the direction of the force, letting you pull down to lift something up.
8. $48 \div 16 = 3$ turns. No; it is a high gear for speed on flat ground. Climbing needs a smaller front sprocket or a bigger back sprocket.
9. The 25-centimeter pendulum. Shorter pendulums swing faster; length sets the timing (about twice as many swings for one-fourth the length).
10. Any good answer: Leonardo kept careful notebooks and sketches; Archimedes proved the rule for levers and tested it with real loads; Huygens published exact labeled drawings so others could build and check his clock. Records and testing let others learn from, repeat and improve the work.

PORTFOLIO PIECE: A TESTED DESK CRANE

Design and build a desk crane from cardboard, craft sticks, spools and string that can lift a cup of 100 pennies at least 30 centimeters. Use the engineering design process and at least one movable pulley, and measure its mechanical advantage with the penny method. In your notebook, include sketches of at least two ideas, a labeled plan, a data table for at least two versions, and a page explaining what you improved and why. If you can, add a gear (a spool turned by a crank and a rubber-band belt) and explain the ratio.

LOOK FOR	WHAT IT MEANS
Design process	Notebook shows criteria and constraints, two or more sketched ideas, a chosen plan with measurements, and an improve round.
It works	The crane lifts 100 pennies at least 30 centimeters without collapsing or tipping.
Measurement	Mechanical advantage is measured ($\text{load} \div \text{effort}$), compared with the number of supporting ropes, and differences are explained.
Science explanation	Uses the words load, effort, mechanical advantage and friction correctly; explains the trade between force and distance.
Craftsmanship	Neat, sturdy build and a dated, labeled notebook that someone else could follow.

UNIT 2

BRIDGES

A bridge is a promise. Every person who walks or drives across it is trusting that the engineers counted every load and chose every beam and cable with care. In this unit you will learn the four forces at work inside every structure, compression, tension, shear and torsion, and see them in the great steel arms of Scotland's Forth Bridge. You will learn why triangles make trusses strong and build and load-test your own craft-stick truss.

Then you will follow the Roebling family through fourteen years of building the Brooklyn Bridge, from the timber caissons sunk under the East River to the steel wires spun high in the air. Finally you will watch a bridge twist itself apart at Tacoma Narrows in 1940 and learn what engineers changed so that it would never happen again. Engineers learn from failure, honestly studied, as much as from success.

PREREQUISITES

- Knows the engineering design process and keeps a dated notebook (Unit 1)
- Can find an average and make a bar graph
- Knows that a force is a push or a pull

MASTERY CHECKLIST

- ☐ I can name and show compression, tension, shear and torsion, and find them in a real bridge.
- ☐ I can explain why a triangle is a rigid shape and identify Pratt and Warren trusses.
- ☐ I can tell how a suspension bridge carries its load from the deck to the anchorages, and how a caisson works.
- ☐ I can explain resonance and how the Tacoma Narrows Bridge failure changed bridge design.
- ☐ I can build a bridge, load-test it fairly, calculate its efficiency and improve it.

OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits:** Best for ages 11 and up with an adult. Balsa sticks, plans and gussets for building a truss bridge that can be weighed and load-tested to failure. A step up from the craft-stick truss in Lesson 2.2 and a good portfolio option.
- **K’NEX building sets:** Ages vary by set. Rods and connectors make it quick to build and compare truss, arch and suspension bridges. Fits Lessons 2.1–2.3.

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

LESSONS IN THIS UNIT

2.1 Forces in Structures: The Forth Bridge	2 sessions of 45 minutes
2.2 Truss Bridges and a Craft-Stick Load Test	2 sessions of 45 minutes
2.3 The Brooklyn Bridge: The Roeblings, Caissons and Steel Wire	2 sessions of 45 minutes
2.4 Tacoma Narrows: Resonance and Learning from Failure	2 sessions of 45 minutes

UNIT 2 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**
Name the four forces that act inside structures and give an everyday example of each.
2. **5 pts**
A plank bridge sags under a heavy load. Which part of the plank is in compression and which part is in tension?
3. **5 pts**
Why are trusses built from triangles instead of squares?

4. **5 pts**

Predict: you test two spaghetti columns, one 20 cm long and one 5 cm long. Which will hold more before it fails, and why?

5. **5 pts**

A craft-stick bridge has a mass of 80 grams and holds 4,000 grams before breaking. What is its efficiency? A second bridge has a mass of 120 grams and holds 4,800 grams. Which is more efficient?

6. **5 pts**

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

7. **5 pts**

What was a caisson, and why did the air inside it have to be under high pressure?

8. **5 pts**

How did the Brooklyn Bridge stay safe after weak wire was found in the cables?

9. **5 pts**

What is resonance? Give an example.

10. **5 pts**

Give two changes engineers made after the Tacoma Narrows Bridge failed.

ANSWER KEY

1. Compression (a table leg), tension (a clothesline or rope), shear (scissors cutting paper), torsion (wringing a towel or turning a key). Other good examples accepted.
2. The top is in compression (squeezed) and the bottom is in tension (stretched).
3. A triangle cannot change shape unless a side changes length, so it is rigid. A square can lean over into a diamond without any side changing length.
4. The 5 cm column. Long, thin columns buckle (bend sideways) at much smaller loads than short ones.
5. First: $4,000 \div 80 = 50$. Second: $4,800 \div 120 = 40$. The first bridge is more efficient, even though it held less.
6. Deck → suspenders (tension) → main cables (tension) → towers (compression) → foundations; the cable ends are held by the anchorages.
7. A huge watertight box open at the bottom, sunk into the riverbed so workers could dig the foundations. The air had to push back as hard as the water outside, which gets stronger the deeper you go, or the water would flood in.
8. John Roebling had designed the cables with a large safety factor (about six times stronger than needed), so they were still strong enough, and Washington Roebling added about 150 extra wires to each cable.
9. When small pushes come at the same rhythm as an object's natural frequency, so the motion grows. Example: pushing a swing at just the right moment each time.
10. Any two: deep, open stiffening trusses; slots or openings to let wind through; wind-tunnel testing of models before building; aerodynamic deck shapes; dampers.

PORTFOLIO PIECE: A LOAD-TESTED TRUSS BRIDGE

Design, build and test a craft-stick (or balsa) truss bridge that spans 35 centimeters and is as efficient as possible. You may use no more than 120 craft sticks. Before building, draw the full-size plan and mark every member as tension or compression. After testing, write a one-page engineer's report: the design, its mass, the load it held, its efficiency, where and why it failed, and what you would change. Include before-and-after photographs.

LOOK FOR	WHAT IT MEANS
Plan	Full-size labeled drawing with tension and compression members marked and the number of sticks listed.
Craftsmanship	Straight, square trusses with well-glued joints and cross-bracing.
Fair test and data	Bridge weighed before testing; load added evenly at the center; load and efficiency recorded correctly.
Failure analysis	Report explains where and why the bridge failed using the words compression, tension, buckling or joint.
Improvement	A sensible, specific change is proposed (or built and tested) based on the failure.

2.1 FORCES IN STRUCTURES: THE FORTH BRIDGE

OBJECTIVES

- Define and show compression, tension, shear and torsion.
- Explain how a beam bends, with compression on top and tension on the bottom.
- Measure how much load spaghetti can carry in tension and in compression, and explain why columns buckle.

Warm-up. Take a kitchen sponge or a piece of foam. Draw straight lines across its side with a marker, about a centimeter apart. Bend it like a bridge with a heavy truck on it. What happens to the lines on top? On the bottom? Now twist it, and then push the top and bottom halves in opposite directions. Sketch what you see.

WATCH

What Makes Bridges So Strong? | Engineering for Kids | STEAM | SciShow Kids

SciShow Kids · 3:45

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

WHEN TO WATCH

After the physics paragraph. Name the force at work each time something squeezes, stretches or bends.

KEY TERMS

compression

A squeezing or pushing force that tries to make something shorter.

tension

A pulling or stretching force that tries to make something longer.

shear

A force that tries to make one part of a material slide past the part next to it, like the blades of scissors.

torsion

A twisting force.

cantilever

A beam or arm that is held at one end and sticks out, carrying a load without support at the other end.

buckling

When a long, thin part under compression suddenly bends sideways and fails.

CORE IDEAS

The story. In December 1879 a long iron railway bridge over the Firth of Tay in Scotland fell during a fierce storm while a train was crossing, and the train and its passengers were lost. People were afraid to trust a big railway bridge again. So when engineers John Fowler and Benjamin Baker designed a new bridge across the nearby Firth of Forth, they had to make it strong beyond doubt and help the public understand why. To explain their design, Baker arranged a famous living model. Two men sat on chairs and held out their arms, gripping poles that pushed back against the chairs. A young Japanese engineer, Kaichi Watanabe, who was studying with them, sat on a board slung between their hands. Piles of bricks at the far ends held everything down. It was a living model of the bridge.

How they figured it out. The inquiry into the Tay Bridge found that its designer had not allowed properly for the force of the wind. Baker did not want to guess. He set up wind gauges on the island of Inchgarvie, in the middle of the Forth, and measured real wind pressures on boards large and small. The bridge was designed to stand a wind pressure of 56 pounds on every square foot, far more than any storm was expected to bring. It opened in 1890 with two main spans of about 1,710 feet each, the longest bridge spans in the world at that time, built from more than 50,000 tons of steel. It still carries trains today.

The physics. Every part of a structure is being squeezed, pulled, slid or twisted.

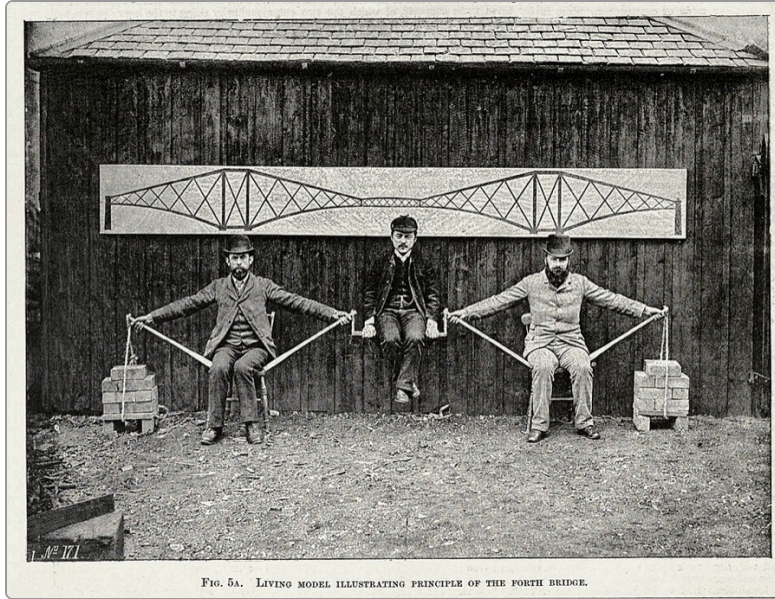
Compression squeezes; it is what the men's arms felt as the poles pushed into them, and what the giant steel tubes of the Forth Bridge carry. **Tension** pulls; the men's hands and the ties to the bricks were in tension. **Shear** tries to slide one part past another, like scissors cutting paper or a bolt being sliced between two plates.

Torsion twists, as when you wring out a towel. When a beam bends under a load, the top is squeezed (compression) and the bottom is stretched (tension), which is just what happened to the lines on your sponge.

The engineering. Engineers choose materials and shapes for the forces they will carry. Stone and concrete are very strong in compression but crack easily in tension.

Steel is strong in both. Ropes and cables can only carry tension; a rope cannot push. A long, thin part in compression may **buckle**, suddenly bowing sideways, long before the material itself is crushed. That is why the Forth Bridge's compression members are huge hollow steel tubes about 12 feet across: a tube resists buckling far better than a solid rod using the same amount of steel. Its tension members are lighter lattice girders, because a part in tension cannot buckle.

PICTURE STUDY



The Human Cantilever, Unknown photographer, about 1887 · Photograph · Made for a lecture on the Forth Bridge, Scotland

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

This photograph shows Benjamin Baker's living model of the Forth Bridge. Each seated man and his poles stand for one of the bridge's great cantilevers, and the man in the middle stands for the short span that hangs between them.

Look closely

- Find the men's arms. Are they being pulled or pushed? (Tension.)
- Find the poles under their hands that rest on the chairs. Are they pushed or pulled? (Compression.)
- Find the bricks at the outer ends. What would happen if they were taken away?
- Find the man in the middle. How is his weight carried down to the ground?

Talk about it

1. Trace the path of the middle man's weight with your finger, from the board to the ground. Name the force in each part.
2. Why do the chairs not tip forward? What does the counterweight do?
3. Why would a living model like this help people trust a new bridge?

Safety first. Wear safety glasses when breaking spaghetti; dry pasta snaps and pieces can fly. Do the human cantilever only with adults and with everyone seated low to the ground.

BUILD

Spaghetti Strength: Tension, Compression and Buckling

You will measure how much load a single strand of dry spaghetti holds when it is pulled (tension) and when it is pushed (compression), then run a fair test to see how length changes the load a spaghetti column can carry before it buckles. Finally you will rebuild Baker's human cantilever with your family.

You will need

- A box of dry spaghetti (all the same kind)
- A small paper cup with a string or paper-clip handle, and pennies (2.5 grams each)
- A kitchen scale
- Tape, a ruler and a craft knife or scissors for the adult to cut spaghetti
- For the human cantilever: two sturdy chairs, two broomsticks, a board or strong towel, and a few heavy books

Steps

1. **Tension test.** Tape the top of one spaghetti strand firmly to the edge of a table so it hangs down. Tape the cup to the bottom end. Add pennies one at a time until the strand snaps. Record the mass in grams (cup plus pennies $\times$ 2.5 g). Do three trials and average.
2. **Compression test.** Have an adult cut a strand to 20 centimeters. Stand it straight up on the kitchen scale and press straight down on the top with a flat piece of cardboard. Watch the scale: write down the highest reading just before the strand bends sideways. Do three trials.
3. Compare the two averages. Which way is spaghetti stronger? Write one sentence explaining why.
4. **Fair test: length and buckling.** Predict how the buckling load will change for shorter columns. Test columns 20, 10 and 5 centimeters long, three trials each, pressing the same way every time.
5. Record your results in a table and make a line graph: column length (across) and buckling load (up).

6. **Improve.** Bundle five 20-centimeter strands with tape every 2 centimeters and test again. Is a bundle of five more than five times as strong as one strand? Why might that be?
7. **Human cantilever.** Rebuild the photograph: two adults sit on chairs facing each other a few feet apart, each holding a broomstick braced against the front of the chair seat, while a towel slung between their hands holds a stack of books in the middle. Have the student say which parts are in tension and which in compression.

Tips

- Press straight down slowly in the compression test. A tilted push makes the column bend early.
- Use the same brand and thickness of spaghetti for every test.
- Long columns buckle at small loads; short columns may crush or snap instead. Notice which happens.

Check your work

- ☐ I can show compression, tension, shear and torsion with my hands or a sponge.
- ☐ I can explain why a long column buckles more easily than a short one.
- ☐ My graph shows how column length changed the buckling load.

ENGINEER'S NOTEBOOK

1. Draw a beam bending under a load. Label the top “compression” and the bottom “tension,” with arrows.
2. Draw the human cantilever and color every part in tension red and every part in compression blue.
3. Find four objects at home, one for each force (for example, a clothesline, a table leg, scissors, a jar lid). Sketch and label each.

From history. Kaichi Watanabe, the young man in the middle of the photograph, returned to Japan and became a leading civil engineer, helping to build railways there. The Forth Bridge was named a World Heritage Site in 2015. Its steel is still painted to protect it from rust, and a new paint system put on in the 2000s is expected to last for decades.

COMMON MISTAKES

- Thinking a cable or rope can push. Ropes carry only tension.
- Mixing up shear and tension. Tension stretches a part along its length; shear tries to slide one section past the next.
- Thinking a material that is strong in compression must also be strong in tension. Concrete and spaghetti are both much weaker in tension or bending.

Make it a game • Name That Force. Use a ruler, a sponge and your hands. Your parent calls out a force, and you demonstrate it on the sponge: compression, tension, shear or torsion. Then flex the ruler and say where compression and tension sit in a bending beam. Three clean demonstrations in a row win. Add one fact about the Forth Bridge cantilevers.

2.2 TRUSS BRIDGES AND A CRAFT-STICK LOAD TEST

OBJECTIVES

- Explain why a triangle is rigid and a square is not.
- Identify Pratt and Warren trusses and find the members in tension and compression.
- Build two craft-stick truss bridges, load-test them fairly, and compare their strength-to-weight efficiency.

Warm-up. Make a square from four craft sticks with a single push pin or brad at each corner. Push on one corner. Now make a triangle from three sticks the same way and push on it. What is different? Add one stick across the square from corner to corner and push again.

WATCH

How Trusses Work! (Structures 5-1).

Paul Kassabian · 11:19

<https://www.youtube.com/watch?v=KJdIbCn4NuE>

WHEN TO WATCH

After the physics paragraph. Watch for which members are pushed and which are pulled.

BACKUP VIDEO

Every Kind of Bridge Explained in 15 Minutes

Practical Engineering · 17:35

https://www.youtube.com/watch?v=DX_zkaK5Pal

To see trusses alongside every other kind of bridge. Optional and longer.

KEY TERMS

truss

A frame made of straight members joined in triangles, used to carry loads across a span.

member

One straight piece of a truss.

chord

The long top or bottom member of a truss.

joint

A place where members meet and are fastened together; on real bridges, often with a steel gusset plate.

span

The distance a bridge crosses between its supports.

efficiency

For a model bridge, the load it holds divided by its own weight.

CORE IDEAS

The story. In the 1800s, America was building canals and railroads faster than ever, and every river, creek and gully needed a bridge. Builders made wooden and iron trusses by rules of thumb passed from one carpenter to another, and some of those bridges sagged or failed. In 1847 Squire Whipple, an engineer who had worked on the Erie Canal, published *A Work on Bridge Building*. It was one of the first books to show how to calculate the force in every member of a truss using mathematics, so that each piece could be made just strong enough. Patented designs quickly followed, named for their inventors: the Howe truss (1840), the Pratt truss of Thomas and Caleb Pratt (1844), and the Warren truss (1848).

How they figured it out. Whipple's key idea was simple: at every joint, all the forces must balance, or the joint would move. If a load pushes down on a joint, the members that meet there must push and pull back in just the right amounts to hold it still. By working joint by joint across the bridge, an engineer can find the force in every member, decide which are in tension and which in compression, and size each one. Engineers still use this "method of joints" today, now often with computers.

The physics. A **triangle** is the only shape that cannot change its shape unless one of its sides changes length. Push on the corner of a square and it leans over into a diamond, even though no side gets longer or shorter. Push on a triangle and it holds. A **truss** is a row of triangles. When a truss bridge carries a load, its top **chord** is squeezed (compression) and its bottom chord is stretched (tension), just like the top and bottom of a bending beam. In a **Pratt truss**, the diagonals slant down toward the middle and are pulled (tension), while the verticals are pushed (compression). In a **Warren truss**, the diagonals form a zigzag of equal triangles and take turns, one in compression, the next in tension.

The engineering. A truss puts material only where it is needed, so it is much lighter than a solid beam of the same strength. Engineers choose the type to fit the materials. The Howe truss used thick wooden diagonals, which are good in compression, and iron rods for the verticals, which are in tension. The Pratt truss flipped that, putting long members in tension, which suits iron and steel because parts in tension do not buckle. The joints matter as much as the members: on real bridges, steel plates called gussets are bolted or riveted at each joint, and inspectors check them regularly. Thousands of old Pratt and Warren trusses still carry country roads and railways across America.

PICTURE STUDY



Alcovy Road Bridge: A Pratt Through Truss, Historic American Engineering Record, Photograph of a bridge built in the early 1900s · Photograph · Library of Congress, Prints and Photographs Division

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

The Historic American Engineering Record photographs and draws important old bridges and machines before they are changed or lost. This photograph shows the side of a steel Pratt truss over the Alcovy River in Georgia. In a “through truss,” cars drive through the middle of the truss, between its two sides.

Look closely

- Find the top chord and the bottom chord. Which one is squeezed and which one is stretched when a truck crosses?
- Find the diagonals. Which way do they slant? Do they slope toward the middle of the bridge?
- Count the triangles from one end to the other.
- Look closely at a joint where several members meet. How are they fastened?

Talk about it

1. In a Pratt truss, the diagonals are in tension. Why do you think they can be thinner than the vertical posts?
2. Why would a bridge builder in 1900 choose a truss instead of a solid steel beam?

3. What would an inspector look for at each joint?

Safety first. An adult handles any hot glue (use a low-temperature glue gun) and cuts sticks with a craft knife or snips. Wear safety glasses during load tests, because craft sticks can snap and fly.

BUILD

Pratt or Warren? A Craft-Stick Truss Load Test

You will build two truss bridges with the same number of craft sticks, one Pratt and one Warren, and load-test both until they fail. Then you will calculate each bridge's efficiency, the load it held divided by its own weight, the way bridge-building contests are judged.

You will need

- About 100 craft sticks (regular size)
- White glue (allow overnight drying) or a low-temperature glue gun with an adult
- Two stacks of books or two chairs to make a 30-centimeter gap
- A small bucket or a plastic bag with a string handle, pennies or sand, and a kitchen scale
- A short dowel or pencil to hang the load from the middle of the bridge
- Graph paper, ruler and engineer's notebook

Steps

1. **Plan.** On graph paper, draw one side of a Pratt truss and one side of a Warren truss at full size, each 40 centimeters long so it can span a 30-centimeter gap with room to rest on each end. Use the same number of sticks for each design and write that number down.
2. **Build.** Lay sticks on your drawing and glue them into one side of the truss. Build two matching sides for each bridge. Overlap the sticks at every joint so the glue has plenty of surface.
3. Connect the two sides of each bridge with cross-sticks along the bottom and top, making a narrow box. Add an X of sticks across the top for bracing. Let the glue dry completely.
4. Weigh each bridge on the kitchen scale and record its mass in grams.
5. **Predict.** Write which bridge you think will hold more and why.
6. **Test.** Set the bridge across the gap. Hang the bucket from the dowel laid across the middle of the bottom chords. Add pennies or sand a little at a time

until the bridge breaks. Weigh the bucket and its load, and record where and how the bridge failed.

7. Test the second bridge in exactly the same way.
8. Calculate efficiency for each: $\text{load held (g)} \div \text{bridge mass (g)}$. Record everything in a table.
9. **Improve.** Look at where each bridge broke. Strengthen only that weak spot (for example, double the sticks in that member or add a gusset of extra stick at that joint), build one improved bridge, and test it. Did the efficiency go up?

Tips

- Most model trusses fail at a joint, not in the middle of a stick. Good glue joints with lots of overlap make the biggest difference.
- Members in compression may buckle; doubling them up side by side helps.
- Take a photograph just before and just after the failure for your notebook.

Check your work

- ☐ I can explain why trusses are made of triangles.
- ☐ I can point to the members in tension and compression on my bridge.
- ☐ I can calculate my bridge's efficiency and explain the change I made to improve it.

ENGINEER'S NOTEBOOK

1. Draw a Pratt truss and a Warren truss side by side. Color members in compression blue and tension red.
2. Draw where each of your bridges failed, with an arrow and a sentence explaining why you think it broke there.
3. Make a table of your bridges: design, number of sticks, mass, load held, efficiency.

From history. Squire Whipple also patented the iron bowstring arch truss in 1841, and many were built over the Erie Canal. A few still stand. Herman Haupt, working on his own, published another early book on calculating the forces in trusses in 1851. Engineers learned quickly once the method was shared.

COMMON MISTAKES

- Testing before the glue is fully dry, so the joints fail instead of the design.

- Placing the load off-center on one bridge and in the middle on the other. Keep the test the same.
- Comparing only the load held. A heavier bridge should hold more; efficiency is the fair comparison.

Make it a game • Pratt or Warren? Your parent sketches truss shapes without labels. Name each as Pratt or Warren, then mark the members in tension and compression using two colors. Explain in a sentence why a triangle is rigid and a square is not. Quick rounds, one minute each. Best of five wins, and the loser draws the next mystery truss.

2.3 THE BROOKLYN BRIDGE: THE ROEBLINGS, CAISSONS AND STEEL WIRE

OBJECTIVES

- Tell the story of John, Washington and Emily Roebling and the building of the Brooklyn Bridge.
- Explain how a caisson uses air pressure to keep water out, and why workers got the bends.
- Build and load-test a model suspension bridge, tracing the load path from deck to anchorage.

Warm-up. Push an empty drinking glass straight down, mouth first, into a sink or tub of water. What keeps the water from filling the glass? Now tuck a crumpled dry paper towel in the bottom of the glass and try again. Is it still dry when you lift it out?

WATCH

One of the most epic engineering feats in history - Alex Gendler

TED-Ed • 5:16

<https://www.youtube.com/watch?v=dyckL6HuLRU>

WHEN TO WATCH

After the story. Then read the rest of the lesson.

KEY TERMS

suspension bridge

A bridge whose deck hangs from cables draped over tall towers and anchored at each end.

anchorage

A massive block, usually of stone or concrete, that holds the ends of a suspension bridge's main cables.

caisson

A huge watertight box, open at the bottom, sunk into a riverbed so workers can dig foundations below the water.

safety factor

How many times stronger a structure is than the greatest load it is expected to carry.

the bends

Caisson disease: pain and illness caused when a person moves too quickly from high-pressure air to normal air, and gas bubbles form in the body.

CORE IDEAS

The story. John A. Roebling came to America from Germany in 1831 and became a builder of suspension bridges and a maker of wire rope. In 1867 he designed a bridge to join the cities of New York and Brooklyn across the busy East River, with a span longer than any bridge in the world. In 1869, while he was surveying for the bridge, his foot was crushed by a ferry boat at a dock, and he died a few weeks later. His son, Washington Roebling, became chief engineer. Work began in January 1870. In 1872 Washington became very ill with the bends after long hours in the caissons, and for most of the next eleven years he could not visit the site. He watched the work from a window in Brooklyn through a telescope, and his wife, **Emily Warren Roebling**, carried his instructions to the engineers. She studied mathematics, the strength of materials and cable building so well that the engineers came to rely on her. Shortly before it opened on May 24, 1883, Emily was the first person to ride across it. Building it was dangerous, and some workers lost their lives.

How they figured it out. The great stone towers had to rest on solid ground far below the river mud. The Roeblings used two **caissons**, enormous upside-down wooden boxes, the Brooklyn one 168 feet long and 102 feet wide, with thick timber roofs. Air was pumped in to keep the water out, just as air kept the water out of your glass. Men worked inside by lamplight, digging away mud and boulders so that the caisson sank lower as the stone tower was built up on its roof. The Manhattan caisson went down about 78 feet. The deeper they went, the higher the air pressure had to be, and workers who came up too quickly suffered the bends. Washington Roebling decided the Manhattan caisson could stop on firm sand rather than going even deeper, partly to protect the men.

The physics. Water pushes harder the deeper you go: about one more “atmosphere” of pressure for every 33 feet of depth. To keep water out of a caisson, the air inside must push back just as hard. Air under pressure dissolves extra gas into a worker’s blood, the way gas is dissolved in a sealed bottle of soda; come up too fast, and

bubbles form, like opening the bottle. In a **suspension bridge**, the deck hangs from vertical suspender ropes, the suspenders hang from the main cables, the cables are in tension and pull down on the tops of the towers, the towers carry that load down in compression to the foundations, and the ends of the cables are held by huge **anchorages**. Roebling also added diagonal stay cables running from the towers to the deck, which make the Brooklyn Bridge stiffer against wind.

The engineering. The Brooklyn Bridge was the first large bridge to use **steel wire** for its cables. Each of its four main cables is about $15\frac{3}{4}$ inches thick and holds about 5,400 wires, spun one by one across the river by wheels that ran back and forth on ropes. During construction, the engineers discovered that a contractor had cheated and delivered weak wire, some of which was already in the cables. It could not be removed. But John Roebling had designed the cables to be about six times stronger than needed, a high **safety factor**, so Washington added about 150 extra wires to each cable and the bridge stayed safe. Its main span is $1,595\frac{1}{2}$ feet, and it still carries thousands of cars, bicycles and people every day. Counting the cost and building in a margin for the unknown is part of an engineer's duty, as Jesus said of a man who would build a tower.

PICTURE STUDY



The East River Bridge: Inside the Caisson, Unknown engravers for *Harper's Weekly*, December 17, 1870 · Wood engravings in a weekly newspaper · Library of Congress, Prints and Photographs Division
Image: [Wikimedia Commons](#), public domain

In 1870 readers all over America followed the building of the East River Bridge, as the Brooklyn Bridge was first called, in illustrated newspapers. This page from *Harper's Weekly* shows the Brooklyn caisson from outside and from inside, where men dug away the riverbed in compressed air.

Look closely

- Find the picture of the whole caisson on the shore. How big is it compared with the people?
- Find the men working inside the caisson. What light are they working by?
- Find the cutaway view at the bottom. Where is the water, and where is the air?
- Look for the shafts the workers climbed through to get in and out.

Talk about it

1. Why did the air inside the caisson have to be pumped in under pressure?
2. Why do you think the newspaper showed readers the inside of the caisson?
3. Which job in these pictures do you think was the hardest or most dangerous? Why?

Safety first. An adult should be present whenever you work with a tub of water. Wear safety glasses during the load test, because a snapping string or slipping tower can send pennies flying.

BUILD

A Model Suspension Bridge and a Caisson Test

You will build a model suspension bridge with towers, cables, suspenders, a deck and anchorages, and load-test it while measuring how much the deck sags. You will also measure how the air in an upside-down glass is squeezed as you push it deeper, the same problem the caisson workers faced.

You will need

- Two towers: tall cereal boxes, cardboard tubes or stacks of plastic cups taped together, about 30 centimeters tall
- Strong string for the main cables, and thread or paper clips for the suspenders
- A strip of card stock or a file folder for the deck, about 60 centimeters by 8 centimeters
- Heavy books for anchorages, tape, a ruler and pennies in a small cup
- A tall clear glass, a deep tub or sink of water, and a marker

Steps

1. Set the two towers 40 centimeters apart on a table. Tape them down. Lay a main cable over the top of both towers on each side, letting it sag between them, and tie or tape each end under a heavy book (the anchorages).
2. Hang suspenders from each main cable every 5 centimeters, using thread loops or chains of paper clips. Hang the card-stock deck from the suspenders so it is level and about 5 centimeters above the table.
3. Measure the height of the deck at the middle of the span. Set the penny cup on the middle of the deck and add pennies 10 at a time. After each 10, measure how far the deck has sagged. Record the results until the deck touches the table or something fails.
4. Notice what fails first: a suspender, a cable, a tower or an anchorage. Write it down.
5. **Fair test.** Change one thing only: either make the main cables sag more (lower) between the towers, or add diagonal stay strings from the tower tops to the deck as Roebling did. Repeat the same load test.

6. Graph pennies (across) and sag in millimeters (up) for both versions on the same graph.
7. **Caisson test.** Put a strip of tape down the side of the glass and mark it every centimeter from the rim. Push the glass straight down, mouth first, into a deep tub. Read how far the water has risen inside the glass at depths of 5, 10 and 20 centimeters.
8. Write what the rising water tells you about the air inside, and what that means for workers in a caisson far deeper than your tub.

Tips

- Make the suspenders all the same length so the deck hangs level.
- Tape the string firmly over the tops of the towers so it does not slide when loaded.
- If the towers lean inward, the anchorages are too weak or too close. Move the books farther out.

Check your work

- ☐ I can trace the load path of a suspension bridge from deck to anchorage.
- ☐ I can explain why the air in a caisson had to be under high pressure.
- ☐ My graph shows how one change affected the sag of my bridge.

ENGINEER'S NOTEBOOK

1. Draw a suspension bridge and label deck, suspenders, main cable, tower, foundation and anchorage. Add red arrows for tension and blue for compression.
2. Draw a cutaway caisson with workers inside, the air pressure pushing out and the water pressure pushing in.
3. Write a short note from Emily Roebling to the engineers giving one instruction about the bridge, using correct engineering words.

From history. When the Brooklyn Bridge opened, some people still doubted it was safe. In May 1884 the showman P. T. Barnum led 21 elephants across it to show how strong it was. The bridge was named a National Historic Landmark in 1964, and engineers still inspect and repair its cables regularly.

COMMON MISTAKES

- Thinking the towers hold the bridge up by themselves. The cables carry the deck, the towers hold up the cables, and the anchorages keep the cables from pulling

the towers over.

- Forgetting the anchorages. Without them, a suspension bridge cannot stand.
- Thinking the bends came from cold or dampness. It came from leaving high-pressure air too quickly.

Make it a game • Roebling Relay. Retell the Brooklyn Bridge story in a relay with your parent: John begins the plan, Washington takes over, Emily finishes. Add one fact each turn about the caisson, the anchorage or the bends. If a fact is wrong, say "safety factor!" and fix it. Keep the story going for two full minutes without stalling.

Scripture. “For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he have sufficient to finish it?” (Luke 14:28, KJV)

The Roeblings counted the cost carefully and built in a large margin of strength. That margin is what kept the bridge safe when bad wire was discovered.

2.4 TACOMA NARROWS: RESONANCE AND LEARNING FROM FAILURE

OBJECTIVES

- Explain resonance and natural frequency with examples.
- Describe what happened to the Tacoma Narrows Bridge and why its twisting motion grew.
- Test model bridge decks in front of a fan and compare a flat deck with a stiffened, slotted deck.

Warm-up. Push a friend or sibling on a swing. Try pushing at random times, then try pushing exactly when the swing comes back to you. Which way makes the swing go higher with small pushes? Write a sentence about the timing.

WATCH

Why the Tacoma Narrows Bridge Collapsed

Practical Engineering • 8:47

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

WHEN TO WATCH

After the story and the physics paragraph.

BACKUP VIDEO

Tacoma Bridge Collapse: The Wobbliest Bridge in the World? (1940) | British Pathé

British Pathé • 1:13

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

Before the story, to see the real film of the bridge in 1940.

KEY TERMS

natural frequency

The rate at which an object swings or vibrates on its own when it is disturbed, like a pendulum's steady swing.

resonance

When small pushes come at the same rhythm as an object's natural frequency, so the motion grows larger and larger.

flutter

A dangerous motion in which a structure's own twisting changes how the wind pushes on it, so the wind feeds the twisting.

aerodynamic

Shaped to let air flow past smoothly, with less push or twist from the wind.

stiffening truss

A deep truss along the deck of a suspension bridge that keeps it from bending and twisting.

CORE IDEAS

The story. The Tacoma Narrows Bridge in Washington State opened on July 1, 1940. With a main span of 2,800 feet, it was the third-longest suspension bridge in the world. To save money and look graceful, its designer used a very thin, shallow deck: solid steel girders only 8 feet deep, instead of the 25-foot-deep open truss first planned. Even during construction the deck rose and fell in waves in a moderate wind, and people drove across just for the ride, calling it “Galloping Gertie.” On the morning of November 7, 1940, in a steady wind of about 40 miles an hour, the motion suddenly changed. The deck began to twist, one side rising as the other fell, more and more violently, until a large part of it tore loose and fell into the water. No people were lost, and because Professor F. B. Farquharson of the University of Washington was there studying the bridge, the failure was filmed.

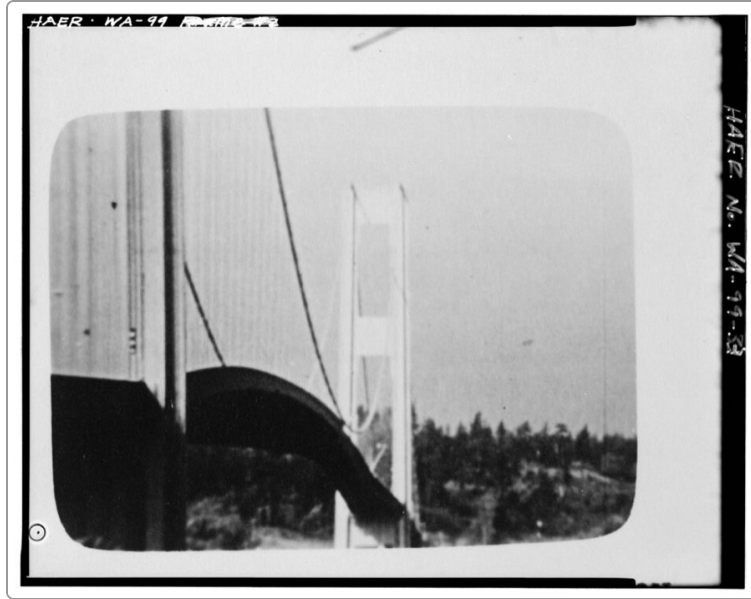
How they figured it out. Engineers had studied the bridge's motion for months before the collapse, measuring it and testing scale models. After the failure, a board of the country's leading engineers, including the famous aeronautical scientist Theodore von Kármán, studied the film, the measurements and wind-tunnel tests of models. They found that the problem was not a stronger-than-expected wind, but the shape and flexibility of the deck. They wrote a full public report, so that every bridge engineer could learn from it. Honest study of a failure is how engineers keep the next bridge safe.

The physics. Everything that can swing or bend has a **natural frequency**, a rhythm it moves at on its own: a swing, a pendulum, a guitar string, a bridge. If you give small pushes at exactly that rhythm, each push adds to the last and the motion grows. That is **resonance**, and it is why timing your pushes makes a swing go high. Wind can also

make a bridge move. The Tacoma Narrows Bridge did something even more dangerous, called **flutter**. Once the thin deck began to twist, its own twisting changed the way the wind pushed on it, and the changed push made the twist larger. The bridge was feeding the wind's energy into its own motion, like a swing that pushes itself higher every time it comes back. The flat, solid sides of the deck, which the wind could not pass through, made this much worse.

The engineering. The new Tacoma Narrows Bridge, opened in 1950, has a deep, open stiffening truss that resists twisting and lets wind pass through, with openings in the roadway. Since then, engineers test models of every long bridge in a wind tunnel before it is built. Many modern bridges have **aerodynamic** decks shaped like a flattened airplane wing so wind flows smoothly around them. Engineers also add dampers, devices that soak up motion, as they did in 2000 when London's new Millennium Footbridge swayed sideways under the footsteps of crowds. A failure studied honestly becomes a lesson that saves many lives.

PICTURE STUDY



The Twisting Deck, From film by F. B. Farquharson, University of Washington, November 7, 1940 · Still from 16 mm film · Historic American Engineering Record, Library of Congress

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

Professor Farquharson had been studying the bridge's strange motion for months, and he filmed it on the day it failed. His film has been shown to engineering students ever since, as a warning and a lesson.

Look closely

- Find the towers and the main cables. Are they moving as much as the deck?
- Look at the deck. How thin does it look compared with the length of the span?
- Find the places where the deck is bending up and the places where it is bending down.
- Look for any openings in the deck where wind could pass through.

Talk about it

1. Why would a thin, flexible deck move more in the wind than a deep, stiff one?
2. Why was it important that the engineers wrote a public report after the failure?
3. What would you test in a wind tunnel before building a long bridge today?

Safety first. Keep fingers, hair and loose paper away from the front and back of the box fan, and have an adult set the fan on a stable, flat surface.

BUILD

Resonant Pendulums and a Fan-Tested Bridge Deck

First you will see resonance with a row of pendulums of different lengths. Then you will hang model bridge decks in front of a box fan and measure how much each one twists, comparing a thin flat deck with one that has a stiffening truss and slots for the wind.

You will need

- String, four metal washers or nuts, tape and two chairs
- A box fan with low, medium and high speeds
- Card stock or file folders, craft sticks or straws, tape and scissors
- A ruler, a marker and engineer's notebook

Steps

1. **Resonant pendulums.** Tie a string tightly between two chair backs. Hang four pendulums from it: lengths 20, 30, 30 and 45 centimeters, each with a washer at the bottom. Hold all still, then start one of the 30-centimeter pendulums swinging. Watch for a minute. Which other pendulum starts to swing the most? Record what you see and explain it with the word resonance.
2. **Deck A, thin and flat.** Cut a strip of card stock 50 centimeters by 6 centimeters. Hang it level by four strings (two at each end) from a craft-stick frame or between two chairs, about 40 centimeters in front of the fan, with the flat face toward the side.
3. Draw a line across the middle of the deck. Turn the fan on low, then medium, then high. At each speed, measure how far the edge of the deck at the middle moves up and down, and record whether it bounces, twists or stays still.
4. **Deck B, stiffened and slotted.** Make a second deck the same size. Tape a row of craft sticks or straws along both edges as a stiffening truss, and cut a few slots along the middle of the deck so air can pass through.
5. Test Deck B in exactly the same place and at the same three speeds. Record the results.

6. Make a table: deck, fan speed, motion seen, size of motion in millimeters.
7. **Improve.** Design a Deck C with a different shape, for example a pointed, wing-like edge made by folding card stock, and test it. Write which design was steadiest and why you think so.

Tips

- Hang the decks loosely enough that they can move. A deck tied tight cannot show the difference.
- Measure by holding a ruler beside the deck's edge and reading the highest and lowest points.
- Watch for twisting (one edge up, the other down) as well as up-and-down motion.

Check your work

- ☐ I can explain resonance using a swing or my pendulums.
- ☐ I can explain why the Tacoma Narrows Bridge twisted itself apart.
- ☐ My data show which deck design moved least in the wind.

ENGINEER'S NOTEBOOK

1. Draw the Tacoma Narrows deck twisting, with arrows showing one side up and the other side down.
2. Draw a cross-section of the 1940 deck (thin, solid girders) next to the 1950 deck (deep, open truss with slots). Label the differences.
3. Write three sentences: what failed, why it failed, and what engineers changed.

From history. Parts of the old Tacoma Narrows deck still lie at the bottom of Puget Sound, where they have become an artificial reef for fish and other sea creatures, and they are protected as a historic site. In 2007 a second parallel bridge opened beside the 1950 bridge to carry more traffic.

COMMON MISTAKES

- Thinking the wind was simply too strong. The wind that day was moderate; the deck's thin, flexible shape was the problem.
- Thinking the wind gusted at exactly the bridge's rhythm. The twisting fed itself; that is flutter.

- Thinking a failure means engineers are careless. Engineering advances when failures are studied honestly and the lessons are shared.

Make it a game • Push at the Right Beat. Hang two pendulums of different string lengths from a table edge. Push the one that matches the other's natural frequency and watch it grow. Explain resonance and why Tacoma Narrows twisted. Your parent plays a bridge inspector and asks "What would you add?" Answer with a stiffening truss and an aerodynamic shape.

UNIT 2

BRIDGES

A bridge is a promise. Every person who walks or drives across it is trusting that the engineers counted every load and chose every beam and cable with care. In this unit you will learn the four forces at work inside every structure, compression, tension, shear and torsion, and see them in the great steel arms of Scotland's Forth Bridge. You will learn why triangles make trusses strong and build and load-test your own craft-stick truss.

Then you will follow the Roebling family through fourteen years of building the Brooklyn Bridge, from the timber caissons sunk under the East River to the steel wires spun high in the air. Finally you will watch a bridge twist itself apart at Tacoma Narrows in 1940 and learn what engineers changed so that it would never happen again. Engineers learn from failure, honestly studied, as much as from success.

PREREQUISITES

- Knows the engineering design process and keeps a dated notebook (Unit 1)
- Can find an average and make a bar graph
- Knows that a force is a push or a pull

MASTERY CHECKLIST

- ☐ I can name and show compression, tension, shear and torsion, and find them in a real bridge.
- ☐ I can explain why a triangle is a rigid shape and identify Pratt and Warren trusses.
- ☐ I can tell how a suspension bridge carries its load from the deck to the anchorages, and how a caisson works.
- ☐ I can explain resonance and how the Tacoma Narrows Bridge failure changed bridge design.
- ☐ I can build a bridge, load-test it fairly, calculate its efficiency and improve it.

OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits:** Best for ages 11 and up with an adult. Balsa sticks, plans and gussets for building a truss bridge that can be weighed and load-tested to failure. A step up from the craft-stick truss in Lesson 2.2 and a good portfolio option.
- **K’NEX building sets:** Ages vary by set. Rods and connectors make it quick to build and compare truss, arch and suspension bridges. Fits Lessons 2.1–2.3.

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

LESSONS IN THIS UNIT

2.1 Forces in Structures: The Forth Bridge	2 sessions of 45 minutes
2.2 Truss Bridges and a Craft-Stick Load Test	2 sessions of 45 minutes
2.3 The Brooklyn Bridge: The Roeblings, Caissons and Steel Wire	2 sessions of 45 minutes
2.4 Tacoma Narrows: Resonance and Learning from Failure	2 sessions of 45 minutes

UNIT 2 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

- 5 pts**
Name the four forces that act inside structures and give an everyday example of each.
- 5 pts**
A plank bridge sags under a heavy load. Which part of the plank is in compression and which part is in tension?
- 5 pts**
Why are trusses built from triangles instead of squares?

4. **5 pts**

Predict: you test two spaghetti columns, one 20 cm long and one 5 cm long. Which will hold more before it fails, and why?

5. **5 pts**

A craft-stick bridge has a mass of 80 grams and holds 4,000 grams before breaking. What is its efficiency? A second bridge has a mass of 120 grams and holds 4,800 grams. Which is more efficient?

6. **5 pts**

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

7. **5 pts**

What was a caisson, and why did the air inside it have to be under high pressure?

8. **5 pts**

How did the Brooklyn Bridge stay safe after weak wire was found in the cables?

9. **5 pts**

What is resonance? Give an example.

10. **5 pts**

Give two changes engineers made after the Tacoma Narrows Bridge failed.

ANSWER KEY

1. Compression (a table leg), tension (a clothesline or rope), shear (scissors cutting paper), torsion (wringing a towel or turning a key). Other good examples accepted.
2. The top is in compression (squeezed) and the bottom is in tension (stretched).
3. A triangle cannot change shape unless a side changes length, so it is rigid. A square can lean over into a diamond without any side changing length.
4. The 5 cm column. Long, thin columns buckle (bend sideways) at much smaller loads than short ones.
5. First: $4,000 \div 80 = 50$. Second: $4,800 \div 120 = 40$. The first bridge is more efficient, even though it held less.
6. Deck → suspenders (tension) → main cables (tension) → towers (compression) → foundations; the cable ends are held by the anchorages.
7. A huge watertight box open at the bottom, sunk into the riverbed so workers could dig the foundations. The air had to push back as hard as the water outside, which gets stronger the deeper you go, or the water would flood in.
8. John Roebling had designed the cables with a large safety factor (about six times stronger than needed), so they were still strong enough, and Washington Roebling added about 150 extra wires to each cable.
9. When small pushes come at the same rhythm as an object's natural frequency, so the motion grows. Example: pushing a swing at just the right moment each time.
10. Any two: deep, open stiffening trusses; slots or openings to let wind through; wind-tunnel testing of models before building; aerodynamic deck shapes; dampers.

PORTFOLIO PIECE: A LOAD-TESTED TRUSS BRIDGE

Design, build and test a craft-stick (or balsa) truss bridge that spans 35 centimeters and is as efficient as possible. You may use no more than 120 craft sticks. Before building, draw the full-size plan and mark every member as tension or compression. After testing, write a one-page engineer's report: the design, its mass, the load it held, its efficiency, where and why it failed, and what you would change. Include before-and-after photographs.

LOOK FOR	WHAT IT MEANS
Plan	Full-size labeled drawing with tension and compression members marked and the number of sticks listed.
Craftsmanship	Straight, square trusses with well-glued joints and cross-bracing.
Fair test and data	Bridge weighed before testing; load added evenly at the center; load and efficiency recorded correctly.
Failure analysis	Report explains where and why the bridge failed using the words compression, tension, buckling or joint.
Improvement	A sensible, specific change is proposed (or built and tested) based on the failure.

UNIT 3

TALL BUILDINGS

People have always wanted to build high, and for most of history the limit was set by stone: the taller a stone wall, the thicker it had to be at the bottom, until there was hardly room inside. In this unit you will learn the loads every building must carry, the dead weight of the building itself, the live weight of people and furniture and snow, and the sideways push of wind and earthquakes. You will see how the builders of the Washington Monument had to strengthen its foundation halfway through.

Then you will follow the great ideas that let buildings rise: the arch, the vault and the flying buttress of the Gothic cathedrals; the steel frame that carries a skyscraper's weight like the bones of a body; Elisha Otis's safety elevator, which made people willing to ride to the top; and the bracing and dampers that keep the Empire State Building and modern towers steady in wind and earthquakes. Jesus told of a wise man who built his house upon a rock. Every tall building starts with that same lesson.

PREREQUISITES

- Knows compression, tension and buckling (Unit 2)
- Knows how pulleys and counterweights work (Unit 1)
- Can multiply and divide to find area and simple averages

MASTERY CHECKLIST

- ☐ I can name dead, live and wind loads and explain why foundations spread a building's weight over a large area.
- ☐ I can explain how arches, vaults and flying buttresses carry loads in compression and resist outward thrust.
- ☐ I can explain how a steel frame carries a tall building and how Otis's safety brake works.
- ☐ I can explain how engineers keep tall buildings steady in wind and earthquakes, including bracing and dampers.
- ☐ I can build a model tower, test it on a shake table, and improve it with bracing.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** All ages. Identical maple planks with no glue or connectors; good for building arches, towers and buttresses and testing what makes them stable. Fits Lessons 3.1, 3.2 and 3.4.
- **Thames & Kosmos engineering kits:** Ages 8 and up. The company makes structural engineering kits with beams and connectors for building model bridges and skyscrapers. Fits Lessons 3.3 and 3.4.

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

LESSONS IN THIS UNIT

3.1 Loads and Foundations: The Washington Monument

2 sessions of 45 minutes

3.2 From Pyramids to Gothic Cathedrals: Arches, Vaults and Buttresses

2 sessions of 45 minutes

3.3 The Steel Frame and Otis's Safety Elevator

2 sessions of 45 minutes

3.4 The Empire State Building: Building for Wind and Earthquakes

2 sessions of 45 minutes

UNIT 3 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

Sort these loads as dead, live or lateral: a concrete floor, a crowd at a party, a strong wind, snow on the roof, the steel beams, an earthquake.

2. **5 pts**

A column carries 1,200 grams. On a footing of 4 square centimeters, what is the pressure? On 16 square centimeters? Which sinks less?

3. (5 pts)

Why did Colonel Casey enlarge the Washington Monument's foundation before finishing it?

4. (5 pts)

What is thrust, and how does a flying buttress deal with it?

5. (5 pts)

Predict: you build two identical card-stock arches but brace only one at the feet. Which holds more pennies, and why?

6. (5 pts)

How did Robert Hooke say to find the best shape for an arch?

7. (5 pts)

Explain how Otis's safety brake worked and why it is fail-safe.

8. (5 pts)

Why did the steel frame make taller buildings possible than load-bearing walls?

9. (5 pts)

Name three ways engineers keep tall buildings from swaying too much in wind or earthquakes.

10. (5 pts)

Predict: a tower sways a lot on the shake table. You add X-braces to every side. What will happen and why?

ANSWER KEY

1. Dead: concrete floor, steel beams. Live: crowd, snow. Lateral: wind, earthquake.
2. $1,200 \div 4 = 300$ g per square centimeter; $1,200 \div 16 = 75$ g per square centimeter.
The larger footing sinks less.
3. The old foundation was too small for the full weight of the finished monument; it would have pressed too hard on the soil, and the monument could have sunk or leaned. A wider foundation spreads the load and lowers the pressure.
4. Thrust is the outward push at the feet of an arch or vault. A flying buttress is a half-arch that carries that thrust across the side aisle to a heavy pier, which carries it down to the ground.
5. The braced arch. Its feet cannot spread, so the thrust is resisted and the arch keeps its shape.
6. Hang a flexible chain and turn its shape upside down. The chain is pulled only in tension, so the upside-down shape is pushed only in compression.
7. The pull of the rope kept a spring flexed and the pawls held in. If the rope broke, the spring snapped straight and pushed the pawls into toothed guide rails, stopping the platform. It is fail-safe because the failure itself sets the brake.
8. With bearing walls, taller buildings needed thicker walls at the bottom (like the Monadnock's six-foot walls), taking up space. A steel frame carries the loads on columns and beams, so the walls can be thin curtain walls.
9. Any three: cross-bracing, a stiff concrete core, a tube frame, a tuned mass damper, base isolation, a wider base.
10. It will sway less and survive longer, because the braces turn each rectangle into stiff triangles that cannot lean over without a member changing length.

PORTFOLIO PIECE: THE SHAKE-TABLE SKYSCRAPER

Design and build a model skyscraper at least 60 centimeters tall from straws, craft sticks or paper, with a mass of 50 pennies on its top floor and a footing sized for the table you build on. It must survive 30 seconds of shaking on your shake table and stand in front of the fan on high. In your notebook, show your sketches, the loads you planned for, at least two test rounds with data, and a labeled drawing of the final design explaining every bracing choice.

LOOK FOR	WHAT IT MEANS
Meets the challenge	At least 60 cm tall, carries 50 pennies on top, survives 30 seconds of shaking and the fan on high.
Structural thinking	Uses triangles, a core, a wide base or a damper on purpose, and the notebook explains why.
Fair testing	The same shake and wind tests are used each round, and results are recorded in a table.
Improvement	At least one change is made from the first to the second round, based on how the first version failed or swayed.
Presentation	A labeled final drawing and a few clear sentences that a visitor at the engineering fair could understand.

3.1 LOADS AND FOUNDATIONS: THE WASHINGTON MONUMENT

OBJECTIVES

- Name and give examples of dead, live, wind and earthquake loads.
- Explain why a foundation must spread a building's weight over a large enough area of ground.
- Measure how footing size changes how far a loaded column sinks into sand.

Warm-up. Stand in a sandbox or on soft ground (or press into a pan of flour). First stand on your heels, then flat on both feet, then lie down flat if you can. Which way sinks deepest? Why do you think snowshoes work?

WATCH

How Buildings Are Engineered To NOT Collapse - What Structural Engineers Actually Do

Mat Picardal · 9:41

<https://www.youtube.com/watch?v=RVcHARzCmg4>

WHEN TO WATCH

After the physics paragraph. Write down every kind of load the engineer names.

KEY TERMS

dead load

The weight of the building itself: its walls, floors, beams, roof and everything built in.

live load

Weight that comes and goes: people, furniture, books, cars, rain and snow.

lateral load

A sideways push on a building, such as wind or the shaking of an earthquake.

foundation

The part of a building below ground that carries all the loads down into the soil or rock.

pressure

How much force pushes on each unit of area. The same force spread over a bigger area makes less pressure.

CORE IDEAS

The story. In 1848 workers laid the cornerstone of a great marble obelisk in Washington, D.C., to honor George Washington. By 1854 it had reached about 152 feet, and then the money ran out and work stopped. For more than twenty years the stump stood unfinished. In 1876 Congress agreed to pay to finish it, and in 1878 the job went to an Army engineer, Lieutenant Colonel Thomas Lincoln Casey. Before adding a single stone, Casey studied the old foundation and found it far too small for the full height. It would have pressed too hard on the soil beneath it, and the tower could have sunk unevenly and leaned.

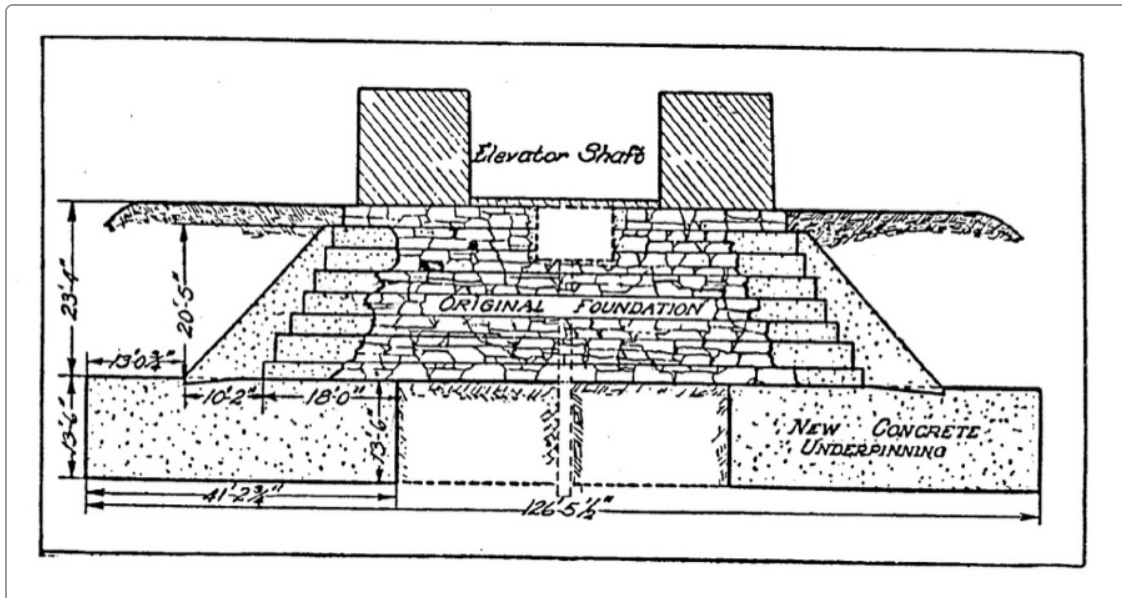
How he figured it out. Casey's engineers calculated the total weight of the finished monument, measured the soil, and worked out how much pressure it could safely bear. Then, carefully and in small sections so the stump would not tip, they dug under the old foundation and poured a wide new slab of concrete beneath and around it, more than doubling the area that carries the load. They also checked that the obelisk's proportions matched ancient Egyptian obelisks, about ten times as tall as it is wide at the base, which set its height at about 555 feet. The capstone was set in December 1884. For a few years the Washington Monument was the tallest structure in the world. You can still see a change in the color of the marble about 150 feet up, where the work stopped and started again.

The physics. Engineers sort the forces on a building into **loads**. The **dead load** is the building's own weight, which never goes away; for a stone monument, it is almost all of the load. The **live load** is weight that comes and goes, such as people, furniture and snow. **Lateral loads** push sideways: wind, and the shaking of the ground in an earthquake. All of these must travel down through the building into the ground. **Pressure** is force divided by area. The same weight spread over a bigger area presses less on each square foot of soil, which is why snowshoes keep you from sinking and why a wider foundation keeps a tall tower from sinking or leaning.

The engineering. Before designing a building today, engineers send a geotechnical crew to drill into the ground and test the soil and rock. On strong rock, a building

can rest on simple footings. On soft soil, engineers use wide mat foundations or drive long piles of steel or concrete deep into the ground until they reach firm layers. They add up every load the building may ever carry and then design for more, with a safety factor. Jesus said the wise man “built his house upon a rock,” and the rain and floods and winds could not knock it down. A building is only as good as what it stands on.

PICTURE STUDY



Strengthening the Washington Monument's Foundation, U.S. Army Corps of Engineers, about 1880 · Engineering drawing · Report on the completion of the Washington Monument

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

This drawing shows what Casey's engineers did underground. The old stone foundation is in the middle, and the wide new concrete slab spreads beneath it like the base of a pyramid.

Look closely

- Find the original foundation and the new concrete around and under it.
- Compare the width of the old foundation with the new one.
- Find the line that shows the ground level.
- Look for any measurements written on the drawing.

Talk about it

1. Why does a wider foundation press less hard on the soil?
2. Why did the workers dig under the old foundation in small sections, not all at once?
3. What might have happened if they had finished the monument on the old foundation?

Safety first. Keep sand out of eyes and wash hands afterward. Lift heavy books with bent knees, and keep toes clear when stacking weights on your column.

BUILD

The Footing Test

You will load a model column with the same weight on footings of different sizes and measure how far each one sinks into damp sand. You will calculate the pressure for each footing and graph how the area changes the sinking, just as Casey's engineers had to reckon how much the soil under the monument could bear.

You will need

- A deep pan or plastic tub of damp sand (or flour, or soil), smoothed flat
- A pencil or short dowel as the column, and a paper cup taped to its top to hold weights
- Three square footings cut from stiff cardboard: 2×2 cm, 4×4 cm and 8×8 cm, each with a small hole in the middle for the column
- Pennies or small washers for weights, a kitchen scale, a ruler with millimeters

Steps

1. Fill the cup with 100 pennies (250 grams). Weigh the whole column, cup and pennies together, and record the load in grams.
2. Find the area of each footing in square centimeters: 4, 16 and 64.
3. Smooth the sand flat. Stand the column straight up with no footing, holding it lightly so it does not tip, and let go. Measure how far the tip sank, in millimeters.
4. Repeat with the column standing on each footing. Smooth the sand the same way before each test. Do two trials for each and average.
5. Calculate the pressure for each footing: load (grams) $\div$ area (square centimeters). Record it in your table next to the sinking.
6. Make a graph of footing area (across) and sinking (up). Describe the pattern.
7. **Live load test.** Now add 50 more pennies to the cup as a "live load" and test the 4×4 and 8×8 footings again. Which footing still keeps the column from sinking much?

8. **Improve.** Design a footing for a tower that must not sink more than 2 millimeters under the heavier load, using the least cardboard. Test it.

Tips

- Pack and smooth the sand the same way every time; loose sand gives very different results.
- Lower the column gently. Dropping it adds a force you are not measuring.
- Stretch your graph so the small differences are easy to see.

Check your work

- ☐ I can name dead, live and lateral loads with examples.
- ☐ I can calculate pressure as force divided by area.
- ☐ My data show how a bigger footing reduces sinking.

ENGINEER'S NOTEBOOK

1. Draw your house or school and label one dead load, three live loads and one lateral load with arrows.
2. Draw the Washington Monument with its old and new foundations in cross-section. Add arrows showing the weight spreading into the ground.
3. Write a short report to Colonel Casey explaining what your footing test shows.

From history. The marble for the first part of the monument came from one quarry in Maryland, and when work started again, the builders could not get matching stone at first, which is why the color changes. Inside the walls are 194 memorial stones given by states, cities, churches, schools and other countries. The aluminum tip on top was one of the largest pieces of aluminum ever cast at the time.

COMMON MISTAKES

- Forgetting the dead load. For many buildings, the building's own weight is the largest load of all.
- Thinking a stronger column is enough. A strong column on a tiny footing will still sink.
- Mixing up force and pressure. The force can stay the same while the pressure changes with area.

Make it a game • Load Sorting Game. Write twelve examples on slips of paper, such as a sofa, a crowd, a gust of wind or a quake. Sort them into dead, live, wind and earthquake loads in sixty seconds. Then explain why a foundation spreads weight over more ground. Your parent challenges any slip, and you defend it with one sentence.

Scripture. “Therefore whosoever heareth these sayings of mine, and doeth them, I will liken him unto a wise man, which built his house upon a rock: And the rain descended, and the floods came, and the winds blew, and beat upon that house; and it fell not: for it was founded upon a rock.” (Matthew 7:24-25, KJV)

Jesus names three loads every builder knows: rain, floods and wind. A house founded on rock stands. A life founded on Christ’s words stands too.

3.2 FROM PYRAMIDS TO GOTHIC CATHEDRALS: ARCHES, VAULTS AND BUTTRESSES

OBJECTIVES

- Explain why pyramids and arches stand by compression.
- Describe the outward thrust of an arch and how buttresses and flying buttresses resist it.
- Build and load-test a model arch with and without buttresses, and use a hanging chain to find a strong arch shape.

Warm-up. Stand two books upright a little apart and try to lean a third book across the top as a roof. Then try leaning two books against each other in an upside-down V. What do the bottoms of the two leaning books try to do? How could you stop them?

WATCH

5. Gothic Cathedrals

Engineering Models · 5:14

<https://www.youtube.com/watch?v=WiX2amY7G-I>

WHEN TO WATCH

After the physics paragraph. Watch for the outward push at the bottom of each arch.

BACKUP VIDEO

Gothic architecture explained

Smarthistory · 4:31

<https://www.youtube.com/watch?v=G94jFWH8NSM>

For a short tour of the parts of a Gothic cathedral.

KEY TERMS

arch

A curved structure that carries weight across an opening by pressing each stone against the next, all in compression.

keystone

The wedge-shaped stone at the top of an arch, set last, that locks the other stones in place.

thrust

The outward, sideways push at the base of an arch or vault.

vault

An arched stone ceiling; a ribbed vault has stone ribs that carry most of the load.

flying buttress

A half-arch outside a building that carries the thrust of the vault across to a heavy pier of stone.

CORE IDEAS

The story. The Great Pyramid of Giza, built for the Egyptian king Khufu about 4,500 years ago, rose about 481 feet and was the tallest structure people had made for thousands of years. It stands because it is almost all compression: a huge, wide base and nearly every stone pressing straight down on the stones below. But a pyramid is nearly solid, with very little room inside. In the 1100s, in France, builders began a new style. At the abbey church of Saint-Denis near Paris, Abbot Suger rebuilt the choir in the 1140s with pointed arches, ribbed stone vaults and great windows of colored glass. Over the next century, master masons raised cathedrals at Chartres, Amiens and Reims, with stone ceilings more than 100 feet above the floor and walls that seemed to be made of light.

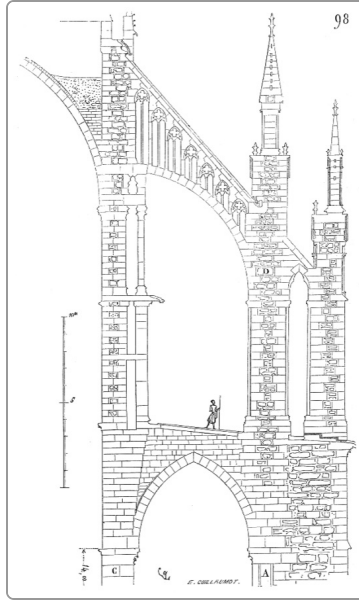
How they figured it out. The master masons had no computers or steel. They used geometry, careful rules of proportion, and the experience of builders who had gone before, watching each building for cracks and learning which shapes stood. Sometimes they pushed too far. At Beauvais the builders tried for the tallest choir of all, about 157 feet, and in 1284 part of its vault fell. They rebuilt it with more piers and buttresses, and it stands today. Four hundred years later, the English scientist Robert Hooke found a simple rule for the best shape of an arch: “As hangs the flexible line, so but inverted will stand the rigid arch.” A hanging chain is pulled only in tension; turn its shape upside down, and you have an arch that is pushed only in compression.

The physics. In an arch, each wedge-shaped stone presses against its neighbors, so the weight above is passed around the curve and down to the ground, all in compression, which stone carries well. While an arch is being built, it rests on a wooden frame called centering; when the **keystone** is set at the top, the arch can

stand on its own. But an arch does not only push down. It also pushes outward at its feet. This sideways push is called **thrust**. If nothing resists it, the walls spread apart and the arch falls. A pointed arch pushes outward less than a round one, which is one reason Gothic builders liked it.

The engineering. Romanesque churches before the Gothic style resisted thrust with thick, heavy walls and small windows. Gothic builders gathered the weight of the stone **vault** onto ribs and slender columns, then carried the thrust outside the building through **flying buttresses**, half-arches that leap over the side aisles to tall stone piers. Heavy pinnacles on top of the piers add weight that helps turn the thrust downward into the ground. With the thrust taken outside, the walls no longer had to hold up the roof, and they could be filled with windows. Engineers still use arches in bridges, dams and tunnels, and they still follow Hooke's chain to find their shapes.

PICTURE STUDY



Section Through a Flying Buttress of Amiens Cathedral, Eugène Viollet-le-Duc, 1854–1868 · Wood engraving from a drawing · From the *Dictionnaire raisonné de l'architecture française*
Image: [Wikimedia Commons](#), public domain

Viollet-le-Duc was a French architect who restored many medieval churches and studied exactly how they were built. In his great dictionary of French architecture he drew cutaways like this one, showing how every stone of a Gothic cathedral carries its load.

Look closely

- Find the high vault inside the cathedral. Where does its weight go?
- Find the flying buttresses. How many are there, one above the other?
- Find the heavy pier and the pinnacle on top of it.
- Look at the tall wall between the buttresses. Why could it be filled with windows?

Talk about it

1. Trace with your finger the path of the vault's thrust from the ceiling to the ground.
2. Why do you think the pinnacle is placed on top of the pier?
3. What would happen to the vault if the flying buttresses were removed?

Safety first. Wear safety glasses during the arch load test in case card stock springs loose. Keep the hanging chain or necklace away from small children.

BUILD

Arches, Buttresses and Hooke's Hanging Chain

You will build a card-stock arch between two blocks, measure how much load it holds and how far its feet spread, and then add buttresses and test again.

You will also use a hanging chain to draw the strongest arch shape, as Robert Hooke described.

You will need

- Card stock or file folders, cut into strips 5 centimeters wide and 30 centimeters long
- Four wooden blocks or small stacks of books for the feet and buttresses
- A small cup and pennies
- A light chain, beaded necklace or string with washers tied on evenly
- A large sheet of cardboard or poster board, pushpins and a marker
- Ruler and engineer's notebook

Steps

1. **Arch without buttresses.** Bend a card-stock strip into an arch and stand its feet on the table about 20 centimeters apart, with a light block just touching the outside of each foot. Mark where the feet start.
2. Set the cup on top of the arch and add pennies 5 at a time. After each 5, measure how far the feet have spread. Record the load when the arch flattens or the feet slide away.
3. **Arch with buttresses.** Make a new arch the same size. Brace each foot firmly with a heavy stack of books (the buttresses) so it cannot slide out. Repeat the load test exactly.
4. **Pointed arch.** Make a pointed arch by leaning two curved strips against each other and taping them at the top. Test it with buttresses. Record all three results in a table.
5. **Hooke's chain.** Pin the two ends of the chain near the top of the poster board, 30 centimeters apart, and let it hang. Trace its curve with a marker.

6. Turn the board upside down. You now have the outline of an arch that stands in pure compression. Cut a card-stock arch to that shape and test it with buttresses.
7. Make a bar graph of the load each arch held. Write which shape was strongest and explain why using the word thrust.
8. **Improve.** Change one thing about your best arch, such as a deeper curve, a second layer of card stock, or a keystone wedge glued at the top, and test again.

Tips

- Use the same kind of card stock for every arch so the test is fair.
- Set the cup gently on the very top of the arch each time.
- Watch the feet closely: arches usually fail by spreading at the bottom, not by breaking at the top.

Check your work

- ☐ I can explain why an arch pushes outward at its feet.
- ☐ I can explain how flying buttresses let Gothic cathedrals have big windows.
- ☐ I can use a hanging chain to find a strong arch shape.

ENGINEER'S NOTEBOOK

1. Draw a round arch and a pointed arch side by side. Label the keystone, the voussoirs (wedge stones) and the thrust arrows at the feet.
2. Draw the cross-section of a Gothic cathedral with its vault, walls, flying buttresses, piers and pinnacles.
3. Draw your hanging chain and the upside-down arch it made.

From history. The spire of Lincoln Cathedral in England, finished around 1311, is thought to have been the first structure to rise higher than the Great Pyramid. It stood for more than two hundred years until a storm blew it down in 1548, and it was never rebuilt.

COMMON MISTAKES

- Thinking the keystone holds the whole arch up by itself. Every stone matters; the keystone is simply the last one that locks the ring together.

- Thinking arches push only down. They also push outward, and that thrust must be resisted.
- Calling every buttress a flying buttress. A flying buttress is the half-arch that “flies” across open space to the pier.

Make it a game • Hanging Chain Arch. Hang a loose chain or string between two fingers and sketch its curve on paper. Flip the picture upside down and you have a strong arch, as Hooke saw. Explain thrust, keystone and flying buttresses to your parent. Teach it back in under a minute while your parent sneaks in one false fact for you to catch.

Scripture. “Thus he shewed me: and, behold, the Lord stood upon a wall made by a plumbline, with a plumbline in his hand.” (Amos 7:7, KJV)

A plumbline is a weight on a string that hangs perfectly straight down, and builders have always used one to make walls true. God measures our lives by His true standard, just as a mason checks a wall.

3.3 THE STEEL FRAME AND OTIS'S SAFETY ELEVATOR

OBJECTIVES

- Explain how a steel frame carries a tall building and why it replaced thick bearing walls.
- Explain how Otis's safety brake works and why it is called fail-safe.
- Build a model elevator with a counterweight and design a brake that catches the car when the rope goes slack.

Warm-up. Imagine you must walk up the stairs of a 20-story building every day. About how many steps would that be, if each floor has 18 steps? Who would want to live on the top floor? Now imagine the elevator rope breaking. What would you want the elevator to have?

WATCH

How does an Elevator work?

Jared Owen · 11:32

<https://www.youtube.com/watch?v=rKp4pe92ljg>

WHEN TO WATCH

After the physics paragraph. Pause at the safety brake and the counterweight.

BACKUP VIDEO

Make Inventions: Otis Safety Elevator

Make: · 4:12

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

Before the build, to see a working model of Otis's safety brake.

KEY TERMS

load-bearing wall

A wall that holds up the floors and roof above it.

steel frame

A framework of steel columns and beams that carries all the loads of a building, so the outer walls only have to keep out the weather.

curtain wall

An outer wall of glass, stone or metal that hangs on the steel frame and does not hold up the building.

counterweight

A heavy weight on the other end of an elevator's cables that balances the car, so the motor does less work.

fail-safe

Designed so that if something breaks, the machine stops in a safe way instead of a dangerous one.

CORE IDEAS

The story. Before the 1850s, hoists were used to lift goods in warehouses, but people feared riding them, because if the rope broke, the platform fell. Elisha Otis, a mechanic working in a bedstead factory in Yonkers, New York, invented a safety device to stop a hoist if the rope failed. In 1854, at an exhibition in New York's Crystal Palace, he rode a platform high above a crowd and had the only rope cut with an axe. The platform dropped a few inches and stopped. In 1857 the first passenger safety elevator was installed in a store in New York City. Meanwhile, buildings were held up by their walls, and tall walls had to be very thick. The 16-story Monadnock Building in Chicago, finished in 1891 with brick bearing walls, needed walls about six feet thick at the bottom. Engineers were already using a better way: the Home Insurance Building in Chicago, designed by William Le Baron Jenney and finished in 1885, carried its weight on a frame of iron and steel. Many people call it the first skyscraper.

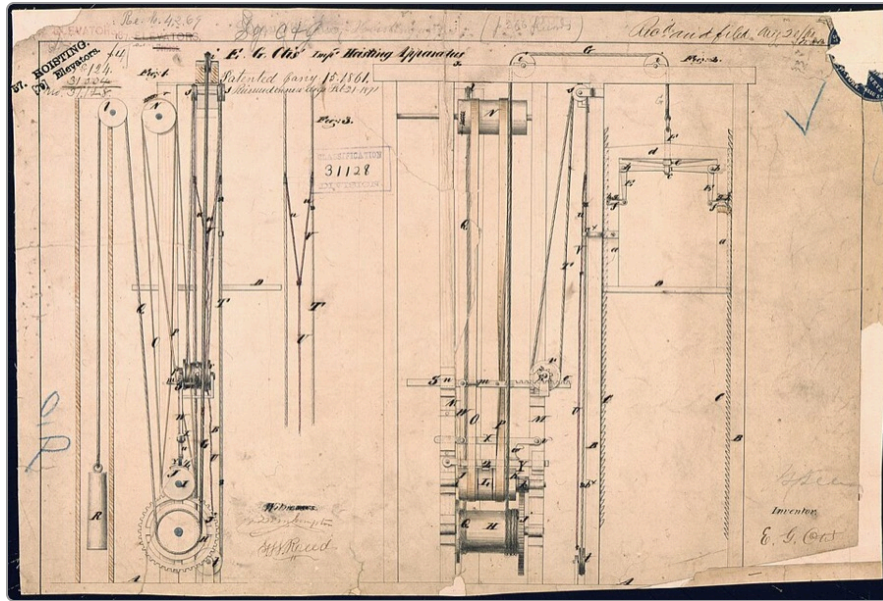
How they figured it out. Otis noticed that as long as the rope was pulling up on the platform, it was safe. He used that pull to hold back a brake. A strong wagon spring at the top of the platform was kept flexed by the tension in the rope. Along both sides of the shaft he fastened wooden guide rails cut with teeth like a ratchet. If the rope broke, the tension vanished, the spring snapped straight, and its ends pushed stout pawls out into the teeth of the rails, catching the platform at once. Jenney, for his part, saw that iron and steel columns could carry the floors directly, letting the walls be thin. Builders proved the steel frame by building it and watching it stand.

The physics. Otis's brake is **fail-safe**: the dangerous event, losing the rope's tension, is the very thing that sets the brake. A modern elevator uses the same idea and more: it hangs from several steel cables, any one of which can hold the car, and a speed

governor sets the safety brakes if the car ever moves too fast. Elevators also use a **counterweight**, just like the pulleys in Unit 1. The counterweight weighs about as much as the car plus part of a typical load, so the motor only has to lift the difference. In a **steel frame**, the columns carry loads down in compression and the beams carry the floors across, bending with compression on top and tension underneath.

The engineering. Together, the steel frame and the safe elevator made the skyscraper possible. Without the frame, tall walls would fill the ground floor; without the elevator, nobody would want the upper floors. Today a steel or concrete frame holds up the building, and the outside is a **curtain wall** of glass and metal that simply hangs on the frame. Engineers protect steel from fire with coatings, because steel weakens when very hot, and building codes require fire stairs, sprinklers and elevators that are inspected regularly. Every time you step into an elevator without a second thought, you are trusting the engineers who designed it and the inspectors who check it.

PICTURE STUDY



Otis's Elevator Patent Drawing, Elisha Graves Otis, 1861 · Patent drawing · National Archives, Washington, D.C.

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

Elisha Otis received this patent for “Improvement in Hoisting Apparatus” in January 1861, a few months before he died. The drawing shows how the platform runs between toothed guide rails and how the safety device would catch it.

Look closely

- Find the guide rails on each side. What shape are their edges?
- Find the spring and the pawls at the top of the platform.
- Find where the rope attaches. What keeps the spring from opening while the rope is pulling?
- Look for the letters that label each part.

Talk about it

1. Explain in your own words what happens to the spring and the pawls the moment the rope breaks.
2. Why is this called a fail-safe design?
3. Why do you think Otis tested his brake in front of a crowd instead of just describing it?

Safety first. Test your elevator brake only with light loads like pennies or clay, never with a pet or anything fragile. Keep fingers out from under the falling car.

BUILD

A Counterweighted Elevator with a Fail-Safe Brake

You will build a model elevator shaft and car, measure how a counterweight reduces the effort needed to lift it, and then design and test a brake that catches the car when the rope goes slack.

You will need

- A tall, narrow cardboard box (such as a cereal or pasta box) with one side cut open as the shaft
- A small box or paper cup as the elevator car
- A thread spool on a pencil axle across the top of the shaft as the pulley
- String, pennies, a second cup for the counterweight, and a kitchen scale
- Craft sticks, rubber bands, clothespins and tape for the brake
- Ruler and engineer's notebook

Steps

1. Mount the spool across the top of the shaft. Tie the car to one end of a string, run it over the spool, and tie an empty cup to the other end.
2. Load the car with 40 pennies. Add pennies to the empty cup until the car just rises. Record the effort in grams.
3. **Counterweight.** Now hang a counterweight cup with 40 pennies on the other end, plus enough extra pennies to lift the car. How many extra pennies did it take? Compare the two efforts and explain.
4. **Design a fail-safe brake.** Remove the counterweight. Sketch at least two brake ideas. The rule: while the rope is pulling up, the brake must be held off; when the rope goes slack, the brake must grab the walls of the shaft. (Hint: two craft sticks on a rubber band or a clothespin that springs open.)
5. Build your best idea on top of the car.
6. **Test.** Raise the car near the top of the shaft, then let go of the string completely. Measure how far the car falls before it stops. Do three trials.
7. Record the results. If the car falls all the way, look closely at why the brake did not grab.

8. **Improve.** Change one thing, such as a stronger rubber band, rougher shaft walls (glue on strips of corrugated cardboard as your “teeth”), or longer arms, and test again. Try to make the car stop within 3 centimeters.

Tips

- Otis’s rails had teeth. Corrugated cardboard ridges give your brake something to catch.
- The brake must not rub while the car is moving normally, or the elevator will jam.
- Video the drop in slow motion with a phone to see exactly what your brake does.

Check your work

- ☐ I can explain how a counterweight saves effort.
- ☐ I can explain why Otis’s brake is fail-safe.
- ☐ My notebook shows two brake designs, test results and an improvement.

ENGINEER’S NOTEBOOK

1. Draw a cutaway of an elevator: car, cables, pulley, motor, counterweight and guide rails. Label each.
2. Draw Otis’s brake twice: once with the rope pulling (brake held off), and once after the rope breaks (pawls in the teeth).
3. Draw a steel frame for a five-story building, then hang a curtain wall on it.

From history. Elisha Otis died in 1861, but his sons Charles and Norton carried on the business, and the company still builds elevators around the world. The E. V. Haughwout Building in New York, where the first passenger safety elevator was installed in 1857, still stands at the corner of Broadway and Broome Street.

COMMON MISTAKES

- Making a brake that needs someone to press a button. A fail-safe brake works by itself when something fails.
- Thinking the counterweight makes the elevator heavier to lift. It balances the car, so the motor lifts only the difference.
- Thinking the outer walls of a skyscraper hold it up. The frame holds it up; the curtain wall keeps out the weather.

Make it a game • Elevator Fail-Safe. Explain how Otis's brake works by acting it out. You are the elevator car, and your parent holds a string. If the string is cut, your arm snaps out like a brake and stops you. Do it three times. Then name the counterweight's job, the steel frame's job and what a curtain wall does.

3.4 THE EMPIRE STATE BUILDING: BUILDING FOR WIND AND EARTHQUAKES

OBJECTIVES

- Tell how the Empire State Building was built in about 13 months.
- Explain how wind and earthquakes push on tall buildings, and how bracing, cores and dampers resist them.
- Build a model tower, test it on a homemade shake table and in front of a fan, and improve it with bracing.

Warm-up. Stand with your feet together and have someone gently push your shoulder. Then stand with your feet wide apart and try again. Then try with your knees slightly bent. Which way is steadiest? How is a tall building like a person standing in the wind?

WATCH

How Tall Buildings Tame the Wind

The B1M • 9:34

<https://www.youtube.com/watch?v=tHMPR7flpf4>

WHEN TO WATCH

After the physics paragraph. Watch for each idea engineers use to stop a building from swaying.

KEY TERMS

sway

The side-to-side movement of a tall building in the wind.

core

A stiff central tube, often of concrete, around the elevators and stairs that helps a tall building resist sideways loads.

cross-bracing

Diagonal members, often in an X, that turn the rectangles of a frame into stiff triangles.

tuned mass damper

A huge weight near the top of a building, free to swing, that moves against the building's sway and calms it.

base isolation

Setting a building on flexible bearings
so the ground can shake beneath it
while the building moves much less.

CORE IDEAS

The story. On March 17, 1930, workers began setting steel for the Empire State Building in New York City. The plans were so carefully made, and the steel, stone and windows so carefully scheduled, that the frame rose about four and a half stories a week. Steel beams made in Pennsylvania were often riveted into place within days of being made. Ironworkers heated rivets red-hot in small forges and tossed them up to the men who drove them in. The photographer Lewis Hine climbed the frame with them to record the work. The building opened on May 1, 1931, after only about 13 months of construction, with 102 stories rising 1,250 feet. It was the tallest building in the world for almost forty years.

How they figured it out. The engineers knew wind would be the great sideways load on such a tall, narrow tower. They designed a stiff steel frame in which beams and columns are joined so firmly with rivets that the joints resist bending, and they wrapped the frame in heavy stone and brick, which added stiffness. They calculated the wind force on each face of the building and made the frame strong enough to carry it down to the bedrock of Manhattan. The building has stood through every storm since and moves only a small amount even in strong winds.

The physics. Wind pushes on the whole side of a building, and the building acts like a giant cantilever beam standing on end, fixed at the ground. The side facing the wind is stretched (tension) and the far side is squeezed (compression), and the top moves sideways, or **sways**. In an earthquake, the ground itself moves back and forth under the building. Like the bridge in Unit 2, every building has a natural frequency, and if the ground shakes at that rhythm, resonance can make the swaying much worse. Tall buildings sway slowly, short buildings quickly, so different earthquakes are dangerous to different buildings.

The engineering. Engineers stiffen tall buildings with **cross-bracing** (triangles again), with concrete **cores** around the elevators and stairs, and with strong outer frames that work like one big tube. To calm sway, some towers have a **tuned mass damper**: Taipei 101 in Taiwan hangs a steel ball weighing about 660 metric tons near

its top, which swings against the building's motion. In earthquake country, engineers may use **base isolation**, setting the building on bearings of rubber and steel so the ground can move while the building above moves much less. Building codes, written from careful study of past earthquakes and storms, tell engineers how strong each building must be.

PICTURE STUDY



A Workman on the Framework of the Empire State Building, Lewis Hine, 1930–1931 · Photograph · National Archives, Washington, D.C.

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

Lewis Hine photographed the men who built the Empire State Building, often climbing out onto the beams with his heavy camera. His pictures show both the courage of the workers and the steel frame that carries the building.

Look closely

- Find the steel beams and columns. Which carry weight down, and which carry floors across?
- Look for rivets or bolts at the joints.
- Find any cables or ropes. What might they be used for?
- Look at the city below. How high up do you think the worker is?

Talk about it

1. How does a rigid joint between a beam and a column help the frame resist wind?
2. What safety equipment do you notice is missing, compared with ironworkers today?
3. Why do you think Hine wanted to photograph the workers, not just the finished building?

Safety first. Keep the shake table on the floor or a low table. Wear safety glasses if your tower uses rubber bands or skewers, and have an adult cut any skewers.

BUILD

Shake Table and Wind Test Tower

You will build a simple shake table and a tower of straws or craft sticks at least 40 centimeters tall. You will test how far the top sways in a fan's wind and how long it survives shaking, then add cross-bracing and test again in exactly the same way.

You will need

- Shake table: two pieces of stiff cardboard or thin plywood about 30 × 30 cm, four tennis balls or eight marbles in bottle caps, and two thick rubber bands
- Tower: drinking straws, craft sticks or wooden skewers, masking tape or white glue, and a paper cup
- Pennies or a lump of modeling clay for a “mass” on the top floor
- A box fan, a ruler, a stopwatch and a phone to video the tests

Steps

1. **Shake table.** Put the tennis balls (or marbles in caps) on the bottom board and set the top board on them so it can roll. Stretch the rubber bands around both boards so the top springs back to center when pulled.
2. **Tower A, no bracing.** Build a square tower at least 40 centimeters tall with four columns and a floor every 10 centimeters. Tape a cup with 20 pennies (or clay) to the top floor. Tape the tower's base firmly to the shake table.
3. **Wind test.** Place the fan 50 centimeters away, on medium. Hold a ruler beside the top of the tower and measure how far it sways.
4. **Shake test.** Pull the top board 3 centimeters to one side and let go, again and again, at a steady rhythm of about two pulls a second, for up to 30 seconds. Time how long the tower survives without falling or breaking. Do the same test three times.
5. **Tower B, braced.** Add diagonal braces (X shapes) to every side of every story. Make no other changes. Repeat the wind and shake tests exactly.

6. Record your results in a table: tower, sway in the wind (mm), shake survival time (s).
7. **Improve.** Try one more idea: a stiff “core” of straws in the center, a wider base, or a hanging damper (a lump of clay on a short string inside the top floor). Test it the same way.
8. Write which change helped most and explain it with the words triangle, stiffness or damper.

Tips

- Keep the shaking the same for every test: same pull distance, same rhythm, same time.
- Video each test; slow-motion replay shows where the tower bends first.
- Most towers fail at the joints. Wrap tape tightly at every joint.

Check your work

- ☐ I can explain how wind and earthquakes push on tall buildings.
- ☐ I can explain why cross-bracing makes a tower stiffer.
- ☐ My data compare an unbraced tower with a braced one.

ENGINEER'S NOTEBOOK

1. Draw a tall building with arrows showing wind pushing on one side, tension on the windward side and compression on the leeward side.
2. Draw three ways engineers stop sway: cross-bracing, a core and a tuned mass damper. Label each.
3. Graph your shake test results and write what you would try next.

From history. Lewis Hine began his career photographing children at work in mills and factories, and his pictures helped change laws to protect them. For the Empire State Building, he swung out in a basket high above the street to photograph the ironworkers. His book *Men at Work*, published in 1932, honored the skill of those who build.

COMMON MISTAKES

- Thinking a tall building should be perfectly rigid. All tall buildings sway a little; engineers keep the sway safe and comfortable.
- Changing the shake rhythm between tests, which is not fair.

- Bracing only one side of the tower. Wind and shaking can come from any direction.

Make it a game · Sway Stoppers. Stack a tower of cards or cups on a tray and shake gently. Explain with your parent how cross-bracing, a core or a tuned mass damper would help. Pick one fix, add it, and shake again. Score a point if the tower survives longer. Add one fact about how fast the Empire State Building went up.

UNIT 3

TALL BUILDINGS

People have always wanted to build high, and for most of history the limit was set by stone: the taller a stone wall, the thicker it had to be at the bottom, until there was hardly room inside. In this unit you will learn the loads every building must carry, the dead weight of the building itself, the live weight of people and furniture and snow, and the sideways push of wind and earthquakes. You will see how the builders of the Washington Monument had to strengthen its foundation halfway through.

Then you will follow the great ideas that let buildings rise: the arch, the vault and the flying buttress of the Gothic cathedrals; the steel frame that carries a skyscraper's weight like the bones of a body; Elisha Otis's safety elevator, which made people willing to ride to the top; and the bracing and dampers that keep the Empire State Building and modern towers steady in wind and earthquakes. Jesus told of a wise man who built his house upon a rock. Every tall building starts with that same lesson.

PREREQUISITES

- Knows compression, tension and buckling (Unit 2)
- Knows how pulleys and counterweights work (Unit 1)
- Can multiply and divide to find area and simple averages

MASTERY CHECKLIST

- ☐ I can name dead, live and wind loads and explain why foundations spread a building's weight over a large area.
- ☐ I can explain how arches, vaults and flying buttresses carry loads in compression and resist outward thrust.
- ☐ I can explain how a steel frame carries a tall building and how Otis's safety brake works.
- ☐ I can explain how engineers keep tall buildings steady in wind and earthquakes, including bracing and dampers.
- ☐ I can build a model tower, test it on a shake table, and improve it with bracing.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** All ages. Identical maple planks with no glue or connectors; good for building arches, towers and buttresses and testing what makes them stable. Fits Lessons 3.1, 3.2 and 3.4.
- **Thames & Kosmos engineering kits:** Ages 8 and up. The company makes structural engineering kits with beams and connectors for building model bridges and skyscrapers. Fits Lessons 3.3 and 3.4.

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

LESSONS IN THIS UNIT

3.1 Loads and Foundations: The Washington Monument

2 sessions of 45 minutes

3.2 From Pyramids to Gothic Cathedrals: Arches, Vaults and Buttresses

2 sessions of 45 minutes

3.3 The Steel Frame and Otis's Safety Elevator

2 sessions of 45 minutes

3.4 The Empire State Building: Building for Wind and Earthquakes

2 sessions of 45 minutes

UNIT 3 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

Sort these loads as dead, live or lateral: a concrete floor, a crowd at a party, a strong wind, snow on the roof, the steel beams, an earthquake.

2. **5 pts**

A column carries 1,200 grams. On a footing of 4 square centimeters, what is the pressure? On 16 square centimeters? Which sinks less?

3. (5 pts)

Why did Colonel Casey enlarge the Washington Monument's foundation before finishing it?

4. (5 pts)

What is thrust, and how does a flying buttress deal with it?

5. (5 pts)

Predict: you build two identical card-stock arches but brace only one at the feet. Which holds more pennies, and why?

6. (5 pts)

How did Robert Hooke say to find the best shape for an arch?

7. (5 pts)

Explain how Otis's safety brake worked and why it is fail-safe.

8. (5 pts)

Why did the steel frame make taller buildings possible than load-bearing walls?

9. (5 pts)

Name three ways engineers keep tall buildings from swaying too much in wind or earthquakes.

10. (5 pts)

Predict: a tower sways a lot on the shake table. You add X-braces to every side. What will happen and why?

ANSWER KEY

1. Dead: concrete floor, steel beams. Live: crowd, snow. Lateral: wind, earthquake.
2. $1,200 \div 4 = 300$ g per square centimeter; $1,200 \div 16 = 75$ g per square centimeter.
The larger footing sinks less.
3. The old foundation was too small for the full weight of the finished monument; it would have pressed too hard on the soil, and the monument could have sunk or leaned. A wider foundation spreads the load and lowers the pressure.
4. Thrust is the outward push at the feet of an arch or vault. A flying buttress is a half-arch that carries that thrust across the side aisle to a heavy pier, which carries it down to the ground.
5. The braced arch. Its feet cannot spread, so the thrust is resisted and the arch keeps its shape.
6. Hang a flexible chain and turn its shape upside down. The chain is pulled only in tension, so the upside-down shape is pushed only in compression.
7. The pull of the rope kept a spring flexed and the pawls held in. If the rope broke, the spring snapped straight and pushed the pawls into toothed guide rails, stopping the platform. It is fail-safe because the failure itself sets the brake.
8. With bearing walls, taller buildings needed thicker walls at the bottom (like the Monadnock's six-foot walls), taking up space. A steel frame carries the loads on columns and beams, so the walls can be thin curtain walls.
9. Any three: cross-bracing, a stiff concrete core, a tube frame, a tuned mass damper, base isolation, a wider base.
10. It will sway less and survive longer, because the braces turn each rectangle into stiff triangles that cannot lean over without a member changing length.

PORTFOLIO PIECE: THE SHAKE-TABLE SKYSCRAPER

Design and build a model skyscraper at least 60 centimeters tall from straws, craft sticks or paper, with a mass of 50 pennies on its top floor and a footing sized for the table you build on. It must survive 30 seconds of shaking on your shake table and stand in front of the fan on high. In your notebook, show your sketches, the loads you planned for, at least two test rounds with data, and a labeled drawing of the final design explaining every bracing choice.

LOOK FOR	WHAT IT MEANS
Meets the challenge	At least 60 cm tall, carries 50 pennies on top, survives 30 seconds of shaking and the fan on high.
Structural thinking	Uses triangles, a core, a wide base or a damper on purpose, and the notebook explains why.
Fair testing	The same shake and wind tests are used each round, and results are recorded in a table.
Improvement	At least one change is made from the first to the second round, based on how the first version failed or swayed.
Presentation	A labeled final drawing and a few clear sentences that a visitor at the engineering fair could understand.

ELECTRICITY AND ELECTRONICS

Two hundred and fifty years ago, electricity was a curiosity: sparks from a rubbed glass globe, a shock from a jar. Then, in the space of one long lifetime, scientists and engineers learned to make a steady current, measure it, turn it into magnetism and motion, and send messages with it across a continent. In this unit you will follow that story from Volta's pile of metal disks to Ohm's law, from Oersted's twitching compass needle to Faraday's spinning wire, and from Samuel Morse's first message, "What hath God wrought," to the LED lights in your home.

You will build circuits you can measure: a pencil-lead dimmer, an electromagnet that lifts paper clips, a motor that spins on a battery, a working telegraph, and LED circuits with switches and resistors. All the electricity in this unit comes from ordinary batteries. Never experiment with the outlets in the wall or anything that plugs into them.

PREREQUISITES

- Knows how to make a simple circuit with a battery, wire and bulb (earlier grades or a quick review)
- Can read a data table and make a bar graph
- Knows the safety rule: batteries only, never the outlets in the wall

MASTERY CHECKLIST

- ☐ I can explain voltage, current and resistance and use $V = I \times R$ in a simple example.
- ☐ I can build an electromagnet, explain what makes it stronger, and explain how a simple motor turns.
- ☐ I can tell how Morse and Vail's telegraph worked and send a message in Morse code.
- ☐ I can build an LED circuit with a resistor and a switch and explain what each part does.
- ☐ I can draw circuits with standard symbols.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco):** Ages 8 and up. Parts snap onto a plastic grid, so you can build dozens of circuits with switches, LEDs, motors, buzzers and electromagnets without wiring. A good companion to Lessons 4.1–4.4. Look for the Snap Circuits Jr. set to start.
- **KiwiCo Tinker Crate:** Ages 9 and up. Some monthly crates include circuits, motors and LEDs with clear explanations of how they work. Fits Lessons 4.2 and 4.4.

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

4.1 Volta, Ohm and the Circuit: Voltage, Current and Resistance

2 sessions of 45 minutes

4.2 Oersted, Faraday and a Homemade Motor

2 sessions of 45 minutes

4.3 Samuel Morse and the Telegraph

2 sessions of 45 minutes

4.4 Switches, LEDs and Resistors: From Edison's Lamp to the LED

2 sessions of 45 minutes

UNIT 4 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

Using the water-pipe picture, explain voltage, current and resistance.

2. **5 pts**

A 6-volt battery pushes current through a 300-ohm resistor. What is the current?

3. **5 pts**

Predict: in the pencil-lead dimmer, what happens to the bulb when you slide the clip to make the graphite in the circuit longer? Why?

4. (5 pts)

What did Oersted discover in 1820?

5. (5 pts)

Name three ways to make an electromagnet stronger.

6. (5 pts)

Why does a simple motor need a commutator (or a half-sanded wire)?

7. (5 pts)

What was the first message sent on Morse's Washington-Baltimore line, and in what year?

8. (5 pts)

Why did long telegraph lines need relays? How did Vail decide which letters got the shortest codes?

9. (5 pts)

An LED circuit has no resistor and the LED burns out. Explain why, and how to fix it.

10. (5 pts)

Predict: two switches are wired in series with an LED. Switch A is on and switch B is off. Does the LED light? What if they are in parallel?

ANSWER KEY

1. Voltage is like the pump's push; current is like the amount of water flowing past each second; resistance is like a narrow part of the pipe that holds the flow back.
2. $I = V \div R = 6 \div 300 = 0.02$ amps.
3. The bulb gets dimmer, because longer graphite has more resistance, so less current flows.
4. That an electric current makes a magnetic force around the wire; a compass needle moved when current flowed in a nearby wire.
5. More turns of wire, more current (more voltage), an iron core (or a bigger iron core).
6. To switch off or reverse the current every half turn, so the magnetic push keeps turning the coil the same way instead of rocking it back and forth.
7. "What hath God wrought," on May 24, 1844.
8. The current weakens in a long wire because of resistance; a relay uses the weak current to switch on a fresh battery for the next section. Vail counted the type in a printer's shop to find which letters were most common.
9. An LED has very little resistance once it lights, so too much current flows and it overheats. Add a resistor in the loop to limit the current.
10. In series (AND), no, because both must be on. In parallel (OR), yes, because one closed switch completes the circuit.

PORTFOLIO PIECE: A TWO-STATION TELEGRAPH

Build a telegraph that can send messages both ways between two rooms, using two keys, two sounders or LEDs, batteries and long wires. Draw the complete circuit with standard symbols, test how long the wire can be before the signal gets too weak, and send a ten-word message in each direction with no more than two errors. In your notebook, explain the circuit, your test results and one improvement you made.

LOOK FOR	WHAT IT MEANS
It works	Messages can be sent and received in both directions with clear clicks or flashes.
Circuit diagram	A neat diagram with correct symbols for batteries, switches, electromagnets or LEDs, and wires.
Testing	The effect of wire length on the signal is tested and recorded; the message test is timed and errors counted.
Science explanation	Explains the key, the electromagnet, resistance in long wires and why relays were needed, using correct words.
Improvement	At least one change made the telegraph clearer, faster or more reliable, and the notebook explains it.

4.1 VOLTA, OHM AND THE CIRCUIT: VOLTAGE, CURRENT AND RESISTANCE

OBJECTIVES

- Explain voltage, current and resistance using the water-pipe picture.
- Use Ohm's law, $V = I \times R$, in a simple example.
- Build a pencil-lead dimmer and run a fair test of how length changes resistance.

Warm-up. Look at a flashlight. Without opening the battery case, draw what you think is inside and how the electricity gets from the battery to the bulb and back. Then open it (with permission) and correct your drawing in a different color.

WATCH

Ohms Law Explained - The basics circuit theory

The Engineering Mindset · 10:00

<https://www.youtube.com/watch?v=HsLLq6Rm5tU>

WHEN TO WATCH

After the physics paragraph. Pause at the water-pipe pictures and explain them back.

Note: The last minute shows practice problems with a lamp plugged into the wall; these are math examples only. Never experiment with outlets.

BACKUP VIDEO

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

SciShow Kids · 4:42

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

Before the build, as a short review of how a circuit works.

KEY TERMS

circuit

A complete, closed path that electric current can flow around.

voltage

The push that drives current around a circuit, measured in volts (V).

current

The flow of electric charge through a circuit, measured in amperes or amps (A).

resistance

How much a material or part holds back the current, measured in ohms (Ω).

Ohm's law

Voltage equals current times resistance: $V = I \times R$.

CORE IDEAS

The story. In 1800 the Italian scientist Alessandro Volta wrote a letter to the Royal Society in London describing a new invention. He had stacked disks of zinc and copper (or silver), with pieces of cardboard soaked in salt water between them, into a pile. Touch the top and the bottom, and a steady electric current flowed. It was the first battery, and it gave scientists, for the first time, a current that kept flowing instead of a single spark. The unit of voltage, the volt, is named for him. Within weeks, scientists all over Europe were building piles and testing what current could do.

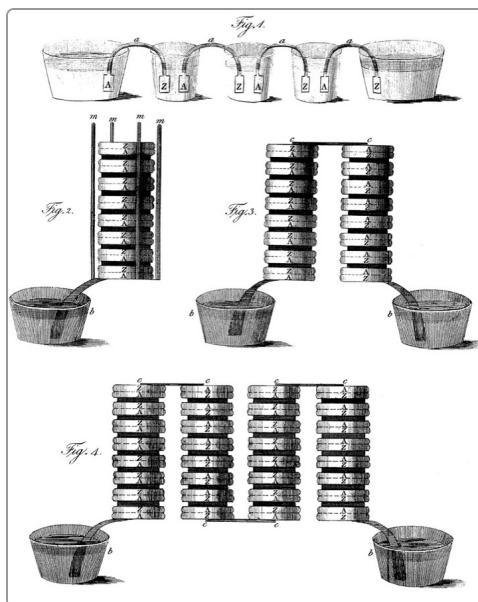
How they figured it out. Georg Simon Ohm was a German schoolteacher who wanted to know exactly how much current would flow through a wire. Early batteries weakened as they ran, which spoiled his measurements, so he switched to a steadier source and built a careful instrument to measure the current by how far it turned a magnetized needle. He tested wires of different lengths and thicknesses, again and again. In 1827 he published his result: the current is larger when the push is larger, and smaller when the wire holds it back more. Some professors ignored his work at first, but his careful measurements won out. Today the unit of resistance, the ohm, is named for him.

The physics. Think of a circuit like water in a closed loop of pipe with a pump. **Voltage** is like the pump's push. **Current** is like how much water flows past a point each second. **Resistance** is like a narrow or clogged part of the pipe that holds the flow back. Ohm's law ties them together: $V = I \times R$. If a 3-volt battery pushes current through a 150-ohm resistor, the current is $3 \div 150 = 0.02$ amps. More volts, more current. More resistance, less current. A long, thin wire has more resistance than a

short, thick one, just as a long, thin straw is harder to drink through. Current only flows if the path is a complete loop; open the loop anywhere, and it stops.

The engineering. Engineers use Ohm's law every day to choose the right battery, the right wire and the right parts. Wires that carry large currents must be thick so they do not get hot, which is why a stove cord is thicker than a lamp cord. Batteries placed end to end, in series, add their voltages: two 1.5-volt AA cells make 3 volts. Fuses and circuit breakers protect a house by opening the circuit if the current ever gets dangerously high. A light dimmer, a volume knob and the speed control on a toy car all work by changing the current in a circuit.

PICTURE STUDY



Volta's Pile and "Crown of Cups", Alessandro Volta, 1800 · Engraving · From Volta's letter in the Philosophical Transactions of the Royal Society, London

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

Volta drew his two inventions for his 1800 letter: the pile of disks, and a row of cups of salt water joined by strips of two different metals. Both are batteries, made by repeating the same simple cell many times.

Look closely

- Find the stack of disks. Can you see that the pattern repeats?
- Find the cups and the bent metal strips connecting them.
- Look for the wires or connections at the ends. Where would current flow out?
- Count the cells in one pile if you can.

Talk about it

1. Why would stacking more cells give a stronger push (more voltage)?
2. How is your flashlight battery like one section of Volta's pile?
3. Why did a steady current matter so much to scientists like Ohm?

Safety first. Use only AA or D batteries, never the outlets in the wall. Pencil lead can get warm when current flows through it; disconnect the circuit between tests. Do not leave a battery connected with a bare wire straight across it, which heats the wire and drains the battery.

BUILD

The Pencil-Lead Dimmer

Pencil “lead” is really graphite, a material that conducts electricity but with some resistance. You will make a dimmer by sliding a clip along a piece of graphite and run a fair test of how the length of graphite in the circuit changes the brightness of a bulb.

You will need

- Two AA batteries in a holder (3 volts) and one D cell for comparison
- A small flashlight bulb (2.5–3 volt) in a holder, or a 3-volt LED with a 100-ohm resistor
- Three alligator clip leads
- A thick graphite art stick, or a mechanical-pencil lead (0.7 mm or larger) taped to a card, at least 8 centimeters long
- A ruler, a dark room or box, and engineer’s notebook
- Optional: a digital multimeter

Steps

1. Draw the circuit with symbols before you build it: battery, bulb, graphite and wires in one loop.
2. Build it: battery to bulb, bulb to one end of the graphite, and a third clip from the battery to a point on the graphite.
3. Make a brightness scale from 0 (off) to 5 (as bright as with a plain wire). Connect the bulb with a plain wire first to see “5.”
4. **Predict.** Will the bulb be brighter with a short or long piece of graphite in the circuit?
5. **Fair test.** Clip the moving lead at 1, 2, 4 and 8 centimeters from the fixed end. At each length, rate the brightness in a dark room. Do two trials.
6. Record a table: graphite length, brightness, and (if you have a multimeter) resistance in ohms.
7. **Voltage test.** Keep the graphite at 2 centimeters and compare one 1.5-volt cell with two cells in series (3 volts). Record the brightness. Explain it with $V = I \times$

R.

8. **Improve.** Make a smoother dimmer by drawing a thick, dark pencil stripe on paper and sliding the clip along it, or by using a longer graphite stick. Test whether you can make a full range from bright to dark.

Tips

- Press the clip firmly on the graphite; a loose contact adds resistance and flickers.
- If the bulb never lights, check that every connection is metal to metal and the loop is complete.
- Rate brightness quickly and in the same light each time.

Check your work

- ☐ I can explain voltage, current and resistance using the water-pipe picture.
- ☐ I can use $V = I \times R$ to find a current.
- ☐ My data show how graphite length changed the brightness.

ENGINEER'S NOTEBOOK

1. Draw the circuit symbols for a battery, a bulb, a resistor, a switch and a wire. Then draw your dimmer circuit using them.
2. Draw the water-pipe picture of a circuit and label which part is like voltage, current and resistance.
3. Solve: a 9-volt battery and a 450-ohm resistor. What is the current? ($9 \div 450 = 0.02$ amps.)

From history. Volta showed his pile to Napoleon in Paris in 1801, and he was given honors for it. But the most important result was the burst of discoveries that followed: within weeks, two English scientists used a pile to split water into hydrogen and oxygen, and a few years later Humphry Davy used a huge battery to discover new metals, including sodium and potassium.

COMMON MISTAKES

- Thinking a battery is “used up” in the bulb. Current flows all the way around the loop; the battery’s energy is used, not the charge.
- Leaving a gap in the circuit. Current flows only in a complete loop.
- Mixing up voltage and current. Voltage is the push; current is the flow.

Make it a game • Water-Pipe Picture. Draw a water-pipe picture on paper: pump, pipe and a narrow section. Label which part is voltage, current and resistance. Your parent calls an Ohm's law puzzle, such as 6 volts across 2 ohms, and you find the current. Race through five problems. Add the one-line story of Volta and Ohm.

4.2 OERSTED, FARADAY AND A HOMEMADE MOTOR

OBJECTIVES

- Describe Oersted's discovery that an electric current makes a magnetic field.
- Tell how Michael Faraday made the first electric motion and explain how a simple motor turns.
- Build an electromagnet and test how the number of coils changes its strength, then build a simple motor.

Warm-up. Lay a compass on the table and let it settle pointing north. Lay a wire on top of it, lined up with the needle. Predict what will happen when you touch the ends of the wire to a D cell for just a second. Try it and record what the needle does. Then reverse the battery and try again.

WATCH

The First Electric Motor | Earth Science

BBC Earth Science · 4:09

<https://www.youtube.com/watch?v=6Ns5tRyvoHY>

WHEN TO WATCH

After the story, before the physics.

BACKUP VIDEO

Build a Simple Electric Motor | Science Project

Science Buddies · 2:36

<https://www.youtube.com/watch?v=WI0pGk0MMhg>

Before you build the motor in Session 2.

KEY TERMS

magnetic field

The region around a magnet or a current where magnetic forces act.

electromagnet

A coil of wire, usually around an iron core, that becomes a magnet when current flows and stops being one when the current stops.

coil

Wire wound around and around in loops.

electric motor

A machine that uses magnetic forces on electric currents to turn electrical energy into motion.

commutator

The part of a motor that reverses the current at just the right moment each turn so the motor keeps spinning.

CORE IDEAS

The story. In April 1820, in Copenhagen, the Danish professor Hans Christian Oersted was giving a lecture with a battery and a wire when he noticed a compass needle nearby swing as the current flowed. He tested it carefully over the next months and announced that an electric current makes a magnetic force around it. In London, a young man named Michael Faraday read the news. Faraday was the son of a blacksmith and had little schooling; he had learned science by reading the books he bound as an apprentice bookbinder and by attending lectures by Humphry Davy, who later hired him as an assistant at the Royal Institution. In September 1821 Faraday made a wire spin around a magnet when current flowed through it: the first electric motor, a device that turned electricity into continuous motion.

How they figured it out. Faraday's gift was experiment. He did not know higher mathematics, so he reasoned with pictures: he imagined invisible "lines of force" curving around magnets and wires, and he designed simple tests to see where they went. He kept a detailed laboratory notebook with thousands of numbered entries. Others built on his work. In 1825 William Sturgeon wrapped wire around an iron bar to make the first electromagnet, and in America Joseph Henry wound many turns of insulated wire to make electromagnets that could lift hundreds, then thousands, of pounds. Faraday was a sincere Christian who served as an elder and preacher in his small church, and he saw his work as reading the book of nature God had written.

The physics. An electric current makes a **magnetic field** in circles around the wire. Wind the wire into a **coil**, and the fields of all the loops add together, making the coil act like a bar magnet with a north and south pole. Put an iron nail inside, and the iron becomes strongly magnetized too, multiplying the effect. More turns, more current or an iron core make an **electromagnet** stronger, and when the current

stops, it lets go. In a **motor**, a coil carrying current sits near a permanent magnet. The magnet pushes one side of the coil up and the other down, so the coil turns. To keep it turning the same way, the current must be switched off or reversed every half turn. In real motors a **commutator** does this; in your homemade motor, scraping the insulation off only half of one wire end does the same job.

The engineering. Electromagnets are everywhere: in doorbells, speakers, junkyard cranes that lift whole cars, and the locks on many doors. Electric motors run fans, refrigerators, washing machines, power tools, elevators, trains and cars. Engineers choose the number of turns, the thickness of the wire and the strength of the magnets to get the speed and turning force they need, and they must keep motors from overheating, because current through wire makes heat. A large share of the electricity used in the world turns electric motors.

PICTURE STUDY



Michael Faraday in His Laboratory, Harriet Jane Moore, 1852 · Watercolor · Royal Institution, London

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

Harriet Jane Moore, a friend of the Faradays, painted several watercolors of the rooms at the Royal Institution where Faraday lived and worked for most of his life. This one shows him at work in his laboratory in the basement.

Look closely

- Find Faraday at his workbench. What is he doing?
- Look for glass bottles, jars and tubes. What might they hold?
- Look for anything that might be a battery, coil or magnet.
- Notice the light. Where does it come from in a basement room?

Talk about it

1. Faraday had very little schooling. What habits helped him become a great scientist?
2. Why would a scientist keep a numbered notebook of every experiment?
3. What do you think Faraday would say if he saw all the motors in your house?

Safety first. Use a D cell, never an outlet in the wall or a lithium battery. Magnet wire connected straight across a battery gets hot within seconds: connect it only for short tests and disconnect between tests. An adult should strip or sand the wire ends. Keep strong magnets away from phones, computers and small children, who could swallow them.

BUILD

Electromagnet Strength Test and a Spinning Motor

First you will build an electromagnet from a nail and wire and run a fair test of how the number of coils changes how many paper clips it can lift. Then you will build a simple motor from a coil of wire, a magnet and a battery, and improve it until it spins steadily.

You will need

- A large iron nail (about 8 centimeters)
- About 2 meters of magnet wire (22–26 gauge) and fine sandpaper
- A D cell in a holder and two alligator clip leads
- A box of small steel paper clips
- For the motor: two large paper clips, a strong ceramic or neodymium disk magnet, rubber bands or tape, and a marker

Steps

1. **Electromagnet.** Leaving 15 centimeters of wire free at the start, wind 10 neat turns of magnet wire around the nail. Have an adult sand the insulation off both wire ends.
2. Connect the ends to the D cell for a few seconds and touch the nail's tip to the pile of paper clips. Count how many it lifts. Disconnect. Do three trials and average.
3. **Fair test.** Predict, then add turns to make 20, then 40 turns, testing three times at each. Keep the same nail, battery and paper clips.
4. Record a table and make a bar graph: number of turns and paper clips lifted.
5. **Motor.** Wind magnet wire 10 times around a marker to make a coil about 2 centimeters across. Wrap each loose end twice around the coil to hold it, and leave 3 centimeters sticking straight out on opposite sides.
6. Have an adult sand all the insulation off one end. On the other end, sand only the top half, leaving the bottom half coated. This is your commutator.
7. Bend two paper clips into cradles and fasten them with rubber bands to the two ends of the D cell. Put the magnet on the side of the battery under where

the coil will sit. Lay the coil's straight ends in the cradles and give it a gentle spin.

8. **Improve.** If it does not keep spinning, check the balance of the coil, the sanding, the height of the coil above the magnet and the stiffness of the cradles. Change one thing at a time and record what helped.

Tips

- Wind the coil turns neatly in one direction; a messy coil still works, but a balanced one spins better.
- Sanding only half of one end is the secret; if the coil only rocks back and forth, check that sanding.
- Feel the battery after a minute. If it is getting warm, disconnect and let it rest.

Check your work

- ☐ I can explain what makes an electromagnet stronger, using my data.
- ☐ I can explain why a motor needs a commutator.
- ☐ I can name four things in my home that use electric motors.

ENGINEER'S NOTEBOOK

1. Draw your electromagnet and label the coil, the iron core, the battery and the north and south poles.
2. Draw your motor and label the coil, magnet, cradles, battery and the half-sanded end. Add arrows showing the push on each side of the coil.
3. Graph your electromagnet results and write one sentence describing the pattern.

From history. In 1831, ten years after his first motor, Faraday discovered the opposite effect: moving a magnet near a coil of wire makes a current flow. That discovery, called electromagnetic induction, is how almost all the electricity in the world is made today, as you will learn in Unit 5.

COMMON MISTAKES

- Forgetting to remove the insulation from the wire ends, so no current can flow.
- Leaving the electromagnet connected for a long time, which heats the wire and drains the battery.
- Changing the battery between tests, so two things change at once.

Make it a game • Needle Tells All. Retell Oersted's discovery in your own words, as if a compass needle is the main character. Then ask your parent to say what a coil of wire around iron does. Race to name four parts of a simple motor: magnetic field, coil, commutator and electromagnet. One point per part, two for Faraday's first electric motion.

4.3 SAMUEL MORSE AND THE TELEGRAPH

OBJECTIVES

- Tell how Samuel Morse, Leonard Gale and Alfred Vail built the telegraph, and how the first line was opened in 1844.
- Explain how a telegraph key, wire and electromagnet sounder send a signal, and why long lines need relays.
- Build a working telegraph and use letter-frequency data to understand why Morse code gives some letters shorter signals.

Warm-up. Before telephones, how long would it take to get a message from your town to a city 40 miles away by horse? By foot? Write your guesses. Then list three ways people sent messages before electricity.

WATCH

Telegraphs and Telephones - How They Work

National Museum of American History · 2:59

<https://www.youtube.com/watch?v=7e522NK7gcM>

WHEN TO WATCH

After the physics paragraph.

BACKUP VIDEO

Samuel Morse and The Telegraph | Simple History

Bedtime History · 4:24

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

With the story of Samuel Morse.

KEY TERMS

telegraph

A system for sending messages over wires by electric pulses.

key

A spring switch pressed by the operator to close the circuit and send a pulse.

sounder

An electromagnet that pulls down a metal bar with a click each time current flows.

relay

A switch worked by an electromagnet, which lets a weak signal turn on a fresh, strong battery for the next part of the line.

Morse code

A code that writes letters with short and long signals, called dots and dashes.

CORE IDEAS

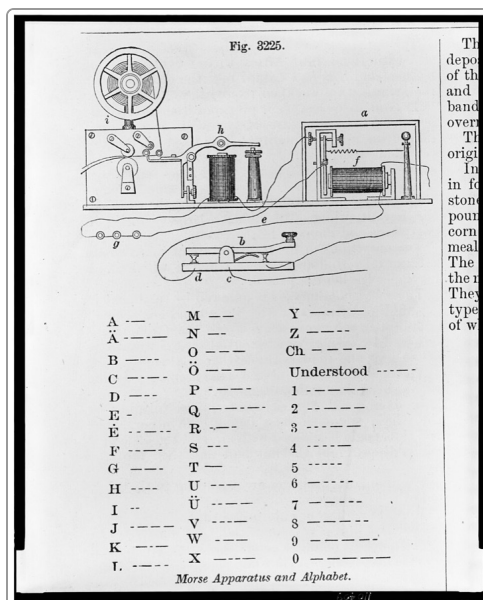
The story. Samuel F. B. Morse was a well-known American painter. In 1825, while he was in Washington painting a portrait, a letter came telling him his wife was ill; by the time he reached home, she had died and been buried. News traveled no faster than a horse or a ship. In 1832, sailing home from Europe, Morse listened to a fellow passenger describe electromagnets, and he began to imagine sending messages by electricity. Working with Leonard Gale, a chemistry professor, and Alfred Vail, a skilled machinist, he built and improved his telegraph for years. In 1843 Congress paid \$30,000 to build a test line about 40 miles long from Washington to Baltimore. On May 24, 1844, sitting in the Capitol, Morse tapped out the first message, chosen from the Bible by a young friend, Annie Ellsworth: “What hath God wrought.” Vail received it in Baltimore and sent it back.

How they figured it out. Morse’s first telegraph worked across a room but not across miles, because the current grew too weak in a long wire. Gale, who knew the research of Joseph Henry, showed Morse how to use a battery of many cells and an electromagnet with many turns of wire. They also used **relays**: at a station along the line, the weak incoming current worked a small electromagnet that closed a switch on a fresh battery, sending a strong signal onward. The workers first tried burying the wire in lead pipe, but the insulation failed, so they strung it on wooden poles instead, and the poles worked. Vail improved the code, too. To give the most common letters the shortest signals, he went to a printer’s shop and counted how many pieces of type were kept for each letter. E, the most common letter in English, became a single dot.

The physics. The telegraph is a circuit with a switch at one end and an electromagnet at the other. When the operator presses the **key**, the circuit closes, current flows down the wire, and the electromagnet in the **sounder** at the far end pulls down an iron bar with a click. Release the key, the current stops, and a spring lifts the bar with a second click. A short gap between clicks is a dot; a longer one is a dash. Because every wire has resistance, the current weakens over a long line, which is why higher voltage, thicker wire and relays were needed. The early lines even used the earth itself as the return half of the circuit, so only one wire had to be strung.

The engineering. Within twenty years, telegraph lines crossed America, reaching California in 1861, and in 1866 a cable laid on the floor of the Atlantic Ocean connected America with Europe. Railroads used the telegraph to run trains safely, and newspapers used it to report events the same day. The telegraph's idea of sending information as on-and-off pulses lives on: computers, phones and the internet still send information as patterns of on and off, now by light in glass fibers and by radio. Morse, a devout believer, saw his first message as giving glory to God, not to himself.

PICTURE STUDY



Morse Apparatus and Alphabet, Unknown engraver, Late 1800s · Engraving · Library of Congress, Prints and Photographs Division

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

This printed figure from an old reference book shows the parts of a Morse telegraph station and the code that operators learned. The register at the top marked dots and dashes on a moving paper tape, as Morse's first instruments did.

Look closely

- Find the key, the switch the operator pressed.
- Find the electromagnet coils. What do they pull on?
- Find the reel of paper tape. Which way does it move?
- Look at the alphabet. Which letters have the shortest codes?

Talk about it

1. Trace the circuit from the key to the electromagnet. What happens when the key is pressed?
2. Why did Vail give E and T the shortest codes?
3. How is this machine like a modern device that receives messages?

Safety first. Use only batteries. Disconnect the battery when you finish sending, because an electromagnet left switched on gets warm and drains the battery.

BUILD

A Working Telegraph and Vail's Letter Count

You will build a telegraph with a key and an electromagnet sounder (and a bulb or LED so you can see each signal), send and receive messages in Morse code, and measure your sending speed. You will also count letters in a page of English, as Alfred Vail did, to see why Morse code gives E and T the shortest signals.

You will need

- A D cell or two AA batteries in a holder
- Your nail electromagnet from Lesson 4.2 (40 turns)
- For the key: a piece of cardboard, two brass paper fasteners and a steel paper clip, or a craft stick and aluminum foil
- For the sounder: a small steel strip (a steel paper clip opened out, or a strip of steel from a bottle-cap opener) taped to a craft stick so it can spring up and down above the nail
- Alligator clip leads, a flashlight bulb or LED with resistor, tape
- A Morse code chart, a book page, a stopwatch and engineer's notebook

Steps

1. **Key.** Push two paper fasteners through the cardboard 3 centimeters apart. Hook a paper clip around one so it can be pressed down to touch the other. Pressing the clip closes the circuit.
2. **Sounder.** Stand the nail electromagnet upright in clay. Fix the craft stick so the steel strip sits just above the nail's head, a few millimeters away, and springs back up when released.
3. **Wire one loop:** battery, key, electromagnet, bulb, back to battery. Press the key. The strip should click down and the bulb light; release, and the strip clicks up.
4. **Adjust.** Change the gap between the strip and the nail until you get a crisp click. Record the best gap.

5. **Long line.** Add two or three meters of extra wire into the loop, as if the stations were far apart. Does the click get weaker? Record what you observe and explain it with the word resistance.
6. **Vail's letter count.** Choose a page from a book. Have each family member count one letter (E, T, A, O, N, Z, Q, X) in the first 500 letters. Make a bar graph. Compare with the Morse chart: do the most common letters have the shortest codes?
7. Send the message "WHAT HATH GOD WROUGHT" to a partner who writes it down. Time it. Then try a sentence of your own. Record your speed in letters per minute and your errors.
8. **Improve.** Practice for ten minutes and send again. Did your speed go up? Did your errors go down?

Tips

- If the strip sticks to the nail, put a small piece of tape on the nail's head as a spacer.
- Dash = three dots long; the gap between letters = three dots; between words = seven dots.
- Real operators learned to hear letters as rhythms rather than counting dots and dashes.

Check your work

- ☐ I can explain how pressing the key makes the sounder click at the other end.
- ☐ I can explain why long telegraph lines needed relays.
- ☐ My letter-count graph shows why E is a single dot.

ENGINEER'S NOTEBOOK

1. Draw your telegraph circuit with standard symbols: battery, switch (key), electromagnet and bulb.
2. Draw a telegraph line with a relay station in the middle. Label the weak incoming current and the fresh battery.
3. Write your name and a short message in Morse code.

From history. Ezra Cornell, who helped string the first telegraph line on poles, became wealthy building telegraph lines and later founded Cornell University. The original strip of paper tape with the first message is kept today at the Library of Congress.

COMMON MISTAKES

- Holding the key down too long between letters, which makes dashes out of dots.
- Setting the sounder strip too far from the nail to be pulled, or so close that it sticks.
- Thinking Morse code was chosen at random. Vail gave the most common letters the shortest codes.

Make it a game • Tap It Out. Tap Morse code on the table. Use a code chart if you need it, then send your parent a short word and have them tap back. Explain how a key, wire and sounder work together and why long lines need relays. Add the fact about the first line opening in 1844. Fewest mistakes wins the round.

Scripture. “What hath God wrought!” (Numbers 23:23, KJV)

Annie Ellsworth chose these words from the book of Numbers for the first telegraph message. Morse wanted the world to remember that the power behind his invention belonged to God.

4.4 SWITCHES, LEDs AND RESISTORS: FROM EDISON'S LAMP TO THE LED

OBJECTIVES

- Tell how Edison's team tested materials to make a lasting light bulb, and how the LED came after it.
- Explain why an LED needs a resistor and only works one way around.
- Build LED circuits with resistors and switches, test how resistance changes brightness, and build AND and OR switch circuits.

Warm-up. Walk through your house and count every light, and notice which ones are LEDs. Feel (do not touch the glass) the air near an old-style bulb and an LED bulb that have been on for a while, if you have both. Which one wastes more energy as heat?

WATCH

LED Circuit Design with No Math

Science Buddies • 5:28

<https://www.youtube.com/watch?v=2pHVIqcyf18>

WHEN TO WATCH

Before the build. Watch for which way the LED must face and where the resistor goes.

BACKUP VIDEO

LED Basics - Electronics with Becky Stern | Digi-Key Electronics

DigiKey • 4:20

<https://www.youtube.com/watch?v=i7LFZxQcCQo>

For more about how LEDs are marked and wired.

KEY TERMS

filament

The thin wire or thread in an old light bulb that glows when current heats it.

LED

Light-emitting diode: a tiny electronic part that gives off light when current flows through it in one direction.

diode

An electronic part that lets current flow one way but not the other.

resistor

A part made to have a set resistance, used to limit the current in a circuit.

switch

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

CORE IDEAS

The story. Many inventors made glowing electric lamps in the 1800s, but none lasted long or cost little enough for homes. At his laboratory in Menlo Park, New Jersey, Thomas Edison and his team set out to make one that would. In October 1879 they found that a filament of carbonized cotton thread, sealed in a glass bulb with almost all the air pumped out, glowed for more than half a day. They kept testing, and soon a carbonized bamboo filament lasted more than a thousand hours. Edison's team then built the whole system around the bulb: the generator, the wires, the meters, the fuses and the switches. A different kind of light came much later. In 1962 Nick Holonyak Jr., an engineer at General Electric, made the first practical LED that glowed with visible red light. Blue LEDs, which made bright white LED lights possible, came in the 1990s.

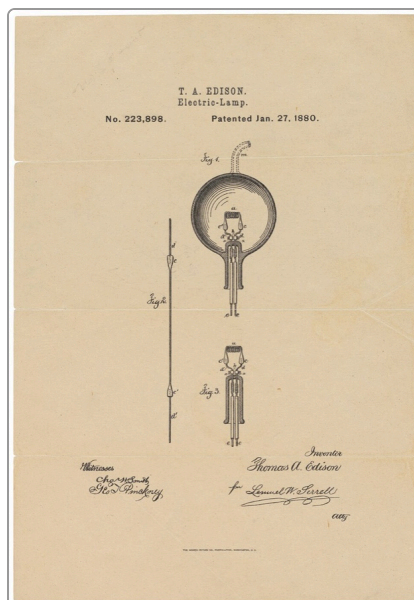
How they figured it out. Edison's team approached the filament as a long series of tests. They tried thousands of materials, including many plant fibers, measuring how long each one lasted and how much current it needed. Edison wanted a filament with high resistance, so that a small current would light it, which meant thinner wires to houses and a cheaper system. The trick was to remove almost all the air from the bulb, because a hot filament burns up quickly in air. Edison is often remembered for saying that every failed test taught him something. Whatever his exact words, his notebooks show a team that measured, recorded and kept going.

The physics. An old bulb makes light by getting a filament white-hot, so most of its energy becomes heat, not light. An LED makes light in a different way, inside a tiny crystal, and turns much more of its energy into light, so it stays cool and lasts for years. An LED is a **diode**, so current can flow through it only one way: the longer leg must connect toward the positive side of the battery. An LED also has almost no resistance once it lights, so without help it would let too much current through and

burn out. A **resistor** in the same loop limits the current. With Ohm's law, an engineer can choose the right resistor: if 1 volt is left over for the resistor and the LED should get 0.01 amps, then $R = 1 \div 0.01 = 100$ ohms.

The engineering. A **switch** opens or closes a circuit. Engineers combine switches to make decisions. Two switches in a row (in series) light the lamp only if switch A *and* switch B are both on, like a machine that runs only when its guard is closed and the start button is pressed. Two switches side by side (in parallel) light the lamp if A *or* B is on, like a doorbell with buttons at the front and back doors. These “AND” and “OR” patterns are the building blocks of every computer chip, which contains billions of tiny electronic switches. Today LED lights have replaced most old bulbs in homes and streets because they use a fraction of the electricity and last far longer. “Neither do men light a candle, and put it under a bushel,” Jesus said; a light is made to shine for others.

PICTURE STUDY



Edison's Drawing for an Electric Lamp, Thomas A. Edison, 1880 · Patent drawing · National Archives, Washington, D.C.

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

Edison filed this drawing with his patent for an electric lamp, granted in January 1880. It shows the carbon filament, coiled to fit more length into the bulb, and the wires that carry current into the sealed glass.

Look closely

- Find the filament. Why do you think it is coiled or looped?
- Find the two wires that carry current in and out.
- Find where the glass is sealed around the wires.
- Look for the letters labeling each part.

Talk about it

1. Why did the air have to be pumped out of the bulb?
2. Trace the path of the current through the lamp. Is it a complete loop?
3. How is an LED different from this lamp in the way it makes light?

Safety first. Use AA batteries only. Never connect an LED straight across a 9-volt battery without a resistor; it can burn out or pop. Keep coin-cell batteries away from small children, who could swallow them.

BUILD

LED Circuits: Resistors, Switches and Logic

You will build an LED circuit, test how different resistors change its brightness, build your own switch, and then wire two switches as AND and OR circuits, the same patterns used in every computer.

You will need

- Two AA batteries in a holder (3 volts)
- Several 5-millimeter LEDs (red works best at 3 volts)
- Resistors: 100, 220, 470 and 1,000 ohms
- Alligator clip leads (at least six)
- For switches: cardboard, brass paper fasteners, steel paper clips, or aluminum foil and tape
- Engineer's notebook

Steps

1. Find the long leg (positive) and short leg (negative) of an LED. Draw it.
2. Build one loop: battery positive → 100-ohm resistor → LED long leg → LED short leg → battery negative. It should light. Now turn the LED around. What happens? Why?
3. **Fair test.** Predict which resistor will give the brightest light. Test the 100, 220, 470 and 1,000-ohm resistors one at a time in the same circuit. Rate the brightness from 1 to 5 in the same light each time.
4. Use Ohm's law to estimate the current for each resistor, if about 1 volt is left for the resistor: $1 \div 100 = 0.01$ A, and so on. Record a table: resistor, estimated current, brightness.
5. **Build a switch.** Make two paper-fastener switches like the telegraph key. Add one to your circuit and test it.
6. **AND circuit.** Put both switches in series in the loop. Test all four combinations (off-off, on-off, off-on, on-on) and record when the LED lights in a truth table.

7. **OR circuit.** Rewire the two switches side by side (in parallel). Test all four combinations again and record a second truth table.
8. **Improve.** Design a useful circuit: for example, a night-light box that lights only when the lid is open AND a switch is on, or a two-door bell that lights an LED from either door. Build and test it.

Tips

- If an LED will not light, turn it around first; most LED problems are backward LEDs.
- Resistors work either way around.
- Draw each circuit with symbols before building it; it makes mistakes easier to find.

Check your work

- ☐ I can explain why an LED needs a resistor and which way it must face.
- ☐ My data show how larger resistors made the LED dimmer.
- ☐ I can build and explain AND and OR circuits with truth tables.

ENGINEER'S NOTEBOOK

1. Draw the LED and resistor circuit with symbols. Mark the long leg of the LED with a plus sign.
2. Make truth tables for your AND and OR circuits.
3. Draw a real-life use for an AND circuit and an OR circuit.

From history. In 1882 Edison's company opened the Pearl Street Station in New York City, one of the first central power plants, lighting buildings in lower Manhattan. Edison's team had to invent the meters, fuses, switches and underground wiring as they went, a whole new industry built around one small glass bulb.

COMMON MISTAKES

- Putting the LED in backward. Current flows through an LED only one way.
- Leaving out the resistor, which can burn out the LED.
- Confusing series and parallel. In series, current must pass through both switches; in parallel, it can choose either path.

Make it a game • Diode Trial. Play judge in a mock trial. Your parent argues that an LED needs no resistor and works any way around. You rule against and explain why with the words diode, resistor and filament. Then tell how Edison's team tested materials for a lasting bulb. Each fact you add earns a pretend gavel tap.

Scripture. “Ye are the light of the world. A city that is set on an hill cannot be hid. 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 5:14-15, KJV)

A lamp is made to give light to everyone in the house. Engineers who bring light into dark places serve their neighbors, and Christians are called to shine in the same way.

ELECTRICITY AND ELECTRONICS

Two hundred and fifty years ago, electricity was a curiosity: sparks from a rubbed glass globe, a shock from a jar. Then, in the space of one long lifetime, scientists and engineers learned to make a steady current, measure it, turn it into magnetism and motion, and send messages with it across a continent. In this unit you will follow that story from Volta's pile of metal disks to Ohm's law, from Oersted's twitching compass needle to Faraday's spinning wire, and from Samuel Morse's first message, "What hath God wrought," to the LED lights in your home.

You will build circuits you can measure: a pencil-lead dimmer, an electromagnet that lifts paper clips, a motor that spins on a battery, a working telegraph, and LED circuits with switches and resistors. All the electricity in this unit comes from ordinary batteries. Never experiment with the outlets in the wall or anything that plugs into them.

PREREQUISITES

- Knows how to make a simple circuit with a battery, wire and bulb (earlier grades or a quick review)
- Can read a data table and make a bar graph
- Knows the safety rule: batteries only, never the outlets in the wall

MASTERY CHECKLIST

- ☐ I can explain voltage, current and resistance and use $V = I \times R$ in a simple example.
- ☐ I can build an electromagnet, explain what makes it stronger, and explain how a simple motor turns.
- ☐ I can tell how Morse and Vail's telegraph worked and send a message in Morse code.
- ☐ I can build an LED circuit with a resistor and a switch and explain what each part does.
- ☐ I can draw circuits with standard symbols.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits (Elenco):** Ages 8 and up. Parts snap onto a plastic grid, so you can build dozens of circuits with switches, LEDs, motors, buzzers and electromagnets without wiring. A good companion to Lessons 4.1–4.4. Look for the Snap Circuits Jr. set to start.
- **KiwiCo Tinker Crate:** Ages 9 and up. Some monthly crates include circuits, motors and LEDs with clear explanations of how they work. Fits Lessons 4.2 and 4.4.

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

4.1 Volta, Ohm and the Circuit: Voltage, Current and Resistance

2 sessions of 45 minutes

4.2 Oersted, Faraday and a Homemade Motor

2 sessions of 45 minutes

4.3 Samuel Morse and the Telegraph

2 sessions of 45 minutes

4.4 Switches, LEDs and Resistors: From Edison's Lamp to the LED

2 sessions of 45 minutes

UNIT 4 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

Using the water-pipe picture, explain voltage, current and resistance.

2. **5 pts**

A 6-volt battery pushes current through a 300-ohm resistor. What is the current?

3. **5 pts**

Predict: in the pencil-lead dimmer, what happens to the bulb when you slide the clip to make the graphite in the circuit longer? Why?

4. (5 pts)

What did Oersted discover in 1820?

5. (5 pts)

Name three ways to make an electromagnet stronger.

6. (5 pts)

Why does a simple motor need a commutator (or a half-sanded wire)?

7. (5 pts)

What was the first message sent on Morse's Washington-Baltimore line, and in what year?

8. (5 pts)

Why did long telegraph lines need relays? How did Vail decide which letters got the shortest codes?

9. (5 pts)

An LED circuit has no resistor and the LED burns out. Explain why, and how to fix it.

10. (5 pts)

Predict: two switches are wired in series with an LED. Switch A is on and switch B is off. Does the LED light? What if they are in parallel?

ANSWER KEY

1. Voltage is like the pump's push; current is like the amount of water flowing past each second; resistance is like a narrow part of the pipe that holds the flow back.
2. $I = V \div R = 6 \div 300 = 0.02$ amps.
3. The bulb gets dimmer, because longer graphite has more resistance, so less current flows.
4. That an electric current makes a magnetic force around the wire; a compass needle moved when current flowed in a nearby wire.
5. More turns of wire, more current (more voltage), an iron core (or a bigger iron core).
6. To switch off or reverse the current every half turn, so the magnetic push keeps turning the coil the same way instead of rocking it back and forth.
7. "What hath God wrought," on May 24, 1844.
8. The current weakens in a long wire because of resistance; a relay uses the weak current to switch on a fresh battery for the next section. Vail counted the type in a printer's shop to find which letters were most common.
9. An LED has very little resistance once it lights, so too much current flows and it overheats. Add a resistor in the loop to limit the current.
10. In series (AND), no, because both must be on. In parallel (OR), yes, because one closed switch completes the circuit.

PORTFOLIO PIECE: A TWO-STATION TELEGRAPH

Build a telegraph that can send messages both ways between two rooms, using two keys, two sounders or LEDs, batteries and long wires. Draw the complete circuit with standard symbols, test how long the wire can be before the signal gets too weak, and send a ten-word message in each direction with no more than two errors. In your notebook, explain the circuit, your test results and one improvement you made.

LOOK FOR	WHAT IT MEANS
It works	Messages can be sent and received in both directions with clear clicks or flashes.
Circuit diagram	A neat diagram with correct symbols for batteries, switches, electromagnets or LEDs, and wires.
Testing	The effect of wire length on the signal is tested and recorded; the message test is timed and errors counted.
Science explanation	Explains the key, the electromagnet, resistance in long wires and why relays were needed, using correct words.
Improvement	At least one change made the telegraph clearer, faster or more reliable, and the notebook explains it.

UNIT 5

PUBLIC UTILITIES

Turn a tap, and clean water comes out. Flush, and the dirty water disappears. Flip a switch, and the light comes on. These things seem ordinary only because thousands of engineers, operators and lineworkers keep them working every hour of every day. In this unit you will follow water from the Roman aqueducts to the modern treatment plant, and wastewater from London’s “Great Stink” to Joseph Bazalgette’s great sewers.

Then you will follow electricity from Faraday’s moving magnet to the generators at Niagara Falls and the Hoover Dam, and along the power lines to your house. You will test a homemade water filter, find the slope a sewer needs, light an LED with a generator you spin yourself, and measure how water pushes harder the deeper it gets. Clean water and safe power are some of the greatest gifts engineers give their neighbors.

PREREQUISITES

- Knows how electromagnets and motors work (Unit 4)
- Knows how arches carry loads (Unit 3)
- Can measure volume in milliliters and time with a stopwatch

MASTERY CHECKLIST

- ☐ I can explain how water is carried by gravity and cleaned in a treatment plant: settling, filtering and disinfecting.
- ☐ I can tell how Bazalgette’s sewers saved London and explain why a sewer needs a steady slope.
- ☐ I can explain how a generator makes electricity by moving a magnet and a coil, and why Niagara Falls used alternating current.
- ☐ I can trace electricity from a power plant through the grid to my home and name the safety rules around power lines.
- ☐ I can explain why a dam is thicker at the bottom.

LESSONS IN THIS UNIT

5.1 Clean Water: From Roman Aqueducts to the Treatment Plant

2 sessions of 45 minutes

5.2 Sewers and Wastewater: Bazalgette and the Great Stink

2 sessions of 45 minutes

5.3 Making Electricity: Faraday, Edison, Tesla and Niagara Falls

2 sessions of 45 minutes

5.4 Dams, the Grid and the Lineworker

2 sessions of 45 minutes

UNIT 5 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

How did Roman aqueducts move water many miles without pumps?

2. **5 pts**

Put the steps of drinking-water treatment in order: filtration, coagulation, disinfection, settling.

3. **5 pts**

Your homemade filter made the water look clear. Is it safe to drink? Explain.

4. **5 pts**

What was the Great Stink, and how did Bazalgette's plan fix the problem?

5. **5 pts**

Predict: a model sewer is almost flat. What happens to the solids? What if it is very steep?

6. **5 pts**

What did Faraday discover in 1831, and how does a generator use it?

7. (5 pts)

Why did the engineers at Niagara Falls choose alternating current?

8. (5 pts)

Predict: a bottle has holes at 5 cm and 20 cm from the bottom. Which jet squirts farther, and why?

9. (5 pts)

Trace electricity from a hydroelectric dam to a lamp in your house, naming at least five parts.

10. (5 pts)

Give three safety rules about power lines and digging.

ANSWER KEY

1. By gravity: the channel sloped steadily and gently downhill all the way from the source to the city, using tunnels and arched bridges to keep the slope.
2. Coagulation, settling, filtration, disinfection.
3. No. The filter removes dirt but not germs or dissolved chemicals, which are invisible. Treatment plants disinfect and test the water.
4. In the hot summer of 1858 the sewage-filled Thames smelled terribly. Bazalgette built intercepting sewers along both banks to catch the sewage before it reached the river and carry it far downstream, with pumping stations where needed.
5. Almost flat: the water moves slowly and solids settle and clog it. Very steep: the solids are carried, but fast water can wear out a real pipe; engineers choose a steady middle slope.
6. That moving a magnet near a coil (a changing magnetic field) makes an electric current. A generator spins coils and magnets past each other to make current from motion.
7. AC can be raised to a high voltage with transformers for long-distance travel (less energy lost in the wires) and lowered again for use; DC at low voltage could only reach about a mile.
8. The 5 cm hole, because it has more water above it, so the water pressure there is greater.
9. Falling water → turbine → generator → step-up transformer → transmission lines → substation (step-down transformer) → distribution lines → pole or pad transformer → house wiring → lamp.
10. Any three: stay far from downed lines and call 911; never climb poles or towers or enter substations; never fly kites, drones or balloons near lines; keep ladders away from lines; call 811 before digging.

PORTFOLIO PIECE: A TOWN WATER AND POWER PLAN

Design the utilities for an imaginary town of 1,000 homes on a large sheet of paper, drawn to a rough scale. Show the water source, treatment plant, water tower and mains; the sewers sloping to a treatment plant, with at least one pumping station; and the power plant, transmission lines, substation and distribution lines. Then build and test one part as a working model: your best water filter, your sewer slope model, or your clay dam. Present the plan and model with a page explaining how each system works and one way engineers keep it safe.

LOOK FOR	WHAT IT MEANS
Complete plan	Water, wastewater and power systems are all shown with their main parts labeled and connected in a sensible order.
Uses the physics	The water tower is on high ground, sewers slope downhill to the plant, pumps are placed where land is low, and transformers are placed correctly.
Working model	One model is built and tested, with a data table from at least two versions.
Safety and service	Explains at least two safety rules and how the system serves the town's families.
Presentation	Neat, readable plan and a clear written explanation.

5.1 CLEAN WATER: FROM ROMAN AQUEDUCTS TO THE TREATMENT PLANT

OBJECTIVES

- Explain how Roman aqueducts carried water many miles using only gravity and a gentle slope.
- Name the main steps of modern water treatment: coagulation, settling, filtration and disinfection.
- Build a water filter, run a fair test of one variable, and measure how clear the water becomes.

Warm-up. Find out where your family's water comes from: a city water system, a well, or a spring. Look at your water bill or the city website with a parent. Then guess: how many gallons of water does your family use in one day? Write your guess and check it later on the bill.

WATCH

How Do Water Treatment Plants Work?

Concerning Reality · 10:49

https://www.youtube.com/watch?v=0_ZcCqqpS2o

WHEN TO WATCH

After the physics paragraph. List each treatment step in order.

BACKUP VIDEO

Roman Aqueducts | Ancient Engineering Made Easy

Bedtime History · 4:44

<https://www.youtube.com/watch?v=tj-4WeOXKco>

With the story of the Roman aqueducts.

KEY TERMS

aqueduct

A channel, tunnel or bridge built to carry water a long distance, usually by gravity.

gradient

The steepness of a slope: how much it drops for each unit of distance.

coagulation

Adding a chemical that makes tiny particles in water clump together into bigger flakes.

filtration

Passing water through sand, gravel or other layers to trap particles.

disinfection

Destroying germs in water, usually with a small, carefully measured amount of chlorine or with ultraviolet light.

CORE IDEAS

The story. Ancient Rome was a city of about a million people, and its engineers brought water to it from springs and rivers in the hills, through eleven aqueducts built over about 500 years. Most of each aqueduct ran underground in stone channels; where it crossed a valley, it was carried high on arches, like the Pont du Gard in southern France, which carried water about 30 miles to the city of Nîmes. In about AD 97 a Roman official named Frontinus was put in charge of Rome's water. He measured the flow of every aqueduct, found and stopped illegal pipes that stole water, and wrote a book about it so that later officials could keep the system in order. Many centuries later, as cities grew crowded again, doctors learned that dirty water spreads sickness. In 1829 James Simpson built a large slow sand filter for a London water company, and in 1908 Jersey City, New Jersey, became one of the first American cities to disinfect its whole water supply with chlorine. Sickness carried by water fell dramatically.

How they figured it out. Roman surveyors used simple tools, such as a long wooden table with a water channel on top to find a level line, to lay out a channel that fell steadily but only a tiny bit. The Nîmes aqueduct drops only about 40 feet over its whole length, on average just a few inches every thousand feet. Too steep, and the rushing water would wear out the channel; too flat, and it would stop flowing. Later engineers learned to clean water by testing: they filled tanks with different layers of sand and gravel, measured how clear the water came out, and checked how much sickness fell in the neighborhoods that drank it.

The physics. Water flows downhill because of gravity, so an aqueduct needs no pump as long as each part is a little lower than the part before. Water also “seeks its

own level”: in connected pipes, it rises to the same height as its source. That is why a city builds a water tower on high ground or pumps water up into it, and the weight of the water in the tower pushes it through the pipes to every house. Cleaning water uses simple physics and chemistry. In **coagulation**, a chemical makes tiny particles stick together into flakes. Heavy flakes sink to the bottom of big still tanks, which is settling. **Filtration** through sand and gravel traps the small particles left.

Disinfection destroys the germs that are too small to filter.

The engineering. A modern treatment plant runs every step around the clock and tests the water many times a day. Licensed water operators adjust the chemicals as the river or lake changes after a storm. Engineers size the pipes, pumps and storage so that there is enough pressure for every faucet and enough water for firefighters. They also keep the system closed and under pressure, so dirty water from outside cannot leak in. A Roman aqueduct served a city for centuries; a well-built water system serves a town for generations, as long as it is cared for. Solomon wrote that the rivers run to the sea and return again to the place they came from. Water engineers work with that great cycle God made.

PICTURE STUDY



The Pont du Gard, Hubert Robert, 1787 · Oil on canvas · Musée du Louvre, Paris

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

Hubert Robert was a French painter who loved ancient ruins. He painted the Pont du Gard, a Roman aqueduct bridge built about 2,000 years ago that still stands in southern France. The water channel ran along the very top.

Look closely

- Count the rows of arches. Are the arches the same size in each row?
- Find the very top of the bridge. Where did the water flow?
- Look at the people. How do they help you judge the bridge's size?
- Look at the stones of the arches. Are they in tension or compression?

Talk about it

1. Why did the Romans build the channel so high across this valley instead of letting the water go down and back up?
2. Why do you think this bridge has lasted for 2,000 years?
3. What would happen to the water if the channel sloped too steeply?

Safety first. Never drink water from your homemade filter, even if it looks clear. A filter like this removes dirt but cannot remove germs or chemicals. An adult should cut the bottles. Wash hands after handling dirty water.

BUILD

Water Filter Test

You will make muddy “river water,” build a filter from layers of gravel, sand and cotton in a cut plastic bottle, and measure how clear the water comes out. Then you will change one thing, such as the order or thickness of the layers, and test again to design the best filter.

You will need

- Two clear 2-liter plastic bottles, cut by an adult about 10 centimeters from the bottom; the top part, turned upside down, is the filter, and the bottom part catches the water
- Coffee filters or cotton balls, clean fine sand, coarse sand, small gravel (rinsed)
- A jar of “river water”: tap water mixed with a spoonful of garden soil, a pinch of grass clippings and a few drops of food coloring
- Measuring cup, stopwatch, a clear tall glass, a ruler and a white card with a black X drawn on it
- Optional: a pinch of alum from the spice aisle, with an adult

Steps

1. Make a **clarity test**: set the clear glass on the card with the X. Slowly pour in water until you can no longer see the X from above. Measure the depth of the water in centimeters. Clearer water lets you see the X through a deeper column. Test your muddy water and write the depth.
2. **Filter A**. Plug the neck of the upside-down bottle with a coffee filter or cotton. Add 3 centimeters of fine sand, 3 centimeters of coarse sand and 3 centimeters of gravel on top. Set it in the bottom half of the bottle.
3. Stir the river water and pour 500 milliliters through the filter. Time how long it takes for the water to stop dripping. Do the clarity test on the filtered water.
4. **Fair test**. Choose one thing to change, and keep everything else the same. For example: reverse the order of the layers, double the depth of fine sand, or leave out the cotton. Build Filter B and test it with fresh river water.
5. Record a table: filter, layers, filtering time, clarity depth.

6. **Settling test.** Let a jar of river water stand still for one hour and test the clarity of water poured gently from the top. If an adult helps, stir a pinch of alum into a second jar first and compare. What does the alum do?
7. **Improve.** Design the best filter you can, using settling first and then filtering. Test it and compare it with Filter A.
8. Write a paragraph explaining why your clear water is still not safe to drink, and what a treatment plant does next.

Tips

- Rinse the sand and gravel first, or they will cloud the water themselves.
- Pour gently onto the top layer so you do not dig a hole through it.
- Slow filters usually make clearer water; notice whether that is true for yours.

Check your work

- ☐ I can name the steps of water treatment in order.
- ☐ I can explain why an aqueduct needs a gentle, steady slope.
- ☐ My data show which filter design made the clearest water.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of a Roman aqueduct bridge with the water channel on top. Label the arches, piers and channel, and show the slope with an arrow.
2. Draw the path of water from a lake to your faucet: intake, coagulation, settling, filtration, disinfection, storage tank or water tower, mains, your house.
3. Make a bar graph comparing the clarity of your filters.

From history. Frontinus's book, *On the Water Supply of the City of Rome*, still survives. It lists each aqueduct, its source, its length and how much water it carried, and it complains about people who secretly tapped the pipes. It is one of the oldest engineering reports in the world.

COMMON MISTAKES

- Thinking clear water must be safe. Germs and some chemicals are invisible.
- Changing more than one thing between filters.
- Thinking aqueducts were mostly bridges. Most of each aqueduct ran underground; bridges were only where valleys had to be crossed.

Make it a game • Aqueduct Tilt. Use a length of paper folded into a gutter and a cup of water. Tilt it just enough that water flows slowly, like a Roman aqueduct. Say what gradient means. Then name the four treatment steps in order: coagulation, settling, filtration and disinfection. Your parent times you. Beat your own score on a second try.

Scripture. “All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.” (Ecclesiastes 1:7, KJV)

Solomon described the water cycle long ago. Water engineers borrow water from that cycle, clean it, use it and return it, so they must work with the order God built into creation.

5.2 SEWERS AND WASTEWATER: BAZALGETTE AND THE GREAT STINK

OBJECTIVES

- Tell how Joseph Bazalgette's sewers cleaned the River Thames and protected London's health.
- Explain why sewers need a steady downhill slope and where pumps are needed.
- Build a model sewer and find the slope needed to carry solids, using a fair test.

Warm-up. Look at the drain under a sink (without taking it apart). Find the U-shaped bend in the pipe. Why do you think it is shaped that way? Hint: it always holds a little water. Write your guess and check it at the end of the lesson.

WATCH

Bazalgette: Saviour of the Great Stink

Institution of Civil Engineers • 5:14

<https://www.youtube.com/watch?v=5k8AnhNkN04>

WHEN TO WATCH

After the story.

BACKUP VIDEO

How to Clean Sewage with Gravity

Practical Engineering • 11:50

<https://www.youtube.com/watch?v=kppxoA3gWco>

After the engineering paragraph, to see how a modern treatment plant cleans wastewater.

KEY TERMS

sewer

An underground pipe or tunnel that carries away wastewater from homes, businesses and streets.

wastewater

Used water from sinks, toilets, showers and washing machines.

intercepting sewer

A large sewer that collects the flow from many smaller sewers before they reach a river and carries it away.

pumping station

A building with pumps that lift wastewater from a low sewer up to a higher one so gravity can carry it on.

treatment plant

A place where wastewater is cleaned with screens, settling tanks and helpful bacteria before it is returned to a river or the sea.

CORE IDEAS

The story. In the 1850s, London was the largest city in the world, with more than two million people, and almost all of its sewage drained straight into the River Thames, the same river from which many people drew their water. Sickness spread through the city again and again. The summer of 1858 was so hot that the river began to smell terribly. People called it the “Great Stink.” Members of Parliament, whose building stands right beside the river, hung curtains soaked in chemicals over the windows to keep out the smell. Within a few weeks they passed a law to pay for a plan that had been waiting: a new system of sewers designed by the chief engineer of London’s Metropolitan Board of Works, Joseph Bazalgette.

How he figured it out. Bazalgette’s idea was to catch the sewage before it reached the river. He built great **intercepting sewers** running east and west along both sides of the Thames, sloping gently downhill, to collect the flow of the old sewers and carry it far downstream, east of the city. Where the land was too low, huge steam-powered **pumping stations**, such as Crossness and Abbey Mills, lifted it up. He planned for London’s future. He estimated how much wastewater each district would produce, then made the pipes much bigger than needed, saying the work could only be done once. He also insisted that every batch of cement be tested for strength before it was used. Workers laid about 82 miles of main intercepting sewers and about 1,100 miles of street sewers, using more than 300 million bricks. Some of the sewers were built inside new river walls called embankments, which also gave London new roads and gardens.

The physics. Sewers work mostly by gravity. A sewer pipe slopes steadily downhill so the water flows on its own. The slope must be just right: too flat, and the water

moves too slowly, so solids settle and block the pipe; too steep, and the fast water wears the pipe away. Bazalgette's main sewers fall only about two feet in every mile. When a sewer gets too deep underground, a pumping station lifts the water up so it can flow downhill again. In your house, the U-shaped trap under the sink always holds a little water, which blocks sewer gases from coming back up into the room.

The engineering. Bazalgette's system worked so well that sickness from dirty water dropped sharply in the parts of London it served, and the river began to recover. At first the sewage was simply released into the Thames far downstream; later, treatment works were added to clean it. A modern **treatment plant** uses screens to catch trash, tanks where solids settle, and tanks of helpful bacteria that eat the waste, before the cleaned water returns to a river. Because Bazalgette built so big, his sewers still carry much of London's wastewater more than 150 years later. In the 2020s, London finished a new "super sewer" tunnel deep under the Thames to add to his system.

PICTURE STUDY



The Northern Outfall Sewer Under Construction, Unknown engraver, about 1859–1865 · Engraving · London

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

This engraving shows part of Bazalgette's Northern Outfall Sewer being built across the flat marshes east of London. A light railway runs beside the works to bring in bricks and cement. Every brick was laid by hand.

Look closely

- Find the workmen. How big is the sewer compared with them?
- Find the railway track. What do you think it carried?
- Look at the sewer's roof and walls. What material are they made of?
- Look at the land. Why might flat, low land be hard for a gravity sewer?

Talk about it

1. Why did Bazalgette make his sewers much larger than London needed in 1860?
2. Why must a sewer slope gently downhill the whole way?
3. Why do you think he tested every batch of cement?

Safety first. Use clean water for the model. Never go near or into real sewers, manholes or storm drains; they can fill with fast water or dangerous gases without warning. Wash hands after the activity.

BUILD

Find the Right Slope: A Model Sewer

You will build a model sewer from a long tube and test how its slope changes how fast water flows and whether it carries “solids” (dried lentils or rice) away or lets them settle. You will find the smallest slope that keeps the pipe clean, the same question Bazalgette had to answer.

You will need

- A long tube: three or four paper towel tubes taped together and lined with plastic wrap, or a 1-meter piece of pool noodle cut in half lengthwise by an adult, or a length of plastic gutter
- Books to prop up one end, a ruler and a tape measure
- A measuring cup, a basin to catch the water and a stopwatch
- Dried lentils or rice (the “solids”)
- Engineer’s notebook

Steps

1. Lay the tube on a table with its low end over the basin. Measure its length.
2. Raise the high end 2 centimeters with a book. Work out the slope: $\text{rise} \div \text{length}$. (For a 100-centimeter tube, $2 \div 100 = 2$ percent.)
3. Put 10 lentils at the high end. Pour 250 milliliters of water steadily in at the high end. Time how long the water takes to reach the basin, and count how many lentils are carried out.
4. **Fair test.** Repeat at slopes of 1, 2, 4 and 8 centimeters of rise, using the same water, the same pouring and the same 10 lentils each time. Do two trials at each slope.
5. Record a table: rise, slope, travel time, lentils carried out.
6. Graph slope (across) and lentils carried out (up). Find the smallest slope that carried nearly all the lentils every time.
7. **Pumping station.** Make your sewer longer by adding a second tube that starts low. When the water reaches the bottom, it must be lifted. Use a cup to

“pump” it up into the next tube. Count how many lifts it takes to move 1 liter, and explain why engineers try to use gravity as much as possible.

8. **Improve.** Try a narrower channel (fold the tube into a V) at your smallest working slope. Does a narrow channel keep solids moving better at low flow? Record what you find.

Tips

- Pour at the same speed each time; use a measuring cup with a spout and count slowly.
- Lentils that stay behind show where a real sewer would clog.
- Have a towel ready.

Check your work

- ☐ I can explain why a sewer needs a slope that is not too flat and not too steep.
- ☐ I can explain what a pumping station does.
- ☐ My graph shows the smallest slope that kept my sewer clean.

ENGINEER’S NOTEBOOK

1. Draw a map of the River Thames with Bazalgette’s intercepting sewers running along both banks toward the outfalls in the east. Add arrows for the flow.
2. Draw the U-shaped trap under a sink and explain in one sentence what it does.
3. Draw the steps of a modern wastewater treatment plant in order.

From history. The Crossness Pumping Station, with its giant steam beam engines and beautifully painted ironwork, opened in 1865. It has been restored by volunteers, and visitors can sometimes see one of its great engines turning. Bazalgette was knighted for his work, and his memorial on the Victoria Embankment reads, in Latin, that he “chained the river.”

COMMON MISTAKES

- Thinking sewers are pumped the whole way. Most of the flow moves by gravity; pumps lift it only where needed.
- Thinking steeper is always better. Very fast flow can wear out the pipe, and a pipe that is too flat clogs.
- Confusing storm drains and sanitary sewers. In many towns, storm drains carry rainwater straight to streams without treatment.

Make it a game • Sewer Slope Stories. Be Joseph Bazalgette addressing a worried city council. Your parent asks questions like "Why must sewers slope?" and "Where do pumps go?" Answer in complete sentences, with at least one term per answer: sewer, wastewater, intercepting sewer or treatment plant. Win by answering five questions without hesitating.

5.3 MAKING ELECTRICITY: FARADAY, EDISON, TESLA AND NIAGARA FALLS

OBJECTIVES

- Explain electromagnetic induction: a moving magnet near a coil makes an electric current.
- Tell how Edison's direct current and Tesla and Westinghouse's alternating current lit cities, and why Niagara Falls used AC.
- Build a coil-and-compass current detector and use a hobby motor as a generator, testing how speed changes its output.

Warm-up. Spin the shaft of a small hobby motor between your fingers while its two wires touch the legs of an LED. Try spinning slowly, then fast, then the other direction. Record what you see. Where is the electricity coming from?

WATCH

AC Electrical Generator Basics - How electricity is generated

The Engineering Mindset • 5:56

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

WHEN TO WATCH

After the physics paragraph. Pause when the magnet passes the coil and describe what happens.

BACKUP VIDEO

Nikola Tesla Harnessed the Power of Niagara Falls

Science Channel • 3:00

<https://www.youtube.com/watch?v=vt-LM5HEo2I>

With the story of Tesla and Niagara Falls.

KEY TERMS

electromagnetic induction

Making an electric current in a wire by moving a magnet near it, or moving the wire near a magnet.

generator

A machine that turns motion into electricity by spinning coils and magnets past each other.

direct current (DC)

Electric current that flows in only one direction, like the current from a battery.

alternating current (AC)

Electric current that reverses direction many times a second; in North America, 60 times a second.

transformer

A device with two coils that changes AC electricity from one voltage to another.

turbine

A wheel with blades turned by moving water, steam or wind, which spins a generator.

CORE IDEAS

The story. In 1831 Michael Faraday wrapped coils of wire around an iron ring and found that when he switched on the current in one coil, a brief current appeared in the other. Then he pushed a magnet into a coil of wire and found the same thing: while the magnet moved, current flowed. When it stopped, the current stopped. He had discovered how to make electricity from motion. Fifty years later, Thomas Edison opened the Pearl Street Station in New York in 1882, with large steam-driven generators sending direct current to light homes and offices. But direct current at low voltage lost much of its energy in the wires and could reach only about a mile from the station. Nikola Tesla, an engineer who came to America from Europe in 1884, designed motors and generators for **alternating current**, and the businessman George Westinghouse bought his patents. In 1895 Westinghouse generators began turning at the new power plant at Niagara Falls, and the next year power from the falls reached the city of Buffalo, more than 20 miles away.

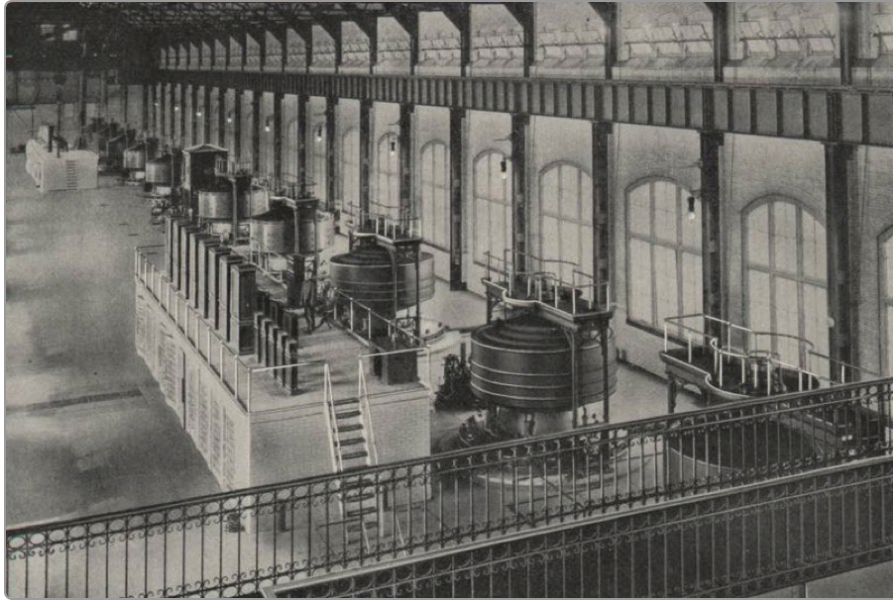
How they figured it out. Faraday found the rule by trying everything: moving the magnet in, out, fast and slow, and watching a needle that showed the current. He saw that the current depended on *change*. The engineers at Niagara faced a different question: how to send power far from the falls. They studied the choices for years, and an international commission of experts compared plans. They chose AC because a **transformer** can raise its voltage for the long trip and lower it again for use. At high voltage the same power travels with a smaller current, and a smaller current wastes much less energy heating the wires. The success at Niagara showed the world how to build a power system.

The physics. A **generator** is a motor working backward. In a motor, current in a coil near a magnet makes motion. In a generator, motion of a coil near a magnet (or a

magnet near a coil) makes current. The current is larger when the magnet is stronger, when the coil has more turns, and when the motion is faster. As a magnet spins past a coil, first its north pole and then its south pole sweep by, so the current flows one way and then the other: alternating current. Something must turn the generator. In a power plant, that is a **turbine**, a wheel of blades pushed around by falling water, by steam, or by the wind.

The engineering. Today almost all of our electricity comes from spinning generators. In a hydroelectric plant, falling water turns the turbine. In coal, natural gas and nuclear plants, heat boils water into high-pressure steam that turns the turbine. Wind turbines are turned by the wind. Solar panels are the main exception: they turn sunlight into electricity directly, with no moving parts. Each source has trade-offs that engineers weigh: what it costs to build and run, whether it can make power at any hour or only when the wind blows or the sun shines, what fuel or land it needs, and how long it lasts. A reliable grid usually uses several kinds together.

PICTURE STUDY



Westinghouse Generators at Niagara Falls, Unknown photographer, about 1896 · Photograph · Edward Dean Adams Power Plant, Niagara Falls, New York

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

These were some of the largest generators in the world when they were built. Each was turned by a water turbine far below the floor, connected by a long vertical shaft. They made alternating current, and their success helped set the pattern for power plants everywhere.

Look closely

- Count the generators in the row.
- Look at the size of the generators compared with the railings and doorways.
- Find where the spinning shaft would come up from below.
- Look for any wires, switches or control panels.

Talk about it

1. Where does the energy that turns these generators come from in the first place?
2. Why was it important that these generators made AC rather than DC?
3. Why do you think the power house was built so clean, bright and orderly?

Safety first. Use only the small hobby motor and batteries; never take apart a generator, appliance or anything that plugs into the wall. Keep magnets away from phones, computers and small children.

BUILD

Faraday's Discovery and a Hand-Spun Generator

First you will make a current detector from a compass and a coil, then push a magnet into a second coil and watch the needle move, repeating Faraday's 1831 discovery. Then you will use a small hobby motor as a generator and test how the speed of spinning changes the light it makes.

You will need

- A compass, about 6 meters of magnet wire, a cardboard tube (toilet-paper tube) and tape
- A strong bar or stack of disk magnets that fits inside the tube
- A small DC hobby motor (1.5–3 volt), an LED, and two alligator clip leads
- String, a pencil, and a ruler
- Optional: a digital multimeter set to DC volts

Steps

1. **Detector.** Wind 20 turns of magnet wire around the compass (over the top and under the bottom), leaving long ends. Turn the compass so its needle lines up along the turns.
2. **Coil.** Wind about 50 turns of wire around the cardboard tube. Have an adult sand the ends of both coils and connect them together with clip leads, so the coil and detector make one loop. Keep the magnet at least an arm's length from the compass.
3. Push the magnet quickly into the tube and watch the compass needle. Pull it out. Hold it still inside. Push it slowly. Record what the needle does each time.
4. **Generator.** Clip the LED to the hobby motor's wires. Wrap the string around the motor shaft several times, hold the motor firmly, and pull the string fast so the shaft spins. Does the LED blink? Turn the LED around and try again, since current flows through an LED only one way.
5. **Fair test.** Pull the string with slow, medium and fast pulls of the same length (30 centimeters). Rate the LED's brightness, or read the voltage on a multimeter if you have one. Do three trials at each speed.

6. Record a table and write a rule: how does speed affect the electricity made?
7. **Improve.** Find a way to spin the generator faster or more steadily, for example by winding the string around a larger spool on the shaft, or by attaching a small propeller and holding it in front of the box fan (a model wind turbine). Test your best design.

Tips

- The compass needle may only flick; watch closely, or film it in slow motion.
- More turns in the coil and a stronger magnet make a bigger flick.
- A red LED lights at the lowest voltage, so it is easiest to see.

Check your work

- ☐ I can explain how moving a magnet near a coil makes a current.
- ☐ I can explain why a generator is like a motor working backward.
- ☐ I can explain why Niagara Falls used AC and transformers.

ENGINEER'S NOTEBOOK

1. Draw Faraday's magnet-and-coil experiment with the compass detector. Show what the needle does when the magnet moves in, stays still and moves out.
2. Draw a hydroelectric plant: water, dam, pipe, turbine, generator, transformer, power lines. Label each.
3. Make a table of power sources (hydro, coal, natural gas, nuclear, wind, solar) with one advantage and one challenge for each.

From history. The 1893 World's Columbian Exposition in Chicago was lit with tens of thousands of lamps powered by Westinghouse alternating current, which helped persuade the Niagara planners. The original Adams power station at Niagara was later replaced by larger plants, but one of its stone buildings, the transformer house, still stands as a historic landmark.

COMMON MISTAKES

- Thinking a still magnet makes current. Only a changing magnetic field does; something must move.
- Thinking a generator makes energy from nothing. It changes motion energy into electrical energy, and something must keep pushing it.
- Thinking high-voltage lines are dangerous only when you touch them. Electricity can jump to a kite string, ladder or pole that gets too close.

Make it a game • AC or DC? Hold a debate. Your parent argues for Edison's direct current, and you argue for Tesla and Westinghouse's alternating current. Each side must give one fact. Then switch sides. Add why Niagara Falls used AC, and explain induction: a moving magnet near a coil makes current. The judge scores clear facts, not volume.

5.4 DAMS, THE GRID AND THE LINeworker

OBJECTIVES

- Explain why a dam is thicker at the bottom, using the idea that water pressure grows with depth.
- Trace electricity from a power plant through the grid to a house: step-up transformer, transmission lines, substation, distribution lines and pole transformer.
- Describe the work of lineworkers and the safety rules around power lines, and test water pressure and dam shapes.

Warm-up. Walk outside with a parent and look up at the power lines on your street. How many wires do you see? Can you find a gray can-shaped transformer on a pole, or a green box on the ground? Sketch what you see. Do not go near or touch anything.

WATCH

How Does the Power Grid Work?

Practical Engineering · 10:25

<https://www.youtube.com/watch?v=v1BMWczn7JM>

WHEN TO WATCH

After the physics paragraph. Follow the electricity from the plant to the house.

Note: Skip the short sponsor message near the end.

BACKUP VIDEO

Day In The Life of a Lineman

Community Electric Cooperative · 6:28

<https://www.youtube.com/watch?v=btnwUQwc-DI>

After the engineering paragraph, to see what lineworkers do.

KEY TERMS

water pressure

The push of water on each unit of area.
It grows greater the deeper you go.

grid

The connected network of power plants, transmission lines, substations and distribution lines that delivers electricity.

transmission line

A high-voltage line, usually on tall steel towers, that carries electricity long distances.

substation

A fenced station with transformers that lowers the voltage and sends power out on local lines.

lineworker

A skilled worker who builds, repairs and maintains power lines.

CORE IDEAS

The story. The Colorado River once flooded farms in the spring and nearly dried up in late summer. To control it, store water for cities and farms, and make electricity, the United States built Hoover Dam in a deep canyon on the border of Nevada and Arizona, from 1931 to 1936. First, workers blasted four tunnels, each 50 feet across, through the canyon walls to carry the river around the building site. Then they poured more than 3 million cubic yards of concrete. The dam rises 726 feet, about the height of a 60-story building, and its generators still supply power to millions of people. Meanwhile, across America, most farm families still had no electricity at all. Starting in 1936, rural electric cooperatives hired crews of lineworkers to set poles and string wire across the countryside, bringing light, refrigerators and electric water pumps to farms for the first time.

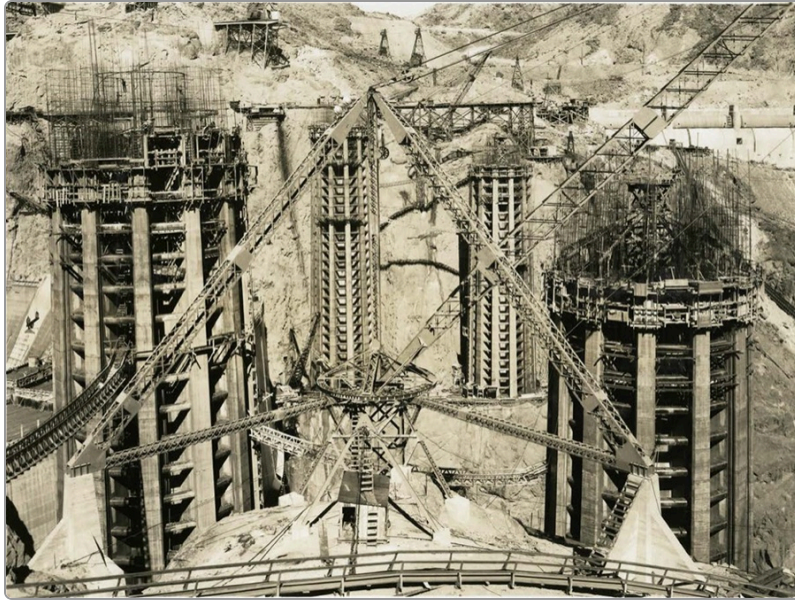
How they figured it out. Engineers knew that a huge block of concrete gives off heat as it hardens. Poured all at once, Hoover Dam would have taken many decades to cool and would have cracked as it shrank. So they poured it in hundreds of separate column-shaped blocks, and ran more than 580 miles of thin steel pipe through the concrete, pumping cold river water and then chilled water through them to cool it quickly. Afterward, the gaps between the blocks were filled with grout to make the

dam one solid piece. Engineers also tested scale models of the dam to check how it would carry the water's push.

The physics. Water presses harder the deeper it is, because of the weight of all the water above. At the bottom of the deep lake behind Hoover Dam, the pressure is enormous, so the dam is about 660 feet thick at its base and only about 45 feet thick at the top. It is also curved, bowing upstream like an arch lying on its side, so part of the water's push is carried into the solid rock walls of the canyon. In the power plant, water rushes down through huge pipes and spins turbines, which turn generators. Then the **grid** takes over. A step-up transformer raises the voltage very high for the long trip on **transmission lines**, because high voltage means low current and less energy lost. At a **substation** near town, transformers lower the voltage for the distribution lines on your street, and a small transformer on a pole or in a green box lowers it again for your house.

The engineering. The grid is one of the largest machines ever built, and it must make exactly as much electricity as people are using, second by second, all day and all night. Control centers watch it constantly and tell power plants when to speed up or slow down. **Lineworkers** keep it running. They climb poles and ride bucket trucks in heat, cold and storms, and after a hurricane or ice storm, crews come from many states to help restore power. They wear rubber gloves and sleeves, use insulated tools, and follow strict safety rules, because the voltage on power lines can be deadly. Their work is a picture of loving your neighbor: going out into the storm so others can have light and heat.

PICTURE STUDY



Building the Intake Towers of Hoover Dam, U.S. Bureau of Reclamation, 1934 · Photograph · Bureau of Reclamation, Boulder City, Nevada

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

The Bureau of Reclamation photographed every stage of building Hoover Dam. These intake towers stand in the lake behind the dam; water enters them and falls through huge pipes to the turbines in the power plant below.

Look closely

- Find the intake towers. How many can you see?
- Look at the canyon walls. Why would solid rock walls be important for a dam?
- Find cables, cranes or scaffolding. How were materials brought into the canyon?
- Look for any workers. How do they help you judge the size of the towers?

Talk about it

1. Why do you think the water is taken in near the top of the towers and sent down to the turbines far below?
2. Why is a dam thicker at the bottom than at the top?
3. What would be the hardest part of building in this canyon?

Safety first. Stay far away from downed power lines, substations and transformers; never climb poles or towers, and never fly kites, drones or balloons near power lines. If a line is down, stay back at least 35 feet and call 911. Before anyone digs in your yard, call 811 so buried lines and pipes can be marked.

BUILD

Water Pressure and the Best Dam Shape

You will measure how water pressure grows with depth by watching jets of water from holes at different heights in a bottle. Then you will build model dams in a pan and test which shape holds back water with the least leaking.

You will need

- A clean 2-liter plastic bottle and a thumbtack or nail (an adult makes the holes)
- Tape, a pitcher of water, a sink or a large baking pan, and a ruler
- A long baking pan or plastic storage box, modeling clay or play dough, and cardboard strips
- A measuring cup and engineer's notebook

Steps

1. **Pressure test.** An adult pokes three small holes in a straight line up the side of the bottle: 5, 12 and 20 centimeters from the bottom. Cover them with one strip of tape.
2. **Predict.** Which hole will squirt farthest? Fill the bottle to the top, stand it at the edge of the sink, and pull off the tape.
3. Measure how far out each jet lands while the bottle is still nearly full. Keep the water topped up to the same level for a fair test, and repeat twice.
4. Record a table: hole height, depth of water above the hole, jet distance. Explain the pattern using the word pressure.
5. **Dam test.** In the pan, build Dam A as a straight wall of clay across the middle, 2 centimeters thick and 6 centimeters tall, pressed firmly onto the pan's floor and sides.
6. Pour water behind the dam to a depth of 5 centimeters. Wait 5 minutes, then measure how much water leaked to the other side with the measuring cup.
7. Build Dam B from the same amount of clay, but thicker at the bottom and thinner at the top, and curved so it bows toward the water. Test it exactly the same way.

8. **Improve.** Design Dam C to leak the least using the same amount of clay. Test it, and explain your design using what you learned about pressure and arches.

Tips

- Press the clay hard into the corners of the pan; most leaks happen at the edges, not through the middle.
- Pour gently behind the dam so you test the dam, not the splash.
- Weigh your clay to be sure each dam uses the same amount.

Check your work

- ☐ I can explain why water squirts farthest from the lowest hole.
- ☐ I can explain why dams are thick at the bottom and often curved.
- ☐ I can trace electricity from a power plant to my house and name three power-line safety rules.

ENGINEER'S NOTEBOOK

1. Draw the grid from a dam to your house: generator, step-up transformer, transmission towers, substation, distribution lines, pole transformer, house. Label each and write the purpose of each transformer.
2. Draw a cross-section of Hoover Dam with arrows showing water pressure growing with depth.
3. Write a thank-you note to a lineworker or water plant operator, explaining what their work makes possible for your family.

From history. In 1935 only about one American farm in ten had electricity. The Rural Electrification Administration, created that year, lent money to farmers' cooperatives to build their own power lines. Within about fifteen years, most farms had electricity, and many of those cooperatives still serve rural families today.

COMMON MISTAKES

- Thinking the amount of water in the lake sets the push on the dam. It is the depth of the water that sets the pressure.
- Thinking transformers make electricity. They only change its voltage.
- Thinking a fallen power line is safe because it is not sparking. Always assume it is live.

Make it a game • Grid Trace Race. Place five cards or objects in a line: power plant, step-up transformer, transmission line, substation and pole transformer. Mix them up. Race to rebuild the line in order, saying each job aloud. Then explain why water pressure makes a dam thicker at the bottom. Best time out of three tries wins.

UNIT 5

PUBLIC UTILITIES

Turn a tap, and clean water comes out. Flush, and the dirty water disappears. Flip a switch, and the light comes on. These things seem ordinary only because thousands of engineers, operators and lineworkers keep them working every hour of every day. In this unit you will follow water from the Roman aqueducts to the modern treatment plant, and wastewater from London’s “Great Stink” to Joseph Bazalgette’s great sewers.

Then you will follow electricity from Faraday’s moving magnet to the generators at Niagara Falls and the Hoover Dam, and along the power lines to your house. You will test a homemade water filter, find the slope a sewer needs, light an LED with a generator you spin yourself, and measure how water pushes harder the deeper it gets. Clean water and safe power are some of the greatest gifts engineers give their neighbors.

PREREQUISITES

- Knows how electromagnets and motors work (Unit 4)
- Knows how arches carry loads (Unit 3)
- Can measure volume in milliliters and time with a stopwatch

MASTERY CHECKLIST

- ☐ I can explain how water is carried by gravity and cleaned in a treatment plant: settling, filtering and disinfecting.
- ☐ I can tell how Bazalgette’s sewers saved London and explain why a sewer needs a steady slope.
- ☐ I can explain how a generator makes electricity by moving a magnet and a coil, and why Niagara Falls used alternating current.
- ☐ I can trace electricity from a power plant through the grid to my home and name the safety rules around power lines.
- ☐ I can explain why a dam is thicker at the bottom.

LESSONS IN THIS UNIT

5.1 Clean Water: From Roman Aqueducts to the Treatment Plant

2 sessions of 45 minutes

5.2 Sewers and Wastewater: Bazalgette and the Great Stink

2 sessions of 45 minutes

5.3 Making Electricity: Faraday, Edison, Tesla and Niagara Falls

2 sessions of 45 minutes

5.4 Dams, the Grid and the Lineworker

2 sessions of 45 minutes

UNIT 5 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

How did Roman aqueducts move water many miles without pumps?

2. **5 pts**

Put the steps of drinking-water treatment in order: filtration, coagulation, disinfection, settling.

3. **5 pts**

Your homemade filter made the water look clear. Is it safe to drink? Explain.

4. **5 pts**

What was the Great Stink, and how did Bazalgette's plan fix the problem?

5. **5 pts**

Predict: a model sewer is almost flat. What happens to the solids? What if it is very steep?

6. **5 pts**

What did Faraday discover in 1831, and how does a generator use it?

7. (5 pts)

Why did the engineers at Niagara Falls choose alternating current?

8. (5 pts)

Predict: a bottle has holes at 5 cm and 20 cm from the bottom. Which jet squirts farther, and why?

9. (5 pts)

Trace electricity from a hydroelectric dam to a lamp in your house, naming at least five parts.

10. (5 pts)

Give three safety rules about power lines and digging.

ANSWER KEY

1. By gravity: the channel sloped steadily and gently downhill all the way from the source to the city, using tunnels and arched bridges to keep the slope.
2. Coagulation, settling, filtration, disinfection.
3. No. The filter removes dirt but not germs or dissolved chemicals, which are invisible. Treatment plants disinfect and test the water.
4. In the hot summer of 1858 the sewage-filled Thames smelled terribly. Bazalgette built intercepting sewers along both banks to catch the sewage before it reached the river and carry it far downstream, with pumping stations where needed.
5. Almost flat: the water moves slowly and solids settle and clog it. Very steep: the solids are carried, but fast water can wear out a real pipe; engineers choose a steady middle slope.
6. That moving a magnet near a coil (a changing magnetic field) makes an electric current. A generator spins coils and magnets past each other to make current from motion.
7. AC can be raised to a high voltage with transformers for long-distance travel (less energy lost in the wires) and lowered again for use; DC at low voltage could only reach about a mile.
8. The 5 cm hole, because it has more water above it, so the water pressure there is greater.
9. Falling water → turbine → generator → step-up transformer → transmission lines → substation (step-down transformer) → distribution lines → pole or pad transformer → house wiring → lamp.
10. Any three: stay far from downed lines and call 911; never climb poles or towers or enter substations; never fly kites, drones or balloons near lines; keep ladders away from lines; call 811 before digging.

PORTFOLIO PIECE: A TOWN WATER AND POWER PLAN

Design the utilities for an imaginary town of 1,000 homes on a large sheet of paper, drawn to a rough scale. Show the water source, treatment plant, water tower and mains; the sewers sloping to a treatment plant, with at least one pumping station; and the power plant, transmission lines, substation and distribution lines. Then build and test one part as a working model: your best water filter, your sewer slope model, or your clay dam. Present the plan and model with a page explaining how each system works and one way engineers keep it safe.

LOOK FOR	WHAT IT MEANS
Complete plan	Water, wastewater and power systems are all shown with their main parts labeled and connected in a sensible order.
Uses the physics	The water tower is on high ground, sewers slope downhill to the plant, pumps are placed where land is low, and transformers are placed correctly.
Working model	One model is built and tested, with a data table from at least two versions.
Safety and service	Explains at least two safety rules and how the system serves the town's families.
Presentation	Neat, readable plan and a clear written explanation.

UNIT 6

BOATS AND SHIPS

Why does a steel ship weighing thousands of tons float, while a small steel bolt sinks? Archimedes answered that question more than two thousand years ago, and every boat ever built has had to obey his answer. In this unit you will measure Archimedes' principle with foil boats and pennies, and learn why floating is not enough: a ship must also stay upright. The Swedish warship *Vasa*, which tipped over on its very first voyage in 1628, will show you why.

Then you will follow ships from sail to steam, from Robert Fulton's paddle-wheel steamboat to the screw propeller that pushes nearly every ship today, and you will study the *Titanic*: how its watertight compartments were meant to keep it afloat, why they were not enough, and what the world changed so that ships would be safer afterward. "They that go down to the sea in ships" have always depended on careful builders.

PREREQUISITES

- Knows Newton’s third law (Unit 1)
- Knows that 1 milliliter of water has a mass of about 1 gram
- Can find the volume of a box: length × width × height

MASTERY CHECKLIST

- ☐ I can state Archimedes’ principle and use it to predict how much a boat can carry.
- ☐ I can explain how the center of gravity and center of buoyancy keep a ship upright, and why the *Vasa* capsized.
Vasa
- ☐ I can explain how paddle wheels and propellers push a ship forward using Newton’s third law, and tell the stories of Fulton and the screw propeller.
- ☐ I can explain how watertight compartments work and name the safety changes made after the *Titanic*.
Titanic
Titanic
- ☐ I can run fair tests on model boats and record and graph the results.

LESSONS IN THIS UNIT

6.1 Archimedes’ Principle Measured

2 sessions of 45 minutes

6.2 Stability and the Warship *Vasa*

2 sessions of 45 minutes

6.3 From Sail to Steam: Fulton and the Screw Propeller

2 sessions of 45 minutes

6.4 The Titanic: Watertight Compartments and What Changed

2 sessions of 45 minutes

UNIT 6 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. (5 pts)

State Archimedes' principle.

2. (5 pts)

A foil boat is 8 cm long, 8 cm wide and 4 cm high, and has a mass of 6 grams. About how many grams can it carry before it sinks? About how many pennies (2.5 g each)?

3. (5 pts)

Why does a steel ship float when a steel bolt sinks?

4. (5 pts)

Name two reasons the *Vasa* capsized.

5. (5 pts)

Predict: you move a model boat's ballast from the top of its mast to the bottom of the hull. Will it tilt more or less when a weight is placed on its edge? Why?

6. (5 pts)

What is an inclining test, and why must every new ship pass one?

7. (5 pts)

How does a propeller push a ship forward? Name the law.

8. (5 pts)

Why did the screw propeller replace the paddle wheel on ocean ships? Describe the test that proved it.

9. (5 pts)

Why did the *Titanic* sink even though it had watertight compartments?

10. (5 pts)

Name three safety changes made after the *Titanic*.

ANSWER KEY

1. The buoyant force on an object equals the weight of the fluid it displaces (pushes aside).
2. Volume = $8 \times 8 \times 4 = 256$ mL, which displaces about 256 g. $256 - 6 = 250$ g of cargo. $250 \div 2.5 = 100$ pennies.
3. The ship's hollow hull displaces a large volume of water that weighs more than the ship, so the buoyant force can hold it up. The solid bolt displaces only a little water, which weighs less than the bolt.
4. Any two: the hull was too narrow for its height; too much weight was high up (heavy cannons on two decks, tall upper works); not enough ballast low down; the gunports were open and close to the water.
5. Less, because the center of gravity is lower, so the buoyant force twists the boat back upright more strongly.
6. Known weights are moved across the deck and the tilt is measured, so engineers can calculate the ship's stability. It proves the ship is stable before it carries people or cargo.
7. Its twisted blades push water backward, and the water pushes the propeller and ship forward. Newton's third law (action and reaction).
8. It stays underwater and protected when the ship rolls in waves and pushes more efficiently. In 1845 the propeller ship *Rattler* and the paddle ship *Alecto* pulled stern to stern, and the *Rattler* towed the *Alecto* backward.
9. At least five forward compartments were opened, more than it could survive, and the bulkheads did not reach the top deck, so as the bow sank, water spilled over them into the next compartments one after another.
10. Any three: lifeboats for everyone aboard; lifeboat drills; radios staffed 24 hours; the International Ice Patrol; higher, stronger bulkheads; double bottoms or hulls (SOLAS rules).

PORTFOLIO PIECE: A CARGO BOAT WITH A MEASURED CAPACITY

Design and build a cargo boat from foil, card stock and tape, or from a plastic container, that is stable, carries as much cargo as possible, and survives one flooded compartment. Before testing, calculate its volume and predict its capacity in pennies using Archimedes' principle. Then test its capacity, its stability with an inclining test, and its survival with one compartment flooded. Record everything and write a short naval architect's report comparing prediction and results.

LOOK FOR	WHAT IT MEANS
Prediction	Volume is measured and capacity is predicted correctly using Archimedes' principle, with work shown.
Capacity test	Pennies are added evenly and the result is recorded and compared with the prediction.
Stability	An inclining test is done, and the boat uses low ballast or a wide hull on purpose.
Compartments	The boat has at least two watertight compartments and survives one flooded compartment.
Report	A clear report explains the results with the words buoyant force, center of gravity and bulkhead.

6.1 ARCHIMEDES' PRINCIPLE MEASURED

OBJECTIVES

- State Archimedes' principle: the buoyant force equals the weight of the water pushed aside.
- Explain why a steel ship floats but a steel bolt sinks, using the shape of the hull.
- Predict how many pennies a foil boat can carry from its volume, then test and compare.

Warm-up. Fill a measuring cup to exactly 500 milliliters. Roll a lump of clay into a tight ball and drop it in. Read the new water level. Now take the clay out, shape it into a little bowl, and float it. Read the level again. What changed? Why do you think one sinks and one floats?

WATCH

Science at Home: Principle of Buoyancy Experiment

North Carolina Museum of Natural Sciences • 4:54

<https://www.youtube.com/watch?v=4tnPfnuY42I>

WHEN TO WATCH

After the physics paragraph.

BACKUP VIDEO

Why do big ships float? [Buoyancy and flotation explained]

Casual Navigation • 4:20

<https://www.youtube.com/watch?v=Z3vgsp4vKQs>

After the engineering paragraph, to see how real ships use the same idea.

KEY TERMS

buoyant force

The upward push of water (or any fluid) on an object in it.

displace

To push aside. An object in water displaces some of the water.

Archimedes' principle

The buoyant force on an object equals the weight of the fluid it displaces.

density

How much mass is packed into a given volume: $\text{mass} \div \text{volume}$. Water's density is about 1 gram per milliliter.

hull

The main body of a boat or ship, the part that sits in the water.

CORE IDEAS

The story. The Roman writer Vitruvius tells a story about Archimedes. King Hiero of Syracuse had given a goldsmith a weight of gold to make a crown. When the crown came back, it weighed the same as the gold, but the king suspected the goldsmith had kept some gold and mixed in cheaper silver. He asked Archimedes to find out without damaging the crown. One day, stepping into a full bath, Archimedes noticed the water spill over the side, and he realized that an object pushes aside water equal to its own volume. Silver is less dense than gold, so a crown mixed with silver would be bigger than pure gold of the same weight, and would spill more water. Archimedes is said to have run home shouting, “Eureka!” which means “I have found it!”

How they figured it out. The bath story may be partly legend, but Archimedes did write a book called *On Floating Bodies* that states the rule exactly. Nearly 1,800 years later, the young Galileo read the story and doubted the spilled-water method, because the difference would be too small to measure. In 1586 he described a better way: hang the crown and an equal weight of pure gold from the two ends of a balance, then lower both into water. The bigger object gets a bigger upward push from the water, so the balance tips. Galileo was checking an old story with a better measurement, which is exactly what scientists and engineers should do.

The physics. When something is placed in water, it pushes some water aside. The water pushes back up with a **buoyant force** equal to the weight of the water that was pushed aside. That is **Archimedes' principle**. One milliliter of water weighs about one gram, so an object that displaces 300 milliliters gets about 300 grams of upward push. If the object weighs less than the water it can displace, it floats, sinking only until it has pushed aside its own weight of water. If it weighs more, it sinks. A solid

steel bolt is much denser than water, so it sinks. But shape the same steel into a wide, hollow **hull**, and it can push aside a large volume of water, enough to weigh more than the steel. That is why a steel ship floats.

The engineering. Ship designers use Archimedes' principle to calculate how deep a ship will float when loaded. A ship's size is often given as its **displacement**, the weight of water it pushes aside, which equals the weight of the ship and everything on it. Load more cargo, and the ship sinks lower until it displaces enough extra water. Engineers must leave enough hull above the water, called freeboard, so that waves do not wash aboard. Since the 1870s, British cargo ships have been marked with a load line, often called the Plimsoll line after the man who campaigned for it, which shows how deep the ship may safely be loaded. Salt water is a little denser than fresh water, so a ship floats a little higher in the ocean than in a river.

PICTURE STUDY



Breezing Up (A Fair Wind), Winslow Homer, 1873–1876 · Oil on canvas · National Gallery of Art, Washington, D.C.

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

Winslow Homer painted many pictures of boats and the sea along the New England coast. In this one, a fisherman and three boys sail a small catboat home in a fresh breeze.

Look closely

- Find the waterline on the boat's hull. How much of the hull is under the water?
- Count the people aboard. How does their weight change how low the boat floats?
- Look at where the boys are sitting. Why do you think they are sitting on the high side?
- Find the sail and the direction the boat is leaning.

Talk about it

1. If two more people climbed aboard, what would happen to the waterline?
Use Archimedes' principle to explain.
2. Why is it important for a small boat to have enough freeboard in waves like these?

3. What keeps this boat from tipping all the way over in the wind?

Safety first. An adult should be present whenever you work with a tub or sink of water. Wipe up spills right away so no one slips.

BUILD

Foil Boats: Predict, Then Test

You will measure a foil boat, calculate its volume, and use Archimedes' principle to predict how many pennies it can carry before it sinks. Then you will test it and compare your prediction with the result. Finally you will run a fair test of boat shapes made from the same size sheet of foil.

You will need

- Aluminum foil cut into squares 20×20 centimeters
- A ruler, a kitchen scale and pennies (2.5 grams each)
- A tub, sink or large pan of water
- Modeling clay and a measuring cup
- Engineer's notebook and a calculator

Steps

1. **Clay check.** Repeat the warm-up carefully and record the water levels for the clay ball and the clay boat. Weigh the clay. Does the floating clay boat displace about its own mass in grams of water?
2. **Boat A.** Fold a foil square into a box-shaped boat with straight sides, 10×10 centimeters across the bottom and 3 centimeters high. Weigh it.
3. Calculate its volume: $10 \times 10 \times 3 = 300$ cubic centimeters (milliliters). That much water weighs about 300 grams.
4. **Predict.** The boat can displace at most 300 grams of water. Subtract the boat's own mass, then divide by 2.5 to predict how many pennies it can carry before water comes over the sides. Write your prediction.
5. Float the boat and add pennies one at a time, spreading them evenly, until it sinks. Record the number that it held. Compare with your prediction and explain any difference.
6. **Fair test.** Make Boats B and C from the same size foil square but with different shapes: for example, 14×14 centimeters with sides 1 centimeter high, and 7×7 centimeters with sides 6 centimeters high. Calculate each volume and predict, then test.

7. Record a table: boat, length, width, height, volume, predicted pennies, actual pennies.

8. **Improve.** Design a boat from one foil square that carries the most pennies. Test it, and explain why its shape works so well.

Tips

- Fold the corners carefully so there are no leaks; a small leak sinks a boat early.
- Place pennies in the middle and spread them out; a pile on one side tips the boat before it is full.
- Very tall, narrow boats may tip over before they fill. You will learn why in the next lesson.

Check your work

- ☐ I can state Archimedes' principle in my own words.
- ☐ I can use a boat's volume to predict how much it can carry.
- ☐ My table compares my predictions with my results.

ENGINEER'S NOTEBOOK

1. Draw a boat floating with arrows for its weight pushing down and the buoyant force pushing up. Label the waterline and freeboard.
2. Draw Galileo's balance with the crown and the gold hanging in water, and explain in one sentence why it would tip.
3. Make a bar graph of your predicted and actual pennies for each boat, side by side.

From history. Archimedes also helped King Hiero launch the *Syracusia*, said to be the largest ship of the ancient world. Ancient writers say it was so large that it was hard to move into the water, and that Archimedes used his machines to launch it. It was later given as a gift to the king of Egypt.

COMMON MISTAKES

- Thinking heavy things sink and light things float. A heavy steel ship floats because of its shape and the large volume of water it displaces.
- Using the area of the bottom instead of the volume to predict capacity.
- Forgetting to subtract the boat's own mass from what it can displace.

Make it a game • Predict and Float. Fold a square of foil into a boat and predict how many pennies it holds. Load until it sinks and compare. Then reshape it and predict again. Explain why a steel bolt sinks but a steel ship floats, using displace and hull. Closest prediction scores. State Archimedes' principle in your own words.

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 see God’s power in the sea every day. Shipbuilders honor Him by learning the laws He set for water and building ships that respect them.

6.2 STABILITY AND THE WARSHIP VASA

OBJECTIVES

- Tell what happened to the *Vasa* in 1628 and why.
- Explain how the center of gravity and the center of buoyancy work together to keep a ship upright.
- Run an inclining test on a model boat to measure how ballast and hull width change its stability.

Warm-up. Stand on one foot with your arms at your sides. Now hold a heavy book high over your head and stand on one foot again. Then hold the book down low by your knees. Which way is easiest to keep your balance? Why do you think so?

WATCH

Why This 17th-Century Warship Was a Disastrous Failure

Smithsonian Channel • 4:05

<https://www.youtube.com/watch?v=1a0PIhMpflU>

WHEN TO WATCH

After the story.

Note: Stop when the end screen of other videos appears.

KEY TERMS

stability

A ship's ability to return upright after it is tipped by wind or waves.

center of gravity

The point where all of a ship's weight seems to act.

center of buoyancy

The center of the underwater part of the hull, where the buoyant force seems to push up.

ballast

Heavy material, such as stones or iron, placed low in a ship to lower its center of gravity.

capsize

To tip over in the water.

inclining test

A test in which known weights are moved across a ship's deck and the tilt is measured to find out how stable the ship is.

CORE IDEAS

The story. In the 1620s, King Gustavus Adolphus of Sweden ordered a great new warship for his navy. The *Vasa* was built in Stockholm under the master shipwright Henrik Hybertsson, who died before it was finished. The king wanted it grand: tall, richly carved, and carrying heavy cannons on two full gun decks, which was unusual for a ship of its size. Before it sailed, the admiral tested it by having thirty men run back and forth across the deck together. The ship rolled so badly that the test was stopped. But the ship was nearly finished, the king was far away and eager, and the voyage went ahead. On August 10, 1628, the *Vasa* set sail in Stockholm harbor. After sailing only about 1,300 meters, a gust of wind heeled it over, water poured in through the open gunports, and it sank. Some of those on board were lost.

How they figured it out. At the inquiry afterward, no one was punished. The ship had been built as ordered, and in those days shipwrights worked from experience and rules of proportion, not from calculations; there was no way to work out a ship's stability on paper. In 1961, after more than 330 years in the cold, muddy water of the harbor, the *Vasa* was raised almost whole, and it now stands in its own museum in Stockholm. Modern engineers measured it carefully. They found that the hull was too narrow for its height, that too much heavy wood and cannon were high up, and that there was not enough ballast low down. And there was no room to add more ballast, because that would have pushed the lower gunports too close to the water.

The physics. Two forces act on a floating ship: its weight pulls down through the **center of gravity**, and the buoyant force pushes up through the **center of buoyancy**. When the wind tips a ship, the underwater shape of the hull changes, and the center of buoyancy moves toward the low side. If the center of gravity is low enough, the upward push on the low side and the downward pull in the middle twist the ship back upright. That is **stability**. But if the center of gravity is too high, the twist goes the wrong way and the ship rolls farther until it **capsizes**. A wide hull and heavy **ballast** low in the ship both help; tall, heavy upper decks hurt.

The engineering. In the 1700s, scientists such as the Frenchman Pierre Bouguer worked out the mathematics of ship stability, and naval architects have used it ever since. Today every new ship must pass an **inclining test**: known weights are moved across the deck and the tilt is measured exactly, so engineers can calculate how stable the ship is before it ever carries passengers or cargo. Engineers also check stability every time a ship is loaded, because cargo stacked high can make a stable ship dangerous. The *Vasa* also teaches a lesson about honesty: the people who saw the test knew something was wrong. An engineer must speak up plainly about danger, even when an important person wants a different answer.

PICTURE STUDY



A Ship on the High Seas Caught by a Squall ("The Gust"), Willem van de Velde the Younger, about 1680 · Oil on canvas · Rijksmuseum, Amsterdam
Image: [Wikimedia Commons](#), public domain

Willem van de Velde the Younger was one of the greatest painters of ships. He knew ships so well that historians use his paintings to learn how they were built and rigged. This ship, from about fifty years after the *Vasa*, is caught by the same kind of sudden gust.

Look closely

- How far is the ship leaning? Estimate the angle.
- Find the sails. Which ones are still set, and which have been taken in?
- Look at the hull. Where do you think the heavy ballast is?
- Look for gunports or openings in the side. How close are they to the water?

Talk about it

1. What will make this ship swing back upright when the gust passes?
2. Why might the crew take in some sails when a squall is coming?
3. What would have happened to the *Vasa* in this same gust, and why?

Safety first. An adult should be present near the tub of water. Keep the weights small so the model does not crack or spill.

BUILD

An Inclining Test with Ballast

You will build a model ship with a tall “upper deck,” then do an inclining test, as real naval architects do: you will place a small weight at the edge of the deck and measure how far the ship tilts. You will test how ballast placed low or high, and a wider hull, change the tilt.

You will need

- Two empty plastic food containers of different widths (for example, a narrow and a wide one about the same length), or two milk-carton boats
- A craft stick or ruler taped upright as a mast, with a card “upper deck” taped across it near the top
- Ballast: 20 pennies or a lump of modeling clay
- A tilt weight: a stack of 5 pennies taped together
- A protractor, a tub of water and engineer’s notebook

Steps

1. Tape the mast upright in the middle of the narrow boat and float it. Tape a protractor to the side of the tub, or hold it beside the mast, so you can read the mast’s tilt.
2. **Test 1, ballast high.** Tape the 20 pennies of ballast to the upper deck, high on the mast. Place the 5-penny tilt weight on the edge of the boat’s rim. Read the tilt angle. Do it three times and average.
3. **Test 2, ballast low.** Move the 20 pennies to the bottom of the boat, in the middle. Repeat the test exactly.
4. **Test 3, wider hull.** Repeat Test 2 with the wider boat, with the ballast low.
5. **Predict** before each test, and record a table: boat, ballast position, tilt angle.
6. **Capsize test.** With the ballast high on the narrow boat, add tilt pennies one at a time at the edge until it capsizes. Count them. Then do the same with the ballast low. Compare.
7. Write a paragraph explaining the *Vasa*’s problem using your data and the words center of gravity and ballast.

8. **Improve.** Design the most stable model ship you can that still carries a tall mast and an upper deck. Test it with the capsizing test.

Tips

- Place the tilt weight in exactly the same spot each time.
- Let the boat stop rocking before you read the angle.
- If the narrow boat tips over with no tilt weight at all, you have found a *Vasa*. Record it.

Check your work

- ☐ I can explain why low ballast makes a ship more stable.
- ☐ I can explain why a wider hull is more stable.
- ☐ My data table shows how ballast position changed the tilt.

ENGINEER'S NOTEBOOK

1. Draw a ship tipped slightly. Mark the center of gravity (G) and the center of buoyancy (B) and show with arrows how they twist the ship back upright.
2. Draw a second, top-heavy ship tipped the same amount. Show how the arrows twist it the wrong way.
3. Write what you would have said to the king if you had watched the thirty men run across the deck.

From history. The *Vasa* is one of the best-preserved ships of its time in the world, because the cold, brackish water of the Baltic Sea lacks the shipworms that eat wood in saltier seas. Today the Vasa Museum in Stockholm keeps the ship in a carefully controlled climate, and engineers have been designing a new steel support for the hull, because even the old ship's own weight slowly bends it.

COMMON MISTAKES

- Thinking that a ship which floats is safe. A ship must float and stay upright.
- Thinking more weight always makes a ship tip. Weight placed low (ballast) makes it steadier.
- Reading the tilt while the model is still rocking.

Make it a game • Vasa Verdict. Be the investigator. Tell your parent what happened to the Vasa in 1628 and why, using center of gravity, ballast and stability. Your parent plays the king asking tough questions. Then show with a toy boat how adding weight low keeps it upright. Three accurate answers and the king pardons you.

6.3 FROM SAIL TO STEAM: FULTON AND THE SCREW PROPELLER

OBJECTIVES

- Tell how Robert Fulton's steamboat and the screw propeller changed travel by water.
- Explain how paddle wheels and propellers push a ship forward using Newton's third law.
- Build a rubber-band paddle boat and run a fair test of one variable.

Warm-up. In a tub, push your flat hand backward through the water, then turn your hand sideways and push again. Which way gives a stronger push on your hand? Which way does the push on your hand point? Write a sentence connecting this to Newton's third law.

WATCH

How Do Propellers Work? The History of the Marine Propeller.

Mariner's Mirror Podcast • 5:04

<https://www.youtube.com/watch?v=YGXsHoc0xKk>

WHEN TO WATCH

After the story of the screw propeller.

BACKUP VIDEO

Invention of the Steamboat

NBC News Learn • 2:01

<https://www.youtube.com/watch?v=2QXq5D37YEw>

With the story of Robert Fulton.

KEY TERMS

steamboat

A boat driven by a steam engine, which burns fuel to boil water into steam that pushes pistons.

paddle wheel

A large wheel with flat boards that dip into the water and push it backward as the wheel turns.

screw propeller

A set of twisted blades on a spinning shaft under the stern that pushes water backward, like a screw turning through the water.

thrust

The forward push on a ship or aircraft from its propeller, paddle wheel or engine.

stern

The back end of a ship. The front is the bow.

CORE IDEAS

The story. For thousands of years, ships moved by oars or by the wind. On rivers, going upstream against the current was slow, hard work. On August 17, 1807, Robert Fulton's steamboat, often called the *Clermont*, left New York City and steamed up the Hudson River to Albany, about 150 miles, in 32 hours, a trip that took sailing sloops several days. Soon steamboats with big paddle wheels were carrying passengers and freight on every major American river. But paddle wheels had weaknesses on the open sea: when a ship rolled in the waves, one wheel lifted out of the water while the other dug in deep. In the 1830s two inventors, the Englishman Francis Pettit Smith and the Swedish engineer John Ericsson, each patented a **screw propeller** fixed under the stern.

How they figured it out. Smith's first propeller was a long wooden screw with two full turns. In 1837, during a trial on a canal near London, half of the screw broke off, and to everyone's surprise the boat went faster. Smith had learned, by accident and by careful watching, that a shorter screw worked better, and he changed his design. In 1839 he built a ship named the *Archimedes*, after the inventor of the water-lifting screw, to prove the idea at sea. In 1845 the British navy settled the question with a famous test: two ships of about the same size and power, the propeller-driven *Rattler* and the paddle-wheel *Alecto*, were tied stern to stern and set to pull against each other. The *Rattler* towed the *Alecto* backward.

The physics. Both paddle wheels and propellers work by Newton's third law. The paddle wheel's boards push water backward, and the water pushes the boat forward. A propeller's blades are twisted, like the threads of a screw or the wings of an airplane turned on their sides. As they spin, they throw water backward, and the water pushes the propeller, and the ship, forward. This forward push is called

thrust. A sailboat is different: its sail acts like an upright wing, so the wind flowing around it can push the boat even when the wind is blowing across its path, not just from behind.

The engineering. The propeller won because it sits deep under the **stern**, where it is protected from waves and stays in the water when the ship rolls, and because it pushes efficiently. Paddle wheels remained useful on shallow rivers, where a propeller would hit bottom. Engineers chose iron and then steel hulls, which could be longer and stronger than wooden ones; in 1843 Isambard Kingdom Brunel's *Great Britain* was the first large ocean ship to combine an iron hull with a screw propeller. Today nearly every ship, from tugboats to container ships, uses propellers, and engineers design each blade's shape with care to push the most water with the least wasted energy. The book of James says that great ships, driven by fierce winds, are turned about by a very small helm. Small parts, well designed, control great things.

PICTURE STUDY



The Fighting Temeraire, J. M. W. Turner, 1839 · Oil on canvas · National Gallery, London

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

The *Temeraire* was a famous sailing warship that had served at the Battle of Trafalgar in 1805. In 1838, worn out, it was towed up the Thames by a small steam tug to be broken up for its timber. Turner painted the moment as the end of the age of sail and the beginning of the age of steam.

Look closely

- Find the steam tug. How big is it compared with the sailing ship it is pulling?
- Look at the tug's smokestack. What is it burning?
- Find the old ship's masts. Are any sails set?
- Look at the sky and the water. How does Turner make the old ship look like a fading memory of the past?

Talk about it

1. How can a small steam tug pull such a huge ship? Think about thrust and what the tug's engine does.
2. Why could a steam tug move a ship when there was no wind at all?
3. What do you think Turner felt about the change from sail to steam?

Safety first. Keep fingers clear of a wound-up paddle, and wear safety glasses while winding, since rubber bands can snap. An adult should be present near the tub.

BUILD

A Rubber-Band Paddle Boat

You will build a paddle-wheel boat powered by a twisted rubber band, then run a fair test of how the number of winds (or the size of the paddle) changes how far the boat travels. You will explain its motion with Newton's third law.

You will need

- A clean half-gallon juice or milk carton cut in half lengthwise by an adult, or a foam tray
- Two pencils or wooden skewers for the paddle supports, taped to the sides so they stick out past the stern
- A rubber band that fits between the supports
- A paddle cut from the leftover carton or a plastic lid, about 4×5 centimeters (and a larger one, 6×5 centimeters, for testing)
- Tape, a tape measure, a stopwatch and a bathtub or long tub of water

Steps

1. Tape the pencils along the sides of the boat so they stick out about 8 centimeters past the stern. Stretch the rubber band between their ends.
2. Slide the paddle into the middle of the rubber band so the band holds it. Check that it can spin without hitting the boat.
3. Wind the paddle backward 10 times, hold it, set the boat in the water, and let go. Measure how far it travels and time it. Do three trials.
4. **Fair test.** Test 10, 20 and 30 winds, three trials each, keeping the same paddle and rubber band.
5. Record a table: winds, distance, time, average distance. Make a line graph.
6. Which way did the paddle push the water, and which way did the boat move? Explain with Newton's third law.
7. **Second fair test.** Keep 20 winds and swap in the larger paddle. Did it go farther or faster? Why might a bigger paddle help, or not?
8. **Improve.** Change one thing to make the boat go farther or straighter, such as a pointed bow cut from card stock, a second rubber band, or a keel strip of

foam under the hull to keep it straight. Test and record.

Tips

- Wind the paddle so its bottom edge moves backward through the water when released.
- If the boat turns in circles, center the paddle and check that the boat is level.
- Mark the tub's side with tape every 10 centimeters to make measuring easier.

Check your work

- ☐ I can explain how a paddle wheel and a propeller make thrust.
- ☐ I can tell why the screw propeller replaced the paddle wheel on ocean ships.
- ☐ My graph shows how the number of winds changed the distance.

ENGINEER'S NOTEBOOK

1. Draw a paddle steamer and a propeller ship side by side. Add arrows showing the water pushed backward and the thrust forward.
2. Draw the *Rattler* and *Alecto* tug-of-war and explain in one sentence what it proved.
3. Graph your paddle boat data and write what you would change next.

From history. Robert Fulton began his career as a painter and wrote a book on improving canals, and he had tested a steamboat on the Seine River in Paris in 1803 before building his Hudson River boat. John Ericsson, the other inventor of the screw propeller, moved to America and designed the USS *Monitor*, an iron ship with a turning gun turret, in 1862.

COMMON MISTAKES

- Thinking the paddle pushes against the bottom of the tub. It pushes against the water, and the water pushes back.
- Winding the paddle the wrong way, so the boat goes backward.
- Changing the paddle and the number of winds in the same test.

Make it a game • Screw or Wheel. Demonstrate in a sink basin with a toy boat and a spoon. Push water backward and watch the boat move forward. Explain Newton's third law out loud. Then compare paddle wheel and screw propeller, and tell which one Robert Fulton used. Take turns, and give a point for each correct comparison.

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 small rudder steers a great ship, and a small propeller drives it. James uses the ship to teach that small things, like our words, have great effects.

6.4 THE TITANIC: WATERTIGHT COMPARTMENTS AND WHAT CHANGED

OBJECTIVES

- Explain how the *Titanic*'s watertight compartments were meant to keep it afloat and why they were not enough.
- Use Archimedes' principle to explain why a ship sinks lower as compartments flood.
- Test a compartment model with low and full-height bulkheads, and list the safety rules made after 1912.

Warm-up. Float an empty plastic ice-cube tray in a sink. Using a spoon, carefully fill one compartment at one end with water. What happens to that end? Keep filling compartments one by one at the same end. Predict how many it can take before water spills over into the next compartment.

WATCH

How did the Iceberg Sink the Titanic?

[Oceanliner Designs](#) • 18:22

<https://www.youtube.com/watch?v=ruM90tNGCVg>

WHEN TO WATCH

After the story, before the physics. This video is longer; the sections on the design and the damage matter most.

Note: Includes a historic illustration of the sinking; preview if your child is sensitive.

KEY TERMS

watertight compartment

A section of a ship's hull closed off by walls so that water flooding into it cannot reach the others.

bulkhead

A wall that divides the inside of a ship into compartments.

reserve buoyancy

The extra floating ability of the watertight hull above the waterline, which keeps a ship afloat when some water gets in.

double bottom

A second watertight layer inside the bottom of a hull, so a hole in the outer layer does not flood the ship.

SOLAS

The International Convention for the Safety of Life at Sea, the set of safety rules for ships first agreed in 1914 after the *Titanic*.

CORE IDEAS

The story. The RMS *Titanic* was built in Belfast, in what is now Northern Ireland, by Harland and Wolff, and in 1912 it was the largest ship in the world, about 882 feet long. Its hull was divided by 15 **bulkheads** into 16 watertight compartments, and it was designed to stay afloat with any two of them flooded, or even the first four. On its first voyage, from Southampton toward New York, at 11:40 p.m. on April 14, 1912, it struck an iceberg in the North Atlantic. The ice scraped along the right side of the bow, buckling the steel plates and opening seams along about 300 feet of the hull. Less than three hours later, the ship sank. There were lifeboats for only about half of the people aboard, and many people were lost.

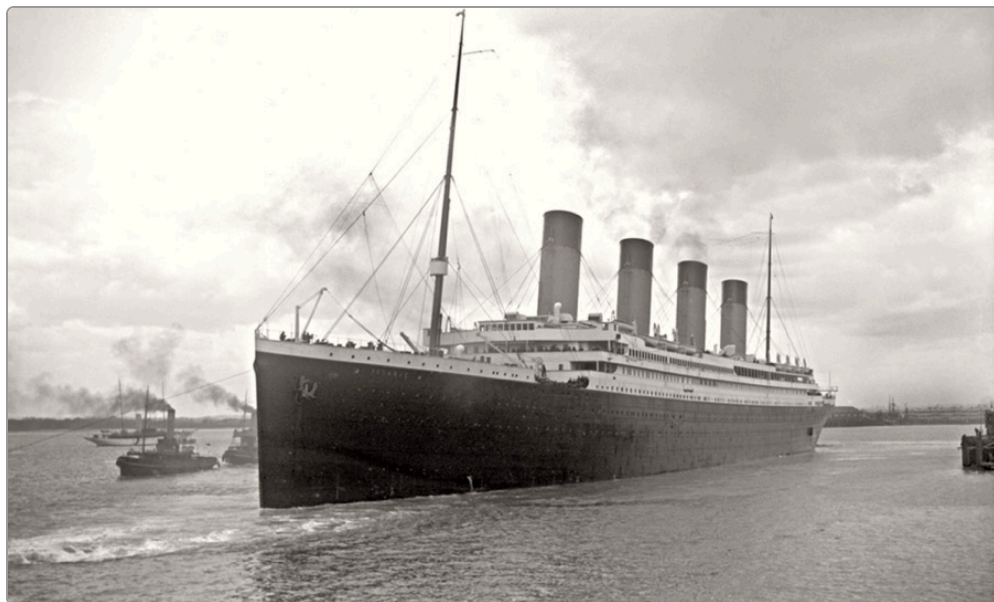
How they figured it out. Within weeks, both the United States Senate and the British government held inquiries and questioned survivors, officers and the ship's builders. They found that the damage had opened at least five of the forward compartments to the sea, one more than the ship could survive. In 1985 a team led by the oceanographer Robert Ballard found the wreck on the ocean floor, more than two miles down, broken in two. Since then, engineers have studied pieces of its steel and rivets and built computer models of the flooding to understand exactly how the ship sank.

The physics. A ship floats because its hull displaces its own weight of water. When water floods a compartment, the ship becomes heavier, so it sinks lower until it displaces enough extra water to balance the new weight. That is why a ship has **reserve buoyancy**: the watertight hull above the waterline that can be pushed under to make up for flooding. But the *Titanic*'s bulkheads did not reach all the way to the

top deck. As the forward compartments filled, the bow sank lower, until water spilled over the top of one bulkhead into the next compartment, then the next, like water spilling along an ice-cube tray tipped at one end.

The engineering. The world changed the rules. In 1914 the nations of the sea agreed to the first International Convention for the Safety of Life at Sea, called **SOLAS**: lifeboats for everyone aboard, lifeboat drills, radios staffed day and night, and stronger rules for watertight bulkheads. The International Ice Patrol was set up to warn ships of icebergs in the North Atlantic, and it still operates today. Ships now have bulkheads that reach higher, **double bottoms** and, on many ships, double hulls, as well as radar and satellite navigation. Engineers learned that no ship should ever be called unsinkable, and that safety means planning for the accident you hope will never happen.

PICTURE STUDY



The Titanic Leaving Southampton, Unknown photographer, April 10, 1912 · Photograph · Southampton, England

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

This photograph shows the *Titanic* setting out on its first voyage. Look at the ship as an engineer would: its long, tall hull, the rows of portholes, and the place where the waterline divides the part that floats from the part above.

Look closely

- Find the waterline. How much of the hull is above it? That is the reserve buoyancy.
- Count the funnels. (One of the four was only for ventilation.)
- Find the lifeboats along the top deck. Do there look like enough for a ship this size?
- Look at the rows of portholes. What would happen if the bow sank low enough for water to reach them?

Talk about it

1. Why did the builders think the ship could survive almost any accident?
2. How would full-height bulkheads have changed what happened?
3. Which of the changes made after 1912 do you think saved the most lives since? Why?

Safety first. An adult should be present near the sink or tub. Use only small amounts of water and wipe up spills.

BUILD

Bulkhead Test: The Ice-Cube-Tray Ship

You will use a plastic ice-cube tray as a model hull with watertight compartments. You will flood compartments at one end, one at a time, and record when the ship would sink. Then you will raise the bulkheads with tape and test again, to see why full-height bulkheads matter.

You will need

- A plastic ice-cube tray with low walls between the cells (the kind where the walls are lower than the sides works best), or a long plastic container divided with strips of card and clay
- Clear packing tape and strips of card stock to raise the bulkheads
- A sink or tub of water, a spoon or medicine dropper, and a small cup of water with a drop of food coloring
- Pennies or clay for cargo, a ruler and engineer's notebook

Steps

1. Load the tray evenly with a few pennies so it floats low but steady, like a loaded ship. Measure how high the sides stand above the water at each end.
2. **Low bulkheads.** Using the dropper, fill the first compartment at one end with colored water until it is full to the top of its wall. Measure how low that end now floats.
3. Keep flooding compartments in order from that end. After each one, record how low the end floats and whether water spills over a wall into the next compartment by itself.
4. Stop when water spills over the side into the tub (the ship sinks). Record how many compartments you flooded.
5. **Full-height bulkheads.** Empty and dry the tray. Raise every wall between compartments to the height of the sides by taping strips of card stock across them and sealing them with tape or clay.
6. Repeat the flooding test exactly. How many compartments can flood now before the ship sinks?

7. Record a table: bulkhead type, compartments flooded, what happened. Write a paragraph explaining your results with the words reserve buoyancy and bulkhead.
8. **Improve.** Add a “double bottom”: float the tray inside a slightly larger container lid and test what happens when you make a small hole in the outer layer. Or design a ship that can survive four flooded compartments at one end. Test it.

Tips

- Fill compartments slowly; you want to see the moment water starts to spill over a wall.
- Keep the cargo the same for each test.
- Take a photograph after each compartment fills.

Check your work

- ☐ I can explain why a flooded ship floats lower.
- ☐ I can explain why the

Titanic’s bulkheads were not enough.

an

ic

- ☐ I can name three safety changes made after 1912.

ENGINEER’S NOTEBOOK

1. Draw a side view of a ship with 16 compartments. Shade the first five, and show how the bow sinks and water spills over the bulkhead tops.
2. Make a two-column chart: “Before 1912” and “After 1912,” listing lifeboats, radio watch, ice patrol and bulkheads.
3. Draw your best model ship design and label its bulkheads and double bottom.

From history. The International Ice Patrol, begun in 1914 and run by the U.S. Coast Guard, now uses airplanes and satellites to find icebergs. Every year on or near April 15, the patrol drops a wreath at the place where the *Titanic* sank, in memory of those who were lost.

COMMON MISTAKES

- Thinking a watertight compartment means a sealed box. The *Titanic*’s compartments were open at the top.

- Thinking the iceberg tore one huge hole. It buckled plates and opened seams along a long stretch of the side.
- Thinking one safety feature is enough. Engineers use many layers of protection.

Make it a game • Flood the Compartment. Use an ice cube tray in a basin as a ship. Predict how many compartments can flood before it sinks, and test by pouring in water cup by cup. Explain why the Titanic's bulkheads were not enough and what reserve buoyancy means. Closest prediction wins. Add one change made by SOLAS.

Scripture. “Then fearing lest we should have fallen upon rocks, they cast four anchors out of the stern, and wished for the day.” (Acts 27:29, KJV)

In Paul’s shipwreck, the sailors measured the depth, saw the danger, and prepared. Good engineers and good sailors plan for danger before it comes.

BOATS AND SHIPS

Why does a steel ship weighing thousands of tons float, while a small steel bolt sinks? Archimedes answered that question more than two thousand years ago, and every boat ever built has had to obey his answer. In this unit you will measure Archimedes' principle with foil boats and pennies, and learn why floating is not enough: a ship must also stay upright. The Swedish warship *Vasa*, which tipped over on its very first voyage in 1628, will show you why.

Then you will follow ships from sail to steam, from Robert Fulton's paddle-wheel steamboat to the screw propeller that pushes nearly every ship today, and you will study the *Titanic*: how its watertight compartments were meant to keep it afloat, why they were not enough, and what the world changed so that ships would be safer afterward. "They that go down to the sea in ships" have always depended on careful builders.

PREREQUISITES

- Knows Newton’s third law (Unit 1)
- Knows that 1 milliliter of water has a mass of about 1 gram
- Can find the volume of a box: length × width × height

MASTERY CHECKLIST

- ☐ I can state Archimedes’ principle and use it to predict how much a boat can carry.
- ☐ I can explain how the center of gravity and center of buoyancy keep a ship upright, and why the *Vasa* capsized.
- ☐ I can explain how paddle wheels and propellers push a ship forward using Newton’s third law, and tell the stories of Fulton and the screw propeller.
- ☐ I can explain how watertight compartments work and name the safety changes made after the *Titanic*.
- ☐ I can run fair tests on model boats and record and graph the results.

LESSONS IN THIS UNIT

6.1 Archimedes’ Principle Measured

2 sessions of 45 minutes

6.2 Stability and the Warship Vasa

2 sessions of 45 minutes

6.3 From Sail to Steam: Fulton and the Screw Propeller

2 sessions of 45 minutes

6.4 The Titanic: Watertight Compartments and What Changed

2 sessions of 45 minutes

UNIT 6 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. (5 pts)

State Archimedes' principle.

2. (5 pts)

A foil boat is 8 cm long, 8 cm wide and 4 cm high, and has a mass of 6 grams. About how many grams can it carry before it sinks? About how many pennies (2.5 g each)?

3. (5 pts)

Why does a steel ship float when a steel bolt sinks?

4. (5 pts)

Name two reasons the *Vasa* capsized.

5. (5 pts)

Predict: you move a model boat's ballast from the top of its mast to the bottom of the hull. Will it tilt more or less when a weight is placed on its edge? Why?

6. (5 pts)

What is an inclining test, and why must every new ship pass one?

7. (5 pts)

How does a propeller push a ship forward? Name the law.

8. (5 pts)

Why did the screw propeller replace the paddle wheel on ocean ships? Describe the test that proved it.

9. (5 pts)

Why did the *Titanic* sink even though it had watertight compartments?

10. (5 pts)

Name three safety changes made after the *Titanic*.

ANSWER KEY

1. The buoyant force on an object equals the weight of the fluid it displaces (pushes aside).
2. Volume = $8 \times 8 \times 4 = 256$ mL, which displaces about 256 g. $256 - 6 = 250$ g of cargo. $250 \div 2.5 = 100$ pennies.
3. The ship's hollow hull displaces a large volume of water that weighs more than the ship, so the buoyant force can hold it up. The solid bolt displaces only a little water, which weighs less than the bolt.
4. Any two: the hull was too narrow for its height; too much weight was high up (heavy cannons on two decks, tall upper works); not enough ballast low down; the gunports were open and close to the water.
5. Less, because the center of gravity is lower, so the buoyant force twists the boat back upright more strongly.
6. Known weights are moved across the deck and the tilt is measured, so engineers can calculate the ship's stability. It proves the ship is stable before it carries people or cargo.
7. Its twisted blades push water backward, and the water pushes the propeller and ship forward. Newton's third law (action and reaction).
8. It stays underwater and protected when the ship rolls in waves and pushes more efficiently. In 1845 the propeller ship *Rattler* and the paddle ship *Alecto* pulled stern to stern, and the *Rattler* towed the *Alecto* backward.
9. At least five forward compartments were opened, more than it could survive, and the bulkheads did not reach the top deck, so as the bow sank, water spilled over them into the next compartments one after another.
10. Any three: lifeboats for everyone aboard; lifeboat drills; radios staffed 24 hours; the International Ice Patrol; higher, stronger bulkheads; double bottoms or hulls (SOLAS rules).

PORTFOLIO PIECE: A CARGO BOAT WITH A MEASURED CAPACITY

Design and build a cargo boat from foil, card stock and tape, or from a plastic container, that is stable, carries as much cargo as possible, and survives one flooded compartment. Before testing, calculate its volume and predict its capacity in pennies using Archimedes' principle. Then test its capacity, its stability with an inclining test, and its survival with one compartment flooded. Record everything and write a short naval architect's report comparing prediction and results.

LOOK FOR	WHAT IT MEANS
Prediction	Volume is measured and capacity is predicted correctly using Archimedes' principle, with work shown.
Capacity test	Pennies are added evenly and the result is recorded and compared with the prediction.
Stability	An inclining test is done, and the boat uses low ballast or a wide hull on purpose.
Compartments	The boat has at least two watertight compartments and survives one flooded compartment.
Report	A clear report explains the results with the words buoyant force, center of gravity and bulkhead.

FLIGHT

For thousands of years people watched birds and wished they could fly. The first to rise into the air did it by floating, in the hot-air balloons of the Montgolfier brothers in 1783. Then Sir George Cayley worked out what a flying machine would need, and Otto Lilienthal flew more than two thousand glides on wings he built himself. In this unit you will follow those dreamers, and then two brothers from Dayton, Ohio, who solved the problem of flight not by daring alone but by careful method: kites, a homemade wind tunnel, notebooks full of data, and three summers of patient testing at Kitty Hawk.

You will learn the four forces of flight and how a wing really makes lift, by turning air downward and lowering the pressure above it. You will measure lift on a balance in front of a box fan, test gliders for the best glide, and launch air rockets to see Newton's third law at work. Finally you will see how propellers, jet engines, rockets and drones all push against air or exhaust to move. "They shall mount up with wings as eagles," wrote Isaiah. By patient study, people learned to do it.

PREREQUISITES

- Knows Newton's three laws (Unit 1) and Archimedes' principle (Unit 6)
- Knows how a lever balances (Unit 1)
- Can measure angles with a protractor

MASTERY CHECKLIST

- ☐ I can explain why a hot-air balloon rises, using Archimedes' principle.
- ☐ I can tell how the Wright brothers solved flight through kites, a wind tunnel, data and control in three directions.
- ☐ I can name the four forces of flight and explain lift correctly: the wing turns air downward and the pressure above it is lower.
- ☐ I can run a fair test on a glider and calculate its glide ratio.
- ☐ I can explain how propellers, jet engines, rockets and drones make thrust, and state the basic safety rules for flying drones.

OPTIONAL KITS FOR THIS UNIT

- **Ryze Tello drone:** For grade 5 and up, flown with an adult. A small indoor drone that weighs about 80 grams and can be flown from a phone or programmed with Scratch-style blocks. Fits Lesson 7.4 and Unit 8. Follow the FAA rules in Lesson 7.4.
- **KiwiCo Tinker Crate:** Ages 9 and up. Some monthly crates are flight projects, such as gliders and launchers, with notes on the science. Fits Lessons 7.3 and 7.4.

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

7.1 The Dreamers: Montgolfier Balloons, Cayley and Lilienthal

2 sessions of 45 minutes

7.2 The Wright Brothers' Method: Kites, Wind Tunnel and Data

2 sessions of 45 minutes

7.3 The Four Forces and the Airfoil: A Glider Test

2 sessions of 45 minutes

7.4 Propellers, Jets, Rockets and Drones

2 sessions of 45 minutes

UNIT 7 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

Why does a hot-air balloon rise? Use the words density and Archimedes' principle.

2. **5 pts**

What did Sir George Cayley and Otto Lilienthal each contribute to flight?

3. **5 pts**

Why did the Wright brothers build a wind tunnel, and what did they find?

4. (5 pts)

Name the three ways an airplane turns and what the Wrights used to control each.

5. (5 pts)

Name the four forces of flight. Which pairs balance in steady, level flight?

6. (5 pts)

Explain how a wing makes lift. Do not use the “catch-up” idea.

7. (5 pts)

Predict: you tilt a wing in your wind tunnel to a very steep angle. What happens to the lift?

8. (5 pts)

A glider launched from 2 meters high lands 9 meters away. What is its glide ratio? Another glider from the same height lands 12 meters away. Which is better?

9. (5 pts)

Why does a rocket work in space, where there is no air?

10. (5 pts)

Give four FAA rules for flying a recreational drone.

ANSWER KEY

1. Hot air is less dense than the cooler air around it. By Archimedes' principle, the buoyant force equals the weight of the cool air the balloon pushes aside; when that is more than the weight of the balloon, basket and hot air, it rises.
2. Cayley worked out the basic airplane shape (fixed wing, tail, separate thrust) and named the forces of flight. Lilienthal made about 2,000 glides, showed curved wings lift better, and published lift measurements.
3. Their gliders made far less lift than the published tables predicted. They built a wind tunnel to measure lift on about 200 wing shapes and found the old numbers were wrong, then used their own data to design the 1902 glider.
4. Pitch (front elevator), roll (wing warping), yaw (rudder).
5. Lift and weight balance; thrust and drag balance.
6. The wing's shape and angle turn the passing air downward; by Newton's third law the air pushes the wing up. Also, air speeds up over the curved top and its pressure drops, so higher pressure below pushes the wing up.
7. The lift rises as the angle increases, then drops suddenly when the wing stalls because the air can no longer follow the top surface.
8. $9 \div 2 = 4.5$. The second glider: $12 \div 2 = 6$, which is better.
9. It pushes its exhaust gas backward, and the gas pushes the rocket forward (Newton's third law). It carries its own oxygen, so it needs no air to burn fuel or to push against.
10. Any four: pass the free TRUST test; register drones of 250 grams or more; fly no higher than 400 feet; keep it in sight; do not fly over people; stay away from airports and emergency scenes; check the FAA's current rules.

PORTFOLIO PIECE: A TESTED GLIDER

Design, build and test a glider that achieves the best glide ratio you can, using card stock, foam, straws, balsa or paper. Launch it from the same height every time. Change only one thing between versions, and test at least three versions with at least three flights each. Present the glider with a data table, a graph of glide ratio for each version, a labeled drawing showing the four forces, and a paragraph explaining what made your best version fly best.

LOOK FOR	WHAT IT MEANS
Fair test	Changed only one thing between versions, launched the same way from the same height, and recorded at least three flights each.
Data and math	Distances are measured and averaged, and glide ratios are calculated correctly and graphed.
Science explanation	Explains lift correctly (air turned downward, lower pressure above), the four forces, and the role of the balance point.
Improvement	The final glider is better than the first, and the notebook explains why.
Craftsmanship	The glider is straight, balanced and neatly built, and the drawing is clearly labeled.

7.1 THE DREAMERS: MONTGOLFIER BALLOONS, CAYLEY AND LILIENTHAL

OBJECTIVES

- Tell how the Montgolfier brothers, Sir George Cayley and Otto Lilienthal each moved people closer to flight.
- Explain why a hot-air balloon rises, using Archimedes' principle and density.
- Build a hot-air bag balloon and measure how much it can lift.

Warm-up. Watch a bird fly, outside or in a video. Write down everything its wings and tail do when it takes off, glides, turns and lands. Which of those things do you think would be hardest for a machine to copy?

WATCH

The Launch of the First Hot Air Balloon | The History of Science | BBC Earth Science

BBC Earth Science · 3:35

<https://www.youtube.com/watch?v=unOrdJtr7HU>

WHEN TO WATCH

With the story of the Montgolfier brothers.

Note: The balloon in this reenactment is filled from a straw fire tended by experienced adults. Never use flames to heat a balloon yourself.

BACKUP VIDEO

How Otto Lilienthal Glided Like a Bird | “Transformational Technologies” Episode 4

Smithsonian National Air and Space Museum · 1:29

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

With the story of Otto Lilienthal.

KEY TERMS

hot-air balloon

A large bag of heated air that rises because hot air is less dense than the cooler air around it.

density

How much mass is packed into a given volume. Warm air is less dense than cool air.

glider

An aircraft with wings but no engine, which flies by gliding down through the air.

camber

The curve of a wing from front to back.

lift

The upward force on a wing or balloon that holds it up in the air.

CORE IDEAS

The story of the balloon. Joseph and Étienne Montgolfier were paper makers in the town of Annonay in France. They noticed that a paper or cloth bag held over a fire would fill and float upward. On June 4, 1783, they sent up a large balloon of cloth and paper in front of a crowd, and it rose thousands of feet. In September, before King Louis XVI at Versailles, a balloon carried a sheep, a duck and a rooster into the air and brought them down safely. On November 21, 1783, two men, Pilâtre de Rozier and the Marquis d'Arlandes, flew over Paris for about 25 minutes in a Montgolfier balloon. For the first time in history, people had flown.

The story of the glider. Balloons could rise but could not be steered against the wind. In England, Sir George Cayley spent his life on the problem of the airplane. In 1799 he engraved a small silver disk with a design that looks like a modern airplane: a fixed wing for lift, a separate way to push it forward, and a tail to steer and steady it. He saw that flight needed lift to overcome weight and thrust to overcome drag. He built model gliders, and in 1853 one of his full-size gliders carried a man across a small valley. In Germany, the engineer Otto Lilienthal studied storks, measured how curved wings lift, and published his findings in 1889. From 1891 to 1896 he made about 2,000 glides on wings of willow and cloth, hanging below them and steering by swinging his body. In 1896 he was badly hurt in a crash and died, but photographs of his flights had gone around the world.

The physics. A hot-air balloon floats in air the way a boat floats in water.

Archimedes' principle works in any fluid, and air is a fluid too. When air is heated, its molecules move faster and spread apart, so a liter of hot air weighs less than a liter of cool air: it is less **dense**. The balloon pushes aside a large volume of cool air, and the buoyant force equals the weight of that cool air. If the hot air inside plus the balloon and its basket weigh less than the cool air pushed aside, the balloon rises. A glider works differently: its wings make **lift** by moving through the air. Lilienthal found that a wing with a gentle upward curve, or **camber**, lifts much better than a flat board.

The engineering. Each dreamer handed something on. The Montgolfiers proved that people could survive in the air; weather balloons still rise from hundreds of stations every day to measure the sky. Cayley named the forces of flight and the basic shape of the airplane. Lilienthal proved that a person could glide on built wings and published tables of measurements so that others could use them. But his weight-shifting control was not enough for gusty winds, and some of his numbers turned out to be wrong. Solving those two problems, control and accurate data, was the work that the Wright brothers took up.

PICTURE STUDY



Otto Lilienthal Gliding, Unknown photographer, about 1895 · Photograph · Library of Congress, Prints and Photographs Division

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

Lilienthal had many of his glides photographed. Pictures like this one, printed in magazines around the world, showed people that a man could truly fly on wings he had built, and they inspired the Wright brothers.

Look closely

- Find the ribs of the wings. What do you think they are made of?
- Look at the shape of the wing from front to back. Is it flat or curved?
- Find Lilienthal's body. How do you think he steered?
- Look for a tail. What might it do?

Talk about it

1. Why would a curved wing lift better than a flat one?
2. What would happen to this glider in a sudden gust if Lilienthal could not swing his body fast enough?
3. What do the Montgolfiers, Cayley and Lilienthal have in common in the way they worked?

Safety first. Only an adult handles the hair dryer or other heat source. Never use flames, candles or matches to heat a balloon. Keep the plastic bag away from small children's faces.

BUILD

A Hot-Air Bag Balloon and Its Payload

You will fill a lightweight plastic bag with hot air from a hair dryer and watch it rise, just as the Montgolfiers did with fire smoke. Then you will measure its lift by adding paper clips until it can no longer rise, and run a fair test of bag size.

You will need

- Two or three very thin plastic bags of different sizes (dry-cleaning bags, thin produce bags or tissue-paper balloons), with any holes taped shut
- A hair dryer, held by an adult
- Paper clips (about 1 gram each) and tape
- A kitchen scale, a stopwatch and a tape measure
- Engineer's notebook

Steps

1. Weigh each bag. Estimate its volume by filling it with cool air and measuring it roughly as a box or cylinder.
2. With an adult holding the hair dryer, hold the bag open upside down above the dryer until it is full of warm air. Let go. Time how long it stays up and how high it rises.
3. Tape one paper clip to the bottom of the bag and try again. Keep adding paper clips, one at a time, until the bag will no longer rise. Record the most it could lift.
4. **Predict** whether a bigger bag will lift more. Then test each bag the same way, heating each for the same number of seconds.
5. Record a table: bag, mass, estimated volume, heating time, paper clips lifted, time aloft.
6. **Fair test.** With your best bag, test heating times of 20, 40 and 60 seconds. How does longer heating change the lift? Why?
7. Explain your results with Archimedes' principle and the word density.
8. **Improve.** Find a way to keep the air warm longer or make the bag lighter, and test again.

Tips

- Do this on a cool day or in a cool room; the bigger the difference in temperature, the more lift.
- Do not let the hair dryer touch or melt the bag.
- Tissue-paper balloons glued from several sheets work very well if you want a bigger project.

Check your work

- ☐ I can explain why hot air rises, using density.
- ☐ I can explain a hot-air balloon with Archimedes' principle.
- ☐ My data show how bag size or heating time changed the lift.

ENGINEER'S NOTEBOOK

1. Draw a hot-air balloon with arrows for its weight and the buoyant force. Label the hot air inside and the cool air outside.
2. Draw Cayley's 1799 silver disk design and label the wing, the tail and the forces of lift, weight, thrust and drag.
3. Make a timeline from 1783 to 1896 with the Montgolfiers, Cayley and Lilienthal.

From history. Ten days after the first Montgolfier flight with people, the scientist Jacques Charles flew over Paris in a balloon filled with hydrogen gas, which is far lighter than air. He carried a thermometer and a barometer and measured the air as he rose, making him one of the first to do science in the sky.

COMMON MISTAKES

- Thinking a balloon rises because of smoke. It rises because the hot air inside is less dense than the air outside.
- Thinking a glider is a balloon with wings. A glider is heavier than air and must keep moving to make lift.
- Heating some bags longer than others in the size test.

Make it a game • Why Does It Rise?. Play three-minute teacher. Explain to your parent why a hot-air balloon rises, using density and Archimedes' principle. Your parent sneaks in one wrong fact. Then take turns naming one thing each from the Montgolfiers, Cayley and Lilienthal. Catch the wrong fact to win a bonus point.

Scripture. “But they that wait upon the LORD shall renew their strength; 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)

Isaiah used the eagle’s flight as a picture of the strength God gives. The dreamers who studied birds were looking at a design God made first.

7.2 THE WRIGHT BROTHERS' METHOD: KITES, WIND TUNNEL AND DATA

OBJECTIVES

- Tell how Wilbur and Orville Wright approached flight as a series of problems and tested each one.
- Explain why the Wrights built a wind tunnel and what they learned from it.
- Build a lift balance in front of a box fan and measure how wing curve and angle change the lift.

Warm-up. Hold a long strip of paper by one end just under your lower lip and blow straight out over the top of it. What does the strip do? Then hold a sheet of paper flat in front of a fan, and slowly tilt its front edge up. Describe the push you feel on your hand.

WATCH

How the Wright Brothers Solved the Problem of Flight | The Henry Ford's Innovation Nation

The Henry Ford • 3:15

<https://www.youtube.com/watch?v=bRWbXXs4Wqc>

WHEN TO WATCH

After the first core idea.

BACKUP VIDEO

Wing Warping the Wright Way

Smithsonian National Air and Space Museum • 2:11

<https://www.youtube.com/watch?v=CiCJTR-hZnY>

With the paragraph on control, to see how wing warping worked.

KEY TERMS

wind tunnel

A tube or box where air is blown steadily past a model so its forces can be measured.

wing warping

The Wrights' method of twisting the wing tips in opposite directions to roll the airplane, before ailerons were used.

angle of attack

The angle between a wing and the air flowing toward it.

pitch, roll and yaw

The three ways an airplane turns: nose up or down (pitch), tipping one wing up and the other down (roll), and nose left or right (yaw).

data

Measurements and observations, carefully recorded.

CORE IDEAS

The story. Wilbur and Orville Wright were the sons of Milton Wright, a bishop of the United Brethren Church, and they grew up in a home full of books. They ran a bicycle shop in Dayton, Ohio, where they built and repaired bicycles. In 1899 Wilbur wrote to the Smithsonian Institution asking for everything that had been published about flight. The brothers read it all and decided that the great unsolved problem was not lift or power, but **control**: how to balance and steer a machine in the shifting wind. Watching birds, Wilbur noticed that they twist the tips of their wings to roll. Twisting a long, empty cardboard box in his hands gave him the idea of **wing warping**, and that summer they tested it on a kite with wires that twisted its wings.

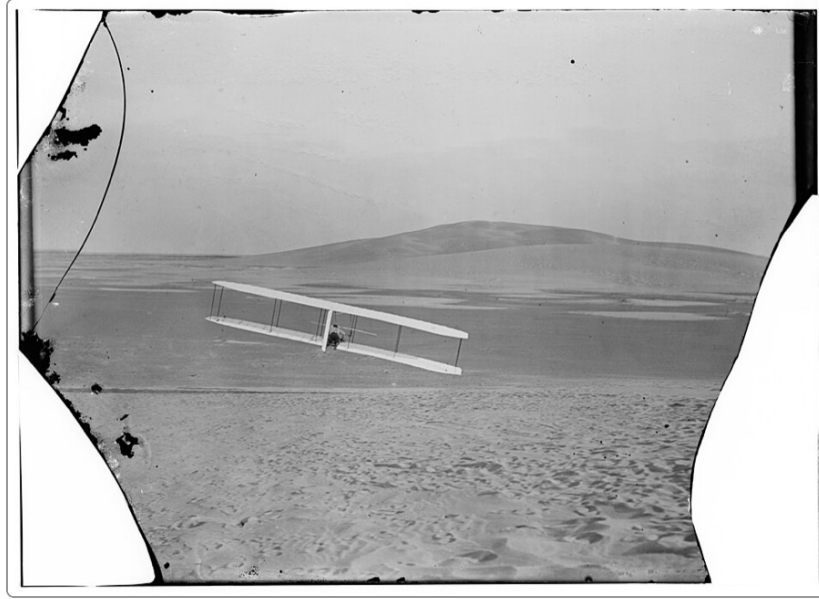
How they figured it out. The Wrights chose Kitty Hawk, on the windy sand dunes of North Carolina, after asking the U.S. Weather Bureau where winds were strong and steady. Their 1900 and 1901 gliders flew, but they made only about a third of the lift that Lilienthal's tables predicted. Instead of giving up, the brothers went home and built a **wind tunnel**: a wooden box about six feet long with a fan at one end driven by the shop's engine. Inside it they placed small balances made from bicycle spokes and hacksaw blades, which measured the lift and drag on little metal wings. In the fall of 1901 they tested about 200 wing shapes, changing one thing at a time and writing down every number. They found that an old number used in everyone's lift calculations was wrong, and they learned which wing shapes worked best. Their 1902 glider, built from their own **data**, flew beautifully, and after adding a movable rudder they could make controlled, banked turns. They made hundreds of glides that fall.

The physics. An airplane can turn in three ways. **Pitch** is nose up or nose down; the Wrights controlled it with a front elevator. **Roll** is one wing up and one wing down;

they controlled it with wing warping. **Yaw** is the nose swinging left or right; they controlled it with the rudder. To turn smoothly, a pilot must use roll and yaw together, as a bird does. The wind tunnel showed how lift changes with the wing's shape and its **angle of attack**: tilt a wing up a little more and it makes more lift, but tilt it too far and the air can no longer follow the top surface, and the lift suddenly drops. That is called a stall.

The engineering. The Wrights did what good engineers do. They broke a huge problem into smaller ones, tested each in the cheapest, safest way first (kites, then gliders, then the wind tunnel), trusted measurements over reputations, and kept careful notebooks. When no engine maker could supply a light enough engine, they designed one with their mechanic, Charlie Taylor. When they found no useful theory for propellers, they worked one out themselves by treating a propeller as a wing that spins. Today every new airplane is tested in wind tunnels and computer models before it flies. “It is the glory of God to conceal a thing,” says Proverbs, “but the honour of kings is to search out a matter.”

PICTURE STUDY



The 1902 Wright Glider in a Turn, Wilbur or Orville Wright, October 1902 · Glass-plate photograph · Library of Congress, Wright Brothers Collection
Image: [Wikimedia Commons](#), public domain

The Wrights took their own photographs with a heavy glass-plate camera, recording their experiments the way they recorded their data. This picture shows the 1902 glider, built from their wind-tunnel results, making a banked turn over the dunes at Kitty Hawk.

Look closely

- Find the pilot. Where is he lying, and why might that reduce drag?
- Find the elevator in front of the wings. What does it control?
- Look at the wings. Can you see that one side is lower than the other in the turn?
- Find the tail at the back. What did the Wrights add to it in 1902?

Talk about it

1. Why did the Wrights test gliders for three years before adding an engine?
2. How did the wind tunnel help them build this glider?
3. Which of the Wrights' habits could you use in your own builds?

Safety first. Keep fingers, hair and loose paper away from the box fan, and have an adult place it on a stable surface.

BUILD

A Box-Fan Wind Tunnel and Lift Balance

You will build a lift balance from a ruler and a pencil, like the Wrights' balances in miniature, and set it in front of a box fan. You will measure the lift of different wings in pennies and run fair tests of wing curve (camber) and angle of attack.

You will need

- A box fan
- A 30-centimeter ruler, a round pencil taped to a block as the pivot, and tape
- Card stock for wings, each 10×15 centimeters
- A small paper cup and pennies; a lump of clay
- A protractor and engineer's notebook
- Optional: a large cardboard box with both ends cut out, to make a straighter airflow in front of the fan

Steps

1. Tape a pencil to a block so it lies flat as a pivot. Lay the ruler across it like a seesaw, at its middle.
2. Tape a flat card-stock wing to one end of the ruler so the wing sticks out sideways into the fan's airflow, lying flat (angle of attack 0°). Tape the penny cup to the other end. Add clay until the ruler balances level with the fan off.
3. Turn the fan on medium. If the wing lifts, add pennies to the cup until the ruler is level again. The number of pennies measures the lift.
4. **Fair test 1, angle of attack.** Tilt the same flat wing to 5° , 10° , 15° and 25° (use the protractor and tape it at that angle). Measure the lift at each. Look for the angle where the lift stops rising: the stall.
5. **Fair test 2, camber.** Make two more wings the same size, one gently curved (bent over a can) and one strongly curved. Test all three at 10° .
6. Record a table: wing, camber, angle, pennies of lift. Make a line graph of lift against angle for the flat wing.

7. **Improve.** Using your data, design the wing that makes the most lift at 10° and test it. Then try one idea of your own, such as a thicker, rounded front edge.
8. Write a short report, as the Wrights would, of what you changed, what you measured and what you learned.

Tips

- Rebalance the ruler with clay each time you change the wing, because different wings weigh different amounts.
- Keep the fan in the same place and at the same speed for every test.
- A cardboard box tunnel in front of the fan smooths the air and gives steadier readings.

Check your work

- ☐ I can explain why the Wrights built a wind tunnel.
- ☐ I can explain how angle of attack and camber change lift, using my data.
- ☐ I can name the three ways an airplane turns and what controls each.

ENGINEER'S NOTEBOOK

1. Draw an airplane and show pitch, roll and yaw with curved arrows. Label the part that controls each on the Wright glider.
2. Draw your lift balance in front of the fan and label the pivot, wing, counterweight and airflow.
3. Graph your angle-of-attack results and circle the stall.

From history. The Wrights' original notebooks, data sheets and glass-plate negatives survive at the Library of Congress. Engineers who have built copies of their wind tunnel and balances have found that the brothers' homemade instruments gave remarkably good results.

COMMON MISTAKES

- Thinking the Wrights were just daring tinkerers. Their success came from careful measurement and patient testing.
- Thinking more angle always means more lift. Past the stall, lift drops.
- Changing the fan speed between tests.

Make it a game • Wright Problems. List the problems the Wrights solved on small slips: lift, control, propulsion. Draw a slip, and tell how they tested that problem. Add pitch, roll or yaw if it applies. Your parent keeps score. Then explain in two sentences why they built a wind tunnel and what the data told them.

Scripture. “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter.” (Proverbs 25:2, KJV)

God hid the secrets of flight in His creation for people to search out. The Wrights’ patient testing is a fine example of searching out a matter.

7.3 THE FOUR FORCES AND THE AIRFOIL: A GLIDER TEST

OBJECTIVES

- Name the four forces of flight and explain how they balance in steady flight.
- Explain lift correctly: the wing turns air downward, and the air pressure above the wing is lower than below.
- Build a glider, measure its glide ratio, and improve it with a fair test of the balance point.

Warm-up. Hold your flat hand out of a moving car window (with a parent driving slowly, or in front of a fan). Tilt the front of your hand up a little, then more. Which way is your hand pushed? Now tilt it down. Write what you felt.

WATCH

The Four Forces of Flight (How Things Fly Demonstration)

Smithsonian National Air and Space Museum • 5:03

<https://www.youtube.com/watch?v=zKSNudPI9UI>

WHEN TO WATCH

After the story, before the physics.

BACKUP VIDEO

How do airplanes actually fly? - Raymond Adkins

TED-Ed • 5:02

<https://www.youtube.com/watch?v=p4VHMsluPmk>

After the physics paragraph, for a closer look at how a wing makes lift.

KEY TERMS

four forces of flight

Lift (up), weight (down), thrust (forward) and drag (backward).

drag

The force of air resisting an object's motion through it.

airfoil

The cross-section shape of a wing, usually rounded at the front, curved on top and thin at the back.

glide ratio

How far a glider travels forward for each unit it drops: distance ÷ height.

center of gravity

The balance point of an aircraft, where its weight seems to act.

CORE IDEAS

The story. On December 17, 1903, on the great sand dunes four miles south of Kitty Hawk, North Carolina, the Wright brothers set their powered Flyer on a 60-foot wooden launching rail. The day was cold, with a strong wind. At 10:35 in the morning, with Orville lying at the controls and Wilbur running beside the wing, the Flyer lifted off and flew for 12 seconds, covering 120 feet. A local man, John T. Daniels, squeezed the camera bulb and took the famous photograph. The brothers took turns and made four flights that day; the last, by Wilbur, lasted 59 seconds and covered 852 feet. For the first time, a powered, heavier-than-air machine carrying a pilot had taken off under its own power, flown under control, and landed on ground as high as where it started.

How they figured it out. To fly with an engine, the Wrights had to balance all four forces. Their wind-tunnel data told them how big the wings must be to lift the machine, the engine and a pilot. Their measurements of drag told them how much thrust they would need, which told them how strong the engine and how good the propellers had to be. They added up the weight of every part before building. They had done the arithmetic, and the Flyer behaved close to what their numbers predicted.

The physics. Four forces act on an airplane. **Weight** pulls it down. **Lift** from the wings pushes it up. **Thrust** from the propeller or engine pushes it forward. **Drag**, the air's resistance, holds it back. In steady, level flight, lift balances weight and thrust balances drag. How does a wing make lift? A wing is shaped and tilted so that it turns the air flowing past it downward. By Newton's third law, if the wing pushes air down, the air pushes the wing up. At the same time, the air flowing over the curved top speeds up and its pressure drops, while the pressure under the wing is higher, so the air presses the wing upward. These are two ways of describing the same flow. (You may hear that air over the top "must catch up" with air underneath. That is not true; air over the top actually arrives at the back edge sooner, and the old explanation gives the wrong answer.) A glider has no engine, so it trades height for thrust: it glides gently downhill, letting gravity pull it forward.

The engineering. Designers shape the **airfoil** for the job: thin and highly curved for slow, heavy-lift flight; thinner and flatter for speed. They make the airplane balance correctly, with its **center of gravity** a little ahead of the center of lift, so that it is stable and does not swoop or tumble. A glider's efficiency is measured by its **glide ratio**. A paper airplane might glide 5 feet for every foot it drops; a large airliner with its engines off can glide roughly 15 feet forward for each foot it drops; and the best sailplanes can glide more than 50 to 1. Long, thin wings and smooth shapes with little drag give the best glide.

PICTURE STUDY



First Flight, John T. Daniels, December 17, 1903 · Glass-plate photograph · Library of Congress

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

The Wrights set up their camera and asked John T. Daniels, a man from the nearby lifesaving station, to squeeze the bulb if the Flyer left the ground. He had never taken a photograph before. His picture is one of the most famous photographs ever made.

Look closely

- Find the rail the Flyer took off from.
- Find Orville at the controls and Wilbur on the sand. Why might Wilbur have been running beside the wing?
- Find the elevator at the front and the propellers at the back.
- Look at how high the Flyer is. Is it climbing?

Talk about it

1. Point to where each of the four forces acts on the Flyer.
2. Why did the Wrights take off into a strong headwind?
3. Why do you think the Wrights cared so much about having a photograph?

Safety first. Fly gliders only where no one can be hit, and never aim them at people or pets. If you launch from a height, stand on a stable stair or deck with an adult, not on a chair.

BUILD

The Glide Ratio Test

You will build a glider from card stock, a straw and a paper clip, launch it from a measured height, and calculate its glide ratio. Then you will run a fair test of where the balance point is, changing only the position of the nose weight, and improve your glider for the longest glide.

You will need

- Card stock or a clean foam tray for wings and tail
- A drinking straw or thin wooden skewer for the body
- Paper clips (for nose weight) and tape
- Scissors, a ruler and a tape measure
- A launch spot about 1.5 to 2 meters high (a stair landing or deck with an adult)
- Engineer's notebook

Steps

1. Cut a main wing 20×4 centimeters and a tail 8×3 centimeters from card stock. Give the wing a gentle curve (camber) by bending it over a pencil.
2. Tape the wing on top of the straw about one-third back from the front, and the tail at the back end. Add a small vertical fin at the tail. Slide one paper clip onto the nose.
3. Find the balance point by resting the glider on your fingertip. Mark it.
4. Measure your launch height. Launch the glider gently and level, the same way each time, and measure how far forward it lands. Do three flights.
5. Calculate the glide ratio: average distance $\div$ launch height. Record it.
6. **Fair test.** Move the nose clip to three positions (or use 1, 2 and 3 clips at the nose). Find and mark the balance point each time. Test each three times and calculate the glide ratio.
7. Record a table: nose weight, balance point (cm from the nose), average distance, glide ratio, how it flew (dove, stalled and swooped, or glided smoothly).

8. **Improve.** Using your best balance, change one thing about the wing, such as its length, its curve or a slight upward bend at the tips. Test it. Try to get the best glide ratio in the family.

Tips

- If the glider swoops up and then dives (stalls), add nose weight. If it dives straight down, remove some.
- Launch with a gentle push, not a throw. You are testing the glide, not your arm.
- Indoor tests are fairer because there is no wind.

Check your work

- ☐ I can name the four forces and show where each acts on my glider.
- ☐ I can explain how a wing makes lift without using the “catch-up” myth.
- ☐ I can calculate a glide ratio and explain how the balance point changed it.

ENGINEER’S NOTEBOOK

1. Draw an airplane in level flight with four arrows for lift, weight, thrust and drag. Make lift equal to weight and thrust equal to drag.
2. Draw an airfoil with air flowing past it. Show the air turned downward behind the wing and mark “lower pressure” above and “higher pressure” below.
3. Graph your glide ratios for each nose weight.

From history. The 1903 Wright Flyer was damaged by a gust of wind after the fourth flight and never flew again. After many years in England, it came home in 1948 and now hangs in the Smithsonian’s National Air and Space Museum in Washington, D.C.

COMMON MISTAKES

- Saying air over the top of a wing must “catch up” with air underneath. It does not; the wing turns the air downward and lowers the pressure above it.
- Thinking a glider has no thrust at all. Gravity pulling it down a gentle slope gives it its forward motion.
- Throwing harder to get a longer flight; a fair glide test uses a gentle, equal launch.

Make it a game • Glide Distance Bet. Make a paper glider. Estimate how far it will glide from a table. Measure the actual glide and compute the glide ratio by dividing distance by height. Adjust weight by a paper clip and predict again. Closest estimate wins. Name the four forces and say which one is largest when the glider flies steadily.

7.4 PROPELLERS, JETS, ROCKETS AND DRONES

OBJECTIVES

- Explain how propellers, jet engines and rockets each make thrust using Newton's third law.
- Tell how Robert Goddard proved that rockets work in empty space, and how a quadcopter drone flies and steers.
- Build and launch paper air rockets and run a fair test of one design change; state the FAA safety rules for drones.

Warm-up. Stand on a skateboard or sit on a wheeled office chair (with a parent watching) holding a heavy ball. Throw the ball forward hard. Which way do you roll? Write a sentence explaining it with Newton's third law.

WATCH

STEMonstrations: Newton's Third Law of Motion

NASA Johnson · 3:07

<https://www.youtube.com/watch?v=dCF--YOjiOw>

WHEN TO WATCH

After the story, before the physics.

BACKUP VIDEO

How Jet Engines Work

Animagraffs · 5:01

<https://www.youtube.com/watch?v=L24Wf0VITE0>

With the paragraph on jet engines.

KEY TERMS

propeller

A set of spinning, twisted blades that push air (or water) backward to make thrust; each blade works like a small spinning wing.

jet engine

An engine that sucks in air, squeezes it, burns fuel in it and blasts the hot gas out the back to make thrust.

rocket

An engine or vehicle that carries both its fuel and the oxygen to burn it, and pushes hot gas out its nozzle; it works even in empty space.

quadcopter

A drone with four rotors; it steers by changing the speed of each rotor.

FAA

The Federal Aviation Administration, the U.S. agency that makes the rules for everything that flies, including drones.

CORE IDEAS

The story. Robert Goddard, an American physics professor, dreamed of rockets that could reach the upper atmosphere and even space. In 1920 a major newspaper wrote that a rocket could not work in empty space because it would have nothing to push against, and it suggested Goddard lacked the knowledge taught in high schools. Goddard kept working. On March 16, 1926, on his aunt's farm in Auburn, Massachusetts, he launched the world's first liquid-fueled rocket. It flew for about two and a half seconds, rose about 41 feet and landed 184 feet away, but it proved his design worked. Forty-three years later, on July 16, 1969, a Saturn V rocket launched Apollo 11 toward the moon. The next day, that same newspaper printed a correction, admitting that a rocket does work in a vacuum.

How they figured it out. Goddard tested his ideas with measurements. In his laboratory he fired small rocket motors inside a sealed chamber with the air pumped out, and measured that they pushed just as well, or better, with no air at all. He also kept careful records of every launch, learning from each failure: changing the fuel feed, the nozzle and the way the rocket was steadied. Newton had already given the answer: a rocket does not push on the air outside. It pushes on its own exhaust gas, and the gas pushes back on the rocket.

The physics. Every kind of thrust is Newton's third law. A **propeller's** twisted blades are small wings that spin, throwing air backward, so the air pushes the airplane forward. A **jet engine** sucks in air at the front, squeezes it with spinning fan blades, sprays in fuel and burns it, and blasts the hot gas out the back at high speed; the faster and more gas it throws backward, the more thrust. A **rocket** carries both its fuel and the oxygen to burn it, so it needs no air at all; it throws its exhaust

backward, and the exhaust pushes it forward. A **quadcopter** drone has four rotors pushing air downward to hold it up. Two spin clockwise and two counterclockwise so the drone does not spin around. To move forward, it speeds up its back rotors and slows its front ones, tipping forward so part of the push points backward.

The engineering. Engineers choose the engine to fit the job. Propellers are efficient for slower airplanes; jet engines carry airliners high and fast; rockets are the only way to reach space. The Saturn V that carried astronauts to the moon stood 363 feet tall. Today, small drones carry cameras for farmers, builders, rescuers and inspectors, who use them to look at bridges and power lines without climbing. Because drones share the sky with airplanes, the **FAA** sets rules. Recreational flyers must pass the free online TRUST safety test, register any drone that weighs 250 grams or more, fly no higher than 400 feet, keep the drone in sight, and never fly over people, near airports or near emergency scenes. Check the FAA's website for current rules before you fly.

PICTURE STUDY



The Launch of Apollo 11, NASA, July 16, 1969 · Photograph · Kennedy Space Center, Florida

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

NASA photographed the launch of Apollo 11, which carried Neil Armstrong, Buzz Aldrin and Michael Collins toward the first landing on the moon. The Saturn V's five first-stage engines together made about 7.5 million pounds of thrust.

Look closely

- Find the flame and exhaust. Which way are they going?
- Find the rocket. Which way is it going?
- Look at the launch tower. How does it help you judge the rocket's size?
- Find the different sections, or stages, of the rocket.

Talk about it

1. Explain the launch using Newton's third law.
2. Why does a rocket need to carry its own oxygen, while a jet engine does not?
3. Why do you think big rockets are built in stages that drop away?

Safety first. Air rockets only: never use chemical rocket motors, fire or fuel. Wear safety glasses. Launch outdoors in an open space, away from power lines, roads and people, and never aim a rocket at a person, pet or window. Drones are flown only with an adult and only following FAA rules.

BUILD

Paper Air Rockets: A Fair Test

You will build paper rockets that are launched by a burst of air from a stomped bottle, measure how far they fly, and run a fair test of one design choice, such as the number of fins. You will explain the launch with Newton's third law.

You will need

- Launcher: an empty 2-liter plastic bottle, about 1 meter of flexible tubing or a long cardboard tube that fits snugly in the bottle neck, and strong tape (or a store-bought stomp rocket launcher)
- Rockets: paper, card stock, tape, and a pencil or tube that just fits over the end of the launch tube to roll the rocket body
- Scissors, a tape measure, a protractor and safety glasses
- Engineer's notebook

Steps

1. Build the launcher: tape the tubing tightly into the bottle neck so no air escapes. Prop the free end at a 45° angle with a stick or block.
2. Roll a sheet of paper around the pencil to make the rocket body, about 20 centimeters long. Tape it. Fold and tape one end closed into a nose cone.
3. Make three rockets the same except for the fins: one with no fins, one with three fins, and one with four fins, all with fins the same size.
4. **Predict** which will fly farthest and straightest.
5. Outdoors, slide a rocket onto the launch tube. With everyone behind the launcher and wearing safety glasses, stomp the bottle hard. Measure the distance. Re-inflate the bottle by blowing into the tube.
6. Launch each rocket three times, stomping as evenly as you can. Record a table: rocket, distance of each flight, average, and whether it flew straight or tumbled.
7. Explain with Newton's third law why the rocket flies, and explain what the fins did.

8. **Improve.** Change one more thing, such as the length of the rocket, the launch angle (30°, 45°, 60°) or the shape of the nose, and test it. Write which change helped most.

Tips

- Make the rocket body slide easily but snugly on the launch tube; too loose wastes air, too tight will not launch.
- Ask one person to stomp every time so the stomps are as equal as possible.
- Fins at the back keep the rocket pointed forward, just as feathers do on an arrow.

Check your work

- ☐ I can explain how a propeller, a jet and a rocket each make thrust.
- ☐ I can explain why a rocket works in space.
- ☐ I can name four FAA safety rules for flying a drone.

ENGINEER'S NOTEBOOK

1. Draw a propeller airplane, a jet and a rocket. Add an arrow for the air or gas pushed backward and an arrow for the thrust forward on each.
2. Draw a quadcopter from above. Mark which rotors spin clockwise and which counterclockwise, and show which rotors speed up to fly forward.
3. Graph your rocket test results and write what you would change next.

From history. Igor Sikorsky, who had dreamed of helicopters since boyhood in Russia, flew his VS-300 helicopter in Connecticut in 1939. It used one large rotor on top and a small tail rotor to keep the body from spinning, the same problem that quadcopters solve by spinning their rotors in opposite directions. Sikorsky was a devout Christian who wrote books about his faith.

COMMON MISTAKES

- Thinking rockets push against the air. They push against their own exhaust and work best in empty space.
- Thinking all four drone rotors spin the same way. Two spin each way so the drone does not twirl.
- Changing the stomp and the rocket in the same test.

Make it a game • Newton's Third Race. Race balloon rockets or paper rockets along a string and measure distance. Before each launch, say what the thrust pushes against, and why a rocket works in empty space as Goddard proved. Your parent names propeller, jet, rocket or quadcopter, and you tell how each makes thrust. Highest total wins.

FLIGHT

For thousands of years people watched birds and wished they could fly. The first to rise into the air did it by floating, in the hot-air balloons of the Montgolfier brothers in 1783. Then Sir George Cayley worked out what a flying machine would need, and Otto Lilienthal flew more than two thousand glides on wings he built himself. In this unit you will follow those dreamers, and then two brothers from Dayton, Ohio, who solved the problem of flight not by daring alone but by careful method: kites, a homemade wind tunnel, notebooks full of data, and three summers of patient testing at Kitty Hawk.

You will learn the four forces of flight and how a wing really makes lift, by turning air downward and lowering the pressure above it. You will measure lift on a balance in front of a box fan, test gliders for the best glide, and launch air rockets to see Newton's third law at work. Finally you will see how propellers, jet engines, rockets and drones all push against air or exhaust to move. "They shall mount up with wings as eagles," wrote Isaiah. By patient study, people learned to do it.

PREREQUISITES

- Knows Newton's three laws (Unit 1) and Archimedes' principle (Unit 6)
- Knows how a lever balances (Unit 1)
- Can measure angles with a protractor

MASTERY CHECKLIST

- ☐ I can explain why a hot-air balloon rises, using Archimedes' principle.
- ☐ I can tell how the Wright brothers solved flight through kites, a wind tunnel, data and control in three directions.
- ☐ I can name the four forces of flight and explain lift correctly: the wing turns air downward and the pressure above it is lower.
- ☐ I can run a fair test on a glider and calculate its glide ratio.
- ☐ I can explain how propellers, jet engines, rockets and drones make thrust, and state the basic safety rules for flying drones.

OPTIONAL KITS FOR THIS UNIT

- **Ryze Tello drone:** For grade 5 and up, flown with an adult. A small indoor drone that weighs about 80 grams and can be flown from a phone or programmed with Scratch-style blocks. Fits Lesson 7.4 and Unit 8. Follow the FAA rules in Lesson 7.4.
- **KiwiCo Tinker Crate:** Ages 9 and up. Some monthly crates are flight projects, such as gliders and launchers, with notes on the science. Fits Lessons 7.3 and 7.4.

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

7.1 The Dreamers: Montgolfier Balloons, Cayley and Lilienthal

2 sessions of 45 minutes

7.2 The Wright Brothers' Method: Kites, Wind Tunnel and Data

2 sessions of 45 minutes

7.3 The Four Forces and the Airfoil: A Glider Test

2 sessions of 45 minutes

7.4 Propellers, Jets, Rockets and Drones

2 sessions of 45 minutes

UNIT 7 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

Why does a hot-air balloon rise? Use the words density and Archimedes' principle.

2. **5 pts**

What did Sir George Cayley and Otto Lilienthal each contribute to flight?

3. **5 pts**

Why did the Wright brothers build a wind tunnel, and what did they find?

4. (5 pts)

Name the three ways an airplane turns and what the Wrights used to control each.

5. (5 pts)

Name the four forces of flight. Which pairs balance in steady, level flight?

6. (5 pts)

Explain how a wing makes lift. Do not use the “catch-up” idea.

7. (5 pts)

Predict: you tilt a wing in your wind tunnel to a very steep angle. What happens to the lift?

8. (5 pts)

A glider launched from 2 meters high lands 9 meters away. What is its glide ratio? Another glider from the same height lands 12 meters away. Which is better?

9. (5 pts)

Why does a rocket work in space, where there is no air?

10. (5 pts)

Give four FAA rules for flying a recreational drone.

ANSWER KEY

1. Hot air is less dense than the cooler air around it. By Archimedes' principle, the buoyant force equals the weight of the cool air the balloon pushes aside; when that is more than the weight of the balloon, basket and hot air, it rises.
2. Cayley worked out the basic airplane shape (fixed wing, tail, separate thrust) and named the forces of flight. Lilienthal made about 2,000 glides, showed curved wings lift better, and published lift measurements.
3. Their gliders made far less lift than the published tables predicted. They built a wind tunnel to measure lift on about 200 wing shapes and found the old numbers were wrong, then used their own data to design the 1902 glider.
4. Pitch (front elevator), roll (wing warping), yaw (rudder).
5. Lift and weight balance; thrust and drag balance.
6. The wing's shape and angle turn the passing air downward; by Newton's third law the air pushes the wing up. Also, air speeds up over the curved top and its pressure drops, so higher pressure below pushes the wing up.
7. The lift rises as the angle increases, then drops suddenly when the wing stalls because the air can no longer follow the top surface.
8. $9 \div 2 = 4.5$. The second glider: $12 \div 2 = 6$, which is better.
9. It pushes its exhaust gas backward, and the gas pushes the rocket forward (Newton's third law). It carries its own oxygen, so it needs no air to burn fuel or to push against.
10. Any four: pass the free TRUST test; register drones of 250 grams or more; fly no higher than 400 feet; keep it in sight; do not fly over people; stay away from airports and emergency scenes; check the FAA's current rules.

PORTFOLIO PIECE: A TESTED GLIDER

Design, build and test a glider that achieves the best glide ratio you can, using card stock, foam, straws, balsa or paper. Launch it from the same height every time. Change only one thing between versions, and test at least three versions with at least three flights each. Present the glider with a data table, a graph of glide ratio for each version, a labeled drawing showing the four forces, and a paragraph explaining what made your best version fly best.

LOOK FOR	WHAT IT MEANS
Fair test	Changed only one thing between versions, launched the same way from the same height, and recorded at least three flights each.
Data and math	Distances are measured and averaged, and glide ratios are calculated correctly and graphed.
Science explanation	Explains lift correctly (air turned downward, lower pressure above), the four forces, and the role of the balance point.
Improvement	The final glider is better than the first, and the notebook explains why.
Craftsmanship	The glider is straight, balanced and neatly built, and the drawing is clearly labeled.

ROBOTS AND INVENTION

A robot is a machine that can sense the world, decide what to do, and act. The first factory robot, Unimate, could only repeat the motions it had been taught. Today's Mars rovers drive themselves around rocks on another planet, because a radio message from Earth takes many minutes to arrive. In this unit you will learn the sense–think–act loop that every robot follows, write algorithms and programs with loops and decisions in Scratch or MakeCode, and see how sensors and feedback let machines correct themselves, from the thermostat on your wall to a robot that follows a line.

The year ends with a capstone. You will choose a real problem, take it all the way through the engineering design process you learned in Unit 1, and present your invention, together with the best build from every unit, at a family engineering fair. Like the engineers who saved the crew of Apollo 13 with duct tape and cardboard, you will learn that good engineering is careful thinking, honest testing and stubborn improvement.

PREREQUISITES

- Knows the engineering design process (Unit 1) and how switches and AND/OR circuits work (Unit 4)
- Can use a computer or tablet with an adult's help to open a free website
- Has a year's worth of notebook pages and builds to choose from for the fair

MASTERY CHECKLIST

- ☐ I can explain the sense–think–act loop and use it to describe a factory robot and a Mars rover.
- ☐ I can write an algorithm and a program that uses sequence, loops and if–then decisions, and I can debug it.
- ☐ I can explain feedback and describe how a thermostat and a line-following robot correct themselves.
- ☐ I can take my own invention through every step of the design process and test and improve it.
- ☐ I can present my work clearly at a family engineering fair.

OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** Ages 8 and up. A pocket-sized computer with buttons, lights, a light sensor, a thermometer and a compass, programmed for free in Microsoft MakeCode blocks. A good choice for Lessons 8.2 and 8.3.
- **Raspberry Pi (Raspberry Pi Foundation projects):** Ages 10 and up with an adult. The Raspberry Pi is a small, inexpensive computer; the foundation's free project site has step-by-step Scratch, Python and electronics projects. Fits Lessons 8.2–8.4.
- **Makeblock mBot:** Ages 8 and up. A small wheeled robot kit with line-following and distance sensors, programmed with Scratch-style blocks. Fits Lessons 8.1 and 8.3.
- **Sphero robots:** Ages 8 and up. Rolling robots programmed with blocks on a tablet; good for practicing loops, sensors and driving a course. Fits Lessons 8.1–8.3.

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

LESSONS IN THIS UNIT

8.1 Sense, Think, Act: From Unimate to the Mars Rovers

2 sessions of 45 minutes

8.2 Algorithms and Coding: Loops and Decisions in Scratch or MakeCode

2 sessions of 45 minutes

8.3 Sensors and Feedback: Thermostats and Line Followers

2 sessions of 45 minutes

8.4 Capstone Design Challenge and the Family Engineering Fair

2 sessions of 45 minutes

UNIT 8 REVIEW

Answer each question. Use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

What are the three steps of the robot loop? Give an example of each for a robot vacuum.

2. **5 pts**
What job did Unimate do, and why was it a good job for a robot?
3. **5 pts**
Why must Mars rovers be able to drive themselves around rocks?
4. **5 pts**
Write a loop algorithm to draw a hexagon. What is the turn angle?
5. **5 pts**
Predict: a maze rover program has the IF-touching-wall block outside the forever loop. What will happen?
6. **5 pts**
What did Ada Lovelace write in 1843, and how is Jacquard's loom connected to computers?
7. **5 pts**
What is the difference between open-loop and closed-loop control? Give an example of each.
8. **5 pts**
How does a bimetallic strip in a thermostat work?
9. **5 pts**
A line-following robot's right sensor sees the dark line. Which way should it turn? Why is this feedback?
10. **5 pts**
How did the Apollo 13 engineers use the engineering design process?

ANSWER KEY

1. Sense (bump or cliff sensors detect a wall or stairs), think (the program decides to turn), act (motors turn the wheels).
2. It lifted hot metal parts from a casting machine and stacked them at a General Motors factory. The work was dangerous and repetitive for people.
3. Radio signals take about 3 to 22 minutes each way between Earth and Mars, so drivers on Earth cannot react in time.
4. Repeat 6 times: move forward, turn 60 degrees. $360 \div 6 = 60$ degrees.
5. The rover checks for the wall only once at the start, so it will drive into the wall and not turn.
6. She published notes with a step-by-step method for Babbage's Analytical Engine to calculate numbers, often called the first published computer program. Jacquard's loom used punched cards to control a machine, an idea Babbage borrowed for his engine's instructions.
7. Open loop follows instructions without checking the result (a toaster on a timer, a sprinkler on a timer). Closed loop measures the result and corrects itself using feedback (a thermostat, cruise control, a line follower).
8. Two metals bonded together expand by different amounts when heated, so the strip bends as the temperature changes and opens or closes the furnace switch.
9. It should turn right, back toward the line. It is feedback because the robot measures where the line is and corrects its path over and over.
10. They defined the problem (square filters, round openings) and constraints (only materials aboard, little time), designed an adapter, built and tested a prototype on the ground, and sent clear instructions to the crew, who built it.

PORTFOLIO PIECE: THE CAPSTONE INVENTION AND THE FAMILY ENGINEERING FAIR

Your capstone invention from Lesson 8.4 is this unit's portfolio, together with your fair display. Present the invention with its full design-process notebook, data and improvement, and set out your best build from each of the eight units with the notebook pages that go with it. Explain your work to family and guests at the fair.

LOOK FOR	WHAT IT MEANS
Design process	Notebook shows the problem, criteria and constraints, three sketched ideas, a plan, a build, tests and an improvement.
Testing and data	At least two rounds of fair tests with a data table and graph, and the improvement is supported by the data.
It works	The invention does what the criteria say, or the notebook honestly explains what still needs work and why.
Year in review	The display includes one build and its notebook pages from each unit, labeled with the unit's main idea.
Presentation	Explains the problem, design, tests and lessons learned clearly to at least three visitors.

8.1 SENSE, THINK, ACT: FROM UNIMATE TO THE MARS ROVERS

OBJECTIVES

- Explain the sense–think–act loop and identify sensors, controllers and actuators in a robot.
- Tell how Unimate became the first factory robot and how Mars rovers drive themselves.
- Test how a communication delay affects driving a “rover,” and design rules that let it drive itself.

Warm-up. Make a list of machines in your house that do something by themselves (a dishwasher, a thermostat, a robot vacuum, an automatic night-light). For each one, what does it notice, and what does it do? Which ones are robots, do you think? Why?

WATCH

Meet the Mars Rovers! | Let's Explore Mars! | SciShow Kids

SciShow Kids · 6:48

<https://www.youtube.com/watch?v=ujh-dtEvylw>

WHEN TO WATCH

After the story, before the physics.

BACKUP VIDEO

First Industrial Robot Ever Installed on an Assembly Line | Innovation Nation

The Henry Ford · 3:20

<https://www.youtube.com/watch?v=-Xl2c91pWGc>

With the story of Unimate.

KEY TERMS

robot

A machine that can sense its surroundings, decide what to do using a program, and act on its own.

sensor

A device that detects something, such as light, distance, touch, temperature or position, and turns it into a signal.

controller

The computer that runs the robot's program and makes its decisions.

actuator

A part that makes the robot move or act, such as a motor, a gripper or a speaker.

autonomous

Able to work on its own, without a person controlling each move.

CORE IDEAS

The story. In 1954 an American inventor named George Devol applied for a patent on a machine arm that could be taught a series of motions and then repeat them exactly. He met an engineer, Joseph Engelberger, who saw how useful it could be, and together they started a company. In 1961 their robot, called Unimate, went to work at a General Motors factory in New Jersey. Its job was to lift red-hot metal parts out of a casting machine and stack them, work that was dangerous for people. Fifty years later, robots were driving on Mars. NASA's small Sojourner rover rolled onto Mars in 1997. The twin rovers Spirit and Opportunity landed in 2004; Opportunity kept working for more than 14 years. Curiosity landed in 2012, and Perseverance landed in 2021, carrying a small helicopter named Ingenuity that made the first powered flights on another planet.

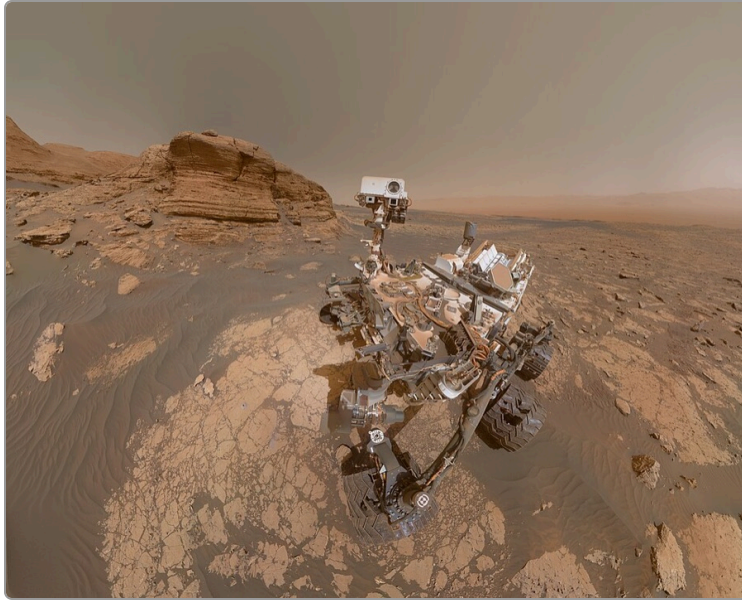
How they figured it out. Unimate had motors and a memory, but almost no senses: it did the same motions every time, so the parts had to be placed exactly where it expected them. Mars rover engineers faced a harder problem. A radio signal between Earth and Mars takes from about 3 to 22 minutes each way, depending on where the planets are. A driver on Earth cannot steer a rover around a rock in real time. So engineers gave the rovers cameras and software to make maps of the ground, judge which paths are safe, and drive around obstacles by themselves. They test every new idea first on full-size copies of the rovers in a "Mars Yard" of sand and rocks in California, before sending the commands to Mars.

The physics and the parts. Every robot works in a loop: **sense, think, act**, and repeat. **Sensors** gather information: cameras, light sensors, touch switches, distance sensors that time an echo of sound or light, and sensors that measure tilt and turning. The **controller**, a computer running a program, decides what to do. **Actuators**, usually

electric motors like the ones you built in Unit 4, move the wheels, arms and grippers. The Mars rovers also use clever mechanics: a six-wheel “rocker-bogie” suspension lets each wheel ride up and over rocks while keeping the rover level, and the wheels are driven by small motors with gears that trade speed for force, as you learned in Unit 1.

The engineering. Today robots weld and paint cars, pack boxes, help surgeons, inspect pipes and bridges, milk cows, and explore the deep sea and other planets. Engineers design robots for jobs that are dangerous, dirty, dull or out of reach. They must plan for things going wrong: robots have emergency stop buttons, safety fences or sensors that slow them when a person comes near, and careful testing before they work alongside people. A robot does only what it is designed and programmed to do, so the wisdom and care of the people who build it matter most.

PICTURE STUDY



Curiosity Rover at Mont Mercou, NASA/JPL-Caltech/MSSS, 2021 · Photograph (a “selfie” made from many images) · Gale Crater, Mars

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

Curiosity took this “selfie” with a camera on the end of its robotic arm, taking dozens of pictures that were stitched together. The arm itself was left out of the final image, which is why you cannot see it.

Look closely

- Find the mast with its camera “head.” What sense does it give the rover?
- Count the wheels. Look at how they are connected to the body.
- Find any tools or instruments on the rover. What might they measure?
- Look at the ground and the cliff. What obstacles would the rover have to steer around?

Talk about it

1. Name one sensor, the controller, and one actuator on Curiosity.
2. Why can’t engineers on Earth steer Curiosity like a remote-control car?
3. What would you want a rover to do by itself if it lost contact with Earth for a day?

Safety first. Clear the floor of anything a blindfolded “rover” could trip over, and have a spotter walk beside them. Use only a soft blindfold the rover can lift at any time.

BUILD

Driving a Rover with a Delay

You will play a rover-driving game. One person is the rover, blindfolded, and another is mission control, giving commands from across the room. First you will drive the course with instant commands, then with a delay like the one between Earth and Mars, and finally with a set of sense–think–act rules the rover follows by itself. You will measure the time and the number of bumps each way.

You will need

- A soft blindfold, masking tape and a few soft obstacles such as pillows or cardboard boxes
- A stopwatch and a timer for the delay
- Index cards and a pencil
- Engineer’s notebook

Steps

1. Mark a start and a goal with tape about 5 meters apart, and set three soft obstacles between them. Have a spotter stay beside the rover the whole time.
2. **Run 1, instant commands.** Mission control gives simple commands (“forward 2 steps,” “turn left a quarter turn”). The rover obeys at once. Time the run and count the bumps.
3. **Run 2, Mars delay.** Rearrange the obstacles. This time, mission control writes each command on a card, and the card is handed to the rover only after a 10-second delay. Time the run and count bumps.
4. **Run 3, autonomous rules.** Write three or four rules the rover follows alone, using its hands as touch sensors, for example: “Walk forward slowly with hands out. IF you touch something, step back, turn right a quarter turn, and try again. IF you touch the wall, you have reached the goal.” Mission control may only say “Go.”
5. Record a table: run, time, bumps, number of commands sent.
6. Label your rules as sense, think and act.

7. **Improve.** Change one rule to make Run 3 faster or safer, and test it with the obstacles in a new place. Did your change help?
8. Write a paragraph explaining why Mars rovers need to drive themselves.

Tips

- Keep the step size the same for every rover command, or the test will not be fair.
- Take turns, so everyone gets to be the rover and mission control.
- Real rover drivers plan a whole day's drive at once, then let the rover carry it out.

Check your work

- ☐ I can explain sense, think and act, and give an example of each.
- ☐ I can explain why a delay makes remote driving slow and risky.
- ☐ My data compare the three ways of driving.

ENGINEER'S NOTEBOOK

1. Draw a robot of your own design. Label at least two sensors, the controller and two actuators.
2. Draw the sense–think–act loop as a circle with arrows, and write what a robot vacuum does at each step.
3. Make a timeline of robots: Unimate (1961), Sojourner (1997), Spirit and Opportunity (2004), Curiosity (2012), Perseverance and Ingenuity (2021).

From history. Opportunity was planned to work on Mars for about 90 days. It kept going for more than 14 years and drove about 28 miles, farther than any vehicle had driven on another world at that time, until a giant dust storm in 2018 covered its solar panels.

COMMON MISTAKES

- Thinking any machine with motors is a robot. A robot must sense and decide, not just move.
- Thinking robots think like people. A robot follows its program; it cannot do what it was not designed for.
- Writing rules that do not say what to do when a sensor detects nothing.

Make it a game · Sense Think Act. Your parent is a rover on Mars and you are mission control. Give single-step commands, like forward two steps. Because of the delay, wait ten seconds between commands. Name the sensor, controller and actuator at each step. Then tell the story of Unimate, the first factory robot, to wrap up.

8.2 ALGORITHMS AND CODING: LOOPS AND DECISIONS IN SCRATCH OR MAKECODE

OBJECTIVES

- Define an algorithm and write one precisely enough for someone else to follow.
- Use sequence, loops, if-then decisions and variables in a block-coding program.
- Find and fix bugs, and compare the length of programs with and without loops.

Warm-up. Write step-by-step instructions for a parent to draw a square on paper, as if the parent were a robot who does exactly what the words say and nothing more. Have the parent follow them exactly. What went wrong? Rewrite the steps until they work.

WATCH

How to Make a Jumping Game in Scratch | Tutorial

Scratch Team · 5:04

<https://www.youtube.com/watch?v=1jHvXakt1qw>

WHEN TO WATCH

At the start of Session 2, with Scratch open beside it. Pause and build each step yourself.

BACKUP VIDEO

How to use a micro:bit | Tutorial #1

Science Buddies · 11:07

<https://www.youtube.com/watch?v=ltcTxWW3c5Q>

If you are using a micro:bit and MakeCode instead of Scratch.

KEY TERMS

algorithm

A precise, step-by-step set of instructions for doing a task.

program

An algorithm written in a language a computer can follow.

loop

An instruction to repeat a set of steps, a certain number of times or forever.

conditional

An if-then instruction: IF something is true, THEN do this (ELSE do that).

variable

A named place in a program to store a number or word that can change, such as a score.

bug

A mistake in a program that makes it do something unintended; finding and fixing it is debugging.

CORE IDEAS

The story. In 1804 the French weaver Joseph-Marie Jacquard built a loom controlled by a chain of punched cards: each card's holes told the loom which threads to lift for one row of the pattern. Change the cards, and the same loom wove a different pattern. In England, the mathematician Charles Babbage designed a mechanical computer he called the Analytical Engine, which would read its instructions from punched cards like Jacquard's. It was never finished in his lifetime. But in 1843 Ada Lovelace, a gifted mathematician who understood Babbage's design, published notes that included a step-by-step method for the engine to calculate a series of numbers. It is often called the first published computer program. She also saw that such a machine might one day work with music and pictures, not just numbers.

How they figured it out. Jacquard, Babbage and Lovelace all saw the same powerful idea: a machine's work could be described as a list of exact steps and stored separately from the machine. Change the steps, and the same machine does a new job. Lovelace's notes even showed how to repeat a group of steps instead of writing them out again and again, which is the idea we now call a loop. A century later, the first electronic computers were programmed by setting switches and plugging cables, and programmers quickly learned that every mistake had to be found and fixed. In 1947 operators of the Harvard Mark II computer found a moth stuck in a switch and taped it into their logbook as the first actual "bug" found.

The ideas of coding. An **algorithm** must be exact; a computer does only what it is told. Programs are built from a few basic ideas. **Sequence:** steps happen in order.

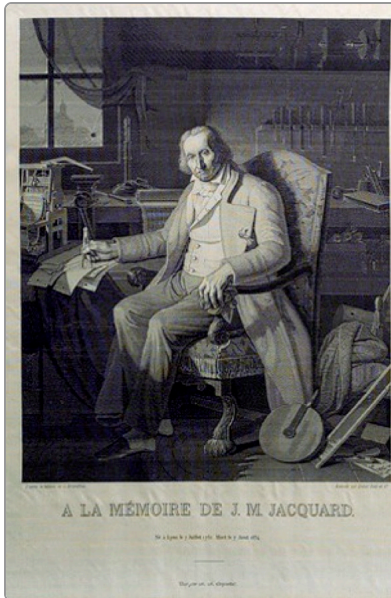
Loops: repeat steps, such as "repeat 4 times: move 100, turn 90 degrees" to draw a square. **Conditionals:** IF the sprite is touching a wall, THEN turn around.

Variables: store values that change, such as a score or a speed. With these four ideas, programmers build everything from games to the software that lands rovers on Mars.

The engineering. Software engineers plan before they code, write small pieces and test each one, and expect bugs. A good debugging habit is to predict what each block

will do, run the program, watch closely where it does something different, and change one thing at a time, just as you have done with every build this year. Scratch, a free block-coding language made at the Massachusetts Institute of Technology, and Microsoft MakeCode, which programs the BBC micro:bit, let you use the same ideas professional programmers use, by snapping blocks together instead of typing.

PICTURE STUDY



Portrait of Joseph-Marie Jacquard, Woven in Silk, Michel-Marie Carquillat, after a painting by Claude Bonnefond, 1839 · Silk woven on a Jacquard loom · Woven in Lyon, France; copies in several museums

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

This is not a drawing or an engraving: it is woven from silk on a Jacquard loom. It took about 24,000 punched cards, each controlling one row of threads, to “program” the loom to weave it. Charles Babbage owned a copy and showed it to visitors to explain what his Analytical Engine could do.

Look closely

- Look closely at the fine shading. How many rows of thread do you think it took?
- Find the small model of a loom on the table beside Jacquard.
- Find his tools. What do they tell you about his work?
- Look for any punched cards in the picture.

Talk about it

1. How is a chain of punched cards like a computer program?
2. Why would a loom that reads cards be faster than a weaver choosing threads by hand?
3. Why do you think Babbage used this portrait to explain his computer?

Safety first. Use the computer with a parent's permission and only on the Scratch or MakeCode websites. Do not share your full name, address or photographs online.

BUILD

Polygons, Loops and a Maze Rover in Scratch (or MakeCode)

You will program a sprite to draw shapes, first without loops and then with loops, and count how many blocks each program needs. Then you will program a “rover” sprite to find its way through a maze using if-then decisions and a variable, keeping a debugging log of every bug you find.

You will need

- A computer or tablet with Scratch (scratch.mit.edu, free; the online editor works without an account) or Microsoft MakeCode (makecode.microbit.org, free)
- Optional: a BBC micro:bit
- Graph paper and engineer’s notebook for planning and the debugging log

Steps

1. **Plan.** On paper, write an algorithm for drawing a square: the moves and the turns.
2. In Scratch, add the Pen extension. Build the square with no loops: move 100 steps, turn 90 degrees, four times. Count the blocks.
3. Now build it with a “repeat 4” loop. Count the blocks again. Record both numbers.
4. Change your loop to draw a triangle, a hexagon and an octagon. Find the rule for the turn: $360 \div \text{number of sides}$. Record a table: shape, sides, turn angle, blocks used.
5. **Maze rover.** Draw a simple maze on the backdrop with walls of one color. Program a rover sprite that moves forward in a “forever” loop and, IF it is touching the wall color, THEN backs up and turns 90 degrees.
6. Add a variable called “bumps” that goes up by one each time the rover touches a wall. Add a goal; IF the rover touches it, THEN it says “Arrived!” and stops.
7. Keep a debugging log: for every bug, write what you expected, what happened and what you changed.

8. **Improve.** Change one thing in your rover's rules, such as the turn angle or which way it turns, and run it three times. Does it reach the goal with fewer bumps? Record the results. (MakeCode version: use the micro:bit's buttons to choose a shape and show its turn angle on the lights, or program a loop that flashes your name in Morse code.)

Tips

- Save your project often.
- If the sprite moves too fast to see, add a short “wait” inside the loop.
- When a program does not work, read it aloud block by block as if you were the computer.

Check your work

- ☐ I can explain what an algorithm is and why it must be exact.
- ☐ I can use a loop and an if-then block in a program.
- ☐ My debugging log shows at least three bugs and how I fixed them.

ENGINEER'S NOTEBOOK

1. Write your square algorithm both ways, with and without a loop, and circle the part that repeats.
2. Draw a flowchart for your maze rover: start, move, “touching wall?” diamond with yes and no arrows, and the goal.
3. Make a table of shapes, sides and turn angles, and write the rule you discovered.

From history. Grace Hopper, a mathematician and U.S. Navy officer, helped program the Harvard Mark I and later built one of the first compilers, a program that translates words people can read into instructions a computer can run. Her work led to programming languages that ordinary people could learn, the great-grandparents of Scratch.

COMMON MISTAKES

- Turning by the inside angle of the shape instead of the outside turn (a square needs 90° turns, a triangle needs 120° turns).
- Putting the if-then block outside the forever loop, so it is checked only once.
- Changing several blocks at once when debugging, so you cannot tell which change fixed it.

Make it a game • Robot Recipe Test. Write an algorithm to draw a square on paper using only these commands: forward, turn, repeat. Your parent follows it exactly and draws. Fix any bug, then shorten it using a loop. Add an "if" step like "if you hit the edge, turn." Fewer steps than your last try is a personal record.

8.3 SENSORS AND FEEDBACK:

THERMOSTATS AND LINE FOLLOWERS

OBJECTIVES

- Explain open-loop and closed-loop (feedback) control with examples.
- Describe how a thermostat, Watt's governor and a line-following robot use sensors and feedback.
- Measure how much feedback improves accuracy in a walking test, and build a bimetal-style temperature sensor.

Warm-up. Stand 4 meters from a tape mark on the floor. Look at it, close your eyes, and walk to stop exactly on it. Measure how far you missed. Now do it with your eyes open. Why is the second try so much better? Write a sentence using the word feedback.

WATCH

How Does A Thermostat Work? (Mr. Wizard)

Official Mr.Wizard's World Channel · 3:47

<https://www.youtube.com/watch?v=6r9UAdb2kDo>

WHEN TO WATCH

After the physics paragraph. Watch what the metal strip does as it warms and cools.

Note: Mr. Wizard heats a strip with a candle; that is for adults only. Use only the hair dryer or warm water method in this lesson, with an adult.

KEY TERMS

feedback

Information about what a system is doing that is sent back to control it.

open-loop control

Control without feedback: the machine follows its instructions without checking the result, like a toaster on a timer.

closed-loop control

Control with feedback: the machine measures the result and corrects itself, like a thermostat.

set point

The goal value a control system tries to reach, such as 68 °F on a thermostat.

bimetallic strip

Two metals bonded together that expand by different amounts when heated, so the strip bends as the temperature changes.

CORE IDEAS

The story. In 1788 James Watt added a spinning “governor” to his steam engines. Two heavy iron balls hung from arms on a shaft turned by the engine. When the engine ran too fast, the balls swung outward and, through a linkage, partly closed the steam valve; when it slowed, the balls dropped and opened the valve again. The engine kept itself at a steady speed with no person watching. About a century later, in 1883, Warren Johnson, a teacher in Wisconsin, tired of the custodian coming into his classroom to adjust the heat, patented an electric thermostat that rang a bell in the boiler room when the room needed more or less heat. Thermostats like his are the ancestors of the one on your wall.

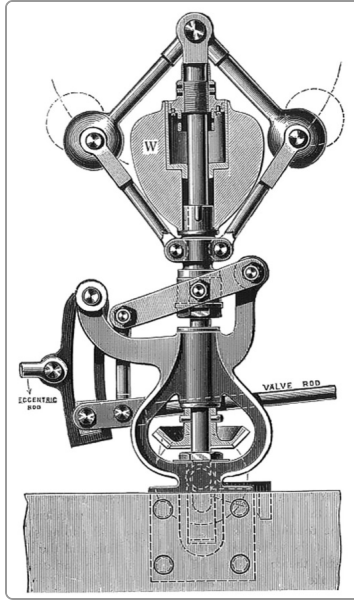
How they figured it out. Both inventors noticed the same pattern: measuring the result and using it to correct the machine works better than setting the machine once and hoping. Engineers later studied feedback with mathematics, after they found that some governors “hunted,” speeding up and slowing down over and over because they corrected too much, too late. They learned to tune a control system so it corrects firmly but smoothly, the same way you slow down as you approach your mark on the floor.

The physics. In **open-loop control**, a machine follows instructions without checking: a toaster on a timer cannot tell whether the bread is burned. In **closed-loop control**, a **sensor** measures the result, the controller compares it with the **set point**, and an actuator makes a correction, again and again. That is **feedback**. An old-style thermostat uses a **bimetallic strip**, two metals bonded together. When warmed, one metal expands more than the other, so the strip bends; when it cools, it bends back. The bending strip opens or closes a switch for the furnace. A line-following robot

shines light on the floor and measures the reflection with two light sensors, one on each side of a dark line. If the left sensor sees the dark line, the robot turns left; if the right one does, it turns right. Many small corrections keep it on the line.

The engineering. Feedback is everywhere engineers want something to stay steady: cruise control in a car, the autopilot in an airplane, the float valve in a toilet tank, the pressure in city water pipes, the speed of the generators at Niagara, and the balance of a two-wheeled scooter or a drone. Automatic carts follow lines or markers through factories and warehouses. Engineers choose sensors that are accurate and reliable, decide how quickly to correct, and plan what the machine should do if a sensor fails.

PICTURE STUDY



*A Centrifugal Governor, Unknown engraver, 1913 · Engraving · From *Heat Engines*, a textbook*

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

The flying-ball governor became the symbol of steam power. This textbook drawing shows how the spinning balls are linked to the valve that controls the steam, a complete feedback loop made of iron.

Look closely

- Find the two heavy balls and the arms that hold them.
- Find the spinning shaft. What turns it?
- Follow the linkage from the balls to the valve.
- Imagine the engine speeding up. Which way do the balls move?

Talk about it

1. Name the sensor, the controller and the actuator in the governor.
2. What happens to the steam valve when the engine runs too fast? Too slow?
3. Why is this a closed-loop system, not an open-loop one?

Safety first. An adult handles the hair dryer or hot water. Do not touch heated foil until it cools. Clear the floor for the walking test, and have a spotter walk beside anyone with eyes closed.

BUILD

The Feedback Walk and a Bimetal Sensor

First you will measure how much feedback improves accuracy by walking to a target with and without it, exactly like a robot with and without sensors. Then you will build a bimetal strip from foil and paper, which bends as it warms because the two layers expand differently, and measure how far it bends.

You will need

- Masking tape, a tape measure and a soft blindfold
- A strip of foil-backed gum wrapper, or aluminum foil glued smoothly to a strip of paper with a glue stick, about 1×10 centimeters
- A clothespin or binder clip, a ruler and a hair dryer (adult only) or a mug of hot water to hold the strip above
- Engineer's notebook
- Optional: a BBC micro:bit, programmed in MakeCode to show the light level or temperature

Steps

1. **Open loop.** Stand 4 meters from a tape target. Look at it, put on the blindfold, and walk to stop on it, with a spotter beside you. Measure how far you missed. Do three trials.
2. **Closed loop with a partner sensor.** Blindfolded again, walk while a partner says only “warmer” or “colder” each step. Measure the miss. Three trials.
3. **Closed loop with your own sensor.** Walk with eyes open. Measure the miss. Three trials.
4. Record a table and a bar graph of average misses for the three methods. Explain the results with the words open loop, closed loop and feedback.
5. **Bimetal sensor.** Clip one end of your foil-and-paper strip so it sticks straight out sideways. Hold a ruler behind the free end and note its position.
6. With an adult, warm the strip gently with the hair dryer on low from 30 centimeters away (or hold it over a mug of hot water) for 20 seconds.

Measure how far the tip moves, and which way: toward the foil side or the paper side. Let it cool and measure again.

7. **Fair test.** Test warming times of 10, 20 and 30 seconds. Record how far the tip moves for each.
8. **Improve.** Design how your strip could switch on an LED circuit when it gets warm, using a piece of foil as a contact (draw it, and build it if you can). Or, with a micro:bit, program it to show an arrow when the room is warmer than your set point and a different picture when cooler.

Tips

- Paper and foil change with heat and moisture differently, so your strip may curl partly from drying; notice whether it returns when cooled.
- Keep the hair dryer at the same distance every time.
- In the walking test, the spotter keeps the walker safe but does not give hints.

Check your work

- ☐ I can explain open-loop and closed-loop control with examples.
- ☐ I can explain how a thermostat and a line follower use feedback.
- ☐ My data show how much feedback improved accuracy.

ENGINEER'S NOTEBOOK

1. Draw a feedback loop diagram for a thermostat: set point, sensor, controller, furnace, room temperature, back to the sensor.
2. Draw a line-following robot from above with two light sensors on either side of a dark line. Write the two IF-THEN rules it follows.
3. List five feedback systems in your home or car.

From history. Warren Johnson's company, founded to make his thermostats, still makes building control systems today. Long before him, around 1620, the Dutch inventor Cornelis Drebbel built an oven for hatching chicks that used a column of mercury to adjust its own air damper, one of the earliest known thermostats.

COMMON MISTAKES

- Thinking a timer is feedback. A timer does not measure the result.
- Thinking more correction is always better. Correcting too hard or too late makes a system overshoot and wobble.

- Forgetting that a sensor can fail; good designs plan for it.

Make it a game · Thermostat Walk. Walk across a room following a line on the floor with your eyes half closed, while your parent says "left" or "right" as feedback. Compare this to walking with no feedback at all. Explain open-loop and closed-loop control. Name the set point in a thermostat and tell how Watt's governor worked.

8.4 CAPSTONE DESIGN CHALLENGE AND THE FAMILY ENGINEERING FAIR

OBJECTIVES

- Take an invention of your own through every step of the engineering design process.
- Test a prototype fairly, record the data, and improve it at least once.
- Present your work and the year's best builds clearly at a family engineering fair.

Warm-up. Look back through your engineer's notebook from the whole year. Mark your three favorite pages with sticky notes. For each one, write one sentence: what did you learn, and what would you do differently now?

WATCH

How Duct Tape Saved the Lives of the Apollo 13 Crew

Smithsonian Channel • 3:24

https://www.youtube.com/watch?v=eeEM_IBUv70

WHEN TO WATCH

After the story of Apollo 13, before you choose your own problem.

KEY TERMS

capstone

A final project that pulls together everything learned in a course.

prototype

A working model built to test an idea before the final version.

presentation

Explaining your problem, design, tests and results clearly to other people.

criteria and constraints

What a design must do, and the limits it must work within (materials, time, cost, size).

trade-off

Giving up some of one good thing to get more of another, such as strength for lightness.

CORE IDEAS

The story. In April 1970, two days into the flight of Apollo 13 toward the moon, an oxygen tank in the service module burst. The three astronauts moved into the small lunar landing module to use it as a lifeboat. Soon a new danger appeared: carbon dioxide from their breathing was building up, because the landing module's air filters were too few for three men for so many days. The square filter canisters from the command module would not fit the round openings in the landing module. On the ground, a team led by engineer Ed Smylie gathered exactly the items the astronauts had on board: plastic bags, cardboard covers from the flight plan, duct tape, hoses and even a sock. They designed an adapter, built it, tested it, and read the instructions up to the crew step by step. The astronauts built the "mailbox," the carbon dioxide level dropped, and all three came home safely.

How they figured it out. The Apollo 13 engineers followed the same design process you learned in Unit 1, under great pressure. They **asked** exactly what the problem was. They listed their **constraints**: only the materials aboard, and very little time. They **imagined** and **planned** a design, **built** a prototype with the same materials, **tested** that it worked, and **improved** the instructions so the tired astronauts could follow them. Careful work, done honestly and quickly, saved three lives.

Your challenge. Now it is your turn. Choose a real problem in your home or for someone you know, something small enough to build in a week. Some ideas: a device that waters a plant when the soil is dry; a better way to carry groceries up the stairs; a bird feeder that keeps squirrels out; a pulley lift for a tree house or toy box; a chain-reaction machine that rings a bell; a coded micro:bit or Scratch alarm; a stronger, lighter bridge or tower than the one you built earlier this year. Write the criteria and constraints, sketch at least three ideas, and choose one, explaining the **trade-offs**.

The engineering fair. Engineers do not finish when the build works; they must explain it so others can use it, check it and learn from it. At your family engineering fair, set out your capstone and your best build from each unit, with its notebook pages. Prepare to tell each visitor four things: the problem, your design, what your tests showed, and what you would improve. God gave Bezalel wisdom and skill "in all manner of workmanship," and He gives each of us gifts to serve others. *Fabricando fit faber*: by making, one becomes a maker.

PICTURE STUDY



The Apollo 13 “Mailbox” at Mission Control, NASA, April 1970 · Photograph · Mission Control, Houston, Texas

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

This photograph shows the prototype adapter that engineers built on the ground from the same materials the Apollo 13 crew had aboard. It was tested here before the instructions were read up to the spacecraft.

Look closely

- Find the square filter canister. What has been added around it?
- Look for tape, plastic and cardboard. Why use only these materials?
- Find the hose. Where would the air go?
- Look at the people. What might they be checking?

Talk about it

1. What were the criteria and constraints of this design problem?
2. Why did the engineers build and test a copy on the ground first?
3. What does this story teach about how to work when things go wrong?

Safety first. Read the safety notes for any skills you use from earlier units (electricity from batteries only, adult help with hot glue and cutting, safety glasses for anything under tension or that can fly). Have an adult approve your plan before you build.

BUILD

My Capstone Invention

Over two sessions (plus extra build time during the week if needed) you will take your own invention from problem to presentation, using every step of the design process and at least one fair test with data.

You will need

- Engineer's notebook and graph paper
- Materials chosen for your design from the year's supply list (cardboard, craft sticks, string, spools, tape, batteries, LEDs, motors, a micro:bit and so on)
- A trifold board or large poster for the fair
- A camera or phone for photographs

Steps

1. **Ask.** Write a one-sentence problem statement. List at least three criteria and three constraints.
2. **Research.** Find out how others have solved similar problems. Look back at the units that might help (machines, structures, circuits, flight, coding). Write down two ideas you borrowed.
3. **Imagine.** Sketch at least three different ideas. Make a simple chart scoring each against your criteria.
4. **Plan.** Draw your chosen design with labels and measurements, and list the materials. Have an adult check the plan for safety.
5. **Build** a prototype.
6. **Test.** Decide what to measure (time, distance, load, number of successes out of 10 tries, and so on) and test at least three times. Record a data table.
7. **Improve.** Change one thing based on your test, and test again the same way. Record the new data and compare.
8. **Present.** Make a board with the problem, sketches, final design, data table, graph and "what I would do next." At the family engineering fair, show your

invention and explain it to at least three visitors. Set out your best build from each unit beside it.

Tips

- Choose a problem small enough to finish. A simple design that works and is well tested is better than a grand one that is not done.
- Photograph each version before you change it.
- Practice your explanation once out loud before the fair; keep it to about two minutes.

Check your work

- ☐ My notebook shows every step of the design process for my invention.
- ☐ I tested fairly, recorded data and made at least one improvement.
- ☐ I explained my work clearly to visitors at the fair.

ENGINEER'S NOTEBOOK

1. Draw your three first ideas side by side and score them in a chart.
2. Draw your final design with labels, measurements and materials.
3. Write a letter to next year's engineer (maybe yourself) with three pieces of advice from this year.

From history. The Apollo 13 crew, Jim Lovell, Jack Swigert and Fred Haise, splashed down safely in the Pacific Ocean on April 17, 1970. The flight is remembered as a “successful failure”: it never landed on the moon, but the teamwork of the astronauts and the engineers on the ground brought everyone home.

COMMON MISTAKES

- Choosing a problem too big to finish in a week.
- Skipping the testing because the prototype “looks done.” Testing is where engineers learn.
- Only telling visitors what you built. Tell them the problem, the tests and what you learned.

Make it a game • Pitch Your Invention. Give a sixty-second pitch of your capstone idea. Your parent plays a judge who must ask one question about criteria and constraints, one about a trade-off, and one about the prototype test. Answer clearly. Add what you would improve first. Earn a point for each answer that mentions data.

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

God filled Bezalel with skill to design and build. Engineering is one of the ways people use God’s gifts of wisdom and workmanship to serve others.

ROBOTS AND INVENTION

A robot is a machine that can sense the world, decide what to do, and act. The first factory robot, Unimate, could only repeat the motions it had been taught. Today's Mars rovers drive themselves around rocks on another planet, because a radio message from Earth takes many minutes to arrive. In this unit you will learn the sense–think–act loop that every robot follows, write algorithms and programs with loops and decisions in Scratch or MakeCode, and see how sensors and feedback let machines correct themselves, from the thermostat on your wall to a robot that follows a line.

The year ends with a capstone. You will choose a real problem, take it all the way through the engineering design process you learned in Unit 1, and present your invention, together with the best build from every unit, at a family engineering fair. Like the engineers who saved the crew of Apollo 13 with duct tape and cardboard, you will learn that good engineering is careful thinking, honest testing and stubborn improvement.

PREREQUISITES

- Knows the engineering design process (Unit 1) and how switches and AND/OR circuits work (Unit 4)
- Can use a computer or tablet with an adult's help to open a free website
- Has a year's worth of notebook pages and builds to choose from for the fair

MASTERY CHECKLIST

- ☐ I can explain the sense–think–act loop and use it to describe a factory robot and a Mars rover.
- ☐ I can write an algorithm and a program that uses sequence, loops and if–then decisions, and I can debug it.
- ☐ I can explain feedback and describe how a thermostat and a line-following robot correct themselves.
- ☐ I can take my own invention through every step of the design process and test and improve it.
- ☐ I can present my work clearly at a family engineering fair.

OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** Ages 8 and up. A pocket-sized computer with buttons, lights, a light sensor, a thermometer and a compass, programmed for free in Microsoft MakeCode blocks. A good choice for Lessons 8.2 and 8.3.
- **Raspberry Pi (Raspberry Pi Foundation projects):** Ages 10 and up with an adult. The Raspberry Pi is a small, inexpensive computer; the foundation's free project site has step-by-step Scratch, Python and electronics projects. Fits Lessons 8.2–8.4.
- **Makeblock mBot:** Ages 8 and up. A small wheeled robot kit with line-following and distance sensors, programmed with Scratch-style blocks. Fits Lessons 8.1 and 8.3.
- **Sphero robots:** Ages 8 and up. Rolling robots programmed with blocks on a tablet; good for practicing loops, sensors and driving a course. Fits Lessons 8.1–8.3.

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

LESSONS IN THIS UNIT

8.1 Sense, Think, Act: From Unimate to the Mars Rovers

2 sessions of 45 minutes

8.2 Algorithms and Coding: Loops and Decisions in Scratch or MakeCode

2 sessions of 45 minutes

8.3 Sensors and Feedback: Thermostats and Line Followers

2 sessions of 45 minutes

8.4 Capstone Design Challenge and the Family Engineering Fair

2 sessions of 45 minutes

UNIT 8 REVIEW

Answer each question. Use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**

What are the three steps of the robot loop? Give an example of each for a robot vacuum.

2. **5 pts**
What job did Unimate do, and why was it a good job for a robot?
3. **5 pts**
Why must Mars rovers be able to drive themselves around rocks?
4. **5 pts**
Write a loop algorithm to draw a hexagon. What is the turn angle?
5. **5 pts**
Predict: a maze rover program has the IF-touching-wall block outside the forever loop. What will happen?
6. **5 pts**
What did Ada Lovelace write in 1843, and how is Jacquard's loom connected to computers?
7. **5 pts**
What is the difference between open-loop and closed-loop control? Give an example of each.
8. **5 pts**
How does a bimetallic strip in a thermostat work?
9. **5 pts**
A line-following robot's right sensor sees the dark line. Which way should it turn? Why is this feedback?
10. **5 pts**
How did the Apollo 13 engineers use the engineering design process?

ANSWER KEY

1. Sense (bump or cliff sensors detect a wall or stairs), think (the program decides to turn), act (motors turn the wheels).
2. It lifted hot metal parts from a casting machine and stacked them at a General Motors factory. The work was dangerous and repetitive for people.
3. Radio signals take about 3 to 22 minutes each way between Earth and Mars, so drivers on Earth cannot react in time.
4. Repeat 6 times: move forward, turn 60 degrees. $360 \div 6 = 60$ degrees.
5. The rover checks for the wall only once at the start, so it will drive into the wall and not turn.
6. She published notes with a step-by-step method for Babbage's Analytical Engine to calculate numbers, often called the first published computer program. Jacquard's loom used punched cards to control a machine, an idea Babbage borrowed for his engine's instructions.
7. Open loop follows instructions without checking the result (a toaster on a timer, a sprinkler on a timer). Closed loop measures the result and corrects itself using feedback (a thermostat, cruise control, a line follower).
8. Two metals bonded together expand by different amounts when heated, so the strip bends as the temperature changes and opens or closes the furnace switch.
9. It should turn right, back toward the line. It is feedback because the robot measures where the line is and corrects its path over and over.
10. They defined the problem (square filters, round openings) and constraints (only materials aboard, little time), designed an adapter, built and tested a prototype on the ground, and sent clear instructions to the crew, who built it.

PORTFOLIO PIECE: THE CAPSTONE INVENTION AND THE FAMILY ENGINEERING FAIR

Your capstone invention from Lesson 8.4 is this unit's portfolio, together with your fair display. Present the invention with its full design-process notebook, data and improvement, and set out your best build from each of the eight units with the notebook pages that go with it. Explain your work to family and guests at the fair.

LOOK FOR	WHAT IT MEANS
Design process	Notebook shows the problem, criteria and constraints, three sketched ideas, a plan, a build, tests and an improvement.
Testing and data	At least two rounds of fair tests with a data table and graph, and the improvement is supported by the data.
It works	The invention does what the criteria say, or the notebook honestly explains what still needs work and why.
Year in review	The display includes one build and its notebook pages from each unit, labeled with the unit's main idea.
Presentation	Explains the problem, design, tests and lessons learned clearly to at least three visitors.

TOY LAB: THE PHYSICS OF PLAY

Toys are some of the cleverest machines in the house. A Frisbee is a spinning wing. A LEGO brick is a piece of precision engineering, molded so exactly that a brick made in 1958 still clicks onto one made today. A Rubik's Cube hides a mechanism so neat that it holds itself together with no glue at all. And every wind-up or battery toy is a small lesson in springs, gears, motors and switches, designed to be cheap, tough and safe for children.

This optional bonus unit is for after the family engineering fair, for the summer, or for any week that needs something fun. Each lesson follows the same path as the rest of the year: the story of the toy and its inventor, how they figured it out, the physics of why it works, and the engineering of how it is made safely and cheaply enough to sell. You will test flying discs, measure LEGO clutch power, take apart a puzzle cube, and carefully tear down an old toy to see how it was designed. “The streets of the city shall be full of boys and girls playing,” wrote the prophet Zechariah. Play is a good gift, and so is understanding it.

PREREQUISITES

- Knows lift and the four forces of flight (Unit 7)
- Knows gears, springs, motors and switches (Units 1 and 4)
- Knows how to run a fair test and keep an engineer's notebook

MASTERY CHECKLIST

- ☐ I can explain how a Frisbee makes lift and why spin keeps it steady.
- ☐ I can explain what tolerance and clutch power mean and how injection molding makes identical parts.
- ☐ I can describe the hidden mechanism that holds a Rubik's Cube together.
- ☐ I can tear down a toy safely, map how its energy flows, and name the safety features its engineers designed in.
- ☐ I can name the main toy-safety rules: small parts, sharp edges, magnets and button batteries.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. Each monthly box is a toy to build that shows one physics idea, with a video explaining the engineering. Exactly the spirit of Lesson 9.4.
- **KiwiCo Tinker Crate:** Ages 9 and up. Many crates are working toys with gears, springs and levers, plus notes on how they work. Fits Lessons 9.1 and 9.4.
- **Snap Circuits (Elenco):** Ages 8 and up. Rebuild the switches, motors and lights you find in a toy teardown without any wiring. Fits Lesson 9.4.
- **LEGO Classic bricks:** Ages 4 and up (small parts). A box of basic bricks is all you need for the clutch-power tests in Lesson 9.2.

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

LESSONS IN THIS UNIT

9.1	The Frisbee: A Spinning Wing	2 sessions of 45 minutes
9.2	The LEGO Brick: Precision, Tolerance and Clutch Power	2 sessions of 45 minutes
9.3	The Rubik's Cube: A Hidden Mechanism	2 sessions of 45 minutes
9.4	Toy Teardown: How a Toy Is Engineered	2 sessions of 45 minutes

UNIT 9 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. **5 pts**
How does a Frisbee make lift?
2. **5 pts**
Predict: you throw a disc without spin. What happens, and why?
3. **5 pts**
Why do disc designers put most of the mass in the rim?

4. (5 pts)

What is clutch power, and what causes it?

5. (5 pts)

What is tolerance, and why must LEGO molds have such tight tolerances?

6. (5 pts)

Predict: two bricks are joined by 2 studs and another pair by 8 studs. Which needs more weight to pull apart, and why?

7. (5 pts)

How many centers, edges and corners does a Rubik's Cube have, and what holds them together?

8. (5 pts)

What happens to a puzzle cube if its center screws are much too tight or much too loose?

9. (5 pts)

Trace the energy path in a wind-up toy.

10. (5 pts)

Name three toy-safety rules engineers must design for.

ANSWER KEY

1. Its rounded edge and domed shape, tilted at a slight angle of attack, turn the passing air downward, so the air pushes the disc up; the pressure above it is lower than below.
2. It tips over and tumbles. Without spin it has no gyroscopic stability, and the lift on the front half flips it.
3. Mass far from the center gives more angular momentum for the same spin, so the disc is steadier.
4. How firmly bricks hold together. It is friction caused by the studs squeezing slightly against the walls and tubes; the elastic plastic pushes back.
5. Tolerance is how much a part's size may differ from the design. Bricks must all be almost exactly the same size so every brick grips every other brick with the same clutch power.
6. The 8-stud pair, because more studs give more contact surfaces and more friction.
7. 6 centers, 12 edges, 8 corners. The centers are screwed to a core; the edges and corners have feet that interlock with their neighbors, so the pieces hold one another in.
8. Too tight: more friction, so it is stiff and hard to turn. Too loose: it wobbles and pieces can pop out.
9. Winding stores energy in the mainspring; the spring turns a gear train (with a governor controlling the speed); the gears turn wheels, cams or cranks that make the toy move.
10. Any three: no small parts for children under 3; no sharp edges or points; button-cell battery doors closed with screws; magnets held so they cannot come loose; no lead paint; strong seams.

PORTFOLIO PIECE: A TOY OF MY OWN DESIGN

Design and build a working toy from household materials that uses at least one physics idea from this year (spin, a spring or rubber band, gears, a lever, lift, buoyancy or a circuit). Test it at least three times, improve it once, and present it with an energy-path diagram, a list of materials and approximate cost, and a safety check showing it has no sharp edges, no loose small parts and no exposed battery. Let a younger child or a sibling play with it (with an adult watching) and write down what you learned from watching them.

LOOK FOR	WHAT IT MEANS
Physics	The toy clearly uses a physics idea, and the notebook explains it correctly.
Testing and improvement	At least three tests are recorded, and one improvement is made based on the results.
Energy path	A clear diagram shows how energy is stored, controlled and turned into motion.
Safety	A safety check is completed, and the design avoids small parts, sharp edges and loose batteries.
User testing	The toy was tried by another child, and the notes describe what worked and what was confusing.

9.1 THE FRISBEE: A SPINNING WING

OBJECTIVES

- Tell how a cake pan tossed on a beach became the Frisbee.
- Explain how a flying disc makes lift and why spin keeps it from tumbling.
- Build paper-plate fliers and run fair tests of spin and rim weight.

Warm-up. Toss a paper plate across the room without spinning it. Then toss it again with a flick of the wrist so it spins. Do each three times. What is different about the flights? Write your guess about why.

WATCH

Why Does a Frisbee Fly | A Moment of Science | PBS

A Moment of Science • 2:08

<https://www.youtube.com/watch?v=IJPaVi2Fxhc>

WHEN TO WATCH

After the story, before the physics.

BACKUP VIDEO

How a Pie Tin Became the Iconic Frisbee | History of the Frisbee

History of Simple Things • 8:25

<https://www.youtube.com/watch?v=QsRlROHGp3E>

With the story of Fred Morrison and the pie tins.

KEY TERMS

flying disc

A spinning, saucer-shaped toy that flies by making lift, like a round wing.

angle of attack

The angle between the disc (or a wing) and the air flowing toward it.

angular momentum

The “spinning momentum” of a turning object, which makes it resist being tipped over.

gyroscopic stability

The steadiness a spinning object gets from its angular momentum, so it keeps pointing the same way.

rim

The thick, curved outer edge of a disc,
where most of its mass is.

CORE IDEAS

The story. In 1937 Fred Morrison and Lucile Nay were tossing a metal cake pan back and forth on a beach in California when someone offered them a quarter for it. They realized people would pay for a good flying toy. After serving as a pilot in World War II, Morrison designed a plastic disc, first called the Flyin-Saucer, and in 1955 an improved one called the Pluto Platter. In 1957 he sold it to a small toy company, Wham-O. The company heard that college students in New England had long tossed the empty pie tins of the Frisbie Pie Company of Bridgeport, Connecticut, and in 1958 it renamed the toy the Frisbee.

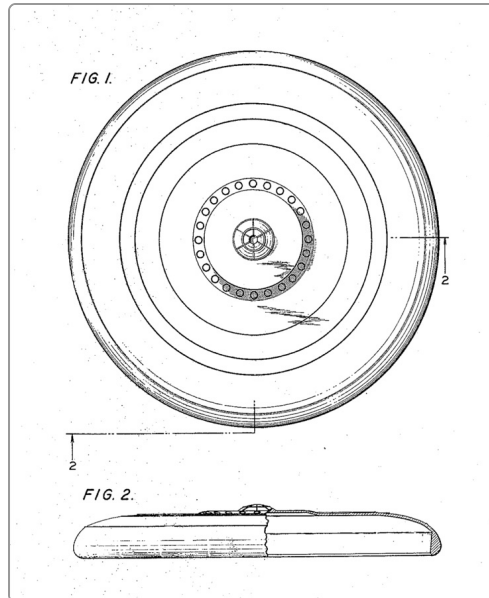
How they figured it out. Morrison learned by throwing, changing and throwing again. Metal pans were heavy and hurt when caught wrong, so he moved to plastic, which was light, slightly flexible and safe to catch. He made the rim thick and rounded and gave the top a gentle dome. In the 1960s Ed Headrick, a designer at Wham-O, studied why discs wobbled and added a ring of small ridges on the top, which made the air flow over it more steadily. He patented the improved disc in 1967, and it flew farther and straighter than any before it.

The physics. A flying disc is a round wing. Its rounded front edge and domed top, tilted up a little at an angle of attack, turn the passing air downward, so the air pushes the disc up (Newton's third law), and the pressure above it is lower than below. That lift is why a thrown disc floats instead of dropping like a plate. But a wing needs to stay pointed the right way, and a disc has no tail. That is the job of spin. A spinning disc has **angular momentum**, which makes it resist tipping, the way a spinning top stays upright: this is **gyroscopic stability**. Without spin, the lift pushes harder on the front half than the back, and the disc flips and tumbles. With spin, that same push only tilts the disc slowly, which is why a Frisbee gently curves to one side near the end of its flight.

The engineering. Disc designers put most of the mass in the **rim**, because mass far from the center gives more angular momentum for the same spin, just as a skater spins slower with arms out. They choose a flexible plastic such as polyethylene so the disc is light, durable and safe to catch, and they shape the edge so it is easy to

grip. Flying discs are made by injection molding: melted plastic is forced into a steel mold, cooled for a few seconds and popped out, so thousands of identical discs can be made each day. Toy designers also test that a disc has no sharp edges and does not crack into sharp pieces when it is dropped or stepped on.

PICTURE STUDY



Morrison's Patent for a Flying Toy, Walter F. Morrison, 1958 · Patent drawing · United States Patent Office
Image: [Wikimedia Commons](#), public domain

Fred Morrison (whose first name was Walter) received this design patent in 1958 for the shape of his flying disc. The drawings show it from several sides, so that anyone could see exactly what shape he was protecting.

Look closely

- Find the view from the side. Is the top flat or domed?
- Find the cross-section. Where is the disc thickest?
- Look at the rim. Why might a thick, curved rim help it fly?
- Look for any ridges or rings on the top.

Talk about it

1. Why does the shape of the edge matter for lift?
2. Why would putting most of the mass in the rim help the disc stay steady when spinning?
3. Why did Morrison want a patent before selling his toy?

Safety first. Throw discs outdoors or in a large open room, never toward people's faces, windows or pets. Throw only when the catcher is ready.

BUILD

Paper-Plate Fliers: Spin and Rim Tests

You will make simple flying discs from paper plates and run two fair tests: does spin matter, and does adding weight to the rim help? You will measure distance and count how many flights go straight.

You will need

- Sturdy paper plates (all the same kind), masking tape and scissors
- Pennies (2.5 grams each) and a kitchen scale
- A tape measure, chalk or markers for distance, and a long hallway or yard
- Engineer's notebook

Steps

1. **Disc A.** Tape two plates rim to rim (one upside down on the other) to make a domed disc. Weigh it.
2. **Spin test.** From a start line, slide-throw Disc A five times without spin (push it flat off your palm) and five times with a strong flick of the wrist. Measure each distance and count how many flights tumbled.
3. Record a table: throw type, distances, average, number that tumbled. Explain the difference using angular momentum.
4. **Disc B, rim weight.** Make a second disc the same way. Tape 8 pennies evenly around the rim. Weigh it.
5. **Disc C, center weight.** Make a third disc and tape 8 pennies in a cluster at the center. Weigh it; it should match Disc B.
6. **Fair test.** Throw Discs B and C five times each with spin, the same way and from the same line. Measure distances and count wobbly or tumbling flights.
7. Make a bar graph of the averages and explain why the rim-weighted disc behaved differently.
8. **Improve.** Try one more change on your best disc, such as cutting off the bottom plate's flat center to make a ring wing, or adding a strip of tape ridges on top like Headrick's rings. Test and record.

Tips

- Have the same person throw every time, or take turns in the same order.
- Throw low and level; a disc thrown upward stalls and drops.
- Mark each landing spot with chalk and measure after five throws.

Check your work

- ☐ I can explain how a flying disc makes lift.
- ☐ I can explain why spin keeps it from tumbling.
- ☐ My data show how rim weight changed the flight.

ENGINEER'S NOTEBOOK

1. Draw a flying disc in cross-section with arrows showing air turned downward and lift pushing up.
2. Draw two discs, one with weight at the rim and one at the center. Circle the one with more angular momentum.
3. Graph your spin and rim-weight results.

From history. Wham-O sold millions of Frisbees in the 1960s, and new sports grew up around the flying disc. Ed Headrick, who improved the disc, also invented disc golf, with a metal basket target made of hanging chains that catch the disc.

COMMON MISTAKES

- Thinking spin makes the lift. The shape and angle make lift; spin keeps the disc steady.
- Comparing discs of different weights in the rim test.
- Throwing harder for some discs than others.

Make it a game • Spin It Straight. Toss a paper plate gently, once flat and once spinning, outside or in an open room. Predict which flies straighter and why. Explain angle of attack, angular momentum and gyroscopic stability. Tell the beach-pan story of the Frisbee. Your parent scores each correct term. Beat your own distance by changing 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)

When God described a city restored and at peace, He pictured children playing in its streets. Good toys and safe play are part of a blessed, ordered life.

9.2 THE LEGO BRICK: PRECISION, TOLERANCE AND CLUTCH POWER

OBJECTIVES

- Tell how a Danish carpenter's family business developed the LEGO brick.
- Explain clutch power as friction from a slight, springy squeeze, and why tight tolerances matter.
- Measure the clutch power of bricks with a fair test of the number of studs connected.

Warm-up. Snap two LEGO (or similar) bricks together and pull them apart. Then try a brick from a different brand, if you have one, or an old, worn brick. Which pair holds best? Look closely at the underside of a brick and sketch what you see.

WATCH

LEGO Bricks In The Making

The LEGO Group • 8:32

<https://www.youtube.com/watch?v=C3oiy9eekzk>

WHEN TO WATCH

After the story, before the physics. Watch for the molds and the checks for accuracy.

BACKUP VIDEO

How is LEGO made? | Maddie Moate

Maddie Moate • 5:44

<https://www.youtube.com/watch?v=57a30ObPBqc>

For a second look inside a LEGO factory, with the injection-molding machines explained.

KEY TERMS

injection molding

Making plastic parts by melting plastic and forcing it under high pressure into a steel mold, then cooling it and popping the part out.

tolerance

How much a part's size is allowed to differ from the exact size on the drawing.

clutch power

LEGO's name for how firmly bricks hold together: tight enough to stay, loose enough to pull apart.

elastic

Able to bend or squeeze a little and spring back to its shape.

ABS plastic

A tough, shiny plastic that holds its shape and color well; LEGO bricks have been made of it since 1963.

CORE IDEAS

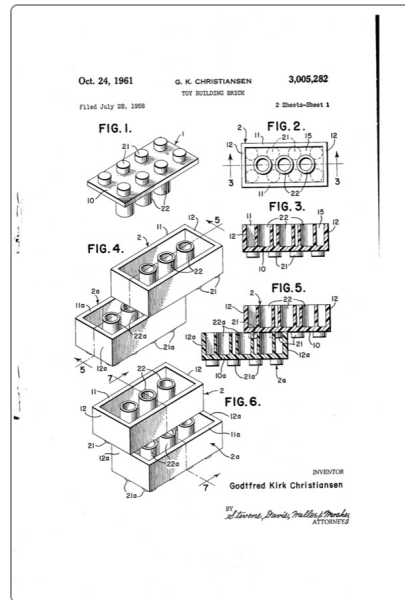
The story. Ole Kirk Christiansen was a carpenter in the village of Billund, Denmark. In the hard years of the 1930s he began making wooden toys, and in 1934 he named his company LEGO, from the Danish words *leg godt*, “play well.” In 1947 the company bought one of the first plastic injection-molding machines in Denmark, and in 1949 it began selling plastic “Automatic Binding Bricks,” based on a British brick called the Kiddicraft Self-Locking Brick. Those early bricks had studs on top but were hollow underneath, and they did not hold together well; buildings came apart easily. Ole Kirk's son, Godtfred Kirk Christiansen, saw that the brick needed a better grip.

How they figured it out. The family tried several designs for the inside of the brick. The answer, patented on January 28, 1958, was to add hollow tubes underneath. The studs of the brick below now press against the walls of the brick on top and against the tubes between them, three points of contact for each stud, which makes the joint firm and the bricks line up exactly. In 1963 LEGO switched from an earlier plastic, which could warp and fade, to ABS, which holds its shape and color for decades. Because the design has stayed the same, a brick molded in 1958 still clicks onto one made today.

The physics. **Clutch power** is friction. When two bricks are pressed together, the studs are a tiny bit too big for the space between the walls and tubes, so the plastic squeezes and bends very slightly, like a spring. Because the plastic is **elastic**, it pushes back, pressing the surfaces together, and that push creates friction that resists pulling apart. More studs connected means more contact surfaces and more friction. If the fit were too loose, there would be no squeeze and no grip; too tight, and the bricks would be hard to separate and might crack.

The engineering. Getting that squeeze exactly right means every brick must be almost exactly the same size. LEGO's steel molds are made to a **tolerance** of a few thousandths of a millimeter, far thinner than a human hair. In **injection molding**, ABS granules are melted, forced into the mold under very high pressure, cooled for a few seconds and pushed out, and machines check the bricks constantly. Safety is engineered in too. Small bricks are a choking hazard for children under 3, so the boxes carry a warning, and in 1969 the company introduced DUPLO bricks, twice as long, wide and tall, too big to swallow, which still fit onto ordinary bricks.

PICTURE STUDY



The LEGO Brick Patent, Godtfred Kirk Christiansen, Filed 1958, granted 1961 · Patent drawing · United States Patent Office (U.S. Patent 3,005,282)

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

This is the American patent for the stud-and-tube brick that Godtfred Kirk Christiansen first patented in Denmark in 1958. The drawings show how the studs of one brick fit between the walls and tubes of the next.

Look closely

- Find the studs on top of the brick.
- Find the tubes on the underside. How many are there?
- Find a drawing of two bricks joined. Where does each stud touch the brick above it?
- Look for letters or numbers labeling the parts.

Talk about it

1. Why do the tubes make the bricks hold together better than a hollow underside?
2. Why must every brick be made to almost exactly the same size?
3. Why do you think the company has kept the same design since 1958?

Safety first. Small bricks and pennies are choking hazards: keep them away from children under 3. Wear safety glasses when loading the cup, in case the bricks snap apart suddenly.

BUILD

The Clutch-Power Test

You will measure how much weight it takes to pull two bricks apart, using a cup of pennies, and run a fair test of how the number of studs connected changes the clutch power. If you have no building bricks, you can do the same test with a press-fit joint you make yourself.

You will need

- Several LEGO or compatible bricks of the same size (2×4 bricks work well) and a few flat plates
- A paper cup with a string handle, tape and pennies (2.5 grams each)
- A kitchen scale, a sturdy table edge and engineer's notebook
- If you have no bricks: drinking straws and a thick piece of cardboard with holes punched just smaller than the straws

Steps

1. Tape the top brick firmly to the underside of the table edge, studs facing down, or clamp it with heavy books so it cannot move.
2. Press a second brick onto it so that only **1 stud** is connected. Tape the cup's string to the bottom brick.
3. Add pennies to the cup one at a time until the bottom brick pulls off. Record the total mass (cup plus pennies). Do three trials.
4. **Predict**, then repeat with 2, 4 and 8 studs connected. Use the same bricks every time if you can.
5. Record a table and make a graph: studs connected (across) and mass to pull apart (up). Is the pattern a straight line?
6. **Brand or age test.** If you have an old, well-used brick or a different brand, test it with 2 studs and compare.
7. Explain your results with the words friction, elastic and tolerance.
8. **Improve.** Design the strongest joint you can between two bricks using no more than four studs (for example, overlapping plates or a brick across a seam). Test it.

Tips

- Press bricks together the same firm way each time; a half-pressed joint is much weaker.
- If 8 studs hold more pennies than your cup can carry, hang a small bag of rice or sand instead and weigh it.
- With straws and cardboard, test 1, 2 and 4 straws pushed into snug holes.

Check your work

- ☐ I can explain clutch power as friction from a springy squeeze.
- ☐ I can explain what tolerance means and why LEGO molds must be so precise.
- ☐ My graph shows how the number of studs changed the clutch power.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of two bricks joined. Show where each stud touches the walls and tube, with small arrows for the squeeze.
2. Draw a DUPLO brick next to a LEGO brick at the right sizes and label why the bigger one is safer for little children.
3. Graph your clutch-power data.

From history. Hilary Page, the British toymaker whose Kiddicraft Self-Locking Bricks inspired LEGO's first plastic bricks, made them in the 1940s. Many good inventions grow from improving someone else's idea, and good engineers give credit to those who came before.

COMMON MISTAKES

- Thinking the bricks hold by suction or magnetism. They hold by friction from a slight elastic squeeze.
- Pulling the bricks off at an angle in some trials and straight in others.
- Thinking tighter is always better. A good fit is tight enough to hold and loose enough to come apart.

Make it a game • Squeeze Test. Press two building bricks together, then pull them apart. Describe the clutch power you felt. Explain why the fit has to be tight but springy and why tolerance matters. Your parent then asks about injection molding and the Danish carpenter. Answer three questions correctly in a row to win.

9.3 THE RUBIK'S CUBE: A HIDDEN MECHANISM

OBJECTIVES

- Tell how Ernő Rubik invented his cube to help students think about moving shapes in space.
- Describe the hidden core, centers, edges and corners that let the cube turn without falling apart.
- Take apart and reassemble a puzzle cube safely, and use counting to see why it has so many positions.

Warm-up. Look at a puzzle cube (do not scramble it if it is solved). Count the small cubes you can see on the outside. Now guess: how many separate pieces does it really have inside? How can each row turn without the whole thing falling apart? Sketch your guess.

WATCH

What's inside of a Rubik's Cube?

Jared Owen · 1:52

<https://www.youtube.com/watch?v=bgcScY7CiMs>

WHEN TO WATCH

After the physics paragraph. Watch it twice: once for the core and once for the corners and edges.

BACKUP VIDEO

Why don't Rubik's cubes fall apart?

Henry Segerman · 3:41

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

Before the teardown, to see a see-through model of how the pieces hold one another in.

KEY TERMS

mechanism

A set of moving parts that work together to make a motion.

core

The hidden center of the cube: a six-armed piece with a center cap screwed to each arm.

edge piece

One of the 12 cube pieces with two colored faces.

corner piece

One of the 8 cube pieces with three colored faces.

interlocking

Held together because the shapes of the pieces hook into one another, without glue or fasteners.

CORE IDEAS

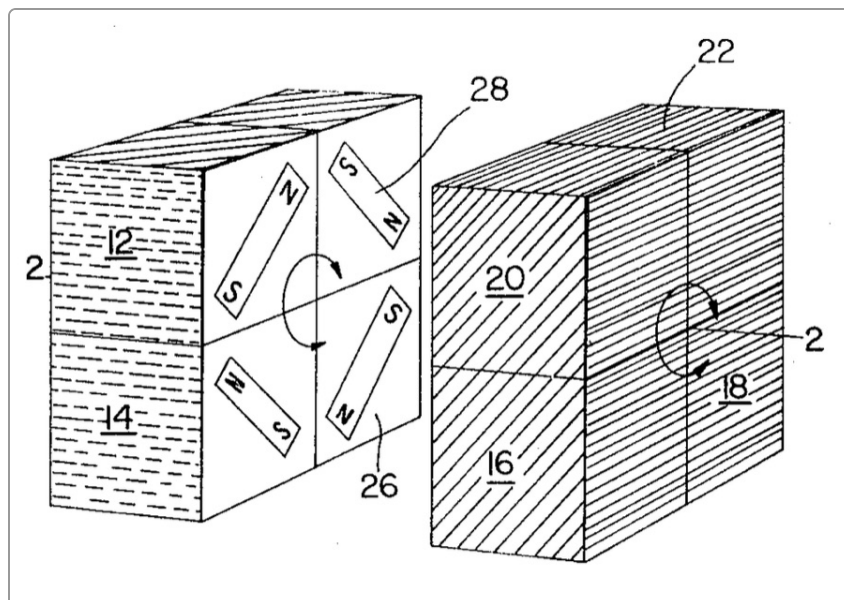
The story. Ernő Rubik was a young teacher of design and architecture in Budapest, Hungary. In the spring of 1974 he wanted to help his students understand how objects can move in three dimensions, so he built a model from small wooden blocks: a cube whose faces could turn while the cube held together. After he scrambled it, it took him about a month to put it back in order. He patented it in Hungary, and it went on sale there in 1977. In 1980 an American toy company began selling it around the world as the Rubik's Cube, and it became one of the best-selling toys in history.

How he figured it out. The hard part was not the colors but the mechanism. How could 26 little cubes turn in every direction without falling apart? Rubik is said to have tried tying pieces together with rubber bands, which soon wore out. Other inventors had tried magnets; an American, Larry Nichols, patented a two-by-two puzzle cube held together by magnets in 1972. Rubik's answer was to shape the pieces themselves so that they hold one another in. He carved and tested wooden pieces by hand until the shapes worked.

The physics and the mechanism. Inside the cube is a **core** with six arms. Each of the six center pieces is screwed to one arm, usually with a spring under the screw, so the centers can spin but never move from their places. The 12 **edge pieces** and 8 **corner pieces** have "feet" on their inner sides that tuck under the pieces next to them and slide in curved grooves around the core. Every piece is held in by its neighbors: the pieces are **interlocking**. When you turn a face, its nine pieces slide together around their center, held on by the pieces of the layer next to it. The springs set how tightly everything presses together, and that pressure sets the friction: too tight and the cube is stiff; too loose and it wobbles or pops apart.

The engineering. To make millions of cubes, every plastic piece must be injection-molded to close tolerances, so that any edge fits any slot. Modern “speed cubes” add rounded corners so a face can turn even when it is not perfectly lined up, smooth surfaces and lubricant to cut friction, and small magnets that help the faces snap into line. The number of different arrangements is enormous: about 43 quintillion (43 followed by 18 zeros). Each piece has a limited number of places it can go, but multiplying all the choices together gives a giant number, which is why a cube can be scrambled so thoroughly. Because the pieces are small, puzzle cubes carry a warning to keep them from children under 3.

PICTURE STUDY



Before Rubik: Nichols's Magnetic Puzzle Cube, Larry D. Nichols, Filed 1970, granted 1972 · Patent drawing · United States Patent Office (U.S. Patent 3,655,201)

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

Larry Nichols patented this two-by-two puzzle cube a few years before Rubik built his. Nichols held his pieces together with magnets. Comparing his drawing with Rubik's design shows two different engineering answers to the same problem: how to let pieces turn without falling apart.

Look closely

- Count the small cubes. How is this cube different in size from a Rubik's Cube?
- Find the magnets marked N and S. How are they arranged?
- Find the curved arrows. What motion do they show?
- Look for the numbers that label each part.

Talk about it

1. What might go wrong with a cube held together only by magnets?
2. Why is Rubik's interlocking design stronger for a toy that will be turned millions of times?
3. Why do inventors study patents that came before them?

Safety first. Take a cube apart only by gently twisting a face 45° and prying up one edge piece with your fingers or a plastic spoon, never a sharp knife. Keep all the small pieces in a bowl and away from children under 3. Do not unscrew a cube with tiny magnets inside; swallowed magnets are dangerous.

BUILD

Inside the Cube: Teardown, Count and Reassemble

You will carefully take apart an inexpensive puzzle cube, sort and count its pieces, sketch how they interlock, and put it back together solved. Then you will test how the tension of the center screws (if your cube has them) changes how it turns, and use counting to see why there are so many positions.

You will need

- An inexpensive 3×3 puzzle cube (one you are allowed to take apart)
- A shallow bowl for pieces, a plastic spoon, and a small screwdriver if your cube has adjustable screws (with an adult)
- A stopwatch, a ruler and engineer's notebook

Steps

1. Before you start, photograph or draw the cube so you know the color arrangement of a solved cube.
2. Turn the top face 45° . Gently lift one edge piece out with your fingers or a plastic spoon. Then remove the rest of the top layer, then the others, placing every piece in the bowl.
3. Sort the pieces: centers, edges and corners. Count each kind and record it. Does it match 6, 12 and 8?
4. Sketch an edge piece and a corner piece from three sides. Label the colored faces and the hidden "foot."
5. Sketch the core, and describe how the centers are attached.
6. Reassemble the cube in the solved position, layer by layer, matching colors to the centers. Notice how the last pieces lock everything in.
7. **Tension test (if your cube has screws).** With an adult, give all six screws the same small turn tighter. Time how long it takes you to turn the right face 20 times. Then loosen them all the same amount and test again. Record which setting is fastest and which feels most stable. Return the screws to the middle setting.

8. Counting. Work out how many ways three different pieces can be put in a row ($3 \times 2 \times 1 = 6$). Then four pieces ($4 \times 3 \times 2 \times 1$). Write a sentence about why 8 corners and 12 edges give an enormous number of arrangements.

Tips

- Never force a piece; if it does not come out, turn the face a little more.
- Put the cube back together solved, so you do not have to solve a scrambled cube to check your work.
- Count the pieces before and after; an edge piece is easy to lose under the table.

Check your work

- ☐ I can name the core, centers, edges and corners and how many of each there are.
- ☐ I can explain how the pieces hold one another in.
- ☐ I can explain how screw tension changes friction and how the cube turns.

ENGINEER'S NOTEBOOK

1. Draw an exploded view of the cube: the core in the middle and a center, an edge and a corner pulled out along arrows.
2. Make a table of your tension test: setting, time for 20 turns, how stable it felt.
3. Write two engineering requirements for a puzzle cube (for example, “must not pop apart in normal play”).

From history. Rubik's Cube competitions began in 1982, and today young speedcubers solve the cube in well under ten seconds. Ernő Rubik has said that he thinks of the cube as a lesson in patience and in how simple parts can make something rich and surprising.

COMMON MISTAKES

- Thinking the cube is 27 solid little cubes. There is no middle cube; there is a core with arms.
- Prying pieces out with a sharp tool and cracking them.
- Reassembling a corner with its colors twisted, which makes the cube impossible to solve.

Make it a game • Cube Quiz Show. Be the quiz show host. Your parent plays contestant and tries to name the cube's parts: core, centers, edges and corners. If they miss, give a clue from its interlocking design. Then trade places. Finish by telling why Ernő Rubik invented it. Whoever answers more correctly gets the pretend trophy.

9.4 TOY TEARDOWN: HOW A TOY IS ENGINEERED

OBJECTIVES

- Describe how toy engineers use springs, gears, cams, motors and switches to make toys move.
- Carry out a safe, organized teardown of an old toy, recording every part and how energy flows through it.
- Identify the design-for-manufacture and safety features in a toy and propose an improvement.

Warm-up. Choose an old wind-up or battery toy that no one needs any more (ask first). Before opening it, watch it work three times. Write down every motion you see, and guess what is inside that makes each one.

WATCH

How does a Pull-Back Toy Car work?

Jared Owen · 5:02

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

WHEN TO WATCH

Before the teardown, as a model of how to follow the energy path through a toy: spring, gears, wheels.

Note: The opening and end screen show other toys and videos; stop when the end screen appears.

BACKUP VIDEO

Toy Figurines | How It's Made

Science Channel · 3:04

<https://www.youtube.com/watch?v=w5KRawOXy4U>

After the engineering paragraph, to see how plastic toy parts are designed, molded and painted.

KEY TERMS

teardown

Taking a product apart carefully, in order, to learn how it was designed and made.

mainspring

A coiled spring that stores energy when a wind-up toy is wound and releases it slowly.

cam

A specially shaped wheel or lobe that turns round-and-round motion into up-and-down or back-and-forth motion.

snap fit

A plastic joint that clicks together using the springiness of the plastic, with no screws or glue.

design for manufacture

Designing a product so it can be made and assembled quickly, cheaply and correctly.

CORE IDEAS

The story. In 1856 George W. Brown, a clockmaker in Forestville, Connecticut, began making tin toys that moved by clockwork springs, among the first wind-up toys made in America. A wound spring turned a train of brass gears, and the toy rolled or spun across the floor, just as a clock's spring turns its hands. More than 150 years later, Mark Rober, an engineer who spent years at NASA's Jet Propulsion Laboratory working on the Curiosity Mars rover, started CrunchLabs in 2022, sending children a toy to build each month along with a video explaining the physics inside it. Both men knew the same thing: a toy is a small machine, and building or opening one is a fine way to learn engineering.

How they figured it out. Engineers learn a great deal by taking things apart. A careful **teardown** is not smashing: you work in order, photograph each step, label every part, and ask of each one, "What does this do? Why is it shaped this way? Why is it made of this material?" Companies tear down their own and others' products to find ways to make them simpler, cheaper, stronger or safer. When Rober designs a toy, his team builds prototypes, tests them with real children, finds what breaks or confuses, and changes the design before thousands are made.

The physics. Most moving toys follow an energy path. Energy is stored, in a wound **mainspring**, a stretched rubber band or a battery. It is released and controlled: in a wind-up toy, a gear train trades the spring's strong, slow push for fast motion (Unit 1), and a small governor or escapement keeps it from unwinding all at once. In a battery toy, a switch closes the circuit and a small motor spins (Unit 4). Then it is turned into the motion you see: wheels, a **cam** that lifts a leg up and down, a crank that swings an arm, a speaker that buzzes. Following that path from start to finish is the key to understanding any toy.

The engineering. Toy engineers design for manufacture: parts are injection-molded with thin walls and ribs for strength using little plastic, many parts click together with **snap fits** instead of screws, and the same part is used in several places to save cost. They also design for safety, because children are the users. In the United States, toys must meet a federal toy-safety standard: no sharp edges or points, no small parts in toys for children under 3, strong seams, and paint without harmful lead. Battery compartments that hold button cells must be closed with a screw, because swallowed button batteries can badly burn a child inside within hours, and toys with strong magnets must hold them so they cannot come loose. Every screw on a battery door is an engineer's act of care for a child they will never meet.

PICTURE STUDY



George W. Brown's Improvement in Mechanical Toys, George W. Brown, June 25, 1872 · Patent drawing · United States Patent Office

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

George W. Brown was a Connecticut clockmaker who became one of America's first makers of mechanical toys. In this 1872 patent for a wheeled push toy, a small figure is linked to the turning wheel so that it moves as a child pushes the toy along. The drawings show how the parts connect.

Look closely

- Find the big wheel and the handle. What makes the wheel turn?
- Find the axle. How might it be linked to the figure on top?
- Compare the front view and the side view. What can you learn from each?
- Look for the letters that label each part, as in Huygens's clock drawing in Unit 1.

Talk about it

1. Trace the energy path from the child's push to the motion of the figure.
2. What part would you add to turn the wheel's round-and-round motion into an up-and-down motion of the figure?
3. What safety features would a modern toy engineer add to this design?

Safety first. Tear down only toys an adult has approved, with an adult present. First remove all batteries. Never open a toy with a lithium battery, a button-cell battery or a wall plug, and never open a sealed battery pack. Wear safety glasses, because springs can fly out when released; an adult releases any wound spring. Keep small parts and magnets away from young children, and throw away sharp metal pieces safely.

BUILD

The Toy Teardown Report

You will measure how an old wind-up or simple battery toy performs, take it apart carefully and in order, lay out and label every part, map how its energy flows, and write a teardown report with one improvement, as an engineer at a toy company would.

You will need

- An old wind-up toy or a simple toy powered by AA or AAA batteries (no lithium batteries, no button cells, no wall plug), approved by an adult
- Small screwdrivers, a plastic spudger or old gift card for prying, tweezers and safety glasses
- An egg carton or muffin tin to hold parts in order, masking tape and a marker for labels
- A phone or camera, a ruler, a stopwatch and engineer's notebook

Steps

1. **Before.** Test the toy: for a wind-up toy, wind it 5, 10 and 15 clicks and measure how far it travels or how long it runs; for a battery toy, time how long each action lasts. Record the results.
2. Remove the batteries (if any) and set them aside. Photograph the toy from every side.
3. Find how it is held together: screws, snap fits or glue. Open it slowly, photographing each step and putting the parts in the egg carton in order, labeled 1, 2, 3 and so on.
4. Lay all the parts out on a sheet of paper. Sort them: energy storage (spring, battery holder), control (gears, switch, governor), motion (wheels, cams, cranks), structure (shell, frame) and safety features.
5. Draw an energy-path diagram from storage to motion, naming each part along the way.
6. Look for design-for-manufacture clues: ribs, snap fits, parts used more than once, molded-in numbers. Look for safety features: rounded edges, screwed

battery doors, enclosed gears.

7. Reassemble the toy if you can, and test it again. Does it work as before?
8. **Improve.** Write a one-page teardown report: what the toy does, how it works, three good design choices, one weakness, and one improvement you would make, with a sketch.

Tips

- If you get stuck, look for a hidden screw under a sticker or label.
- Never force a part; plastic snap fits break if pried the wrong way.
- An adult should release a wound spring slowly while holding it inside its case.

Check your work

- ☐ I can trace the energy path through a toy from storage to motion.
- ☐ I can name design-for-manufacture and safety features I found.
- ☐ My teardown report includes labeled photographs or drawings and one improvement.

ENGINEER'S NOTEBOOK

1. Draw an exploded view of your toy with every part labeled and numbered.
2. Draw the energy path as a chain of boxes and arrows: spring or battery → gears or switch → motor or cam → motion.
3. Design a toy of your own on paper. Show its energy path and list three safety features.

From history. In the 1800s, Connecticut's clock towns became centers of American toymaking, because clockmakers already had the tools and skills to cut small gears and wind springs. Many of their tin toys survive in museums today, and some still run when wound.

COMMON MISTAKES

- Opening a toy without removing the batteries, or opening one with a lithium or button-cell battery.
- Taking parts out without recording the order, so the toy cannot be put back together.

- Thinking a cheap toy is badly designed. Making a toy that works, survives children and costs little is hard engineering.

Make it a game • Energy Flow Map. Pick a toy that moves, such as a wind-up toy, and draw a map of how energy flows from the spring through gears or cams to the movement. Label springs, switches and snap fits. Your parent asks about each part. Answer without peeking. Add why designers use design for manufacture.

Scripture. “Seest thou a man diligent in his business? he shall stand before kings;” (Proverbs 22:29, KJV)

Careful, diligent work is honored, even in something as small as a toy. A well-made toy that is safe for children is work worth doing well.

TOY LAB: THE PHYSICS OF PLAY

Toys are some of the cleverest machines in the house. A Frisbee is a spinning wing. A LEGO brick is a piece of precision engineering, molded so exactly that a brick made in 1958 still clicks onto one made today. A Rubik's Cube hides a mechanism so neat that it holds itself together with no glue at all. And every wind-up or battery toy is a small lesson in springs, gears, motors and switches, designed to be cheap, tough and safe for children.

This optional bonus unit is for after the family engineering fair, for the summer, or for any week that needs something fun. Each lesson follows the same path as the rest of the year: the story of the toy and its inventor, how they figured it out, the physics of why it works, and the engineering of how it is made safely and cheaply enough to sell. You will test flying discs, measure LEGO clutch power, take apart a puzzle cube, and carefully tear down an old toy to see how it was designed. “The streets of the city shall be full of boys and girls playing,” wrote the prophet Zechariah. Play is a good gift, and so is understanding it.

PREREQUISITES

- Knows lift and the four forces of flight (Unit 7)
- Knows gears, springs, motors and switches (Units 1 and 4)
- Knows how to run a fair test and keep an engineer's notebook

MASTERY CHECKLIST

- ☐ I can explain how a Frisbee makes lift and why spin keeps it steady.
- ☐ I can explain what tolerance and clutch power mean and how injection molding makes identical parts.
- ☐ I can describe the hidden mechanism that holds a Rubik's Cube together.
- ☐ I can tear down a toy safely, map how its energy flows, and name the safety features its engineers designed in.
- ☐ I can name the main toy-safety rules: small parts, sharp edges, magnets and button batteries.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box (Mark Rober):** Ages 8 and up. Each monthly box is a toy to build that shows one physics idea, with a video explaining the engineering. Exactly the spirit of Lesson 9.4.
- **KiwiCo Tinker Crate:** Ages 9 and up. Many crates are working toys with gears, springs and levers, plus notes on how they work. Fits Lessons 9.1 and 9.4.
- **Snap Circuits (Elenco):** Ages 8 and up. Rebuild the switches, motors and lights you find in a toy teardown without any wiring. Fits Lesson 9.4.
- **LEGO Classic bricks:** Ages 4 and up (small parts). A box of basic bricks is all you need for the clutch-power tests in Lesson 9.2.

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

LESSONS IN THIS UNIT

9.1	The Frisbee: A Spinning Wing	2 sessions of 45 minutes
9.2	The LEGO Brick: Precision, Tolerance and Clutch Power	2 sessions of 45 minutes
9.3	The Rubik's Cube: A Hidden Mechanism	2 sessions of 45 minutes
9.4	Toy Teardown: How a Toy Is Engineered	2 sessions of 45 minutes

UNIT 9 REVIEW

Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 50 points.

1. 5 pts

How does a Frisbee make lift?

2. 5 pts

Predict: you throw a disc without spin. What happens, and why?

3. 5 pts

Why do disc designers put most of the mass in the rim?

4. **5 pts**

What is clutch power, and what causes it?

5. **5 pts**

What is tolerance, and why must LEGO molds have such tight tolerances?

6. **5 pts**

Predict: two bricks are joined by 2 studs and another pair by 8 studs. Which needs more weight to pull apart, and why?

7. **5 pts**

How many centers, edges and corners does a Rubik's Cube have, and what holds them together?

8. **5 pts**

What happens to a puzzle cube if its center screws are much too tight or much too loose?

9. **5 pts**

Trace the energy path in a wind-up toy.

10. **5 pts**

Name three toy-safety rules engineers must design for.

ANSWER KEY

1. Its rounded edge and domed shape, tilted at a slight angle of attack, turn the passing air downward, so the air pushes the disc up; the pressure above it is lower than below.
2. It tips over and tumbles. Without spin it has no gyroscopic stability, and the lift on the front half flips it.
3. Mass far from the center gives more angular momentum for the same spin, so the disc is steadier.
4. How firmly bricks hold together. It is friction caused by the studs squeezing slightly against the walls and tubes; the elastic plastic pushes back.
5. Tolerance is how much a part's size may differ from the design. Bricks must all be almost exactly the same size so every brick grips every other brick with the same clutch power.
6. The 8-stud pair, because more studs give more contact surfaces and more friction.
7. 6 centers, 12 edges, 8 corners. The centers are screwed to a core; the edges and corners have feet that interlock with their neighbors, so the pieces hold one another in.
8. Too tight: more friction, so it is stiff and hard to turn. Too loose: it wobbles and pieces can pop out.
9. Winding stores energy in the mainspring; the spring turns a gear train (with a governor controlling the speed); the gears turn wheels, cams or cranks that make the toy move.
10. Any three: no small parts for children under 3; no sharp edges or points; button-cell battery doors closed with screws; magnets held so they cannot come loose; no lead paint; strong seams.

PORTFOLIO PIECE: A TOY OF MY OWN DESIGN

Design and build a working toy from household materials that uses at least one physics idea from this year (spin, a spring or rubber band, gears, a lever, lift, buoyancy or a circuit). Test it at least three times, improve it once, and present it with an energy-path diagram, a list of materials and approximate cost, and a safety check showing it has no sharp edges, no loose small parts and no exposed battery. Let a younger child or a sibling play with it (with an adult watching) and write down what you learned from watching them.

LOOK FOR	WHAT IT MEANS
Physics	The toy clearly uses a physics idea, and the notebook explains it correctly.
Testing and improvement	At least three tests are recorded, and one improvement is made based on the results.
Energy path	A clear diagram shows how energy is stored, controlled and turned into motion.
Safety	A safety check is completed, and the design avoids small parts, sharp edges and loose batteries.
User testing	The toy was tried by another child, and the notes describe what worked and what was confusing.