

GRADE 3 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, buildings, electricity, public utilities, boats, flight, and robots. Each unit is built around real moments from history: Archimedes lifting water with a screw, the Roebling family building the Brooklyn Bridge, Gustave Eiffel's team riveting a tower of iron lace, Stephen Gray sending electricity along more than 700 feet of string, Chicago jacking up its own streets to make room for sewers, Otto Lilienthal leaping from his hill on wings of willow and cloth, and the Wright brothers twisting a cardboard box and seeing how to steer an airplane.

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 and what they changed. Then **the physics** underneath, explained for a third grader, and **the engineering**: how people turn that idea into something safe and useful. Last, the student repeats the discovery in miniature with cardboard, paper cups, pennies, batteries and a box fan, recording each test in an engineer's notebook and trying again to make it better.

God made an orderly world that can be measured and understood, and He made people in His image to be makers. Building well is a way to love our neighbors: a bridge that holds, clean water in the tap, 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. An optional ninth unit, the **Toy Lab**, looks at the physics and design of four favorite toys and can be used after the family engineering fair, over the summer, or any week that needs something fun.

Most videos come from museums and trusted teaching channels: the Smithsonian National Air and Space Museum, NASA's Jet Propulsion Laboratory, Science Buddies, SciShow Kids, Science Max, Homeschool Pop, The Henry Ford and a few others chosen lesson by lesson. Every video was checked in preview for content and accuracy.

A few channels open or close with a short sponsor message or an invitation to subscribe; the lesson notes say so, and you can skip those parts. Watch together, and pause when the lesson tells you to predict what will happen next.

Start with Lesson 1.1 →

WHO IT IS FOR

Written for students in grade 3 (about ages 8–9) who are reading well on their own but still enjoy being read to. The student should be able to measure to the nearest centimeter or half inch, add and subtract, and count by 2s, 5s and 10s. 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.** Read the core ideas aloud together, or let the student read them. The paragraphs marked *The story* and *How they figured it out* tell what happened; *The physics* explains why it works; *The engineering* tells how people use the idea to build real things. 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 let the student tell everything he or she remembers. Bring it back and work through the “look for” items and the 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 fill in a simple data 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 trying again.** Most builds change only one thing at a time and test each version more than once. Every build ends with an “improve it” round. A design that fails and is then made better has taught more than one that worked the first time.
6. **Optional kits.** Some units list kits such as KiwiCo crates, KEVA planks, Snap Circuits or a CrunchLabs Build Box. They are extras for families who enjoy them. Every lesson can be finished 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 beam bridge, a braced tower that survives the fan, a working telegraph or a tested glider. Keep the portfolio pages and photographs in a folder for the year.
8. **Safety.** Read the safety box before each build. Electricity in this course comes only from AA, C or D batteries, never from the outlets in the wall. An adult handles hot glue guns and craft knives. Wear safety glasses for anything that flies, snaps or is stretched tight.
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 Unit 9).** Four bonus lessons on the Etch A Sketch, Newton’s cradle, the gyroscope top and the Erector set. Use them after the fair, over the summer, or slip one in whenever a week needs something fun.

SCOPE AND SEQUENCE

UNIT 1 • WEEKS 1–4

Forces and Machines

Newton's first law and why a heavy train is hard to stop; pulleys and the Portsmouth block mills; gears and the ancient Antikythera mechanism; and Archimedes' water screw.

- 1.1 Newton's First Law: Why a Heavy Train Is Hard to Stop
- 1.2 Pulleys and the Portsmouth Block Mills
- 1.3 Gears and the Antikythera Mechanism
- 1.4 Archimedes' Water Screw

UNIT 3 • WEEKS 9–12

Buildings

The Great Pyramid and the strength of a wide base; Gothic cathedrals and flying buttresses; the iron lattice of the Eiffel Tower; and the first steel-frame skyscraper in Chicago.

- 3.1 The Great Pyramid: The Strength of a Wide Base
- 3.2 Gothic Cathedrals and Flying Buttresses
- 3.3 The Eiffel Tower: Iron Lace in the Wind
- 3.4 The Steel Frame: Chicago's First Skyscraper

UNIT 2 • WEEKS 5–8

Bridges

Compression and tension in an Inca grass bridge; beams, spans and the covered bridges of New England; Roman arches and the keystone; and the Roebling family's Brooklyn Bridge.

- 2.1 Compression and Tension: The Inca Grass Bridge
- 2.2 Beams and Spans: The Covered Bridges of New England
- 2.3 Roman Arches and the Keystone
- 2.4 The Roeblings and the Brooklyn Bridge

UNIT 4 • WEEKS 13–16

Electricity and Magnets

Series and parallel circuits and why Edison wired houses in parallel; Stephen Gray and the discovery of conductors and insulators; William Gilbert, magnets and the compass; and Samuel Morse's telegraph.

- 4.1 Series and Parallel: Why Edison Wired Houses in Parallel
- 4.2 Stephen Gray Discovers Conductors and Insulators
- 4.3 William Gilbert, Magnets and the Compass
- 4.4 Samuel Morse and the Telegraph

UNIT 5 • WEEKS 17–20

Water, Power and Telephones

Clean water from the Croton Aqueduct to the sand filter; how Chicago raised its streets to build sewers; how electricity travels from the power plant to your house; and Alexander Graham Bell's telephone.

- 5.1 Clean Water: The Croton Aqueduct and the Sand Filter
- 5.2 Sewers: Chicago Lifts Its Streets
- 5.3 From the Power Plant to Your Outlet
- 5.4 Alexander Graham Bell and the Telephone

UNIT 7 • WEEKS 25–28

Flight

Air pressure, the Magdeburg hemispheres and a stomp rocket; George Cayley and how a wing makes lift; Otto Lilienthal's gliders and balance; and the Wright brothers' wing warping.

- 7.1 Air Pressure: The Magdeburg Hemispheres and a Stomp Rocket
- 7.2 George Cayley and How a Wing Makes Lift
- 7.3 Otto Lilienthal's Gliders and the Secret of Balance
- 7.4 The Wright Brothers Twist Their Wings

UNIT 6 • WEEKS 21–24

Boats and Ships

Density and buoyancy and Brunel's iron ship; sails and the clipper *Flying Cloud*; paddle wheels, propellers and Newton's third law; and John Smeaton's Eddystone lighthouse.

- 6.1 Density and Buoyancy: Brunel's Iron Ship
- 6.2 Sails and the Clipper Ship *Flying Cloud*
- 6.3 Paddle Wheels, Propellers and Newton's Third Law
- 6.4 John Smeaton's Lighthouse and the Light That Guides Ships

UNIT 8 • WEEKS 29–32

Robots and Inventions

Sense, think and act with the Mars rover Sojourner; Ada Lovelace and loops in code; levers and tendons in a cardboard hand; and Abraham Lincoln's patent and our own invention fair.

- 8.1 Sense, Think, Act: Sojourner on Mars
- 8.2 Ada Lovelace and Loops
- 8.3 Levers and Tendons: Building a Helping Hand
- 8.4 Abraham Lincoln's Patent and Our Invention Fair

UNIT 9 • WEEKS 33–36

Toy Lab: The Physics of Play

Optional Toy Lab: strings and pulleys inside the Etch A Sketch; energy passing through Newton's cradle; why a spinning gyroscope top stays up; and building with girders and bolts like A. C. Gilbert's Erector set.

9.1 Inside the Etch A Sketch: Strings, Pulleys and Two Knobs

9.2 Newton's Cradle: Passing the Push

9.3 The Gyroscope Top: Why Spinning Things Stay Up

9.4 A. C. Gilbert's Erector Set: Building with Girders and Bolts

WEEKLY PACING CALENDAR

WEEK	PLAN
1	• Session 1: Lesson 1.1 Newton's First Law: Why a Heavy Train Is Hard to Stop: 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 Pulleys and the Portsmouth Block Mills: warm-up, video, teaching and picture study • Session 2: Lesson 1.2 build project and engineer's notebook
3	• Session 1: Lesson 1.3 Gears and the Antikythera Mechanism: warm-up, video, teaching and picture study • Session 2: Lesson 1.3 build project and engineer's notebook
4	• Session 1: Lesson 1.4 Archimedes' Water Screw: 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 Compression and Tension: The Inca Grass 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 Beams and Spans: The Covered Bridges of New England: warm-up, video, teaching and picture study • Session 2: Lesson 2.2 build project and engineer's notebook
7	• Session 1: Lesson 2.3 Roman Arches and the Keystone: warm-up, video, teaching and picture study • Session 2: Lesson 2.3 build project and engineer's notebook
8	• Session 1: Lesson 2.4 The Roeblings and the Brooklyn Bridge: warm-up, video, teaching and picture study • Session 2: Lesson 2.4 build project and engineer's notebook • Session 3: Unit 2 review and portfolio project
9	• Session 1: Lesson 3.1 The Great Pyramid: The Strength of a Wide Base: warm-up, video, teaching and picture study • Session 2: Lesson 3.1 build project and engineer's notebook
10	• Session 1: Lesson 3.2 Gothic Cathedrals and Flying 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 Eiffel Tower: Iron Lace in the Wind: 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 Steel Frame: Chicago's First Skyscraper: 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 Series and Parallel: Why Edison Wired Houses in Parallel: 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 Stephen Gray Discovers Conductors and Insulators: warm-up, video, teaching and picture study • Session 2: Lesson 4.2 build project and engineer's notebook
15	• Session 1: Lesson 4.3 William Gilbert, Magnets and the Compass: warm-up, video, teaching and picture study • Session 2: Lesson 4.3 build project and engineer's notebook
16	• Session 1: Lesson 4.4 Samuel Morse and the Telegraph: 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: The Croton Aqueduct and the Sand Filter: 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: Chicago Lifts Its Streets: warm-up, video, teaching and picture study • Session 2: Lesson 5.2 build project and engineer's notebook
19	• Session 1: Lesson 5.3 From the Power Plant to Your Outlet: warm-up, video, teaching and picture study • Session 2: Lesson 5.3 build project and engineer's notebook
20	• Session 1: Lesson 5.4 Alexander Graham Bell and the Telephone: 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 Density and Buoyancy: Brunel's Iron Ship: warm-up, video, teaching and picture study • Session 2: Lesson 6.1 build project and engineer's notebook
22	• Session 1: Lesson 6.2 Sails and the Clipper Ship <i>Flying Cloud</i>: 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 Paddle Wheels, Propellers and Newton's Third Law: warm-up, video, teaching and picture study • Session 2: Lesson 6.3 build project and engineer's notebook
24	• Session 1: Lesson 6.4 John Smeaton's Lighthouse and the Light That Guides Ships: 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 Air Pressure: The Magdeburg Hemispheres and a Stomp Rocket: warm-up, video, teaching and picture study • Session 2: Lesson 7.1 build project and engineer's notebook
26	• Session 1: Lesson 7.2 George Cayley and How a Wing Makes Lift: warm-up, video, teaching and picture study • Session 2: Lesson 7.2 build project and engineer's notebook
27	• Session 1: Lesson 7.3 Otto Lilienthal's Gliders and the Secret of Balance: warm-up, video, teaching and picture study • Session 2: Lesson 7.3 build project and engineer's notebook
28	• Session 1: Lesson 7.4 The Wright Brothers Twist Their Wings: warm-up, video, teaching and picture study • Session 2: Lesson 7.4 build project and engineer's notebook • Session 3: Unit 7 review and portfolio project
29	• Session 1: Lesson 8.1 Sense, Think, Act: Sojourner on Mars: warm-up, video, teaching and picture study • Session 2: Lesson 8.1 build project and engineer's notebook
30	• Session 1: Lesson 8.2 Ada Lovelace and Loops: warm-up, video, teaching and picture study • Session 2: Lesson 8.2 build project and engineer's notebook
31	• Session 1: Lesson 8.3 Levers and Tendons: Building a Helping Hand: 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 Abraham Lincoln’s Patent and Our Invention 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 Inside the Etch A Sketch: Strings, Pulleys and Two Knobs: 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 Newton’s Cradle: Passing the Push: 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 Gyroscope Top: Why Spinning Things Stay Up: warm-up, video, teaching and picture study • Session 2: Lesson 9.3 build project and engineer’s notebook
36	• Session 1: Lesson 9.4 A. C. Gilbert’s Erector Set: Building with Girders and Bolts: 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 and a kitchen scale that reads in grams

Measuring is the heart of every build.

Smartphone or stopwatch

For timing rolling cars, boats, gliders and spinning tops.

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

The main building materials all year.

Craft sticks (about 100), plastic straws, wooden skewers, string, rubber bands and brass paper fasteners

For beams, towers, pulleys, the robot hand and the Toy Lab.

About 200 pennies, paper cups and a few toy cars

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

Empty thread spools, a broom handle and a small bucket or basket

For the pulley build in Unit 1.

AA or D-cell batteries with holders, alligator clip leads, two or three small bulbs with holders (or LEDs), and aluminum foil

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

Bar or ceramic magnets, a sewing needle, a cork and a compass

For the compass build in Unit 4.

A small hobby motor (1.5–3 volt) and an LED

For the generator build in Unit 5.

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 plastic tub or the bathtub, aluminum foil and modeling clay

For the boat builds in Unit 6. An adult is always present near water.

A box fan

The “wind tunnel” for towers, sails and wings.

A 2-liter bottle, about 2 feet of ½-inch PVC pipe or vinyl tubing, and duct tape

For the stomp rocket in Unit 7.

Free software: ScratchJr (tablets) or Scratch (scratch.mit.edu)

For the coding lesson in Unit 8. Can also be done unplugged with paper cards.

Safety glasses

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

Optional: one kit, such as a KiwiCo crate, KEVA planks, Snap Circuits Jr. 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)	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 the review together.

- Grade the process, not just the result. Did the student predict, change one thing at a time, measure carefully, record honestly and try an improvement?
- A notebook page earns full marks when it has a date, a labeled sketch, a small data table with units, and one sentence about what to change.
- Unit reviews may be done aloud. The parent writes down the answers, and the student may point, draw or build to explain.
- 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 helper 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. Towers will tip, boats will sink and gliders will dive. The Wright brothers crashed gliders for three summers before they flew, and this course is built to show that failure, carefully studied, is how engineers learn. Praise careful testing and honest records more than a winning result. *Fabricando fit faber*: by making, one becomes a maker.

A few lessons tell of accidents or hard times, such as the bridge builder who was hurt on the job or the glider pioneer who crashed. They are told gently and briefly, with the focus on what people learned and changed so that others would be safe.

UNIT 1

FORCES AND MACHINES

Every machine, from a wagon to a crane, works by pushing and pulling. In this unit you will learn Isaac Newton's first law: things keep doing what they are doing until a force changes them. You will see why a heavy train is hard to stop and why cars have seat belts. Then you will meet three of the oldest machines in the world and the people who put them to work: the pulley that lifted the sails of the great navy ships, the gears hidden inside a bronze box found in a shipwreck, and the water screw of Archimedes.

You will also learn the engineer's way of working: ask a question, plan, build, test, and make it better. Each build has a fair test, where you change only one thing, and a notebook page where you write down what really happened.

PREREQUISITES

- Knows that a force is a push or a pull
- Can measure length with a ruler to the nearest centimeter
- Can count by 2s, 5s and 10s

MASTERY CHECKLIST

- ☐ I can explain Newton's first law with an example from a car, a bike or a train.
- ☐ I can show how a fixed pulley and a movable pulley change a pull, and explain the trade-off.
- ☐ I can tell which way two meshing gears turn and which one turns faster.
- ☐ I can explain how an Archimedes screw lifts water and why its angle matters.
- ☐ I can run a fair test, changing only one thing, and record the results in a table.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Tinker Crate:** Ages 9 and up, so best with a parent at this age. Monthly engineering crates that often include gears, levers, pulleys and hydraulics. A good extra for Lessons 1.2–1.4.
- **LEGO Technic:** Sets vary by age. Technic gears, axles and beams make it easy to build and count gear trains for Lesson 1.3.

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

LESSONS IN THIS UNIT

1.1	Newton's First Law: Why a Heavy Train Is Hard to Stop	2 sessions of 45 minutes
1.2	Pulleys and the Portsmouth Block Mills	2 sessions of 45 minutes
1.3	Gears and the Antikythera Mechanism	2 sessions of 45 minutes
1.4	Archimedes' Water Screw	2 sessions of 45 minutes

UNIT 1 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
Say Newton's first law in your own words.
2. **5 pts**
A car stops suddenly. Why do the people inside lean forward? What keeps them safe?
3. **5 pts**
Predict: a toy car rolls down a ramp onto a smooth floor and onto a carpet. On which one will it roll farther? Why?
4. **5 pts**
What does a fixed pulley do? What does a movable pulley do?

5. (5 pts)

A movable pulley lets you lift a bucket with half the force. What do you have to give up?

6. (5 pts)

Why did Marc Brunel's Block Mills matter to the navy?

7. (5 pts)

Two gears mesh. The big one turns clockwise. Which way does the small one turn, and does it turn faster or slower?

8. (5 pts)

Predict: a gear with 30 teeth turns a gear with 10 teeth. If the big gear turns once, how many times does the small gear turn?

9. (5 pts)

How does an Archimedes screw lift water?

10. (5 pts)

What is a fair test? Give an example from this unit.

ANSWER KEY

1. A thing that is still stays still, and a thing that is moving keeps moving the same way, unless a force pushes or pulls it.
2. Inertia: their bodies keep moving forward when the car stops. Seat belts (and airbags) give the force that stops them gently.
3. The smooth floor, because there is less friction to slow it down.
4. A fixed pulley changes the direction of the pull (pull down to lift up). A movable pulley lets you lift with about half the force.
5. You must pull twice as much rope (twice the distance).
6. Machines made pulley blocks quickly and all the same size, so a few workers could make the many thousands of blocks the ships needed.
7. Counterclockwise (the opposite way), and faster.
8. 3 times ($30 \div 10 = 3$).
9. Water is trapped in pockets of the spiral. When the screw turns, the pockets move up the tube, carrying the water to the top. The screw is a ramp wrapped around a pole.
10. A test where you change only one thing and keep everything else the same, such as changing only the ramp height while using the same car and passenger.

PORTFOLIO PIECE: A MACHINE THAT LIFTS

Design and build a small machine that lifts a cup of 50 pennies at least 30 centimeters, using a pulley, gears, a screw or a mix of them. Before you build, draw a labeled plan. Test it three times, record how hard you had to pull or how many turns it took, then make one improvement and test again. Present your machine and your notebook page to your family.

LOOK FOR	WHAT IT MEANS
Plan	A labeled drawing shows the machine's parts and which simple machine each one is.
It works	The machine lifts the cup of pennies at least 30 centimeters.
Fair test and data	Three trials are recorded in a table with units (centimeters of stretch, turns or rope pulled).
Improvement	One change was made because of the test results, and the new result was recorded.
Explanation	The student explains the trade-off: less force means more rope or more turns.

1.1 NEWTON'S FIRST LAW: WHY A HEAVY TRAIN IS HARD TO STOP

OBJECTIVES

- State Newton's first law in your own words.
- Explain inertia with examples from cars, bikes and trains.
- Run a fair test with a toy car and a clay passenger, changing only the ramp height.

Warm-up. Put an index card on top of a cup and a coin on the card. Predict: if you flick the card sideways very fast, where will the coin go? Try it three times. Then try pulling the card slowly. What is different?

WATCH

Science Max | INERTIA | Experiments

Science Max - Scholastic • 10:03

<https://www.youtube.com/watch?v=u58Ulg9rFm0>

WHEN TO WATCH

After the story. Pause after the first experiment and predict what the bigger version will do.

KEY TERMS

force

A push or a pull.

inertia

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

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.

friction

A force that slows things down when two surfaces rub together.

mass

How much stuff is in an object. More mass means more inertia.

CORE IDEAS

The story. About four hundred years ago in Italy, Galileo Galilei rolled bronze balls down smooth wooden ramps and watched them carefully. A ball rolled down one ramp and up another rose almost to the height where it started. When he made the second ramp less steep, the ball rolled farther to reach that height. Galileo asked a bold question: what if the second ramp were perfectly flat? The ball would never reach its starting height, so it would just keep rolling. Many years later, in 1687, the English scientist Isaac Newton wrote this idea down as his first law of motion. Newton was a believing Christian who thought the laws of nature showed the faithful order of the God who made them.

How they figured it out. People had long believed that moving things slow down and stop all by themselves. Galileo noticed that a ball stops sooner on a rough floor and later on a smooth one. If roughness slows it, then something is acting on it. That something is a force we now call friction. Take away friction, and nothing would slow the ball at all. Newton put Galileo's idea together with his own and wrote it as a law that works for everything, from a rolling marble to the moon.

The physics. Newton's first law says that an object at rest stays at rest, and an object in motion keeps moving at the same speed in a straight line, unless a force acts on it. This stubbornness is called **inertia**. The more mass something has, the more inertia it has. In the warm-up, the card moved but the coin had inertia: it stayed where it was and dropped into the cup. A heavy freight train has enormous inertia. Once it is rolling, its brakes may need more than a mile to stop it.

The engineering. Engineers design for inertia everywhere. When a car stops suddenly, the people inside keep moving forward, so engineers add seat belts and airbags to supply the force that stops them gently. Trucks use straps so their loads do not keep sliding when the truck stops. Railroads put warning signs far before crossings because trains cannot stop quickly. Even a bicycle helmet is designed for inertia: it cushions your head when your body stops suddenly but your head wants to keep going.

PICTURE STUDY



Rain, Steam and Speed – The Great Western Railway, J. M. W. Turner, 1844 · Oil on canvas · National Gallery, London

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

When Turner painted this, trains were new and seemed astonishingly fast. He shows a steam locomotive racing across a bridge over the River Thames in the rain. Look for how he makes it feel heavy and fast at the same time.

Look closely

- Find the black front of the locomotive. Where is it heading?
- Find the bridge the train is crossing. What holds it up?
- Look on the tracks ahead of the train for a small hare running. (It is hard to see!)
- Find the boat on the river below and the people in the field. Which things in the picture are moving and which are still?

Talk about it

1. If the engine driver saw something on the track, could the train stop quickly? Why not?
2. Which has more inertia, the train or the hare? Which could stop or turn faster?
3. How does Turner use blur and color to make you feel speed?

Safety first. Keep the ramp low and the toy cars on the floor. Do not do inertia tests with real people on bikes, wagons or skateboards.

BUILD

The Clay Passenger: A Seat-Belt Test

You will roll a toy car with a clay passenger down a ramp into a wall and watch inertia throw the passenger forward. Then you will run a fair test of ramp height and design a seat belt that keeps your passenger safe.

You will need

- A toy car or a small wagon made from a box and four bottle caps
- A ball of modeling clay about the size of a grape (the passenger)
- A ramp: a long piece of stiff cardboard or a board, with books to prop it up
- A heavy book or block for a wall at the bottom
- Ruler or tape measure, string, tape and rubber bands
- Engineer's notebook

Steps

1. Set the ramp on books so its top end is 10 centimeters high. Put the wall about 30 centimeters past the bottom of the ramp.
2. Set the clay passenger on top of the car without sticking it down. **Predict** in your notebook: when the car hits the wall, where will the passenger go?
3. Let the car go from the top (do not push it). Measure how far the passenger flew past the wall, in centimeters. Do three trials.
4. **Fair test.** Change only the ramp height: try 10, 20 and 30 centimeters. Keep the same car, the same passenger and the same starting point. Do three trials at each height.
5. Record each distance in a table: ramp height, trial 1, trial 2, trial 3. Circle the middle value of each set of three.
6. Write one sentence: how did ramp height change how far the passenger flew? Why?
7. **Improve it.** Design a seat belt from string, tape or a rubber band. Test it at the 30-centimeter height. Does the passenger stay in the car? Does the clay get squashed? Try a wider belt and compare.

Tips

- Mark the starting line on the ramp with tape so every trial starts in the same place.
- Make a new clay ball the same size if your passenger gets flattened.
- A wide belt spreads the force over more of the passenger, just as real seat belts do.

Check your work

- ☐ I can explain why the passenger kept going when the car stopped.
- ☐ I changed only one thing in my fair test and did three trials each time.
- ☐ I can explain why a wide seat belt works better than a thin one.

ENGINEER'S NOTEBOOK

1. Draw the car hitting the wall, with an arrow showing which way the passenger moves. Label it “inertia.”
2. Make a bar graph of ramp height and passenger distance.
3. Find three places at home or in the car where something is designed to deal with inertia (seat belt, cup holder, strap). Sketch and label each one.

From history. Newton's book of 1687 is usually called the *Principia*. In it he also wrote his second and third laws of motion, which you will meet in the boats and flight units. In a section he added at the end of the second edition in 1713, Newton wrote about the wisdom and power of the Creator who made such an orderly world.

COMMON MISTAKES

- Thinking a moving thing stops by itself. Something always stops it: friction, a wall, the air or the ground.
- Thinking inertia is a force that pushes the passenger forward. Nothing pushes the passenger; it simply keeps going while the car is stopped.
- Changing two things at once, such as the ramp height and the car. Then you cannot tell which change made the difference.

Make it a game • Inertia Seat-Belt Quiz. Slide a toy car with a clay passenger into a wall, with and without a paper seat belt. Before each crash, predict whether the passenger will fly forward. Then state Newton's first law in your own words in under 20 seconds. Your parent names a vehicle, such as a train, a bike or a car, and you explain its inertia. Score one point per right answer.

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

Galileo and Newton could find laws of motion because the world holds together in a faithful, orderly way. The same law works for a marble and a freight train.

1.2 PULLEYS AND THE PORTSMOUTH BLOCK MILLS

OBJECTIVES

- Explain what a fixed pulley and a movable pulley each do.
- Explain mechanical advantage and its trade-off: less force, more rope.
- Build a two-pulley system, measure the force to lift a load, and compare.

Warm-up. Tie a string to a small bag of pennies. Lift it straight up with the string. Now loop the string over a smooth broom handle held between two chairs and pull down to lift the bag. Which way feels easier to pull? Did the bag feel lighter, or just easier?

WATCH

Need a Lift? Try a Pulley!

SciShow Kids · 3:27

<https://www.youtube.com/watch?v=Nj4J7QNeBNk>

WHEN TO WATCH

Before the physics paragraph. Watch for the difference between one pulley and two.

KEY TERMS

pulley

A wheel with a groove that a rope runs over, used to lift or move loads.

block

The wooden or metal case that holds a pulley wheel. Sailors call a pulley a block.

fixed pulley

A pulley that stays in one place. It changes the direction of your pull.

movable pulley

A pulley that moves with the load. It lets you lift with less force.

mechanical advantage

How many times a machine multiplies your force.

CORE IDEAS

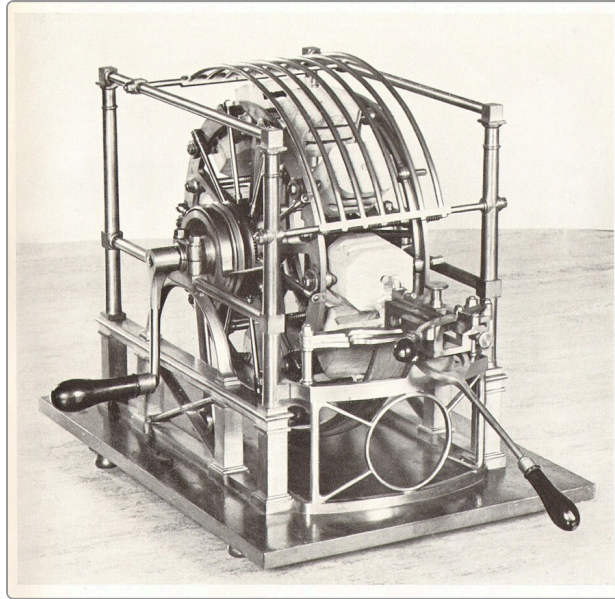
The story. Two hundred years ago, a great sailing warship of the British navy needed more than a thousand wooden pulley blocks to raise and lower its sails, yards and anchors. The navy needed about 100,000 new blocks every year, and each one was carved by hand by skilled craftsmen. A French-born engineer named Marc Isambard Brunel had a better idea. He designed a set of machines, each doing one step: one sawed the wood, one drilled the hole, one shaped the outside, one cut the groove for the rope, and so on. A master machine-maker named Henry Maudslay built them out of iron. In 1803 the machines began work in the Block Mills at Portsmouth.

How they figured it out. Brunel watched how the craftsmen made each block and broke the job into small steps. He made drawings of each machine in his sketchbook. Maudslay built the machines so carefully that every block came out the same size, and any pulley wheel would fit any block. By 1808 the Block Mills were making about 130,000 blocks a year, and ten workers with the machines could do the work that 110 skilled craftsmen had done before. It was one of the first factories in the world to make the same part over and over with machines.

The physics. A **fixed pulley** hangs in one place. It does not make the load lighter, but it changes the direction of the pull: you pull down, and the load goes up. That is easier because you can use your own weight. A **movable pulley** hangs on the load and moves up with it. Now two parts of the rope hold the load, so each part carries only half. You pull with about half the force. But there is a trade-off: to lift the load 1 meter, you must pull 2 meters of rope. With more pulleys, the force gets smaller and the rope gets longer. Count the ropes holding up the load, and you have the **mechanical advantage**.

The engineering. Sailors used blocks and tackle to lift heavy sails and cargo with only a few people. Today, construction cranes, elevators, window-washing platforms, flagpoles and tow trucks all use pulleys. Engineers choose how many pulleys to use by balancing force, rope length and time. They also check the rope's strength and the pulley's bearings, because a pulley system is only as strong as its weakest part.

PICTURE STUDY



A Model of Brunel's Shaping Engine, Photograph published by K. R. Gilbert, Machine designed about 1803; photograph published 1965 · Photograph of a model · From *The Portsmouth Block-making Machinery* (London, 1965)

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

This is a model of one of the machines Brunel designed for the Block Mills. The shaping engine held many wooden blocks around the rim of a wheel and shaped their outsides while the wheel turned, so every block came out with the same smooth curve.

Look closely

- Find the big wheel with curved bars around it. The wooden blocks were clamped around its rim.
- Find the hand cranks. In the factory, what do you think turned this machine?
- Find the cutting tool that would press against the blocks as they turned past.
- Notice how solid and heavy the iron frame is. Why would a machine need to be so stiff?

Talk about it

1. Why is it helpful if every pulley block comes out exactly the same size?
2. This machine used pulleys and belts to make pulleys. Can you find any other machines that make parts for other machines?
3. What jobs would the old craftsmen still need to do?

Safety first. Hang the broom handle low between two sturdy chairs of the same height. Keep the load light (no more than a small bag of pennies or a half-full water bottle) and keep feet out from under it.

BUILD

Spool Pulleys: Measuring Mechanical Advantage

You will build a fixed pulley and a movable pulley from thread spools and string, lift the same load with each, and measure how hard you have to pull with a rubber-band force meter. Then you will measure how much rope you pull.

You will need

- Two empty thread spools and two pencils or skewers to be their axles
- A broom handle laid across two chairs
- Strong string (about 2 meters), tape and a paper clip hook
- A small bag or cup with about 100 pennies (the load)
- A rubber band and a ruler to make a force meter
- Engineer's notebook

Steps

1. **Make a force meter.** Hang the rubber band from a paper clip. Tape a ruler beside it. Pull on the bottom of the band to lift the load, and read how many centimeters the band stretches. More stretch means more force.
2. **No pulley.** Hook the load to the rubber band and lift it straight up. Record the stretch. Do it three times.
3. **Fixed pulley.** Push a pencil through a spool and tie it under the broom handle. Run the string over the spool: load on one end, rubber band on the other. Pull down slowly and record the stretch. Did the force change, or only the direction?
4. **Movable pulley.** Tie one end of the string to the broom handle. Run the string down under a second spool, which holds the load on its pencil, and back up over the fixed spool. Pull on the free end with your rubber band. Record the stretch.
5. **Rope length.** For each setup, mark the rope with tape, lift the load 10 centimeters, and measure how far you pulled the rope.
6. Put all your numbers in a table: setup, stretch (force), rope pulled.

7. **Improve it.** Add a little soap or wax to the pencil axles to cut friction. Test the movable pulley again. Did the force go down?

Tips

- Pull slowly and steadily; jerking makes the rubber band jump.
- Friction in the spools makes the force a little more than half. That is normal; real pulleys have bearings to cut friction.
- Ask a helper to read the ruler while you pull.

Check your work

- ☐ I can show that a fixed pulley changes the direction of a pull.
- ☐ I measured that a movable pulley needs less force but more rope.
- ☐ I can explain why the Navy needed so many pulley blocks.

ENGINEER'S NOTEBOOK

1. Draw your fixed pulley and your movable pulley. Use arrows to show which way you pull and which way the load moves.
2. Make a table of force (stretch) and rope pulled for each setup. Write one sentence about the trade-off.
3. Draw a sailing ship and mark three places where you think sailors used blocks and tackle.

From history. Marc Brunel's son, Isambard Kingdom Brunel, grew up to be one of the most famous engineers in history. He built bridges, railways and the iron ship *Great Britain*, which you will meet in Unit 6. Some of the Portsmouth block-making machines kept working for more than a hundred years, and a few are now in the Science Museum in London.

COMMON MISTAKES

- Thinking a single fixed pulley makes the load lighter. It only changes the direction of the pull.
- Forgetting the trade-off: a pulley that halves the force doubles the rope you must pull.
- Counting the rope you pull as one of the ropes holding the load in a simple fixed pulley.

Make it a game • Rope Versus Force Duel. Lift a book with a single spool pulley, then with a movable pulley, and compare the pull with your fingers. Measure the rope you pull in hand-spans each time. Say fixed pulley, movable pulley and mechanical advantage. Then teach your parent the trade-off: less force, more rope. Your parent sneaks in one wrong fact to catch.

1.3 GEARS AND THE ANTIKYTHERA MECHANISM

OBJECTIVES

- Explain how meshing gears turn each other and which way each one turns.
- Predict which gear turns faster by counting teeth.
- Build cardboard gears and test how gear size changes speed.

Warm-up. Find something at home with gears: an egg beater, a bicycle, a can opener, a wind-up toy or a pepper grinder. Turn it slowly and watch. Count how many times the small part turns when the big part turns once.

WATCH

O Wow Moment: What's a Gear to Do?

[Children's Museum Houston](https://www.youtube.com/watch?v=vX1-9C58-VM) · 3:08

<https://www.youtube.com/watch?v=vX1-9C58-VM>

WHEN TO WATCH

Before the build. Watch which gear is the driver and which is the follower.

BACKUP VIDEO

Gears Explained - mechanical engineering

[The Engineering Mindset](https://www.youtube.com/watch?v=4ROtKKuSaBI) · 8:48

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

For a parent or an eager student, after the build. Pause at each gear ratio and count the teeth together.

KEY TERMS

gear

A wheel with teeth around its edge that fit into the teeth of another gear.

mesh

When the teeth of two gears fit together so one can turn the other.

driver gear

The gear that is turned by a hand, motor or crank and turns the others.

follower gear

A gear that is turned by another gear.

gear train

A row of gears that pass motion from one to the next.

CORE IDEAS

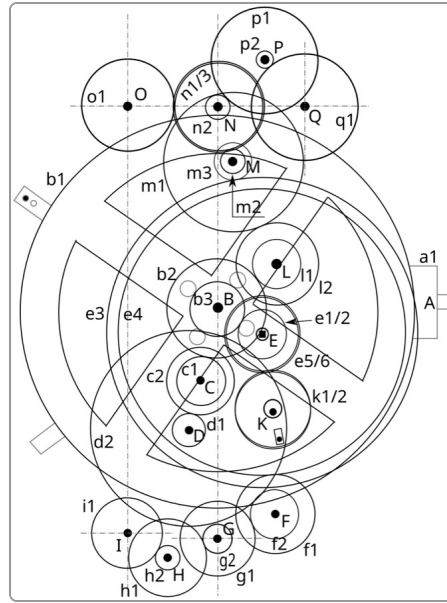
The story. In 1900, sponge divers sheltering from a storm near the little Greek island of Antikythera found an ancient shipwreck on the sea floor. They brought up bronze statues, pottery and some lumps of crusty, green bronze. In 1902, one lump cracked open, and inside it an archaeologist named Valerios Stais saw something nobody expected: tiny gear wheels with triangle-shaped teeth. The ship had sunk more than two thousand years ago. Someone in ancient Greece had built a machine full of gears.

How they figured it out. The pieces were broken, worn and stuck together, so nobody could take them apart. For many years scientists studied the outsides and counted the teeth they could see. In the 1950s and 1970s, a scientist named Derek de Solla Price took X-ray pictures to look inside. In 2005, a team used powerful scanners to see through the bronze layer by layer and read tiny letters written on it. They found at least 30 gears. Turning a handle made the gears move pointers that showed where the sun and moon would be in the sky and when an eclipse would come. It was like a calculator made of bronze.

The physics. When two gears **mesh**, turning one pushes the teeth of the other, so the second gear turns too, but in the opposite direction. If a big gear with 40 teeth drives a small gear with 10 teeth, the small gear turns 4 times for each turn of the big one. It goes faster, but it turns with less force. If the small gear drives the big one, the big gear turns slower but with more force. Count the teeth, and you can predict the speed. That is how the Antikythera maker made a pointer for the moon go around faster than the pointer for the sun.

The engineering. Engineers use gears to trade speed for force or force for speed. A bicycle in a low gear makes climbing hills easier; a high gear makes you go fast on flat ground. Clocks use gear trains so that the minute hand goes around 12 times while the hour hand goes around once. Cars, washing machines, drills and robot arms all have gears inside. Engineers choose the number of teeth, the size and the material so the gears are strong, quiet and long-lasting.

PICTURE STUDY



The Gears of the Antikythera Mechanism, Diagram by a Wikimedia Commons contributor, after the research of Derek de Solla Price and later scientists, Mechanism made about 2,100 years ago; diagram modern · Diagram · The original pieces are in the National Archaeological Museum, Athens

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

The real pieces of the mechanism are green and broken, so scientists drew diagrams like this one to show how its gears fit together. Each circle is a gear. The letters are the names scientists gave them.

Look closely

- Find the biggest circle. That is the main gear that the handle turned.
- Find two circles that touch. Those gears mesh.
- Find a small gear and a big gear sitting on the same spot, one on top of the other. They turn together on one axle.
- Count how many gears you can find in the diagram.

Talk about it

1. If the big main gear turns once, will a small gear that touches it turn more or less than once?
2. Why would the maker need so many gears to show the sun and the moon?
3. What does this machine tell you about the people who made it?

Safety first. An adult cuts thick cardboard. Use push pins carefully and keep them in a small cup when not in use.

BUILD

Cardboard Gear Train

You will make gears from round lids and the bumpy middle layer of corrugated cardboard, pin them to a board, and test how the size of the gears changes the speed and direction of turning.

You will need

- Three round lids of different sizes (for example, from a jar, a yogurt cup and a peanut butter jar)
- Corrugated cardboard (from a shipping box)
- Glue, scissors and a marker
- Push pins or brass fasteners and a thick piece of cardboard for a base board
- Engineer's notebook

Steps

1. Ask an adult to cut strips of corrugated cardboard about 1 centimeter wide. Peel off one flat paper side so the wavy middle shows. The waves are your gear teeth.
2. Glue a strip around the edge of each lid with the waves facing out. Trim the strip so the teeth meet evenly.
3. Count the teeth on each gear and write the number on the gear.
4. Put a push pin through the center of the biggest gear into the base board. Pin a smaller gear right next to it so the teeth mesh. Make sure each gear turns freely.
5. Put a marker dot on each gear. **Predict:** if you turn the big gear once, how many times will the small gear turn, and which direction?
6. **Test.** Turn the big gear exactly once and count the small gear's turns. Do three trials. Then turn the small gear once and watch the big gear.
7. **Fair test.** Keep the same driver gear and try each of the other gears as the follower. Record teeth and turns in a table.

8. **Improve it.** Add a third gear to make a gear train. Which way does the last gear turn? Can you make it turn the same way as the first?

Tips

- If the gears slip, push them closer together so the teeth sink in.
- Count turns by watching the marker dot come back to the top.
- Teeth divided by teeth gives the turns: 30 teeth driving 10 teeth gives 3 turns.

Check your work

- ☐ I can predict which way a follower gear turns.
- ☐ I counted teeth and turns and found that small gears turn faster.
- ☐ I can explain how a gear train can make one pointer turn faster than another.

ENGINEER'S NOTEBOOK

1. Draw two meshing gears with arrows showing the direction each one turns.
2. Make a table: driver teeth, follower teeth, predicted turns, real turns.
3. Draw the gears inside one machine at home (or what you imagine is inside) and label the driver and the follower.

From history. The Antikythera mechanism is the oldest known machine with a gear train. Nothing as complicated is known to have been made again for more than a thousand years, until the great clocks of medieval Europe. Clockmakers then built gear trains that still tick in church towers today.

COMMON MISTAKES

- Thinking meshing gears turn the same way. Two touching gears always turn in opposite directions.
- Thinking the big gear is always faster. The smaller gear turns more times.
- Forgetting the trade-off: a gear that turns faster turns with less force.

Make it a game • Gear Teeth Predictor. Cut two cardboard gears with different numbers of teeth and mesh them. Before each turn, predict which gear spins faster and which direction each turns. Score one point for each right call, and give your parent a chance too. Say driver, follower and gear train. Tell how the Antikythera mechanism used gears, and play to ten points.

1.4 ARCHIMEDES' WATER SCREW

OBJECTIVES

- Explain how an Archimedes screw lifts water.
- Recognize the screw as an inclined plane wrapped around a pole.
- Build a screw from tubing and test how its angle changes how much water it lifts.

Warm-up. Look closely at a screw or a bolt from the toolbox. Run your fingernail along the ridge from the bottom to the top. Now wrap a paper triangle around a pencil, starting at the wide end. What shape does the slanted edge make?

WATCH

Archimedes Screw: Because Hauling Water is Awful

Good and Basic • 3:08

<https://www.youtube.com/watch?v=3h5oBb9O-dw>

WHEN TO WATCH

After the story. Watch the man turn the old wooden screw at an outdoor museum in the Netherlands.

BACKUP VIDEO

How to Make an Archimedes Screw - STEM Activity

Science Buddies • 2:00

<https://www.youtube.com/watch?v=PszGCm1PqSo>

Before the build, to see the steps.

KEY TERMS

Archimedes screw

A tube or pipe with a spiral inside (or wrapped around it) that lifts water when it is turned.

spiral

A line that winds around and around a center.

inclined plane

A flat, slanted surface, like a ramp, that makes it easier to raise a load.

irrigation

Bringing water to fields so crops can grow.

CORE IDEAS

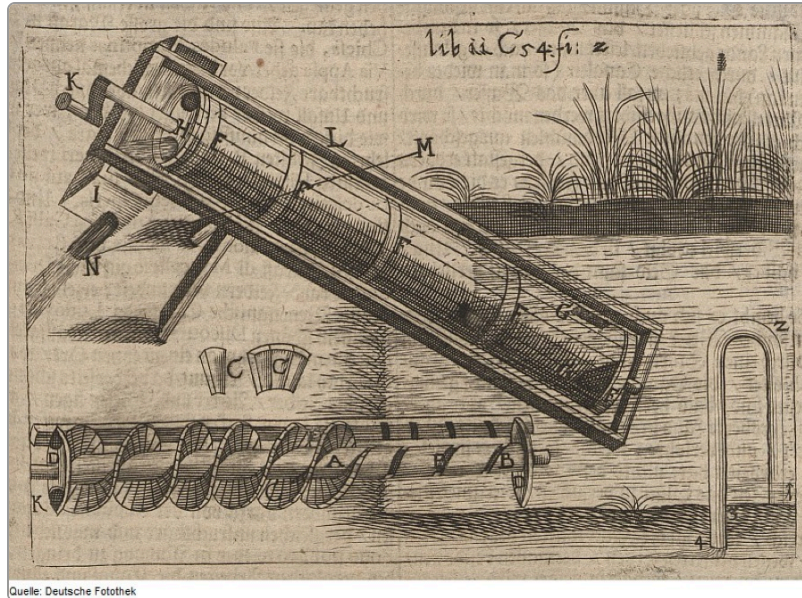
The story. Archimedes lived more than two thousand years ago in the city of Syracuse, on the island of Sicily. He was a great mathematician and a builder of machines. Old writers tell that he visited Egypt, where farmers along the Nile River had to lift water from the river to their fields, bucket by heavy bucket. A machine that came to bear his name, the Archimedes screw, could lift a steady stream of water with only a person turning a handle. Ships used it too, to pump water out of the bottom of the hull.

How they figured it out. Archimedes understood the ramp, or inclined plane: it is easier to roll a load up a long slope than to lift it straight up. A screw is a ramp wrapped around a pole. If you tilt a tube with a spiral inside and dip the low end in water, each turn scoops a little pocket of water into the spiral. As you keep turning, the pocket slides along the ramp, always staying at the bottom of its loop, but the loop itself climbs. People tried screws at different angles and found that if the screw is too steep, the water spills back down instead of climbing.

The physics. Gravity always pulls the water down to the lowest part of each turn of the spiral. But when you rotate the screw, the lowest part of each turn moves upward along the tube. So the water rides up, pocket by pocket, even though it is only ever sliding downhill inside its own little section. The screw turns your circular push into a lift. The gentler the slope, the more water each pocket can hold, but the longer the screw must be to reach the same height. That is a trade-off.

The engineering. Archimedes screws are still used today. In the Netherlands, much of the land is below the level of the sea, and huge screw pumps help keep it dry. Water treatment plants use giant screws to lift wastewater, because they do not clog easily with sticks and trash. Some modern screws run backward as turbines: falling water turns them to make electricity, and fish can swim through safely. The same shape is in drills, meat grinders and the auger of a snow blower.

PICTURE STUDY



A Water Screw in an Old Engraving, Unknown engraver, 1600s–1700s · Engraving · Deutsche Fotothek (Saxon State and University Library), Dresden

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

This engraving comes from an old book about machines for moving water. It shows an Archimedes screw from the outside and from the inside, so readers could understand how it was made.

Look closely

- Find the long slanted tube. Which end is in the water?
- Find the handle that a person would turn.
- Find the drawing of the spiral by itself at the bottom. Trace the spiral with your finger.
- Find where the water would pour out at the top.

Talk about it

1. Why do you think the artist drew the spiral separately as well as inside the tube?
2. What would happen if the screw stood straight up?
3. Who might have used a machine like this, and for what?

Safety first. Do this build outdoors, in a bathtub or over a towel. An adult cuts any pipe or bottle.

BUILD

Build an Archimedes Screw and Test Its Angle

You will wrap clear tubing around a pipe or bottle to make a working Archimedes screw, then run a fair test to find the best angle for lifting water.

You will need

- About 1.5 meters of clear vinyl tubing (about 1 centimeter wide, from a hardware store)
- A length of PVC pipe, a cardboard tube wrapped in plastic, or an empty 2-liter bottle
- Duct tape or strong tape
- Two bowls or containers, one with water (add a drop of food coloring) and one empty
- A measuring cup, books to prop up the screw, and a protractor or a phone level app
- Engineer's notebook

Steps

1. Tape one end of the tubing to one end of the pipe. Wrap the tubing around the pipe in a tight spiral, with the turns about 3 centimeters apart, and tape the other end.
2. Set the water bowl low and the empty bowl higher, on a book. Rest the low end of the screw in the water and the high end over the empty bowl.
3. **Predict:** will the screw lift more water at a gentle angle or a steep one?
4. Tilt the screw to about 30 degrees (use the protractor or a level app). Turn it 20 times at a steady speed. Measure the water in the top bowl with the measuring cup.
5. **Fair test.** Pour the water back. Try 20, 30, 45 and 60 degrees. Keep everything else the same: 20 turns, the same speed, the same water depth.
6. Record angle and water lifted in a table. Do two trials at each angle.
7. **Improve it.** Make a second screw with the turns closer together or farther apart. Test it at your best angle. Which spacing lifts more?

Tips

- Turn the screw in the direction that scoops water into the low end. If no water comes out, turn the other way.
- Food coloring makes it easy to see the little pockets of water climbing.
- Count your turns out loud so a helper can keep track.

Check your work

- ☐ I can explain how a screw is a ramp wrapped around a pole.
- ☐ I found the angle that lifted the most water and wrote it in my table.
- ☐ I can name one place Archimedes screws are used today.

ENGINEER'S NOTEBOOK

1. Draw your screw and show one pocket of water at three moments as it climbs.
2. Make a bar graph: angle of the screw and water lifted.
3. Write two sentences explaining why a screw that is too steep does not work.

From history. Some historians think screws like this were used in Egypt or Assyria before Archimedes was born, and that he may have improved or explained a machine that already existed. Either way, it has carried his name ever since. The same idea, a screw pushing something along, became the screw propeller that drives ships, which you will see in Unit 6.

COMMON MISTAKES

- Thinking the water is pulled up. It is always sliding down inside its pocket; the pocket is what rises.
- Turning the screw the wrong way and deciding it does not work.
- Changing the angle and the number of turns at the same time.

Make it a game • Screw Angle Challenge. Wrap a paper triangle around a pencil to show that a screw is a ramp wound around a pole. Then test your Archimedes screw at a shallow angle and a steeper one, and count how many beads or rice grains it lifts in one minute. Say inclined plane and spiral. Beat your own best count.

UNIT 1

FORCES AND MACHINES

Every machine, from a wagon to a crane, works by pushing and pulling. In this unit you will learn Isaac Newton's first law: things keep doing what they are doing until a force changes them. You will see why a heavy train is hard to stop and why cars have seat belts. Then you will meet three of the oldest machines in the world and the people who put them to work: the pulley that lifted the sails of the great navy ships, the gears hidden inside a bronze box found in a shipwreck, and the water screw of Archimedes.

You will also learn the engineer's way of working: ask a question, plan, build, test, and make it better. Each build has a fair test, where you change only one thing, and a notebook page where you write down what really happened.

PREREQUISITES

- Knows that a force is a push or a pull
- Can measure length with a ruler to the nearest centimeter
- Can count by 2s, 5s and 10s

MASTERY CHECKLIST

- ☐ I can explain Newton's first law with an example from a car, a bike or a train.
- ☐ I can show how a fixed pulley and a movable pulley change a pull, and explain the trade-off.
- ☐ I can tell which way two meshing gears turn and which one turns faster.
- ☐ I can explain how an Archimedes screw lifts water and why its angle matters.
- ☐ I can run a fair test, changing only one thing, and record the results in a table.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Tinker Crate:** Ages 9 and up, so best with a parent at this age. Monthly engineering crates that often include gears, levers, pulleys and hydraulics. A good extra for Lessons 1.2–1.4.
- **LEGO Technic:** Sets vary by age. Technic gears, axles and beams make it easy to build and count gear trains for Lesson 1.3.

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

LESSONS IN THIS UNIT

1.1	Newton's First Law: Why a Heavy Train Is Hard to Stop	2 sessions of 45 minutes
1.2	Pulleys and the Portsmouth Block Mills	2 sessions of 45 minutes
1.3	Gears and the Antikythera Mechanism	2 sessions of 45 minutes
1.4	Archimedes' Water Screw	2 sessions of 45 minutes

UNIT 1 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
Say Newton's first law in your own words.
2. **5 pts**
A car stops suddenly. Why do the people inside lean forward? What keeps them safe?
3. **5 pts**
Predict: a toy car rolls down a ramp onto a smooth floor and onto a carpet. On which one will it roll farther? Why?
4. **5 pts**
What does a fixed pulley do? What does a movable pulley do?

5. (5 pts)

A movable pulley lets you lift a bucket with half the force. What do you have to give up?

6. (5 pts)

Why did Marc Brunel's Block Mills matter to the navy?

7. (5 pts)

Two gears mesh. The big one turns clockwise. Which way does the small one turn, and does it turn faster or slower?

8. (5 pts)

Predict: a gear with 30 teeth turns a gear with 10 teeth. If the big gear turns once, how many times does the small gear turn?

9. (5 pts)

How does an Archimedes screw lift water?

10. (5 pts)

What is a fair test? Give an example from this unit.

ANSWER KEY

1. A thing that is still stays still, and a thing that is moving keeps moving the same way, unless a force pushes or pulls it.
2. Inertia: their bodies keep moving forward when the car stops. Seat belts (and airbags) give the force that stops them gently.
3. The smooth floor, because there is less friction to slow it down.
4. A fixed pulley changes the direction of the pull (pull down to lift up). A movable pulley lets you lift with about half the force.
5. You must pull twice as much rope (twice the distance).
6. Machines made pulley blocks quickly and all the same size, so a few workers could make the many thousands of blocks the ships needed.
7. Counterclockwise (the opposite way), and faster.
8. 3 times ($30 \div 10 = 3$).
9. Water is trapped in pockets of the spiral. When the screw turns, the pockets move up the tube, carrying the water to the top. The screw is a ramp wrapped around a pole.
10. A test where you change only one thing and keep everything else the same, such as changing only the ramp height while using the same car and passenger.

PORTFOLIO PIECE: A MACHINE THAT LIFTS

Design and build a small machine that lifts a cup of 50 pennies at least 30 centimeters, using a pulley, gears, a screw or a mix of them. Before you build, draw a labeled plan. Test it three times, record how hard you had to pull or how many turns it took, then make one improvement and test again. Present your machine and your notebook page to your family.

LOOK FOR	WHAT IT MEANS
Plan	A labeled drawing shows the machine's parts and which simple machine each one is.
It works	The machine lifts the cup of pennies at least 30 centimeters.
Fair test and data	Three trials are recorded in a table with units (centimeters of stretch, turns or rope pulled).
Improvement	One change was made because of the test results, and the new result was recorded.
Explanation	The student explains the trade-off: less force means more rope or more turns.

UNIT 2

BRIDGES

A bridge is a promise. Everyone who walks or drives across it is trusting that the builders knew what they were doing. In this unit you will learn the two great forces inside every bridge: **compression**, which squeezes, and **tension**, which pulls. You will see them in a grass rope bridge in the mountains of Peru, rebuilt by hand every year, and in the wooden covered bridges of New England.

Then you will learn how the Romans built stone arches that still stand after two thousand years, and follow the Roebling family through fourteen years of building the Brooklyn Bridge. In every build, you will load your bridge with pennies until it fails, look closely at how it failed, and make it stronger.

PREREQUISITES

- Knows how to run a fair test and record three trials (Unit 1)
- Can measure in centimeters and count pennies by 5s and 10s
- Knows that a force is a push or a pull

MASTERY CHECKLIST

- ☐ I can show compression and tension with my hands and find them in a bridge.
- ☐ I can explain why a longer beam sags more and a deeper beam sags less.
- ☐ I can explain how an arch carries its load and what the keystone does.
- ☐ I can trace the load in a suspension bridge from the deck to the ground.
- ☐ I can load-test a bridge fairly, describe how it failed, and improve it.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** All ages. Identical maple planks with no connectors, so every bridge and arch must balance its forces. Excellent for Lessons 2.2 and 2.3.
- **KiwiCo Tinker Crate:** Ages 9 and up, with a parent. Some crates build trusses and bridges; check the crate list for a bridge project.

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

LESSONS IN THIS UNIT

2.1 Compression and Tension: The Inca Grass Bridge	2 sessions of 45 minutes
2.2 Beams and Spans: The Covered Bridges of New England	2 sessions of 45 minutes
2.3 Roman Arches and the Keystone	2 sessions of 45 minutes
2.4 The Roeblings and the Brooklyn Bridge	2 sessions of 45 minutes

UNIT 2 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
What is the difference between compression and tension? Give an example of each.
2. **5 pts**
Why did the Inca twist many thin grass cords into one thick cable?
3. **5 pts**
A beam bends under a load. Which side is squeezed and which side is stretched?
4. **5 pts**
Predict: one beam spans 10 centimeters and another spans 30 centimeters. Which will sag more with the same load?

5. (5 pts)

Why did builders put roofs on wooden bridges?

6. (5 pts)

What does the keystone do? What do the abutments do?

7. (5 pts)

Why is stone a good material for an arch?

8. (5 pts)

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

9. (5 pts)

How did Emily Roebling help build the Brooklyn Bridge?

10. (5 pts)

What is a safety factor, and how did it help the Brooklyn Bridge?

ANSWER KEY

1. Compression squeezes or pushes (a table leg, a stone column). Tension pulls or stretches (a rope, a clothesline, a bridge cable).
2. One cord is weak, but many twisted together share the load and are strong enough to carry people.
3. The top is squeezed (compression) and the bottom is stretched (tension).
4. The 30-centimeter beam. Longer spans sag more.
5. To keep the wooden truss dry so it would not rot. A covered bridge lasts much longer.
6. The keystone is the last stone at the top that locks the arch together. The abutments push back at the ends so the arch cannot spread apart.
7. Every part of an arch is squeezed (compression), and stone is very strong in compression.
8. Car → deck → suspenders → main cables → towers → ground (and the cable ends are held by the anchorages).
9. When her husband Washington was too sick to go to the bridge, she learned the engineering and carried his instructions to the builders, and answered their questions.
10. Extra strength beyond what is needed. The cables were made about six times stronger than needed, so they were still safe when some bad wire was found.

PORTFOLIO PIECE: A LOAD-TESTED BEAM BRIDGE

Design and build a bridge from card stock, craft sticks or paper that spans 30 centimeters and holds as many pennies as possible. You may use folds, a truss, an arch or cables. Before building, draw your plan and mark which parts are in compression and which in tension. Load-test it, record the number of pennies, describe how it failed, then build an improved version and test again.

LOOK FOR	WHAT IT MEANS
Plan	A labeled drawing shows the span, the bridge type and which parts are squeezed or pulled.
Fair test	The load was added slowly in the middle, and the number of pennies was recorded.
How it failed	The student describes where and how the bridge failed using the words compression, tension, sag or buckle.
Improvement	A second version fixes the weak spot, and its result is recorded.

2.1 COMPRESSION AND TENSION: THE INCA GRASS BRIDGE

OBJECTIVES

- Define compression and tension and show each one with your body.
- Explain why a rope can carry tension but not compression.
- Test paper in tension and in compression and compare.

Warm-up. Stand facing a partner, palms together, and lean in a little. You are in compression: pushing. Now hold hands and lean back. You are in tension: pulling. Try it with a piece of string: can you pull with it? Can you push with it?

WATCH

Compression and Tension

Builder Bunch • 2:05

https://www.youtube.com/watch?v=N_DLcS1BVc4

WHEN TO WATCH

After the physics paragraph. Name the force each time something squeezes or stretches.

BACKUP VIDEO

Weaving the Bridge at Q'eswachaka

SmithsonianNMAI • 3:15

<https://www.youtube.com/watch?v=dql-D6JQ1Bc>

After the story, to watch the families braid the grass ropes and pull them across the canyon.

KEY TERMS

compression

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

load

The weight a structure must carry, including people, cars, snow and its own weight.

tension

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

cable

A thick rope or bundle of wires that carries tension.

anchor

A strong, heavy fixing at each end that holds a cable in place.

CORE IDEAS

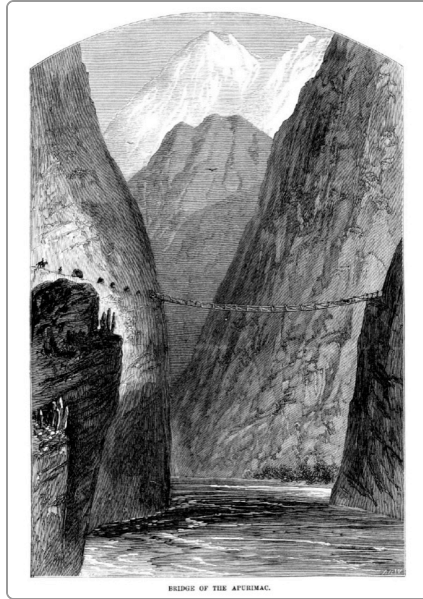
The story. High in the Andes Mountains of Peru, the Apurímac River runs through a deep, rocky canyon. More than five hundred years ago, the Inca people built a great road system through these mountains, and wherever the road met a canyon, they built a bridge of rope. One of these bridges, called Q'eswachaka, still hangs there today, nearly 100 feet long. Every year in June, families from the villages on both sides gather. Each family braids thin cords from a tough mountain grass called *q'oya*. In a few days, they twist the cords into thick cables, stretch them across the canyon, and weave a new bridge. Then they cut the old one loose.

How they figured it out. The Inca had no iron and no wheels for carts, but they knew grass well. One blade of grass breaks easily. But twist many blades into a cord, and many cords into a rope, and many ropes into a cable as thick as a person's leg, and it becomes strong enough to carry people and llamas. They tied the cables to big stone anchors on each side of the canyon. They learned from long experience that grass rots in the rain, so the bridge must be rebuilt every year to stay safe.

The physics. Every part of a bridge is being squeezed or pulled. **Compression** squeezes: a table leg, a stone wall and your palms pushing together are in compression. **Tension** pulls: a clothesline, a rope in a tug-of-war and the cables of Q'eswachaka are in tension. A rope is very strong in tension, but it cannot push at all; push on a rope and it just goes limp. Stone is the opposite: very strong when squeezed, but it cracks when pulled.

The engineering. Engineers choose materials for the force each part will carry. Ropes, cables and steel wires are used for parts in tension. Stone, brick and concrete are used for parts in compression. Steel is strong both ways, so it is used for both. A rope bridge hangs in tension from strong anchors, and the anchors must be heavy and deep so that the cables cannot pull them out. Today's great suspension bridges work the same way, with steel cables instead of grass.

PICTURE STUDY



*Bridge over the Apurímac, After a drawing by E. George Squier, 1877 · Wood engraving · From Squier's book *Peru: Incidents of Travel and Exploration in the Land of the Incas**

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

The American explorer E. George Squier crossed an Inca rope bridge over the Apurímac River in the 1860s. He wrote that it swayed in the wind high above the water. This engraving from his book shows how deep the canyon was and how thin the bridge looked.

Look closely

- Find the bridge. How does it hang: straight, or in a curve?
- Find where each end of the bridge meets the cliff. That is where the anchors are.
- Look at the canyon walls and the river far below. Why couldn't people build a stone bridge here easily?
- Find the mountains in the background.

Talk about it

1. Are the bridge's ropes in tension or compression?
2. Why does a rope bridge sag in the middle?
3. What would happen if one of the anchors came loose?

BUILD

Paper in Tension and Compression

You will test strips of paper pulled in tension and paper columns squeezed in compression, compare the results, and then braid paper strips into a stronger “cable,” just as the Inca braided grass.

You will need

- Printer paper (all the same kind), scissors and tape
- A paper cup with a string or paper-clip handle
- About 200 pennies
- A ruler and a few books
- Engineer’s notebook

Steps

1. **Tension test.** Cut a strip of paper 2 centimeters wide and 20 centimeters long. Tape the top end firmly under the edge of a table. Hang the cup from the bottom end. Add pennies one at a time until the strip tears. Record the number of pennies. Do three trials with new strips.
2. **Compression test.** Roll a half sheet of paper into a tube 2 centimeters across and tape it. Stand it on the table. Lay a book flat on top and add pennies (or more books) until the tube crushes or buckles. Record the result. Do three trials.
3. **Predict**, then compare: is paper stronger when pulled or when pushed? Write your answer and your numbers.
4. **Fair test: shape.** Make three compression columns from the same size of paper: a round tube, a square tube and a triangle tube. Test each one the same way and record.
5. **Improve it.** Cut three thin strips and braid or twist them together into a “cable.” Test it in tension. Is it stronger than three single strips added together?

Tips

- Add pennies gently; dropping them makes a sudden jerk that breaks the paper early.
- Tape the strips the same way every time so the test is fair.
- Watch closely how each one fails: does it tear, crush or bend sideways?

Check your work

- ☐ I can name which force pulls and which force pushes.
- ☐ I tested paper both ways and recorded three trials each.
- ☐ I can explain why the Inca twisted many small cords into one big cable.

ENGINEER'S NOTEBOOK

1. Draw the rope bridge and label the cables (tension) and the stone anchors.
2. Make a table: test, trial 1, trial 2, trial 3. Circle your strongest result.
3. Draw four things at home: two in tension and two in compression. Label each.

From history. The Inca road system stretched about 25,000 miles through the mountains and along the coast. It had hundreds of rope bridges. Q'eswachaka is the last one still rebuilt in the old way, and the families who rebuild it are carrying on a skill their great-great-grandparents taught them.

COMMON MISTAKES

- Thinking a rope can push. Ropes and cables carry only tension.
- Mixing up the two words. Remember: compression compresses (squeezes); tension tugs.
- Testing one strip only. One result may be a fluke; three trials show the pattern.

Make it a game • Body Tension Compression. Act out compression by pushing your palms together, and tension by pulling a rope or towel with your parent. Your parent shouts one of the two words and you show it within two seconds. Then explain why a rope carries tension but not compression. Tell the Inca grass bridge story in three sentences, with one fact to hide.

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

The Inca builders did not have engines or steel, but they had wisdom learned over many years about grass, rope and stone. Good building always begins with understanding how things really work.

2.2 BEAMS AND SPANS: THE COVERED BRIDGES OF NEW ENGLAND

OBJECTIVES

- Explain how a beam bends: squeezed on top, stretched on the bottom.
- Predict how span length and beam depth change how much a beam sags.
- Run a fair test of span length with a card-stock beam bridge.

Warm-up. Lay a ruler across the gap between two stacks of books and press down gently in the middle. Watch it bend. Now turn the ruler on its edge and press again. Which way is stiffer? Why might that be?

WATCH

History of Covered Bridges | The Henry Ford's Innovation Nation

The Henry Ford • 3:23

<https://www.youtube.com/watch?v=YRAov0q1nHM>

WHEN TO WATCH

After the story. Look inside the bridge at the wooden truss.

BACKUP VIDEO

Paper Bridges STEM Activity

Science Buddies • 2:05

<https://www.youtube.com/watch?v=CqYGVW2Eu6Y>

Before the build.

KEY TERMS

beam

A long, straight part that carries a load across a gap by bending a little.

sag

How far a beam bends down under a load.

span

The distance a bridge crosses between its supports.

truss

A frame of straight pieces joined in triangles, used to make a long, stiff beam.

pier

A support that holds up a bridge in the middle.

CORE IDEAS

The story. In the 1800s, New England was full of rivers and streams, and farmers and travelers needed bridges everywhere. There was plenty of good timber, so builders made bridges of wood. But they noticed something: an open wooden bridge, left out in the rain and snow, began to rot in ten or twenty years. So they put a roof and walls on it. The covered bridge was born. The Cornish–Windsor Bridge, built in 1866 across the Connecticut River between New Hampshire and Vermont, is one of the longest wooden covered bridges in America, and cars still cross it today.

How they figured it out. A single log works as a beam for a little creek, but logs are only so long. To cross a wide river, builders needed something longer and stiffer. Carpenters learned to join many boards into a tall frame of triangles called a **truss**. In 1820, an architect named Ithiel Town patented a “lattice” truss made of crisscrossing planks pegged together, which ordinary carpenters could build. The roof kept the truss dry, and a dry wooden truss could last a hundred years or more.

The physics. When a load presses down on the middle of a **beam**, the beam bends a little. Its top is squeezed (compression) and its bottom is stretched (tension). A longer **span** bends much more than a short one, so builders add piers to cut a long bridge into shorter spans. A deeper beam, one that is taller from top to bottom, is much stiffer than a thin one, even if it uses the same material. That is why the ruler was stiffer on its edge, and why a tall truss can cross a long span.

The engineering. Engineers choose the span, the depth and the material to keep the sag small and the bridge safe. Simple beam bridges are the most common bridges in the world: think of highway overpasses made of concrete or steel beams. Engineers also plan for **maintenance**, the care a bridge needs to last. For a covered bridge, that means a good roof. For a steel bridge, it means paint to stop rust. Bridges are inspected regularly so that small problems are fixed before they grow.

PICTURE STUDY



The Cornish-Windsor Covered Bridge, Historic American Engineering Record, Bridge built 1866; photograph late 1900s · Photograph · Library of Congress, Prints and Photographs Division

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

The Historic American Engineering Record photographs important old bridges so that their design is never forgotten. This is the Cornish-Windsor Bridge over the Connecticut River. Hidden inside its walls is a wooden lattice truss.

Look closely

- Find the roof. What does it protect?
- Find the stone pier in the river. How many spans does the bridge have?
- Look at the walls. Can you guess how tall the truss inside must be?
- Find the reflection of the bridge in the water.

Talk about it

1. Why did builders put the middle support in the river?
2. Which part of the bridge is squeezed and which part is stretched when a truck crosses?
3. What would happen to the wooden truss if the roof leaked for many years?

Safety first. Wear safety glasses when loading beams; a beam can snap and pennies can fly.

BUILD

How Far Can a Beam Reach? A Span Test

You will make card-stock beams and test how much they sag at different spans, then make a deeper beam by folding the card and see how much stronger it is.

You will need

- Card stock or index cards (all the same kind)
- Two equal stacks of books
- A paper cup and about 100 pennies
- A ruler, tape and a pencil
- Engineer's notebook

Steps

1. Cut card-stock strips 5 centimeters wide and 30 centimeters long.
2. Set the book stacks 10 centimeters apart. Lay a strip across them. Set the cup in the middle.
3. Stand a ruler on the table next to the middle of the beam. Add pennies 5 at a time. After every 5, measure how far the beam has sagged (how much lower it is than before).
4. Stop at 20 pennies, or when the beam touches the table. Record sag for each number of pennies.
5. **Fair test.** Do it again with the books 15 centimeters apart and 20 centimeters apart. Use a new strip each time and load it the same way.
6. **Predict, then improve.** Fold a new strip into a U shape or a W shape (accordion) to make it deeper. Test it at a 20-centimeter span. How many pennies does it hold before it sags 2 centimeters?
7. Make a table and write one sentence about span and one about depth.

Tips

- Use the same spot in the middle of the beam for the cup every time.
- Measure from the table to the bottom of the beam before and after loading; the difference is the sag.

- Tape the ends of folded beams so they keep their shape.

Check your work

- ☐ I can explain why a longer span sags more.
- ☐ I showed that folding the card made it deeper and stiffer.
- ☐ I can explain why covered bridges have roofs.

ENGINEER'S NOTEBOOK

1. Draw a beam bending under a load. Label the top “compression” and the bottom “tension,” with arrows.
2. Make a line graph: number of pennies (across) and sag (up), with one line for each span.
3. Sketch a covered bridge and draw the lattice truss that is hidden inside the walls.

From history. About 14,000 covered bridges were built in the United States in the 1800s. Fewer than a thousand remain. Many towns now take great care of their covered bridges, repairing the roof and the timbers so that the bridges can serve for another hundred years.

COMMON MISTAKES

- Thinking a beam that does not break is fine. Too much sag can make a bridge unsafe or uncomfortable long before it breaks.
- Forgetting that the bridge’s own weight is a load too.
- Moving the cup to a different spot on different tests.

Make it a game • Span Sag Estimation Duel. Lay paper strips between books at three different spans, and add pennies in the middle. Before each test, estimate how many pennies it will hold. Closest guess earns a point. Say beam, span, sag and pier. Predict what happens if the beam is deeper, and tell your parent about covered bridges in New England.

2.3 ROMAN ARCHES AND THE KEYSTONE

OBJECTIVES

- Explain how an arch turns a downward load into compression.
- Explain what the keystone and the abutments do.
- Test a paper arch with and without abutments, and build a block arch.

Warm-up. Stand facing a partner about an arm's length apart. Lean toward each other and press your palms together above your heads to make an arch with your arms. Now ask someone to press down gently on your hands. What do your feet want to do? (Slide outward!)

WATCH

How Do Arches Work? (with Demo!): Structures 2-1

Paul Kassabian · 5:34

<https://www.youtube.com/watch?v=ld2NYntHBMg>

WHEN TO WATCH

After the physics paragraph. Watch what happens to the ends of the arch when he adds weight.

KEY TERMS

arch

A curved structure that carries a load over an opening by squeezing its parts together.

keystone

The wedge-shaped stone at the very top of an arch, put in last.

centering

A wooden frame that holds up the stones of an arch while it is being built.

vousoir

One of the wedge-shaped stones that make up an arch. (Say “voo-SWAHR.”)

abutment

The strong support at each end of an arch that stops it from spreading apart.

CORE IDEAS

The story. Two thousand years ago, the Romans built roads across their whole empire, and their roads needed bridges that would last. They had no steel. They used cut stone, and they shaped it into arches. Many Roman arch bridges are still standing, and some still carry cars. Near the city of Rome, the Ponte Salaro carried the old Salt Road over the Aniene River for many centuries; an Italian artist named Giovanni Battista Piranesi drew it in the 1750s.

How they figured it out. Roman builders learned that stones cut into wedges, called **voussoirs**, could lean against each other in a curve. But a half-built arch would fall down! So they first built a wooden frame called **centering** shaped like the curve. They laid the stones on top of it from both sides, working up toward the middle. The last stone, the **keystone**, was pushed into the gap at the top. Only then could they take the centering away, and the arch stood on its own.

The physics. When a load presses down on an arch, the curve passes the push around the arch from stone to stone, down to the ground. Every stone is squeezed tightly against its neighbors: the whole arch is in **compression**. That is perfect for stone, which is very strong when squeezed. But the arch also pushes outward at its feet, just as your feet wanted to slide in the warm-up. Strong **abutments**, often the rock of the riverbank, push back so the arch cannot spread apart.

The engineering. Arches let builders cross wide gaps with stone, brick or concrete, which cannot be used for long beams because they crack in tension. Engineers today build arch bridges of steel and concrete, and they use arches in doorways, tunnels and dams. They pay great attention to the abutments, because an arch is only as strong as the ground that holds its ends. A well-built arch with good abutments can last for thousands of years.

PICTURE STUDY



View of the Ponte Salario, Giovanni Battista Piranesi, 1756–1757 · Etching · National Gallery of Art, Washington

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

Piranesi loved the old Roman ruins and drew them with great care. Here is the Ponte Salario, an ancient bridge near Rome, with a tower that was added on top in the Middle Ages. Look for the stones of the arch.

Look closely

- Find the big arch. Can you see the wedge-shaped stones that run around its curve?
- Find the very top stone of the arch. That is where the keystone is.
- Find the thick stone walls at each end of the arch, the abutments.
- Find the small people. How big is the arch compared with them?

Talk about it

1. Every stone in the arch is being squeezed. Why is stone a good choice for that?
2. What do you think held the stones up while the Romans were building the arch?
3. Why would the Romans build the ends of the bridge so thick and heavy?

Safety first. Wear safety glasses during load tests.

BUILD

Arch or Flat? A Paper Arch Test

You will compare a flat paper bridge with an arched one, test the arch with and without abutments, and then build a self-standing arch from blocks or foam wedges.

You will need

- Card stock (all the same kind) and tape
- Four stacks of books
- A paper cup and about 100 pennies
- Building blocks, sugar cubes or wedges cut from a foam meat tray or thick cardboard
- A cardboard shape for centering (cut in a half-circle)
- Engineer's notebook

Steps

1. **Flat bridge.** Lay a strip of card stock 5 centimeters wide across a 15-centimeter gap between books. Set the cup in the middle and add pennies until it sags to the table. Record the number.
2. **Arch with no abutments.** Bend a second strip into an arch under the flat strip so that its ends rest on the table between the books, but nothing holds the ends. Load the flat strip again. Watch the ends of the arch.
3. **Arch with abutments.** Now push the books right up against the ends of the arch so they cannot slide. Load it again. **Predict** first: more or fewer pennies?
4. Record all three results and do each test twice.
5. **Build a block arch.** Stand your half-circle of cardboard (the centering) on the table. Lay blocks or wedges over it from both ends toward the middle. Put the keystone in last. Gently slide the centering out. Does it stand?
6. **Improve it.** If your block arch fell, look at where it spread or slipped. Add “abutments” of books at each end and try again.

Tips

- Make sure both ends of the arch are the same height.

- Wedges work better than square blocks, because they fit the curve.
- Press the abutments in firmly; a tiny gap lets the arch spread.

Check your work

- ☐ I can explain why the arch held more than the flat card.
- ☐ I saw what happens to an arch without abutments.
- ☐ I built an arch with a keystone and centering, like the Romans.

ENGINEER'S NOTEBOOK

1. Draw an arch. Use arrows to show the load going around the curve and pushing outward at the feet.
2. Make a bar graph: flat bridge, arch without abutments, arch with abutments.
3. Find three arches at home, at church or in town (doorways, windows, bridges). Sketch them.

From history. The Romans also built arches on top of arches to make aqueducts that carried water to their cities, like the famous Pont du Gard in France. You will learn more about bringing water to cities in Unit 5.

COMMON MISTAKES

- Thinking the keystone holds up the whole arch by itself. Every stone matters; the keystone just locks them together.
- Forgetting the outward push at the feet of the arch.
- Taking the centering out before the keystone is in.

Make it a game • Arch Versus Flat. Test a flat paper bridge and an arch bridge with pennies, and write the result of each in a quick chart. Before testing, vote on the winner. Say arch, keystone, voussoir and abutment. Then explain how an arch turns a downward load into compression. Your parent gives you ten seconds to explain it to a toy audience.

2.4 THE ROEBLINGS AND THE BROOKLYN BRIDGE

OBJECTIVES

- Tell the story of John, Washington and Emily Roebling and the Brooklyn Bridge.
- Trace the load in a suspension bridge from the deck to the ground.
- Build a model suspension bridge and test it with and without anchors.

Warm-up. Tie a string between the backs of two chairs. Hang a paper cup from the middle with a paper clip and add a few pennies. What happens to the string? Now slide one chair a little toward the other. What happens to the cup?

WATCH

Brooklyn Bridge | How It Was Built

Structures Simplified · 6:50

https://www.youtube.com/watch?v=Y5Mc97_rW14

WHEN TO WATCH

After the story. Watch the part about the caissons and the bedrock.

Note: Early on, a slide about the bridge's cost lists the number of workers who died during construction. You may want to talk about it briefly or skip ahead.

BACKUP VIDEO

The Story of the Brooklyn Bridge | History Made Easy

Bedtime History · 5:04

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

Any time, as a gentle retelling of the story with old pictures.

KEY TERMS

suspension bridge

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

deck

The flat part of a bridge that people and cars travel on.

tower

A tall support that holds up the main cables of a suspension bridge.

suspender

A vertical cable that hangs the deck from the main cable.

anchorage

A huge block at each end of a suspension bridge that holds the main cables down.

CORE IDEAS

The story. In the 1860s, Brooklyn and New York were two busy cities on either side of the East River, and the only way across was by ferry. In winter the river filled with ice. John A. Roebling, an engineer who made steel wire rope, designed a bridge with a span longer than any in the world. In 1869, just before work began, he was hurt in an accident at the ferry dock and did not recover. His son, Washington Roebling, became chief engineer. A few years later, Washington became very sick from working deep under the river and could no longer go to the bridge. His wife, Emily Warren Roebling, learned the engineering herself and carried his instructions to the builders for eleven years. When the bridge opened on May 24, 1883, Emily was the first to ride across.

How they figured it out. The towers had to stand on solid rock far below the mud of the riverbed. Washington Roebling used **caissons**: giant wooden boxes, open at the bottom, sunk into the river. Air was pumped in to keep the water out while workers dug away the mud underneath, and the caisson slowly sank under the weight of the stone tower being built on top. For the cables, the Roeblings chose steel wire, which was new and very strong. Workers strung more than 5,000 wires into each of the four great cables, wire by wire, back and forth across the river.

The physics. In a suspension bridge, the deck hangs from **suspenders**, which hang from the main **cables**. All of these are in tension. The cables run over the tops of the towers, which are squeezed in compression, and down to the **anchorages** at each end, which hold the cables down. Follow a car's weight: deck, suspenders, main cables, towers, ground. The anchorages keep the cables from pulling the towers over.

The engineering. John Roebling designed the cables to be about six times stronger than they needed to be. This extra strength is called a safety factor. It mattered: during construction, a dishonest supplier sold the bridge some bad wire, but because of the safety factor, the cables were still strong enough, and Washington added extra wires to make up for it. Engineers still inspect and repair the Brooklyn Bridge today, more than 140 years after it opened.

PICTURE STUDY



The Great East River Suspension Bridge, Currier & Ives, after a drawing by Parsons & Atwater, 1883 ·

Hand-colored lithograph · Library of Congress, Prints and Photographs Division

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

When the bridge opened, the printmakers Currier & Ives sold this colorful picture of it. People hung prints like this in their homes because the bridge was the wonder of its day.

Look closely

- Find the two stone towers. How many pointed arches does each have?
- Follow one main cable from one end of the bridge, over a tower, and down to the other end.
- Find the thin vertical lines hanging down from the cables. Those are the suspenders.
- Find the boats under the bridge. Why did the deck have to be so high?

Talk about it

1. Which parts of the bridge are in tension? Which are in compression?
2. Where are the anchorages? What would happen without them?
3. Why do you think people were so proud of this bridge?

Safety first. Use sturdy chairs that will not tip. Wear safety glasses during the load test.

BUILD

A Model Suspension Bridge

You will build a suspension bridge with two towers, string cables, a card-stock deck and book anchorages. You will load it with pennies, then test what happens when the anchors are taken away.

You will need

- Two paper-towel tubes or two stacks of blocks for towers, taped to a base
- Strong string, tape and paper clips
- A strip of card stock about 50 centimeters long for the deck
- Heavy books for anchorages
- A paper cup and pennies
- Engineer's notebook

Steps

1. Stand the two towers about 30 centimeters apart. Lay two long strings over the tops of the towers so they hang in a gentle curve between them. These are your main cables.
2. Tie or tape the ends of each cable under a heavy book on each side. These are your anchorages.
3. Hang the card-stock deck below the cables with short strings or bent paper clips (suspenders) every 5 centimeters.
4. **Predict** how many pennies the bridge will hold in a cup set in the middle of the deck. Then add pennies 5 at a time and record when it sags badly or slips.
5. **Fair test.** Now remove one anchorage book and hold the cable with just a small piece of tape. Load it again the same way. What happens to the towers?
6. **Improve it.** Try adding more suspenders, or making the towers taller so the cables curve more. Test again and record.

Tips

- Keep both cables the same length so the deck hangs level.
- Tape the bottoms of the towers firmly; they want to lean toward the middle.

- Look at which part fails first: the cable, a suspender, a tower or an anchorage.

Check your work

- ☐ I can trace the load from the deck to the ground.
- ☐ I showed that the anchorages hold the cables down.
- ☐ I can explain what a safety factor is and why the Roeblings used one.

ENGINEER'S NOTEBOOK

1. Draw a suspension bridge. Color the parts in tension red and the parts in compression blue.
2. Write a short diary entry as Emily Roebling on the day the bridge opened.
3. Record your load tests in a table and write what failed first.

From history. A year after the bridge opened, some people still doubted that it was safe. In 1884 the showman P. T. Barnum led 21 elephants across it to show how strong it was. Emily Roebling later studied law and wrote and spoke about her work. A plaque on the bridge honors all three Roeblings.

COMMON MISTAKES

- Thinking the deck holds up the cables. The cables hold up the deck.
- Forgetting the anchorages. Without them, the cables would pull the towers toward the middle.
- Thinking a safety factor is wasted material. It protects against mistakes, bad materials and loads no one expected.

Make it a game • Trace the Load. Draw a suspension bridge quickly, then trace the path of a car's weight with your finger from the deck, up through the suspenders and the cables, over the towers and down to the anchorage. Say each part aloud. Do it three times, getting faster each round. Then tell the Roebling family story in under a minute.

Scripture. “Whatsoever thy hand findeth to do, do it with thy might” (Ecclesiastes 9:10, KJV)

The Roeblings faced injury, sickness and years of hard work, but they kept going and did their work with care. The bridge they finished still serves millions of people.

UNIT 2

BRIDGES

A bridge is a promise. Everyone who walks or drives across it is trusting that the builders knew what they were doing. In this unit you will learn the two great forces inside every bridge: **compression**, which squeezes, and **tension**, which pulls. You will see them in a grass rope bridge in the mountains of Peru, rebuilt by hand every year, and in the wooden covered bridges of New England.

Then you will learn how the Romans built stone arches that still stand after two thousand years, and follow the Roebling family through fourteen years of building the Brooklyn Bridge. In every build, you will load your bridge with pennies until it fails, look closely at how it failed, and make it stronger.

PREREQUISITES

- Knows how to run a fair test and record three trials (Unit 1)
- Can measure in centimeters and count pennies by 5s and 10s
- Knows that a force is a push or a pull

MASTERY CHECKLIST

- ☐ I can show compression and tension with my hands and find them in a bridge.
- ☐ I can explain why a longer beam sags more and a deeper beam sags less.
- ☐ I can explain how an arch carries its load and what the keystone does.
- ☐ I can trace the load in a suspension bridge from the deck to the ground.
- ☐ I can load-test a bridge fairly, describe how it failed, and improve it.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** All ages. Identical maple planks with no connectors, so every bridge and arch must balance its forces. Excellent for Lessons 2.2 and 2.3.
- **KiwiCo Tinker Crate:** Ages 9 and up, with a parent. Some crates build trusses and bridges; check the crate list for a bridge project.

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

LESSONS IN THIS UNIT

2.1 Compression and Tension: The Inca Grass Bridge	2 sessions of 45 minutes
2.2 Beams and Spans: The Covered Bridges of New England	2 sessions of 45 minutes
2.3 Roman Arches and the Keystone	2 sessions of 45 minutes
2.4 The Roeblings and the Brooklyn Bridge	2 sessions of 45 minutes

UNIT 2 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
What is the difference between compression and tension? Give an example of each.
2. **5 pts**
Why did the Inca twist many thin grass cords into one thick cable?
3. **5 pts**
A beam bends under a load. Which side is squeezed and which side is stretched?
4. **5 pts**
Predict: one beam spans 10 centimeters and another spans 30 centimeters. Which will sag more with the same load?

5. (5 pts)

Why did builders put roofs on wooden bridges?

6. (5 pts)

What does the keystone do? What do the abutments do?

7. (5 pts)

Why is stone a good material for an arch?

8. (5 pts)

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

9. (5 pts)

How did Emily Roebling help build the Brooklyn Bridge?

10. (5 pts)

What is a safety factor, and how did it help the Brooklyn Bridge?

ANSWER KEY

1. Compression squeezes or pushes (a table leg, a stone column). Tension pulls or stretches (a rope, a clothesline, a bridge cable).
2. One cord is weak, but many twisted together share the load and are strong enough to carry people.
3. The top is squeezed (compression) and the bottom is stretched (tension).
4. The 30-centimeter beam. Longer spans sag more.
5. To keep the wooden truss dry so it would not rot. A covered bridge lasts much longer.
6. The keystone is the last stone at the top that locks the arch together. The abutments push back at the ends so the arch cannot spread apart.
7. Every part of an arch is squeezed (compression), and stone is very strong in compression.
8. Car → deck → suspenders → main cables → towers → ground (and the cable ends are held by the anchorages).
9. When her husband Washington was too sick to go to the bridge, she learned the engineering and carried his instructions to the builders, and answered their questions.
10. Extra strength beyond what is needed. The cables were made about six times stronger than needed, so they were still safe when some bad wire was found.

PORTFOLIO PIECE: A LOAD-TESTED BEAM BRIDGE

Design and build a bridge from card stock, craft sticks or paper that spans 30 centimeters and holds as many pennies as possible. You may use folds, a truss, an arch or cables. Before building, draw your plan and mark which parts are in compression and which in tension. Load-test it, record the number of pennies, describe how it failed, then build an improved version and test again.

LOOK FOR	WHAT IT MEANS
Plan	A labeled drawing shows the span, the bridge type and which parts are squeezed or pulled.
Fair test	The load was added slowly in the middle, and the number of pennies was recorded.
How it failed	The student describes where and how the bridge failed using the words compression, tension, sag or buckle.
Improvement	A second version fixes the weak spot, and its result is recorded.

UNIT 3

BUILDINGS

People have always wanted to build high: to see far, to stand out on the skyline, and to fit many people onto a small piece of land. In this unit you will follow four great steps in tall building. First, the Great Pyramid of Egypt, which stood as the tallest building on earth for thousands of years because of its wide, heavy base. Then the Gothic cathedrals of France, where builders learned to prop up thin stone walls with flying buttresses so they could fill them with colored glass.

Next comes the Eiffel Tower, a lattice of iron triangles that the wind blows right through, and finally the first steel-frame skyscraper in Chicago, where a frame of steel carried the weight so the walls no longer had to. In every build, you will test a tower against weight and wind, and make it stronger.

PREREQUISITES

- Knows compression and tension (Unit 2)
- Knows why triangles are strong and arches push outward (Unit 2)
- Can measure height in centimeters and record three trials

MASTERY CHECKLIST

- ☐ I can explain why a wide base makes a building stable.
- ☐ I can explain what a flying buttress does and why Gothic walls could have big windows.
- ☐ I can explain why the Eiffel Tower is made of open lattice instead of solid walls.
- ☐ I can explain how a steel frame carries a skyscraper's weight.
- ☐ I can build a tower, test it fairly against weight and wind, and improve it.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** All ages. Plain wooden planks for building towers, domes and walls with nothing but balance. Good for Lessons 3.1–3.3.
- **LEGO Technic:** Sets vary by age. Beams and connectors make good model frames and trusses for 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	The Great Pyramid: The Strength of a Wide Base	2 sessions of 45 minutes
3.2	Gothic Cathedrals and Flying Buttresses	2 sessions of 45 minutes
3.3	The Eiffel Tower: Iron Lace in the Wind	2 sessions of 45 minutes
3.4	The Steel Frame: Chicago's First Skyscraper	2 sessions of 45 minutes

UNIT 3 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
Why is a pyramid so hard to tip over?
2. **5 pts**
How did wet sand help the Egyptians move heavy stones?
3. **5 pts**
Predict: you push a tall, thin tower and a short, wide tower made of the same blocks. Which tips over first?
4. **5 pts**
What is thrust? Where does it come from in a cathedral?

5. (5 pts)

How does a flying buttress help a cathedral have big windows?

6. (5 pts)

Why is the Eiffel Tower made of open lattice instead of solid iron walls?

7. (5 pts)

What does prefabricated mean? How did it help build the Eiffel Tower quickly?

8. (5 pts)

What holds up a steel-frame skyscraper: the walls or the frame?

9. (5 pts)

Why did old brick buildings have very thick walls at the bottom?

10. (5 pts)

Name the two inventions that made skyscrapers possible.

ANSWER KEY

1. It has a very wide base and most of its weight is low down near the ground.
2. Damp sand is firmer and lets a sledge slide more easily, with about half the pulling force.
3. The tall, thin tower.
4. Thrust is the outward push of an arch or vault. The heavy stone vault (ceiling) pushes outward on the tops of the walls.
5. It holds the wall in from outside and carries the push to the ground, so the wall can be thin and full of windows.
6. The triangles make it stiff and light, and the wind blows through the openings instead of pushing on a solid surface.
7. Made ahead of time in a factory. The parts were made and drilled exactly in Eiffel's factory and then fit together at the site.
8. The steel frame of columns and beams. The walls just hang on the frame (curtain walls).
9. The bottom walls had to carry the weight of all the floors and walls above, so the taller the building, the thicker the walls.
10. The steel (iron and steel) frame and the safety elevator.

PORTFOLIO PIECE: THE TALLEST TOWER THAT SURVIVES THE FAN

Using only 20 sheets of newspaper and one roll of masking tape, design and build the tallest tower you can that holds a tennis ball on top for 30 seconds while a box fan blows on it from 1 meter away on medium. Draw your plan first. Test it, record the height and what happened, make one improvement, and test again. Explain which ideas you borrowed from the pyramid, the cathedral, the Eiffel Tower or the skyscraper.

LOOK FOR	WHAT IT MEANS
Plan	A labeled drawing shows the base, the bracing and where the load sits.
Triangles and base	The tower uses triangles for bracing and a base wide enough to resist the wind.
Fair test and data	Height is measured, and the fan test is done at the same distance and speed each time.
Improvement	One change was made because of the first test, and the new result was recorded.
Explanation	The student names at least one idea borrowed from a building in this unit and explains why it helps.

3.1 THE GREAT PYRAMID: THE STRENGTH OF A WIDE BASE

OBJECTIVES

- Explain why a wide base and a low center of weight make a structure stable.
- Describe how the Egyptians moved and placed huge stone blocks.
- Test towers of different shapes for how hard a push they can take before tipping.

Warm-up. Stand on one foot with your feet together. Have someone give your shoulder a gentle push. Now stand with your feet wide apart and try again. Which way is harder to tip over? Why?

WATCH

The INCREDIBLE Ancient Engineering That Built the Pyramids

Be Smart • 7:01

<https://www.youtube.com/watch?v=52V9jmrgSbl>

WHEN TO WATCH

After the story. Watch for the copper tools, the water level and the wet sand.

Note: The video opens with a short sponsor message; you can skip the first few seconds.

KEY TERMS

stable

Hard to tip over or knock down.

base

The bottom part of a structure that rests on the ground.

foundation

The solid ground or built footing that holds up a structure.

sledge

A wooden sled used to drag heavy loads.

level

Perfectly flat, with no part higher than another.

CORE IDEAS

The story. About 4,500 years ago, the Egyptian king Khufu ordered a tomb at Giza, near the Nile River. It became the Great Pyramid, about 481 feet tall when it was finished. For nearly four thousand years, nothing built by people anywhere on earth was taller. It is made of more than two million stone blocks, most of them heavier than a car. Thousands of skilled workers lived in a town nearby, with bakeries and storehouses, and worked in teams for about twenty years.

How they figured it out. The builders chose a site on a flat plateau of solid rock, a strong foundation. To make the base level, they may have used water, which always lies flat, to mark a level line. They lined up the sides with the north, south, east and west almost perfectly by watching the stars. They cut stone with copper chisels, saws and sand, and moved blocks on wooden sledges. A painting in another Egyptian tomb shows a man pouring water on the sand in front of a sledge carrying a giant statue. In 2014, scientists tested this and found that sand with the right amount of water lets a sledge slide with about half the pulling force.

The physics. A pyramid is the most stable shape a pile of stones can have. Its base is very wide, and most of its weight is low down, near the ground. To tip something over, you must lift its weight up over the edge of its base. A wide, low shape is very hard to tip; a tall, thin one tips easily. Every block in a pyramid is pressed down by the blocks above it, so the whole thing is in compression, which is just right for stone.

The engineering. Engineers still think about the base and the foundation first. Tall towers today have deep foundations reaching down to rock and wide bases that spread their weight. But a pyramid uses a huge amount of material to make very little room inside. Later builders looked for ways to build tall with much less stone, and that search leads to the cathedrals, the Eiffel Tower and the skyscraper in the rest of this unit.

PICTURE STUDY



Pyramids of El-Geezeh, from the Southwest, Francis Frith, About 1857 · Albumen photograph · Google Art Project; prints in many museum collections

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

Francis Frith was an English photographer who carried heavy glass-plate cameras to Egypt in the 1850s, when photography was still new. This is one of the first photographs ever taken of the pyramids of Giza.

Look closely

- Find the three large pyramids. Which looks tallest?
- Find the camel and the people. How big are they compared with the pyramids?
- Look at the edges of the pyramids. Are they smooth or stepped?
- Look at the ground. Is it hilly or flat?

Talk about it

1. Why would a flat, rocky place be a good place to build a pyramid?
2. Why is a pyramid so hard to knock over?
3. The pyramids once had smooth white outer stones. What do you think happened to them?

Safety first. Keep towers low on the floor or table, and test them gently with one finger or the pencil push described in the build.

BUILD

Which Shape Stands Best? A Tipping Test

You will build towers of the same number of blocks in three shapes, a thin stack, a wide stack and a pyramid, and test how hard a push each one takes before it tips. Then you will test sliding a heavy “block” on dry and wet sand.

You will need

- About 30 building blocks, sugar cubes or small boxes of the same size
- A rubber band and a ruler (your force meter from Unit 1)
- A pencil and some tape
- A shallow tray of sand, a cup of water, a small box with a heavy load (such as a can) for a “sledge”
- Engineer’s notebook

Steps

1. Build three towers with the same number of blocks (for example, 10): a tall single stack, a stack two blocks wide, and a pyramid with the widest layer at the bottom.
2. Measure the height of each tower in centimeters.
3. **Predict:** which will take the hardest push before it tips?
4. **Fair test.** Hook your rubber band to a pencil. Press the pencil against each tower at the same height, 5 centimeters from the table, and push slowly. Record how far the band stretched just before the tower tipped or slid. Do three trials for each tower.
5. Record your results in a table and circle the most stable tower.
6. **Sand test.** Set the loaded box in the dry sand. Pull it with the rubber band and record the stretch. Now sprinkle water on the sand in front of it until the sand is damp, but not muddy, and pull again. Do three trials each.
7. **Improve it.** Using the same number of blocks, build the tallest tower you can that still takes at least as hard a push as your wide stack. What shape did you use?

Tips

- Push at the same height on every tower; pushing higher makes any tower tip more easily.
- Pull the sledge slowly and steadily, and read the stretch just as it starts to move.
- Too much water makes mud, which is harder to pull through. Find the “just right” amount.

Check your work

- ☐ I can explain why the wide, low tower was hardest to tip.
- ☐ I tested each tower the same way with three trials.
- ☐ I found that damp sand made the sledge easier to pull.

ENGINEER'S NOTEBOOK

1. Draw your three towers side by side. Under each, write how far the rubber band stretched.
2. Draw an Egyptian sledge on sand with a worker pouring water in front of it.
3. Find two things at home designed with a wide base so they will not tip (a lamp, a cup, a ladder). Sketch them.

From history. The Great Pyramid lost its title as the tallest building on earth in the 1300s, when the spire of Lincoln Cathedral in England rose higher. The spire later blew down in a storm, which shows how much harder it is to build tall and thin than wide and low.

COMMON MISTAKES

- Thinking the heaviest tower is always the most stable. Shape matters as much as weight.
- Pushing towers at different heights and calling it a fair test.
- Thinking pyramids were built with modern machines. The builders used ramps, sledges, levers and a great deal of careful teamwork.

Make it a game • Tipping Point Shape Test. Cut paper into a tall shape, a wide shape and a pyramid shape, and tilt each until it tips. Estimate the angle each one can lean before tipping, then check by measuring with a protractor or by eye. Say stable, base and sledge. Explain how the Egyptians moved huge stones. Closest guess wins a point.

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)

The Great Pyramid stands on solid rock, and it has stood for thousands of years. Jesus used the same idea to teach that a life built on His words stands firm.

3.2 GOTHIC CATHEDRALS AND FLYING BUTTRESSES

OBJECTIVES

- Explain why a heavy stone roof pushes walls outward.
- Explain how a flying buttress catches that push and carries it to the ground.
- Build a model wall and roof and test it with and without buttresses.

Warm-up. Stand two books upright, a little apart, like two walls. Lay a bent piece of card stock between their tops like a curved roof. Press down gently on the roof. What do the books do? How could you stop them?

WATCH

How to Build a Gothic Cathedral

ThinkingWest · 6:48

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

WHEN TO WATCH

After the story. Watch the old pictures of builders, cranes and scaffolds.

BACKUP VIDEO

What's a Flying Buttress? Engineer Explains Medieval Cathedral Architecture at Reims

Around the World with Erin · 5:03

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

After the physics paragraph, to see an engineer trace the push through a real cathedral.

KEY TERMS

cathedral

A large, important church, the home church of a bishop.

thrust

The outward push of an arch or vault at its sides.

vault

An arched stone ceiling or roof.

buttress

A thick support built against a wall to keep it from being pushed over.

flying buttress

An arched stone prop that reaches out from a wall to a separate pillar, carrying the push of the roof down to the ground.

pinnacle

A small, heavy, pointed tower on top of a buttress that helps hold it down.

CORE IDEAS

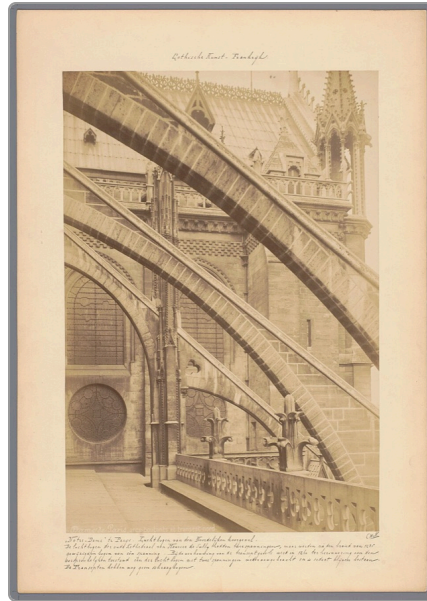
The story. About 900 years ago, in France, people began to build churches that soared higher than any before. They wanted the inside to be filled with light, as a picture of heaven. The cathedral of Notre-Dame in Paris was begun in 1163. Its builders stretched a stone ceiling high over the long middle aisle and filled the walls with tall windows of colored glass. Around 1180, they added something new on the outside: long stone arms that leap from the wall to pillars standing out in the churchyard. We call them **flying buttresses**.

How they figured it out. The master masons did not have the mathematics engineers use today. They learned by building, watching and remembering, and by passing their rules down from master to apprentice. They knew that a stone vault pushes outward on the walls. Older churches had thick, dark walls to resist that push. The new idea was to move the strength outside the wall, so the wall itself could be thin and full of windows. When a cathedral cracked or a vault fell, as one did at Beauvais in 1284, builders studied it and made the next one stronger.

The physics. A stone vault is an arch, and just like the arches in Unit 2, it pushes outward at its sides. This outward push is called **thrust**. High up on a tall, thin wall, thrust would tip the wall over. A **flying buttress** is a half arch that presses against the wall right where the thrust is, and carries the push across, out and down to a heavy pillar on the ground. A **pinnacle** on top of the pillar adds weight, which helps turn the sideways push downward into the earth.

The engineering. The Gothic builders found a way to separate two jobs: the wall keeps out the weather, and the buttresses hold up the roof. Modern buildings do the same thing with steel frames and glass walls, as you will see in Lesson 3.4. Engineers still use buttresses on dams, retaining walls and old buildings that need extra support. And restoring the great cathedrals takes stonemasons, carpenters and engineers working together, just as building them did.

PICTURE STUDY



Flying Buttresses of Notre-Dame, Paris, Unknown photographer, About 1875–1900 · Photograph · Rijksmuseum, Amsterdam

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

This old photograph was taken from the roof or a high gallery of Notre-Dame. You are looking right along the flying buttresses, so you can see how they reach from the pillars to the high wall.

Look closely

- Find the long, curved stone arms. How many can you count?
- Follow one buttress from the pillar to where it touches the wall.
- Find the pointed pinnacle on top of a pillar.
- Find the round window. Where would its light go?

Talk about it

1. What push is each flying buttress holding back?
2. Why is the buttress curved like part of an arch?
3. Why could the walls of this cathedral be thin and full of windows?

BUILD

Hold Up the Roof: A Buttress Test

You will build two card-stock walls with a curved card “vault” between them, load the vault with pennies, and see how far the walls spread. Then you will add buttresses and test again.

You will need

- Card stock or cereal-box cardboard
- Tape, scissors and a ruler
- About 100 pennies and a small paper cup
- Craft sticks, more cardboard or small boxes for buttresses
- Engineer’s notebook

Steps

1. Fold two pieces of card stock into L shapes to make two walls 15 centimeters tall that stand on their own. Set them 15 centimeters apart.
2. Bend a strip of card stock into a curve and rest its ends on the tops of the walls. This is your vault.
3. **Test with no buttresses.** Put the cup on top of the vault and add pennies 5 at a time. Measure how far apart the tops of the walls are after each 5 pennies. Stop when the vault falls.
4. **Predict:** how many more pennies will it hold with buttresses?
5. **Add flying buttresses.** Tape a slanted craft stick or a strip of cardboard from the outside of each wall, near the top, down to a small box or stack of coins on the table a few centimeters away. Test again the same way.
6. **Fair test.** Try buttresses that touch the wall at three heights: low, middle and near the top. Which works best? Do two trials each.
7. **Improve it.** Add a “pinnacle” (a few pennies taped on top of each outer pillar) and test again.

Tips

- Make both walls exactly the same so the test is fair.
- Measure the gap between the wall tops with a ruler held across them.

- Notice where the walls fail: do they lean out, slide, or fold?

Check your work

- ☐ I can show the outward push of a vault on its walls.
- ☐ I found where on the wall a buttress works best.
- ☐ I can explain how buttresses let Gothic walls have big windows.

ENGINEER'S NOTEBOOK

1. Draw a cross-section of a cathedral: the vault, the high wall, a flying buttress, the pillar and the pinnacle. Draw arrows for the push.
2. Make a table: buttress height, pennies held, how the walls failed.
3. Design a stained-glass window for a wall made thin by buttresses. Color it.

From history. Many Gothic cathedrals took a hundred years or more to finish, so the people who laid the foundations never saw the finished church. Villard de Honnecourt, a French builder of the 1200s, left a sketchbook of drawings of cathedrals, machines and tools that still survives.

COMMON MISTAKES

- Thinking the buttress holds the roof up from below. It holds the wall in from the side.
- Placing the buttress too low, where the thrust is not.
- Forgetting that the outer pillar needs weight, or it will be pushed over too.

Make it a game • Buttress Holds the Roof. Build a two-wall paper arch with books on top. Watch the walls spread out. Then add a leaning stick on each side as a buttress and test again. Say thrust, vault and flying buttress. Teach your parent why a stone roof pushes walls outward and how a buttress catches that push. Explain it in under a minute.

Scripture. “Except the LORD build the house, they labour in vain that build it: except the LORD keep the city, the watchman waketh but in vain.” (Psalm 127:1, KJV)

The cathedral builders worked for the glory of God, and they knew their work depended on Him. Good building is done with skill, but also with humility and thanks.

3.3 THE EIFFEL TOWER: IRON LACE IN THE WIND

OBJECTIVES

- Explain why the Eiffel Tower is an open lattice of triangles.
- Explain how wind pushes on a tall structure and why open frames resist wind well.
- Build a newspaper-and-tape lattice tower and test it against weight and a fan.

Warm-up. Hold a sheet of paper flat in front of a fan, and then hold a piece of window screen or a mesh bag the same size. Which one does the wind push harder? Why?

WATCH

The Eiffel Tower for Kids

Homeschool Pop • 6:33

<https://www.youtube.com/watch?v=-LYh7Npoj0>

WHEN TO WATCH

Before the story, to meet the tower and its builder.

BACKUP VIDEO

How was the Eiffel Tower built? I Head Squeeze

BBC Earth Science • 3:10

<https://www.youtube.com/watch?v=9W8qkf96Hp8>

After the engineering paragraph, to see the foundations and the prefabricated parts.

KEY TERMS

lattice

A crisscross pattern of thin strips with open spaces between them.

rivet

A metal pin, heated red-hot and hammered flat at both ends, used to fasten metal parts together.

wrought iron

A tough kind of iron that can be shaped by hammering; the Eiffel Tower is made of it.

wind load

The push of the wind against a structure.

prefabricated

Made in a factory ahead of time and then put together at the building site.

CORE IDEAS

The story. In 1889, Paris held a great World's Fair, and the organizers wanted a tower to amaze the visitors. The company of Gustave Eiffel, a bridge builder, won the contest. Two of his engineers, Maurice Koechlin and Émile Nouguier, had drawn the first idea: four curving legs of iron lattice meeting high in the sky. At about 300 meters (984 feet), it would be the tallest structure in the world. Some famous artists wrote angry letters saying it would be ugly. Eiffel built it anyway, in two years, two months and five days.

How they figured it out. Eiffel had built many iron railway bridges and knew that the real danger to a tall tower is not its weight but the **wind**. His engineers calculated the push of strong winds at every height and shaped the legs so they curve in just the way that resists that push. Nearly every one of the 18,038 iron parts was drawn exactly, made in Eiffel's factory outside Paris with its holes already drilled, and numbered. At the site, workers fit the parts together like a giant kit and fastened them with about 2.5 million rivets.

The physics. The tower is made of triangles, just like the trusses of a bridge. A triangle cannot change shape unless one of its sides changes length, so a frame of triangles is stiff and strong while using little material. Because the frame is open, most of the wind blows straight through the gaps. A solid tower would catch the wind like a sail. The wide base keeps the tower stable, as with the pyramid, but the open lattice makes it far lighter: the whole iron tower weighs less than the air in a cylinder around it of the same height.

The engineering. Prefabrication, making parts in a factory and assembling them on site, made the tower fast and accurate to build, and builders still use the idea today. The tower also needs care: it is repainted about every seven years to keep the iron from rusting, using about 60 tons of paint. On a hot day, the iron grows a little, and the top can move a few inches away from the sun. Engineers measure these movements to make sure the tower stays healthy.

PICTURE STUDY



The Eiffel Tower Under Construction, July 1888, From Louis Rousselet's book on the 1889 World's Fair, July 1888 · Photograph (printed in a book) · From *L'Exposition universelle de 1889* by Louis Rousselet

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

This photograph was taken when the tower was about half finished. You can see the legs, the first platform and the beginning of the upper tower. Look closely at the pattern of the iron.

Look closely

- Find the four legs. How do they lean?
- Find the big arch shapes between the legs at the bottom.
- Look for triangles in the iron lattice. How many can you find in one leg?
- Find the wooden scaffolding near the top where the workers are building.

Talk about it

1. Why do the legs spread out so wide at the bottom?
2. Why is the tower full of holes instead of solid?
3. How do you think the workers lifted the iron parts so high?

Safety first. Use the fan on a low or medium setting and keep fingers away from the blades.

BUILD

Newspaper Lattice Tower: Weight and Wind

You will roll newspaper into tubes and tape them into a tower with triangles, test how tall it can be while still holding a weight, and then test it in front of a fan. You will compare a braced tower with an unbraced one.

You will need

- Several sheets of newspaper (or printer paper) and a pencil to roll them around
- Masking tape
- A tennis ball or a cup with 20 pennies (the load)
- A box fan and a tape measure
- Engineer's notebook

Steps

1. Roll newspaper sheets tightly around a pencil from corner to corner, slide out the pencil, and tape the tubes. Make about 20 tubes.
2. Build a square base with four tubes. Stand four tubes up at the corners and tape a square of tubes on top. This is one "story."
3. **Unbraced test.** Set the load on top and gently push the side with one finger. Does the square lean into a diamond? Record what happens.
4. **Add bracing.** Tape a diagonal tube across each side of the story to make triangles. Test the push again. **Predict** first.
5. Keep building stories with triangles until your tower is as tall as you can make it while it still holds the load for 10 seconds. Measure the height.
6. **Wind test.** Place the fan 1 meter away on low. Does the tower stand? Try medium. Record how it moves.
7. **Improve it.** Make the base wider, or curve the legs inward like the Eiffel Tower, and test again in the wind. Record the new height and how it held up.

Tips

- Tight tubes are much stronger than loose ones.
- Tape every joint all the way around; weak joints are where most towers fail.

- Tape the base to the table only if the rules of your family contest allow it. Decide before you start.

Check your work

- ☐ I can show that triangles make my tower stiff.
- ☐ I measured my tower's height and tested it with the load and the fan.
- ☐ I can explain why the Eiffel Tower is an open lattice.

ENGINEER'S NOTEBOOK

1. Draw one side of your tower and color every triangle.
2. Make a table: version, height, held the load (yes/no), fan low, fan medium.
3. Draw the Eiffel Tower's outline and label the legs, the first platform and the top.

From history. The tower was meant to stand for only twenty years. It was saved partly because it was useful: scientists used it for experiments with weather and radio, and it carried antennas. Gustave Eiffel's company also built the iron framework inside the Statue of Liberty, which was finished in 1886.

COMMON MISTAKES

- Thinking a solid tower would be stronger in the wind. It would catch more wind and be much heavier.
- Leaving squares without diagonals. Squares can fold into diamonds; triangles cannot.
- Building tall first and then trying to brace it. Brace each story as you go.

Make it a game • Wind Load Lattice Test. Build two newspaper towers, one solid roll and one open lattice of triangles. Use a fan or your breath to test wind, and time how long each stays up. Say lattice, rivet and wind load. Predict the winner before the test. Explain why Eiffel left the tower open, and give yourself a point if you are right.

3.4 THE STEEL FRAME: CHICAGO'S FIRST SKYSCRAPER

OBJECTIVES

- Explain the difference between a building with load-bearing walls and one with a steel frame.
- Explain why the steel frame and the safety elevator made skyscrapers possible.
- Build a frame tower and a solid-wall tower from the same paper and compare their strength for their weight.

Warm-up. Feel your arm. What is hard inside it? Your bones are a frame that holds you up, and your skin covers them. Now think of a cardboard box. What holds it up? Which is more like a skyscraper?

WATCH

How do sky scrapers work? - Lonely Planet Kids

Lonely Planet · 2:38

<https://www.youtube.com/watch?v=TXRsmRRh3po>

WHEN TO WATCH

After the physics paragraph.

KEY TERMS

skyscraper

A very tall building with many floors.

load-bearing wall

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

steel frame

A framework of steel columns and beams that carries a building's weight.

column

An upright post that carries weight down to the foundation.

curtain wall

An outside wall that hangs on the frame and carries only its own weight, like a curtain.

CORE IDEAS

The story. In 1871, a great fire burned much of the city of Chicago. As the city rebuilt, land downtown became very costly, and business owners wanted to fit more offices onto each lot. The only way to go was up. In 1885, an engineer and architect named William Le Baron Jenney finished the Home Insurance Building: ten stories tall, with a hidden frame of iron and steel inside. Many people call it the first skyscraper.

How they figured it out. Before Jenney, tall buildings had thick brick or stone walls that held up all the floors. The taller the building, the thicker the walls had to be at the bottom. A sixteen-story brick building in Chicago, the Monadnock, needed walls six feet thick at the ground floor! That left little room for windows or offices. Jenney put the weight on a frame of metal columns and beams instead, and the walls just wrapped around the outside. A story is often told that he got the idea when his wife set a heavy book on a light metal birdcage and it held. Whether or not that is true, the frame was much lighter than solid walls of the same strength.

The physics. In a steel-frame building, the weight of each floor rests on steel **beams**, which carry it sideways to **columns**. The columns carry it straight down, in compression, to the foundation. The outside walls carry almost nothing but themselves, so they can be thin and full of glass. Steel is very strong both in compression and tension, so slender columns can hold up many floors. The frame is braced with diagonals or stiff joints so it does not lean in the wind.

The engineering. Two inventions made skyscrapers useful: the steel frame and the safe elevator. In 1854, Elisha Otis stood on a raised platform at a fair in New York and had the rope cut; a spring-loaded safety catch grabbed the rails and stopped the fall. Without elevators, nobody would climb twenty floors. Engineers today design frames of steel and concrete for the building's weight, the people and furniture inside, wind and even earthquakes, and they protect the steel from fire with special coatings.

PICTURE STUDY



The Home Insurance Building, Chicago, Chicago Architectural Photographing Company, About the 1920s (building finished 1885) · Photograph · Chicago

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

This photograph was taken many years after the building opened, when two more floors had been added on top. It was torn down in 1931 to make room for a newer, taller skyscraper.

Look closely

- Count the floors. How many can you see?
- Look at the windows. Are they bigger or smaller than in an old stone house?
- Look at the walls near the ground. Are they very thick, or about the same as higher up?
- Find the cars and the street. How tall is the building compared with them?

Talk about it

1. You cannot see the steel frame in this picture. Where is it?
2. How did the frame make bigger windows possible?
3. What other invention did people need before they would work on the top floor?

Safety first. An adult cuts any thick cardboard. Wear safety glasses for the load test.

BUILD

Frame or Wall? A Strength-for-Weight Test

You will use the same amount of paper to build two towers of the same height: one with solid walls and one with a frame of rolled-paper columns and beams. You will weigh them, load them with books, and compare which one is stronger for its weight.

You will need

- Six sheets of printer paper for each tower (the same paper for both)
- Tape, a ruler and scissors
- A kitchen scale
- Several paperback books of about the same size for loads
- Engineer's notebook

Steps

1. **Wall tower.** Fold and tape six sheets into a square tube about 20 centimeters tall with solid walls.
2. **Frame tower.** Roll the other six sheets into thin columns and beams. Tape four columns at the corners, 20 centimeters tall, and tape beams around the top and middle to tie them together. Add a diagonal brace on each side.
3. Weigh each tower and record its mass in grams.
4. **Predict:** which will hold more books?
5. **Test.** Lay a piece of cardboard on top of each tower and add books one at a time until it crushes or buckles. Record the number of books. Do two trials if you have enough paper.
6. Weigh one book. Work out how many grams each tower held, and compare it with the tower's own mass.
7. **Improve it.** Find where your frame tower failed (a column bent, a joint slipped). Fix only that weak spot and test again.

Tips

- Roll columns tightly and the same size so they share the load evenly.
- Set the books gently in the center so the load is even.

- A tower that holds slightly fewer books but weighs much less may be the better design.

Check your work

- ☐ I can explain how a steel frame carries a building's weight to the ground.
- ☐ I weighed both towers and compared what each held.
- ☐ I can name the two inventions that made skyscrapers possible.

ENGINEER'S NOTEBOOK

1. Draw a building with load-bearing walls and a building with a steel frame side by side. Use arrows to show where the weight goes.
2. Make a table: tower, mass, books held.
3. Design a skyscraper for your town. Draw the frame first, then the curtain wall and windows.

From history. Chicago became famous for its new tall buildings, and architects there, like Louis Sullivan, taught that a tall building should look tall and proud. New York soon began building ever higher too, with buildings like the Woolworth Building (1913) and the Empire State Building (1931).

COMMON MISTAKES

- Thinking the walls of a skyscraper hold it up. The frame does; the walls are a covering.
- Forgetting the diagonals. A frame of squares can lean over like a parallelogram.
- Comparing only which tower held more, without comparing their weights.

Make it a game • Skyscraper Frame Quiz. Quiz yourself with two columns on paper: load-bearing wall and steel frame. Your parent reads a statement, such as the walls carry the weight, and you point to the right column. Eight statements, one point each. Then explain why the steel frame and the safety elevator made skyscrapers possible.

UNIT 3

BUILDINGS

People have always wanted to build high: to see far, to stand out on the skyline, and to fit many people onto a small piece of land. In this unit you will follow four great steps in tall building. First, the Great Pyramid of Egypt, which stood as the tallest building on earth for thousands of years because of its wide, heavy base. Then the Gothic cathedrals of France, where builders learned to prop up thin stone walls with flying buttresses so they could fill them with colored glass.

Next comes the Eiffel Tower, a lattice of iron triangles that the wind blows right through, and finally the first steel-frame skyscraper in Chicago, where a frame of steel carried the weight so the walls no longer had to. In every build, you will test a tower against weight and wind, and make it stronger.

PREREQUISITES

- Knows compression and tension (Unit 2)
- Knows why triangles are strong and arches push outward (Unit 2)
- Can measure height in centimeters and record three trials

MASTERY CHECKLIST

- ☐ I can explain why a wide base makes a building stable.
- ☐ I can explain what a flying buttress does and why Gothic walls could have big windows.
- ☐ I can explain why the Eiffel Tower is made of open lattice instead of solid walls.
- ☐ I can explain how a steel frame carries a skyscraper's weight.
- ☐ I can build a tower, test it fairly against weight and wind, and improve it.

OPTIONAL KITS FOR THIS UNIT

- **KEVA Planks:** All ages. Plain wooden planks for building towers, domes and walls with nothing but balance. Good for Lessons 3.1–3.3.
- **LEGO Technic:** Sets vary by age. Beams and connectors make good model frames and trusses for 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	The Great Pyramid: The Strength of a Wide Base	2 sessions of 45 minutes
3.2	Gothic Cathedrals and Flying Buttresses	2 sessions of 45 minutes
3.3	The Eiffel Tower: Iron Lace in the Wind	2 sessions of 45 minutes
3.4	The Steel Frame: Chicago's First Skyscraper	2 sessions of 45 minutes

UNIT 3 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
Why is a pyramid so hard to tip over?
2. **5 pts**
How did wet sand help the Egyptians move heavy stones?
3. **5 pts**
Predict: you push a tall, thin tower and a short, wide tower made of the same blocks. Which tips over first?
4. **5 pts**
What is thrust? Where does it come from in a cathedral?

5. (5 pts)

How does a flying buttress help a cathedral have big windows?

6. (5 pts)

Why is the Eiffel Tower made of open lattice instead of solid iron walls?

7. (5 pts)

What does prefabricated mean? How did it help build the Eiffel Tower quickly?

8. (5 pts)

What holds up a steel-frame skyscraper: the walls or the frame?

9. (5 pts)

Why did old brick buildings have very thick walls at the bottom?

10. (5 pts)

Name the two inventions that made skyscrapers possible.

ANSWER KEY

1. It has a very wide base and most of its weight is low down near the ground.
2. Damp sand is firmer and lets a sledge slide more easily, with about half the pulling force.
3. The tall, thin tower.
4. Thrust is the outward push of an arch or vault. The heavy stone vault (ceiling) pushes outward on the tops of the walls.
5. It holds the wall in from outside and carries the push to the ground, so the wall can be thin and full of windows.
6. The triangles make it stiff and light, and the wind blows through the openings instead of pushing on a solid surface.
7. Made ahead of time in a factory. The parts were made and drilled exactly in Eiffel's factory and then fit together at the site.
8. The steel frame of columns and beams. The walls just hang on the frame (curtain walls).
9. The bottom walls had to carry the weight of all the floors and walls above, so the taller the building, the thicker the walls.
10. The steel (iron and steel) frame and the safety elevator.

PORTFOLIO PIECE: THE TALLEST TOWER THAT SURVIVES THE FAN

Using only 20 sheets of newspaper and one roll of masking tape, design and build the tallest tower you can that holds a tennis ball on top for 30 seconds while a box fan blows on it from 1 meter away on medium. Draw your plan first. Test it, record the height and what happened, make one improvement, and test again. Explain which ideas you borrowed from the pyramid, the cathedral, the Eiffel Tower or the skyscraper.

LOOK FOR	WHAT IT MEANS
Plan	A labeled drawing shows the base, the bracing and where the load sits.
Triangles and base	The tower uses triangles for bracing and a base wide enough to resist the wind.
Fair test and data	Height is measured, and the fan test is done at the same distance and speed each time.
Improvement	One change was made because of the first test, and the new result was recorded.
Explanation	The student names at least one idea borrowed from a building in this unit and explains why it helps.

UNIT 4

ELECTRICITY AND MAGNETS

Electricity is hidden. You cannot see it move through a wire, but you can see what it does: a bulb glows, a buzzer buzzes, a compass needle swings. In this unit you will build circuits with batteries and bulbs, and learn why Thomas Edison wired houses so that one lamp could be switched off without turning off all the others. You will repeat Stephen Gray's discovery of conductors and insulators with string and silk, and follow William Gilbert as he learned that the whole earth is a giant magnet.

Finally, you will put electricity and magnets together, just as Samuel Morse did, to send messages across a room in dots and dashes. All of our electricity in this unit comes from batteries. Never use the outlets in the wall.

PREREQUISITES

- Knows how to run a fair test and record results in a table
- Can follow a simple diagram
- Knows that electricity from the outlets in the wall is dangerous and is never used for experiments

MASTERY CHECKLIST

- ☐ I can build a complete circuit and explain why it must be a closed loop.
- ☐ I can build series and parallel circuits and explain how they behave differently.
- ☐ I can sort materials into conductors and insulators by testing them.
- ☐ I can make a compass and explain why it points north.
- ☐ I can send and receive a message in Morse code with a homemade telegraph.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits Jr.:** Ages 8 and up. Snap-together parts build lamps, switches, buzzers and series and parallel circuits with no wiring. A great companion to Lessons 4.1, 4.2 and 4.4.
- **Thames & Kosmos electricity kits:** Ages vary by kit. Several beginner kits cover circuits, magnets and electromagnets with battery power. Fits Lessons 4.1–4.4.

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 Series and Parallel: Why Edison Wired Houses in Parallel

2 sessions of 45 minutes

4.2 Stephen Gray Discovers Conductors and Insulators

2 sessions of 45 minutes

4.3 William Gilbert, Magnets and the Compass

2 sessions of 45 minutes

4.4 Samuel Morse and the Telegraph

2 sessions of 45 minutes

UNIT 4 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

Why does a bulb light only when the circuit is a complete loop?

2. **5 pts**

Predict: two bulbs are in series. You unscrew one. What happens to the other?

3. **5 pts**

Why are the lights in a house wired in parallel?

4. **5 pts**

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

5. (5 pts)

Why did Stephen Gray's experiment fail when he held up the thread with brass wire?

6. (5 pts)

Why does an electric cord have copper inside and plastic outside?

7. (5 pts)

What happens when you bring the north poles of two magnets together? A north and a south?

8. (5 pts)

What did William Gilbert discover with his terrella?

9. (5 pts)

How does a telegraph send a dot and a dash?

10. (5 pts)

What was the first official telegraph message, and why did Morse choose it?

ANSWER KEY

1. Electricity must flow all the way from the battery, through the bulb and back to the battery. A gap stops the flow.
2. It goes out too, because the only path is broken.
3. So each light has its own path and can be switched on and off separately; if one goes out, the others stay on.
4. A conductor lets electricity flow (copper, foil, a paper clip). An insulator does not (plastic, rubber, glass, silk).
5. Brass is a conductor, so the electricity leaked away through the wire. Silk is an insulator and kept it in the thread.
6. The copper conducts electricity to the device, and the plastic insulates it so it cannot reach your hands.
7. Two north poles repel (push apart). North and south attract (pull together).
8. That the earth itself is a giant magnet, which is why a compass needle points north.
9. Pressing the key closes the circuit and the electromagnet at the far end pulls the arm or lights the bulb. A short press is a dot, a long press is a dash.
10. "What hath God wrought," words from the Bible (Numbers 23:23). Morse believed the invention was a gift from God.

PORTFOLIO PIECE: A WORKING TELEGRAPH AND CODE BOOK

Build a telegraph with a key that springs back, a battery and a bulb or buzzer, long enough to reach from one room to another. Make a code book with the Morse alphabet. Send a three-word message to a family member, who writes it down and decodes it. Record your tries, your mistakes and one improvement you made to the key or the code.

LOOK FOR	WHAT IT MEANS
Working circuit	The key reliably turns the bulb or buzzer on and off from the other room.
Diagram	A labeled drawing shows the complete circuit, including the conductors and the insulated wires.
Message	A three-word message is sent and correctly decoded.
Improvement	One change to the key or the method is made and tested, and the results are recorded.

4.1 SERIES AND PARALLEL: WHY EDISON WIRED HOUSES IN PARALLEL

OBJECTIVES

- Build a complete circuit with a battery, wires and a bulb.
- Build a series circuit and a parallel circuit with two bulbs and compare them.
- Explain why houses are wired in parallel.

Warm-up. Look at a strand of old holiday lights, a flashlight and a lamp. Where does the electricity come from in each? Talk about it: if one bulb on a light strand burns out, do all of them go dark, or just one?

WATCH

Series & Parallel Circuits

Patrick Haney · 5:02

<https://www.youtube.com/watch?v=Dq6zbNWB0VI>

WHEN TO WATCH

After the physics paragraph. Pause each time a switch opens and predict which bulbs go out.

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, to review what a complete circuit is.

KEY TERMS

circuit

A complete loop that electricity travels around, from the battery, through wires and parts, and back to the battery.

series circuit

A circuit with only one path, where the parts are lined up one after another.

parallel circuit

A circuit with more than one path, where each part has its own branch.

switch

A part that opens or closes a gap in a circuit to turn something off or on.

filament

The thin thread inside an old-style light bulb that glows when electricity passes through it.

CORE IDEAS

The story. In the 1870s, a few city streets were lit by blinding electric arc lamps. Many of them were wired in a single line, one after another. Thomas Edison, an inventor in Menlo Park, New Jersey, wanted something different: a small, gentle electric lamp for every room of every home, which each family could turn on and off by itself. In 1879 his team made a light bulb with a thin carbon filament that glowed for many hours, and in 1882 they opened a power station in New York City to light homes and offices.

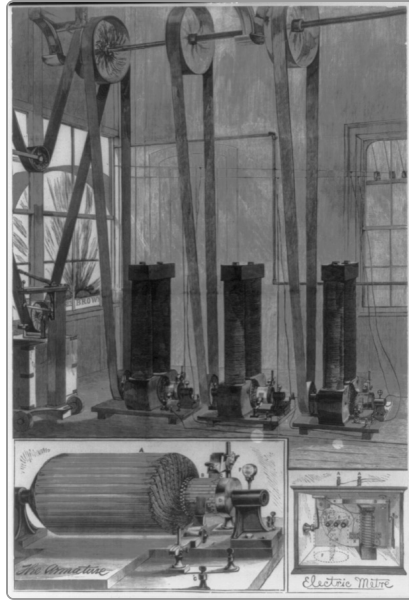
How they figured it out. Edison saw a problem with lamps wired in one line: if one lamp is switched off or burns out, the path is broken and every lamp goes dark. So he planned to give each lamp its own path from the main wires, so every lamp could be switched separately. But many paths would draw a lot of electricity, and that would need thick, costly copper wires. Edison worked out that if each lamp had a very thin filament that let only a little electricity through, the wires could be thinner and cheaper. That is one reason his team tested thousands of filament materials before they found ones that worked.

The physics. Electricity only flows when there is a complete loop, a **circuit**, from one end of the battery back to the other. In a **series circuit**, the parts are in one line. The electricity must pass through every part, so if one bulb is removed, the loop is broken and all the bulbs go out. Two bulbs in series also share the battery's push, so each glows dimmer. In a **parallel circuit**, each bulb has its own branch. Take one bulb out, and the others keep glowing, each about as brightly as one bulb alone.

The engineering. The outlets and lights in your house are wired in parallel, so you can turn on the kitchen light without turning on the porch light. Each branch also has a safety device, a breaker or fuse, that cuts the power if too much electricity

flows. Engineers use series circuits when they want one switch to control everything, such as the power switch on a flashlight. Some holiday light strands are wired in series, and others are wired in parallel or in small groups, so that one dead bulb does not darken the whole strand.

PICTURE STUDY



Edison's Electric Light: The Generator, the Armature and the Electric Meter, Unknown engraver, 1880 ·
Wood engraving · Library of Congress, Prints and Photographs Division
Image: [Wikimedia Commons](#), public domain

This engraving appeared in 1880, when newspapers and magazines were full of excitement about Edison's electric light. It shows the machines that made the electricity and a meter that measured how much each customer used.

Look closely

- Find the tall machines at the top. These are generators that made electricity.
- Find the long belts that turn the generators. What do you think turned the belts?
- Find the striped drum in the small picture at the bottom. It is the spinning part of a generator, called the armature.
- Find the meter. Why would the company need to measure the electricity in each house?

Talk about it

1. Edison wanted each lamp to have its own switch. Would he wire them in series or in parallel?
2. Why do you think Edison's company needed a meter for each customer?
3. What would happen to every lamp if the generator stopped?

Safety first. Use only AA, C or D batteries. Never connect the two ends of a battery directly with a wire and nothing else; the wire gets hot and the battery is ruined. Never use outlets in the wall, and never open an appliance.

BUILD

Two Bulbs, Two Ways: A Circuit Test

You will build a simple circuit, then wire two bulbs in series and in parallel. You will compare their brightness and find out what happens when one bulb is taken out.

You will need

- Two D-cell or AA batteries in a battery holder
- Two or three small bulbs (1.5 to 3 volt) in bulb holders, or LEDs
- Five or six alligator clip leads
- A paper clip and two brass fasteners on a piece of cardboard to make a switch
- Engineer's notebook

Steps

1. **One bulb.** Connect one clip lead from the + end of the battery holder to one side of a bulb holder, and another lead from the other side of the bulb holder back to the – end. Does it light? Draw your circuit.
2. **Make a switch.** Push two brass fasteners through cardboard about 3 centimeters apart. Hook a paper clip over one so that it can swing to touch the other. Put the switch into your loop and test it.
3. **Series.** Connect two bulbs one after another in a single loop. **Predict:** brighter, dimmer or the same as one bulb? Look and record. Unscrew one bulb. What happens to the other?
4. **Parallel.** Connect each bulb on its own branch: both bulbs connect to the + lead and both to the – lead. Compare the brightness with one bulb. Unscrew one bulb. What happens?
5. Record your results in a table: circuit, brightness (bright, medium, dim), what happens when one bulb is removed.
6. **Improve it.** Add a third bulb to each circuit. How does the brightness change in series? In parallel? Then design a circuit where one switch controls one bulb and a second switch controls the other.

Tips

- If nothing lights, check every connection; one loose clip breaks the loop.
- Brightness is easier to compare in a dim room.
- Disconnect the battery when you finish so it does not run down.

Check your work

- ☐ I can build a complete circuit and a working switch.
- ☐ I saw that series bulbs are dimmer and go out together.
- ☐ I can explain why Edison wanted houses wired in parallel.

ENGINEER'S NOTEBOOK

1. Draw your series circuit and your parallel circuit. Use arrows to show the path of the electricity.
2. Make a table of brightness and what happened when one bulb was removed.
3. Walk through your house with a parent and find three things that can be switched on and off separately. Explain how that shows parallel wiring.

From history. Lewis Latimer, a skilled draftsman and inventor who later joined Edison's company, patented a better way to make carbon filaments in the early 1880s and wrote one of the first books on electric lighting. Edison's team kept careful notebooks of every filament they tested, so that they could learn from each failure.

COMMON MISTAKES

- Leaving a gap in the loop. Electricity must go all the way around and back to the battery.
- Thinking a battery is "full of electricity" that pours out one end. The battery pushes electricity around the loop, which must come back to the other end.
- Connecting the battery ends with only a wire (a short circuit). It gets hot and wastes the battery.

Make it a game • Bulb Circuit Predictor. With a grown-up, build a series circuit with two bulbs, and then a parallel one. Before connecting, predict which will be brighter and what happens if one bulb is unscrewed. Score a point for each right prediction. Say series, parallel and filament. Tell why Edison wired houses in parallel. Explain in a sentence.

4.2 STEPHEN GRAY DISCOVERS CONDUCTORS AND INSULATORS

OBJECTIVES

- Tell how Stephen Gray discovered that some materials carry electricity and others do not.
- Define conductor and insulator and give examples of each.
- Build a conductor tester and sort household objects by testing them.

Warm-up. Rub a balloon on your hair or a wool sweater. Hold it near tiny bits of tissue paper. What happens? Now touch the balloon all over with your hand and try again. Did it change?

WATCH

Basic Circuits Kit: Conductors and Insulators | Science Project

Science Buddies • 4:32

<https://www.youtube.com/watch?v=7KXkjoJr8kU>

WHEN TO WATCH

Before the build. Watch how the tester is made and which objects make the bulb light.

KEY TERMS

conductor

A material that lets electricity flow through it easily, such as copper, aluminum and other metals.

insulator

A material that does not let electricity flow through it easily, such as plastic, rubber, glass, silk and dry wood.

static electricity

Electric charge that builds up on the surface of an object, often from rubbing.

packthread

Strong string, once used for tying up packages.

CORE IDEAS

The story. Three hundred years ago, in England, a cloth dyer named Stephen Gray loved to do science experiments. People knew that if you rubbed a glass tube, it would pull bits of feather and paper toward it. In 1729, Gray noticed that the cork in

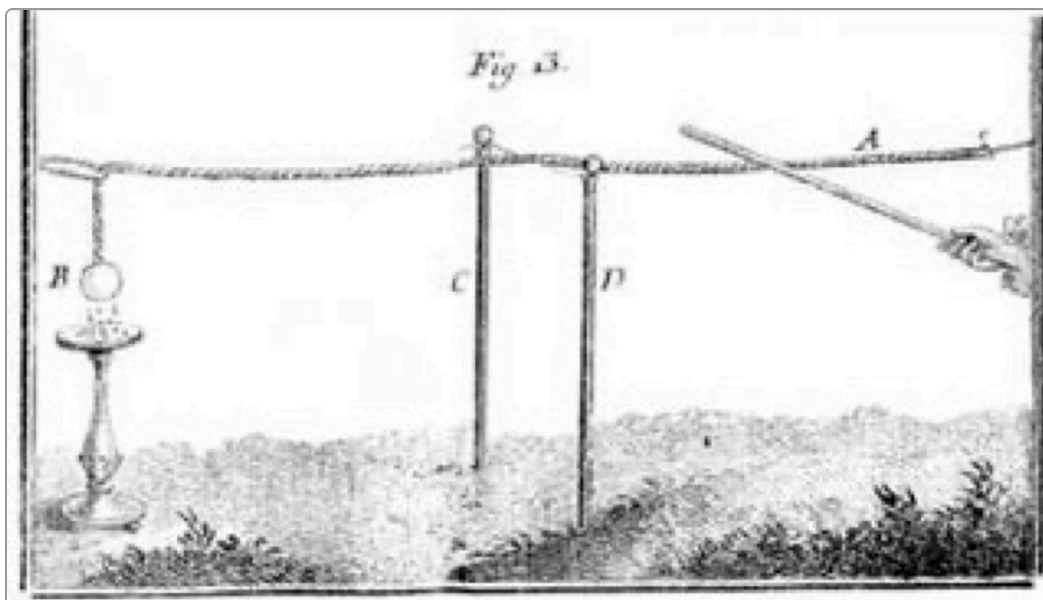
the end of his rubbed glass tube attracted feathers too, even though he had not rubbed the cork. The “electric virtue,” as he called it, had traveled from the glass into the cork. He stuck a stick into the cork and an ivory ball on the stick, and the ball attracted feathers too. Then he tried a long string.

How they figured it out. Gray and his friend Granville Wheler hung a long packthread across a big room, with a ball at the far end, and held it up with loops of silk thread. When Gray rubbed the glass tube at one end, the ball at the other end attracted brass leaf. But when the silk loops broke and they used thin brass wire instead, the experiment failed: the electricity leaked away through the brass. It was not the thickness that mattered; it was the material. Silk held the electricity in, and brass let it escape. With silk supports, they sent electricity more than 700 feet down the thread. Gray had discovered that materials come in two kinds.

The physics. A **conductor** is a material that electricity can flow through easily. Metals like copper, aluminum and iron are good conductors. Water with anything dissolved in it, including the water in your body, conducts too. An **insulator** is a material that electricity cannot easily flow through: plastic, rubber, glass, dry wood, silk and air. A circuit needs both: conductors to make the path, and insulators to keep the electricity from leaking where it should not go.

The engineering. Every electric cord is made of both. Inside is copper wire, a conductor, to carry electricity. Outside is plastic or rubber, an insulator, to keep it away from your hands. Power lines hang from glass or ceramic insulators on the poles. Electricians wear rubber gloves and use tools with insulated handles. This is why you must never touch a frayed cord or go near a fallen power line, and never put anything into an outlet: your body is a conductor.

PICTURE STUDY



Gray and Wheler's Long-Thread Experiment, Unknown engraver, About 1730 · Engraving · Illustration of the experiments of Stephen Gray and Granville Wheler

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

This small engraving shows the kind of setup Gray and Wheler used: a long thread carried on supports, with the rubbed glass tube at one end and a ball at the other.

Look closely

- Find the long thread. Where does it start and where does it end?
- Find the poles that hold the thread up. What do you think the thread hangs from at the top of each pole?
- Find the ball at the end of the thread and the little stand under it, where the light bits of brass or paper were.
- Find the rod at the other end, where the electricity came in.

Talk about it

1. Why did the experiment fail when they used brass wire to hold up the thread?
2. Which parts of this setup are conductors and which are insulators?
3. What would happen if the thread touched the wooden pole directly?

Safety first. Use only batteries. Test only small, dry household objects, never anything plugged in. Do not put coins or keys in your mouth.

BUILD

The Conductor Tester

You will build a circuit with a gap in it. When you touch the two loose ends to an object, the bulb lights only if the object is a conductor. Then you will predict and test at least twelve objects.

You will need

- A battery in a holder, a bulb in a holder (or an LED) and three alligator clip leads
- Twelve or more small, dry objects: a coin, a paper clip, aluminum foil, a key, a pencil (the wood and the point), an eraser, a plastic spoon, a rubber band, a glass marble, a piece of string, a craft stick, a cotton ball
- A cup of plain water and a cup of salty water
- Engineer's notebook

Steps

1. Build a circuit with the battery and bulb, but leave one gap: two loose clip ends. Touch the two clips together. The bulb should light.
2. Make a table with three columns: object, my prediction (conductor or insulator), result.
3. **Predict** for every object before you test.
4. **Test.** Touch both clips to the object at the same time, a little apart. Record whether the bulb lights brightly, dimly or not at all.
5. Test the pencil twice: once on the painted wood and once on the gray graphite at both ends. What did you find?
6. **Water test.** Dip both clips into the plain water without letting them touch. Then try the salty water. Is there a difference? (Use an LED if the bulb is too faint to see.)
7. **Improve it.** Sort your objects into two piles. Look for a pattern: what do all the conductors have in common?

Tips

- Hold the clips against the object firmly; a light touch can give a false “no.”

- Count how many predictions you got right. Scientists are often surprised too.
- Dry the clips after the water test.

Check your work

- ☐ I built a tester and checked it by touching the clips together.
- ☐ I predicted and tested at least twelve objects.
- ☐ I can explain why electric cords have copper inside and plastic outside.

ENGINEER'S NOTEBOOK

1. Draw your conductor tester and label the battery, the bulb, the wires and the gap.
2. Make two lists: conductors and insulators. Circle any surprises.
3. Draw an electric cord cut in half. Label the conductor and the insulator.

From history. In 1730, Gray hung a boy from silk cords and showed that when the boy was charged with the glass tube, his hands and face attracted light bits of paper. Gray's work was soon taken up by other scientists across Europe, including Benjamin Franklin in America.

COMMON MISTAKES

- Thinking all metal-colored things are metal. Some shiny things are plastic painted silver.
- Thinking water is always safe. Water can carry electricity, which is why we keep electric things away from sinks and tubs.
- Testing an object with the clips touching each other. Then the bulb lights no matter what is between them.

Make it a game • Gray's Thread Teach-Back. Tell your parent how Stephen Gray found that some materials carry electricity and others do not, as if you were Gray's assistant. Your parent writes down any wrong fact you say and counts the mistakes. Then test five objects on your conductor tester. Say conductor and insulator for each. Fewer than two mistakes wins.

4.3 WILLIAM GILBERT, MAGNETS AND THE COMPASS

OBJECTIVES

- Explain how magnets attract and repel.
- Explain why a compass points north, using Gilbert's idea that the earth is a magnet.
- Make a compass from a needle and test how the number of strokes changes its strength.

Warm-up. Bring two magnets close together end to end. Then flip one and try again. Write what you feel. Then test a few things around the house: which ones does a magnet pick up?

WATCH

How does a compass work? | General KnOWLedge

Owlkids · 2:10

<https://www.youtube.com/watch?v=LroX6ThIDpw>

WHEN TO WATCH

After the story.

KEY TERMS

magnet

An object that pulls on iron and steel and has a north pole and a south pole.

pole

One of the two ends of a magnet, where its pull is strongest.

attract

To pull toward. Opposite poles attract.

repel

To push away. Like poles repel.

compass

A tool with a magnetized needle that turns to point north.

lodestone

A natural rock that is magnetic.

CORE IDEAS

The story. For hundreds of years, sailors had used a magnetized needle to find their way at sea when clouds hid the sun and stars. But nobody knew why the needle pointed north. Some said it was pulled by the North Star. Others told stories of a

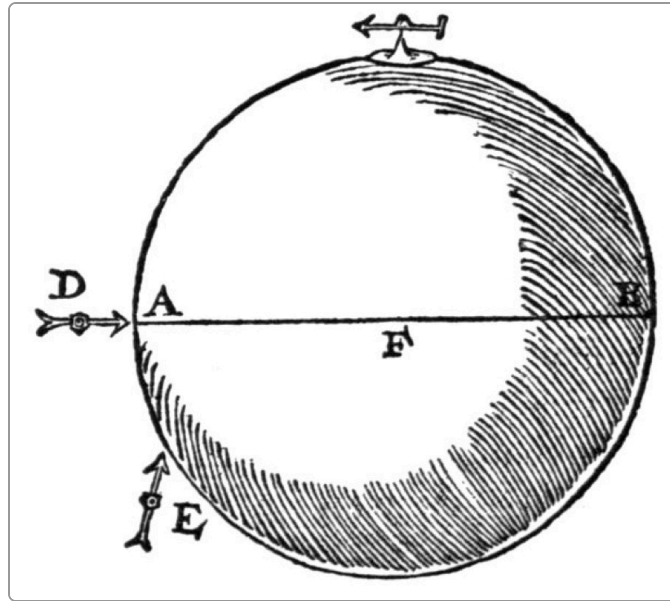
magnetic mountain at the top of the world. William Gilbert, a doctor in London who served Queen Elizabeth I, decided to find out by doing experiments instead of repeating old stories. In 1600 he published a book called *De Magnete*, “On the Magnet.”

How they figured it out. Gilbert carved a ball out of lodestone, a natural magnetic rock, and called it a *terrella*, “little earth.” He moved a tiny compass needle, balanced on a point, all over its surface. The needle pointed toward the ball’s poles, just as a ship’s compass points toward the north. Near the poles, the needle even tipped downward, just as sailors had noticed real compasses do in the far north. Gilbert concluded that the earth itself is a giant magnet. He tested every claim he could, and he wrote that we should trust careful experiments over guesses.

The physics. Every magnet has two **poles**, called north and south. Opposite poles **attract**; like poles **repel**. A magnet pulls on iron and steel but not on paper, plastic, wood, copper or aluminum. The earth acts like a huge magnet, so a free-swinging magnetized needle lines up with it. The end of the needle that points north is called its north-seeking pole. You can make a steel needle into a magnet by stroking it many times in the same direction with a magnet.

The engineering. The compass made long ocean voyages possible and is still carried by hikers, pilots and sailors as a backup to GPS. Engineers use magnets in motors, speakers, refrigerator doors, cabinet latches, credit-card strips and the hard drives of older computers. Engineers also must keep strong magnets away from compasses and some electronics, because a nearby magnet can make a compass point the wrong way.

PICTURE STUDY



Compass Needles Around a Terrella, William Gilbert, 1600 · Woodcut · From Gilbert's book *De Magnete*

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

This small picture comes from Gilbert's book. The big circle is his terrella, the "little earth" made of lodestone. The small arrow shapes are compass needles placed at different spots around it.

Look closely

- Find the big ball. What did Gilbert carve it from?
- Find the little needles around its edge. Which way does each one point?
- Find the letters on the drawing. Gilbert used them to explain the picture in his book.
- Find the line drawn through the middle of the ball. What might it stand for?

Talk about it

1. How did a little lodestone ball help Gilbert understand the whole earth?
2. Why did Gilbert do experiments instead of just repeating what other people said?
3. If you carried a compass to the North Pole, what do you think the needle would do?

Safety first. Strong magnets can pinch fingers and should be kept away from small children, who might swallow small magnets. Handle the needle carefully and keep it in a cork when not in use. An adult is present near the bowl of water.

BUILD

Make a Floating Compass

You will magnetize a sewing needle, float it on a cork in water, and see it turn to point north. Then you will run a fair test to find how the number of strokes changes how strong your needle magnet is.

You will need

- Two or three steel sewing needles (or straightened steel paper clips)
- A bar or ceramic magnet
- A slice of cork or a small piece of foam, and a bowl of water
- A real compass to check your results
- Small steel paper clips or staples
- Engineer's notebook

Steps

1. Test the needle first: does it pick up a staple? It should not.
2. Stroke the needle with one end of the magnet 10 times, always in the same direction, from the eye to the point, lifting the magnet away between strokes.
3. Lay the needle on the cork and float it in the middle of the bowl. Wait for it to settle. Check with the real compass: does your needle point north and south?
4. **Predict:** will more strokes make a stronger needle magnet?
5. **Fair test.** Use three new needles. Stroke one 10 times, one 25 times and one 50 times, in the same way. Count how many staples each needle can pick up in a chain or a cluster. Do two trials each.
6. Record strokes and staples in a table.
7. **Improve it.** Bring the magnet near your floating compass. What happens? Then move the magnet away and see if your compass still points north.

Tips

- Keep the bowl away from metal sinks, refrigerators and other magnets while testing.
- Stroke in only one direction; back-and-forth strokes cancel each other out.

- Mark the end of the needle that points north with a dot of marker.

Check your work

- ☐ I made a needle compass that points north.
- ☐ I tested how the number of strokes changes the needle's strength.
- ☐ I can explain Gilbert's idea that the earth is a giant magnet.

ENGINEER'S NOTEBOOK

1. Draw two bar magnets attracting and two repelling. Label the poles N and S.
2. Make a table: number of strokes and number of staples picked up.
3. Draw your floating compass and the directions north, south, east and west around it.

From history. Gilbert also studied the “electric” pull of rubbed amber and glass, and he made up the word *electricus* from the Greek word for amber. Two hundred years later, in 1820, Hans Christian Ørsted saw a compass needle jump when electricity flowed in a nearby wire. Electricity and magnetism turned out to be partners, which is the idea behind the telegraph in Lesson 4.4.

COMMON MISTAKES

- Thinking magnets pick up all metals. They pull on iron and steel, but not on aluminum, copper or most coins.
- Stroking the needle back and forth.
- Testing the compass right next to a magnet or a metal sink, which pulls the needle off north.

Make it a game • Float the Compass. Float your needle compass in a bowl and spin the bowl. Count how many seconds it takes to settle. Say magnet, pole, attract and repel. Then predict which way it points when you hold a magnet nearby, and test it. Explain Gilbert's idea in 20 seconds, with the word lodestone in your sentence.

4.4 SAMUEL MORSE AND THE TELEGRAPH

OBJECTIVES

- Tell the story of Samuel Morse and the first telegraph line.
- Explain how a switch can send a message in dots and dashes.
- Build a battery telegraph and send a message in Morse code.

Warm-up. Tap out the rhythm of a song you know on the table, and see if someone can guess it. Now agree on a code: one tap means yes, two taps means no. Ask each other questions using only taps.

WATCH

Samuel Morse and The Telegraph | History For Kids

Bedtime History · 3:59

<https://www.youtube.com/watch?v=CjVxVd9rWYc>

WHEN TO WATCH

Before the story, as an introduction.

BACKUP VIDEO

How Does Morse Code Work?

Concerning Reality · 3:29

https://www.youtube.com/watch?v=iy8BaMs_Jul

Before the build, to hear how dots, dashes and spaces work.

KEY TERMS

telegraph

A machine that sends messages over long wires using pulses of electricity.

electromagnet

A magnet made by sending electricity through a coil of wire, which can be switched on and off.

Morse code

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

key

A springy switch that a telegraph operator presses to send signals.

relay

A device that uses a weak signal to switch on a fresh battery, so a message can travel farther.

CORE IDEAS

The story. Samuel F. B. Morse was a famous American painter. In 1832, on a ship sailing home from Europe, he heard other passengers talking about the new electromagnet, and an idea gripped him: if electricity could travel instantly along a wire, it could carry messages. He spent twelve years working on it, often with very little money. At last, in 1843, Congress paid for a test line from Washington to Baltimore, about 40 miles. On May 24, 1844, in the Capitol building, Morse tapped out a message chosen from the Bible: “What hath God wrought.” In Baltimore, his partner Alfred Vail received it and sent it right back.

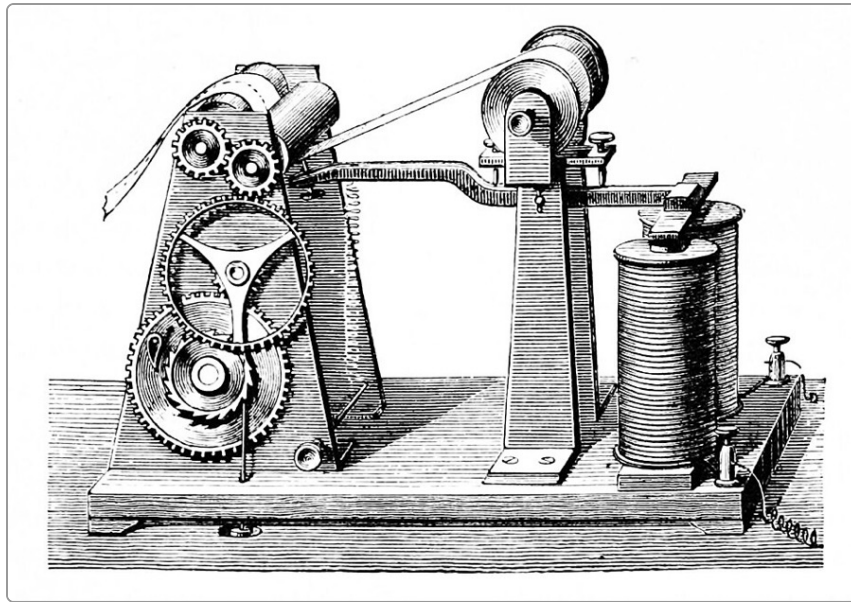
How they figured it out. Morse was not an engineer, so he learned from others. The scientist Joseph Henry had shown how to make strong electromagnets and how a weak current could switch on a fresh battery farther down the line. Leonard Gale helped Morse with the electrical parts, and Alfred Vail, a skilled mechanic, improved the machines. To make the code fast, they gave the shortest signals to the letters used most often. E, the most common letter in English, is a single dot. Vail is said to have counted the pieces of type in a printer’s shop to find which letters were used most.

The physics. A telegraph is a long circuit with a switch at one end and an electromagnet at the other. When the operator presses the **key**, the circuit is closed and electricity flows. Far away, the coil of wire becomes a magnet and pulls down a small iron arm, which clicks or marks a paper tape. When the key is released, the circuit opens and the arm springs back. A short press makes a dot; a long press makes a dash. The electricity travels through the wire so fast that the message arrives almost at once.

The engineering. Within twenty years, telegraph wires crossed America, carried on poles beside the railroads, and in 1866 a cable on the bottom of the ocean joined America and Britain. Engineers had to solve real problems: wires that lost their signal over long distances (relays fixed that), wires that touched wet poles (glass insulators fixed that), and storms that knocked lines down. The telegraph was the

first step toward the telephone, radio and the internet, which still send information as a code of on-and-off signals.

PICTURE STUDY



A Morse Telegraph Register, Unknown engraver, 1872–1873 · Engraving · From *Popular Science Monthly*
Image: [Wikimedia Commons](#), public domain

This machine was a telegraph “register.” It received messages and marked them as dots and dashes on a long strip of paper, so that the operator could read them later.

Look closely

- Find the coil of wire standing up on the right. That is the electromagnet.
- Find the lever arm above the coil. What do you think happens to it when electricity flows?
- Find the rollers and the paper tape. Where does the tape go?
- Find the gears on the left. They are clockwork that pulls the paper along at a steady speed.

Talk about it

1. Why does the paper need to move at a steady speed?
2. What would a dash look like on the tape compared with a dot?
3. Why was it helpful to have the message written down on paper?

Safety first. Use only batteries. Keep the wires on the floor where no one will trip, and disconnect the battery when you finish.

BUILD

Build a Battery Telegraph

You will build a telegraph with a homemade key, long wires and a bulb or buzzer at the other end. Then you will send messages in Morse code and test how fast and accurately you can send.

You will need

- A battery in a holder and a bulb in a holder (or a small buzzer made for batteries)
- Two long pieces of wire (several meters each) or many alligator clip leads joined together
- For the key: a piece of cardboard, two brass fasteners, a strip of aluminum foil and a rubber band or folded card for a spring
- A Morse code chart (written in your notebook)
- Engineer's notebook

Steps

1. **Make the key.** Push two brass fasteners through a piece of cardboard about 4 centimeters apart. Wrap foil around a craft stick or card strip and fasten it to one brass fastener so it can be pressed down to touch the other fastener and spring back up.
2. Connect the battery, the key and the bulb in one loop with long wires, so the key is in one room (or at one end of a long hallway) and the bulb is in the other.
3. Test it: press the key and have a helper call out when the bulb lights.
4. Copy the Morse code alphabet into your notebook. Practice: a dot is a quick press, a dash is a press three times as long.
5. **Send a message.** Send your name. Your partner writes down the dots and dashes and decodes them.
6. **Fair test.** Send the same five-letter word three times. Time each try and count the mistakes. Do you get faster? Record your results.

7. **Improve it.** Make a better key that springs back cleanly, or agree on a pause between letters and a longer pause between words. Test whether your mistakes go down.

Tips

- Leave a short pause between letters and a longer pause between words, or the message runs together.
- Common letters are short: E is · and T is –. Learn those first.
- Send slowly at first. Accuracy is more important than speed.

Check your work

- ☐ I built a telegraph that lights a bulb in another room.
- ☐ I sent and received a word in Morse code.
- ☐ I can explain how a key opens and closes a circuit.

ENGINEER'S NOTEBOOK

1. Draw your telegraph circuit from the key to the bulb, with arrows showing the path of electricity.
2. Write a short message in Morse code for someone in your family to decode.
3. Make a table: try number, time, mistakes.

From history. The words “What hath God wrought” were suggested by Annie Ellsworth, the young daughter of a friend who had helped Morse win the money from Congress. Morse said the words gave the honor to God, where he believed it belonged. The paper tape from that first message is kept in the Library of Congress.

COMMON MISTAKES

- Thinking a telegraph sends sound or words along the wire. It sends on-and-off pulses of electricity.
- Running letters together without pauses.
- Thinking Morse did everything alone. Henry, Gale and Vail all helped make the telegraph work.

Make it a game • Dots and Dashes Relay. Build a battery telegraph, and send your parent a three-letter word in Morse code with a key. They decode it from your blinks or clicks. Then switch. Say telegraph, key and relay. Tell the story of Samuel Morse and the first telegraph line. Beat your best time for sending a word.

Scripture. “according to this time it shall be said of Jacob and of Israel, What hath God wrought!” (Numbers 23:23, KJV)

Morse chose to send these words first because he believed the telegraph was something God had made possible, not something to boast about.

UNIT 4

ELECTRICITY AND MAGNETS

Electricity is hidden. You cannot see it move through a wire, but you can see what it does: a bulb glows, a buzzer buzzes, a compass needle swings. In this unit you will build circuits with batteries and bulbs, and learn why Thomas Edison wired houses so that one lamp could be switched off without turning off all the others. You will repeat Stephen Gray's discovery of conductors and insulators with string and silk, and follow William Gilbert as he learned that the whole earth is a giant magnet.

Finally, you will put electricity and magnets together, just as Samuel Morse did, to send messages across a room in dots and dashes. All of our electricity in this unit comes from batteries. Never use the outlets in the wall.

PREREQUISITES

- Knows how to run a fair test and record results in a table
- Can follow a simple diagram
- Knows that electricity from the outlets in the wall is dangerous and is never used for experiments

MASTERY CHECKLIST

- ☐ I can build a complete circuit and explain why it must be a closed loop.
- ☐ I can build series and parallel circuits and explain how they behave differently.
- ☐ I can sort materials into conductors and insulators by testing them.
- ☐ I can make a compass and explain why it points north.
- ☐ I can send and receive a message in Morse code with a homemade telegraph.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits Jr.:** Ages 8 and up. Snap-together parts build lamps, switches, buzzers and series and parallel circuits with no wiring. A great companion to Lessons 4.1, 4.2 and 4.4.
- **Thames & Kosmos electricity kits:** Ages vary by kit. Several beginner kits cover circuits, magnets and electromagnets with battery power. Fits Lessons 4.1–4.4.

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 Series and Parallel: Why Edison Wired Houses in Parallel

2 sessions of 45 minutes

4.2 Stephen Gray Discovers Conductors and Insulators

2 sessions of 45 minutes

4.3 William Gilbert, Magnets and the Compass

2 sessions of 45 minutes

4.4 Samuel Morse and the Telegraph

2 sessions of 45 minutes

UNIT 4 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

Why does a bulb light only when the circuit is a complete loop?

2. **5 pts**

Predict: two bulbs are in series. You unscrew one. What happens to the other?

3. **5 pts**

Why are the lights in a house wired in parallel?

4. **5 pts**

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

5. (5 pts)

Why did Stephen Gray's experiment fail when he held up the thread with brass wire?

6. (5 pts)

Why does an electric cord have copper inside and plastic outside?

7. (5 pts)

What happens when you bring the north poles of two magnets together? A north and a south?

8. (5 pts)

What did William Gilbert discover with his terrella?

9. (5 pts)

How does a telegraph send a dot and a dash?

10. (5 pts)

What was the first official telegraph message, and why did Morse choose it?

ANSWER KEY

1. Electricity must flow all the way from the battery, through the bulb and back to the battery. A gap stops the flow.
2. It goes out too, because the only path is broken.
3. So each light has its own path and can be switched on and off separately; if one goes out, the others stay on.
4. A conductor lets electricity flow (copper, foil, a paper clip). An insulator does not (plastic, rubber, glass, silk).
5. Brass is a conductor, so the electricity leaked away through the wire. Silk is an insulator and kept it in the thread.
6. The copper conducts electricity to the device, and the plastic insulates it so it cannot reach your hands.
7. Two north poles repel (push apart). North and south attract (pull together).
8. That the earth itself is a giant magnet, which is why a compass needle points north.
9. Pressing the key closes the circuit and the electromagnet at the far end pulls the arm or lights the bulb. A short press is a dot, a long press is a dash.
10. “What hath God wrought,” words from the Bible (Numbers 23:23). Morse believed the invention was a gift from God.

PORTFOLIO PIECE: A WORKING TELEGRAPH AND CODE BOOK

Build a telegraph with a key that springs back, a battery and a bulb or buzzer, long enough to reach from one room to another. Make a code book with the Morse alphabet. Send a three-word message to a family member, who writes it down and decodes it. Record your tries, your mistakes and one improvement you made to the key or the code.

LOOK FOR	WHAT IT MEANS
Working circuit	The key reliably turns the bulb or buzzer on and off from the other room.
Diagram	A labeled drawing shows the complete circuit, including the conductors and the insulated wires.
Message	A three-word message is sent and correctly decoded.
Improvement	One change to the key or the method is made and tested, and the results are recorded.

UNIT 5

WATER, POWER AND TELEPHONES

Turn on a faucet, flush a toilet, flip a light switch or make a phone call, and you are using a great hidden machine that engineers built and that workers keep running day and night. These systems are called **public utilities**, because they serve everyone. In this unit you will follow water from a river to your faucet, as New York did when it built the Croton Aqueduct, and test your own sand filter.

Then you will see how Chicago lifted whole streets and buildings to make room for its sewers, follow electricity from the power plant to the outlet in your wall, and learn how Alexander Graham Bell taught a wire to carry a voice. Engineering is service: clean water, safe sewers and light in the dark are ways of loving our neighbors.

PREREQUISITES

- Knows how to build a complete circuit (Unit 4)
- Knows that conductors carry electricity and insulators block it (Unit 4)
- Can run a fair test and record three trials

MASTERY CHECKLIST

- ☐ I can describe the path of water from a river or well to my faucet, and the main steps that clean it.
- ☐ I can explain why sewers must slope downhill and how Chicago solved its sewer problem.
- ☐ I can describe the path of electricity from a generator to an outlet, and name the safety rules for power lines.
- ☐ I can explain that sound is vibration and how a telephone carries it.
- ☐ I can build and fairly test a water filter, a model sewer and a string telephone.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits Jr.**: Ages 8 and up. Includes a motor and lamps for exploring how electricity is made and used, with battery power only. Fits Lesson 5.3.
- **Thames & Kosmos science kits**: Ages vary by kit. Several kits explore water, hydropower and renewable energy with small working models. Fits Lessons 5.1 and 5.3.

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

5.1 Clean Water: The Croton Aqueduct and the Sand Filter	2 sessions of 45 minutes
5.2 Sewers: Chicago Lifts Its Streets	2 sessions of 45 minutes
5.3 From the Power Plant to Your Outlet	2 sessions of 45 minutes
5.4 Alexander Graham Bell and the Telephone	2 sessions of 45 minutes

UNIT 5 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
What force moved the water of the Croton Aqueduct 41 miles to New York City?
2. **5 pts**
Name three steps that clean drinking water at a treatment plant.
3. **5 pts**
Predict: you build a filter with gravel on top and fine sand on the bottom, and another with fine sand on top. Which will clog faster?
4. **5 pts**
Why must a sewer pipe slope downhill?

5. (5 pts)

Why did Chicago raise its streets and buildings in the 1850s and 1860s?

6. (5 pts)

How can 600 men with jackscrews lift a whole row of brick buildings?

7. (5 pts)

What does a generator do? Name two things that can spin a generator.

8. (5 pts)

Name two safety rules about power lines.

9. (5 pts)

What is sound?

10. (5 pts)

Why does a string telephone stop working if you pinch the string?

ANSWER KEY

1. Gravity. The tunnel sloped gently downhill the whole way.
2. Any three: clumping the dirt, settling, filtering through sand and gravel, disinfecting with chlorine, testing.
3. The one with fine sand on top, because the big dirt fills the tiny spaces right away. Gravel on top catches big pieces first.
4. Wastewater moves by gravity. Without a steady slope, it stops and the waste settles and clogs the pipe.
5. The city was too flat and low to dig sewers deep enough, so the pipes were laid on the old streets and covered, and the streets and buildings were raised.
6. A jackscrew is a screw (an inclined plane wrapped around a pole). Each turn lifts a little with a small force, and many screws turned together share the load.
7. It turns spinning motion into electricity. Steam (from coal, gas or nuclear), falling water or wind can spin it.
8. Any two: never touch them; stay far away from fallen lines; never fly kites or drones near them; stay out of substations; call 811 before digging.
9. Vibration that travels through air, water or solid things to our ears.
10. Pinching stops the string from vibrating, so the vibrations cannot travel to the other cup.

PORTFOLIO PIECE: A TESTED WATER FILTER AND REPORT

Design the best water filter you can from household materials (sand, gravel, cotton, coffee filters, cloth). Test at least two designs with the same muddy water, measuring the drip time and the clarity with your clarity card. Choose the best design and write a short report for a pretend town council: what you built, what you measured, which design won and why. Remember to warn the council that real drinking water must also be disinfected and tested.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the layers and the reason for their order.
Fair test	At least two designs were tested with the same amount of the same muddy water.
Data	Drip time and clarity are recorded in a table for each design.
Report	The report explains which design won and why, and includes the safety warning about disinfecting and never drinking filter water.

5.1 CLEAN WATER: THE CROTON AQUEDUCT AND THE SAND FILTER

OBJECTIVES

- Describe how a city brings water from far away using gravity.
- Name the main steps in cleaning drinking water.
- Build a layered sand filter and fairly test how well it clears muddy water.

Warm-up. Fill a clear jar with water and stir in a spoonful of garden soil. Let it sit for ten minutes while you read the story. What happens to the dirt? Is the water on top clean enough to drink? (No! Some dirt and germs are too small to see.)

WATCH

How Does Water Get to Your House?

[SciShow Kids](#) · 3:36

<https://www.youtube.com/watch?v=cGi4PugN4qY>

WHEN TO WATCH

Before the story.

BACKUP VIDEO

Water and You: The Water Treatment Process

[New Jersey American Water](#) · 4:20

<https://www.youtube.com/watch?v=tuYB8nMFxQA>

After the physics paragraph, to see each step at a real treatment plant.

KEY TERMS

aqueduct

A pipe, tunnel or channel that carries water a long way, usually sloping gently downhill.

reservoir

A large lake or tank where water is stored.

filter

Something that lets water pass through but catches dirt.

treatment plant

A place where water is cleaned to make it safe to drink.

disinfect

To destroy germs, often with a small amount of chlorine.

CORE IDEAS

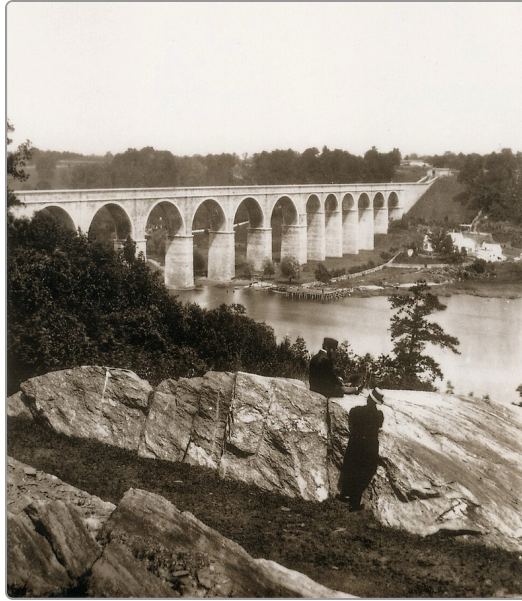
The story. In the early 1800s, New York City got its water from wells, springs and rain barrels, and much of it was dirty. When a terrible fire broke out in 1835, there was not enough water to fight it, and hundreds of buildings burned. The city decided to bring clean water from the Croton River, 41 miles to the north. On October 14, 1842, the city held a huge celebration with parades and fountains: the water of the Croton Aqueduct had arrived.

How they figured it out. The chief engineer, John B. Jervis, had no pumps powerful enough to push water 41 miles. So he used gravity. He built a dam on the Croton River and a covered brick tunnel that sloped gently downhill the whole way, dropping only about a foot every mile. Where the tunnel crossed valleys and rivers, it ran on bridges of stone arches, like the Roman aqueducts. The most famous is High Bridge, finished in 1848 over the Harlem River. The water flowed into big reservoirs in the city and then through iron pipes under the streets.

The physics. Water always flows downhill, pulled by gravity. If an aqueduct slopes too steeply, the water rushes and wears away the channel; too gently, and it barely moves. Water also seeps through sand. As it trickles between the tiny grains, bits of dirt get stuck in the narrow spaces. Big pieces are caught by gravel, smaller ones by sand, and the smallest by fine sand or charcoal. That is how a **filter** works.

The engineering. Today, water is cleaned at a **treatment plant** before it reaches your faucet. First, a chemical makes tiny bits of dirt clump together. The clumps sink to the bottom of a settling tank. The water then passes through filters of sand and gravel. Finally, a small amount of chlorine is added to destroy germs. Water operators test the water many times a day. Then pumps and water towers send it through pipes to every home. Clean water has saved more lives than almost any other invention.

PICTURE STUDY



High Bridge, Harlem River, New York, William England, 1859 · Photograph · London Stereoscopic Company series on America

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

The English photographer William England traveled across America in 1859 taking pictures for people at home to see. Here he photographed High Bridge, which carried the Croton Aqueduct's water across the Harlem River into New York City.

Look closely

- Count the arches. Are they all the same size?
- Find the top of the bridge. The water flowed through pipes hidden under the walkway on top.
- Find the man standing on the rocks. How big is the bridge compared with him?
- Look at the river. Why did the aqueduct need a bridge here?

Talk about it

1. Why did the engineers build the aqueduct on a bridge instead of letting the water run down into the valley and back up?
2. What force moved the water all the way from the Croton River to the city?
3. How is this bridge like the Roman arches you learned about in Unit 2?

Safety first. Never drink the water from your homemade filter, no matter how clear it looks. Wash your hands after handling soil. An adult cuts the bottle.

BUILD

The Layered Sand Filter Test

You will build a filter in a plastic bottle with layers of gravel, sand and cotton, pour muddy water through it, and measure how clear the water comes out. Then you will run a fair test by changing the order of the layers.

You will need

- Two clear plastic bottles, with the bottoms cut off by an adult
- Coffee filters or cotton balls, clean sand, and small gravel or pebbles (rinsed)
- Muddy water (water stirred with garden soil) and a measuring cup
- Clear jars or cups to catch the water
- A “clarity card”: a card with letters of different sizes written on it
- A stopwatch and the engineer’s notebook

Steps

1. Turn a bottle upside down with the cap off, like a funnel, and stand it in a jar. Put a coffee filter or a layer of cotton in the neck.
2. Add layers from the bottom up: 3 centimeters of fine sand, then 3 centimeters of coarse sand, then 3 centimeters of gravel.
3. **Predict:** how clear will the water be after the filter?
4. Pour 1 cup of muddy water slowly into the top. Time how long it takes to drip through.
5. **Measure clarity.** Hold the clarity card behind the jar of filtered water. What is the smallest letter you can read? Do the same with unfiltered muddy water. Record both.
6. **Fair test.** Build a second filter with the same materials in a different order: gravel on the bottom and fine sand on top. Pour the same amount of the same muddy water and measure the time and clarity.
7. Record both filters in a table and decide which order works better and why.
8. **Improve it.** Add one change, such as a thicker sand layer or pouring the water through twice, and test again.

Tips

- Stir the muddy water before every pour so each filter gets the same mix.
- The first water through may carry loose sand. You can pour it through again.
- A filter that is very slow but very clear may still be the better design. That is a trade-off.

Check your work

- ☐ I can explain how gravity brought water to New York.
- ☐ I measured the time and clarity for two filters and compared them.
- ☐ I can name the steps at a water treatment plant, and I know never to drink filter water.

ENGINEER'S NOTEBOOK

1. Draw your filter and label each layer. Draw arrows to show the water's path.
2. Make a table: filter, time to drip, smallest letter I could read.
3. Draw the path of water from a river or well to your kitchen sink.

From history. Engineers had been filtering water through sand since 1804, when John Gibb built a sand filter for his bleaching works in Paisley, Scotland, and sold the extra clean water to the town. In 1829, James Simpson built a large sand filter for a water company in London, and cities around the world soon copied it.

COMMON MISTAKES

- Thinking clear water is clean water. Germs are too small to see; real water plants also disinfect.
- Pouring different amounts of muddy water into each filter.
- Forgetting that gravity is doing the work in an aqueduct and in your filter.

Make it a game • Sand Filter Ranking. Pour muddy water through layers of sand, gravel and cloth in a bottle funnel, over a bowl. Before each pour, guess how clear it will be on a scale of one to five. Compare to your guess. Say aqueduct, reservoir and filter. Name the main steps in cleaning drinking water, in order. Do not drink the water.

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)

God made water to travel in a great circle, from the sea to the clouds to the rivers and back. Water engineers work with that design to bring clean water to every home.

5.2 SEWERS: CHICAGO LIFTS ITS STREETS

OBJECTIVES

- Explain why sewers must slope downhill.
- Tell how Chicago raised its streets and buildings to build sewers.
- Build a model sewer and test how much slope it needs to carry “waste.”

Warm-up. Tilt a cookie sheet very slightly and pour a little water at the top. Then tilt it more. How much tilt does the water need to run to the bottom? Sprinkle some rice in the water. Does it take more tilt to carry the rice?

WATCH

The Met Council Presents: Wastewater Treatment for Kids

Metropolitan Council · 9:58

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

WHEN TO WATCH

After the engineering paragraph.

Note: A small but trustworthy channel from a regional government in Minnesota that runs real wastewater plants. Its cartoon tour of a treatment plant is the clearest one we found for this age.

KEY TERMS

sewer

A pipe under the ground that carries used water and waste away from homes.

slope

How much something tilts. Sewers need a steady downhill slope.

wastewater treatment plant

A place where used water is cleaned before it goes back into a river or lake.

wastewater

Water that has been used in sinks, tubs, washing machines and toilets.

jackscrew

A big screw that lifts a heavy load a little at each turn.

CORE IDEAS

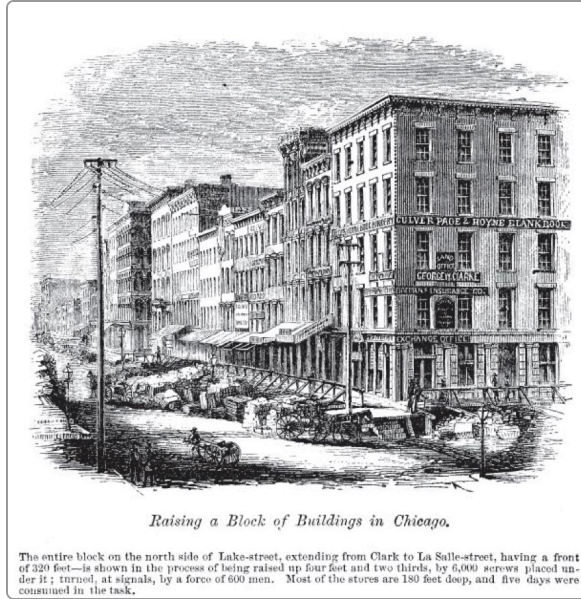
The story. In the 1850s, Chicago was growing fast, but it was built on flat, swampy ground barely above Lake Michigan. When it rained, the streets turned to deep mud, and there was nowhere for dirty water to go. Waste soaked into the ground and the water supply, and many people became sick. In 1855 the city hired an engineer named Ellis S. Chesbrough to build the first complete sewer system in any big American city.

How they figured it out. Chesbrough had a problem: sewers must slope downhill, but the city was so flat and so low that there was no room to dig them deep enough. His bold answer was to lay the sewer pipes on top of the old streets, cover them with dirt, and build new streets on top. The streets rose by several feet, and some by much more. That left the buildings sunk below the new streets! So the people of Chicago lifted their buildings. Workers put hundreds of **jackscrews** under a building and turned them all together, a little at a time. In 1860, a whole block of brick stores on Lake Street, more than 300 feet long, was raised over four feet in five days by 600 men turning 6,000 jackscrews, while the shops stayed open.

The physics. Wastewater moves through sewers by gravity, the same as water in an aqueduct. The pipe must slope downhill steadily, or the water stops and the waste settles and clogs the pipe. A jackscrew is a screw, which is an inclined plane wrapped around a pole (remember the Archimedes screw in Unit 1). Each turn lifts the load only a tiny bit, but it takes only a small force, so many workers together could lift a heavy building.

The engineering. Today, sewers carry wastewater to a **wastewater treatment plant**. There, screens catch trash, the heavy solids settle out, and tiny helpful living things called bacteria eat much of what is left. The cleaned water goes back to a river or lake. Engineers plan the slope of every pipe, and where the land is too flat, they add pump stations to lift the water. Never flush wipes, toys or trash: they clog the pipes and pumps that keep a whole city healthy.

PICTURE STUDY



Raising a Block of Buildings in Chicago, From John Barber and Henry Howe's book *Our Whole Country*, Event 1860; published 1861–1865 · Wood engraving · From *Our Whole Country* by John Warner Barber and Henry Howe

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

This engraving shows the Lake Street block being raised in 1860. The caption under it tells the numbers: more than 300 feet of buildings, raised over four feet by 6,000 screws turned by 600 men in five days.

Look closely

- Find the bottom of the buildings. What is holding them up?
- Find the sidewalk and the street. Are they higher or lower than the buildings' old doorways?
- Find the people and carts. Is the street still being used while the buildings are lifted?
- Read the caption under the picture with a parent.

Talk about it

1. Why did 600 men have to turn their screws at the same time, on a signal?
2. What would happen if one end of the building were lifted faster than the other?
3. Why did Chicago need to raise its streets at all?

Safety first. Do this build over a sink, tub or outdoors. Use only clean water and dry rice or peppercorns as “waste.”

BUILD

How Much Slope Does a Sewer Need?

You will build a model sewer from paper-towel tubes or a foil channel and test how much slope it needs to carry water and “waste” all the way to the end without clogging.

You will need

- Three or four paper-towel tubes, cut in half the long way and lined with foil (or a long strip of foil folded into a channel)
- Tape, a ruler and a stack of books or blocks
- A cup of water and a spoonful of dry rice or peppercorns
- A tub or pan to catch the water
- Engineer’s notebook

Steps

1. Tape the tubes end to end to make a channel about 1 meter long. Make sure the joints are smooth.
2. Rest one end on the edge of the tub and the other end on books so the high end is 2 centimeters up.
3. **Predict:** how high must the top end be for the water to carry all the rice to the tub?
4. Pour a half cup of water with a spoonful of rice in at the top. Count how many grains are left stuck in the channel.
5. **Fair test.** Test with the high end at 2, 4, 8 and 12 centimeters. Use the same amount of water and rice each time. Do two trials at each height.
6. Record height and grains left behind in a table.
7. **Improve it.** Add a “sag” in the middle of the channel (a low spot). What happens? Then try fixing the sag or adding more water. Explain why real sewer pipes must slope evenly.

Tips

- Count the grains left behind quickly before they dry.
- Smooth joints matter: a bump can catch waste, just as in a real pipe.

- Measure the height from the table to the bottom of the channel.

Check your work

- ☐ I found the smallest slope that carried the rice to the end.
- ☐ I can explain why Chicago raised its streets to build sewers.
- ☐ I can explain how a jackscrew lifts a heavy load with a small force.

ENGINEER'S NOTEBOOK

1. Draw a cut-away of a Chicago street before and after it was raised, with the sewer pipe underneath.
2. Make a bar graph: slope height and grains left behind.
3. List five things that should never be flushed down a toilet, and explain why.

From history. Even after the sewers were built, Chicago's waste still flowed into the river and out into Lake Michigan, where the city got its drinking water. In 1900, engineers finished a canal that made the Chicago River flow backward, away from the lake. Later, the city built treatment plants, so the water is cleaned before it leaves.

COMMON MISTAKES

- Thinking sewers are pumped all the way. Most of the time, gravity does the work.
- Making the slope uneven. A low spot collects waste and clogs.
- Thinking wastewater just goes into the ground. In a city, it travels to a treatment plant.

Make it a game • Sewer Slope Duel. Pour water down a tube at three slopes, one flat, one gentle and one steep, and time how long the water takes to reach the end. Predict the order first. Say sewer, slope and wastewater. Then tell how Chicago raised its streets with jackscrews. Your parent has you explain it in ten seconds.

5.3 FROM THE POWER PLANT TO YOUR OUTLET

OBJECTIVES

- Explain that a generator makes electricity by spinning magnets and coils of wire.
- Trace the path of electricity from a power plant to an outlet.
- Use a hobby motor as a generator and test how spinning speed changes the light it makes.

Warm-up. Look out the window or take a short walk with a parent. Find power lines, a pole, a transformer (a gray can on a pole or a green box on the ground) and the electric meter on your house. Do not touch any of them. Sketch what you find.

WATCH

How Power Gets to Your House

EPCOR • 2:35

https://www.youtube.com/watch?v=_eKivDH3w0w

WHEN TO WATCH

After the story. Name each step as you see it.

KEY TERMS

generator

A machine that makes electricity by spinning magnets and coils of wire past each other.

transformer

A device that changes electricity to a higher or lower voltage.

meter

A device that measures how much electricity a home uses.

power plant

A place where large generators make electricity for a whole region.

power line

Wires on tall towers or poles, or underground, that carry electricity.

lineworker

A trained worker who builds and repairs power lines.

CORE IDEAS

The story. On September 4, 1882, at three o'clock in the afternoon, Thomas Edison's workers switched on the Pearl Street Station in New York City. Steam engines spun giant generators nicknamed "Jumbos," and about 400 lamps lit up in the offices and stores around it. For the first time, a power station sent electricity through wires under the streets to many customers at once. Today, power plants send electricity to millions of homes.

How they figured it out. Fifty years earlier, in 1831, the English scientist Michael Faraday, a devout Christian, discovered that moving a magnet near a coil of wire makes electricity flow in the wire. Spin a coil between magnets, and you get a steady supply. Edison's team built huge spinning generators, laid copper wires in pipes under the streets, and invented meters, switches and fuses so the system was safe and useful. Others soon learned to send electricity much farther by raising its voltage, which led to the long power lines we see today.

The physics. A **generator** turns spinning motion into electricity. Something has to do the spinning: steam from burning coal or gas, steam heated by a nuclear reactor, falling water at a dam, or wind turning a windmill's blades. (Solar panels work differently: sunlight makes electricity directly.) A small hobby motor is a generator too: if you spin its shaft, it makes a little electricity.

The engineering. Electricity leaves the power plant and goes to a **transformer** that raises the voltage very high, so it can travel far along tall **power lines** without wasting much. Near your town, a substation lowers the voltage. A transformer on a pole or in a green box lowers it again for your house. It passes through the **meter**, then a panel of breakers, then wires in the walls to your outlets. **Lineworkers** climb poles in storms to fix broken lines and get the lights back on. Power lines are very dangerous: never touch them, never fly kites near them, and stay far away from a fallen line or a substation.

PICTURE STUDY



Nine Mile Dam and Powerhouse, Historic American Engineering Record, Powerhouse built 1908; photograph late 1900s · Photograph · Library of Congress, Prints and Photographs Division

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

This hydroelectric plant on the Spokane River in Washington State was built in 1908. Water held back by the dam falls through turbines inside the powerhouse, spinning generators. The small houses were built for the families of the workers who ran the plant.

Look closely

- Find the dam. Which side of it is the water higher?
- Find the powerhouse. Where do you think the water goes in and comes out?
- Find the cottages where the plant's operators lived. Why would workers need to live close by?
- Look for power lines or towers leaving the plant.

Talk about it

1. What does the falling water spin inside the powerhouse?
2. How does electricity get from here to a house many miles away?
3. Why does a power plant need people watching it day and night?

Safety first. Use only a small hobby motor and an LED. Never use outlets in the wall, never open an appliance, and never go near power lines, transformers or substations. Before anyone digs in a yard, call 811 so workers can mark where buried lines and pipes are.

BUILD

Spin a Generator

You will turn a small hobby motor into a generator by spinning its shaft with a string, and see it light an LED. Then you will test how spinning speed changes the light.

You will need

- A small hobby motor (1.5–3 volt)
- A red LED and two alligator clip leads
- An empty thread spool or a bottle cap pushed onto the motor shaft
- About 1 meter of string
- A stopwatch and the engineer's notebook

Steps

1. Push the spool or cap firmly onto the motor shaft. Wind the string around it.
2. Clip the motor's two wires to the two legs of the LED.
3. Hold the motor steady on the table and pull the string quickly. Does the LED flash? If not, swap the clips on the LED legs (an LED only works one way) and try again.
4. **Predict:** will a faster pull make a brighter or longer flash?
5. **Fair test.** Pull the full string slowly (count “one-two-three”), at medium speed, and as fast as you can. Rate the flash each time: none, dim, bright. Do three trials each.
6. Record the results in a table.
7. **Improve it.** Connect a second motor instead of the LED. Spin the first motor and watch the second. What happens? Draw the path from your hand to the second motor, and compare it with a power plant and your house.

Tips

- Hold the motor still; only the shaft should spin.
- The light is faint, so try it in a dim room.
- If the string slips, wrap a bit of tape around the spool for grip.

Check your work

- ☐ I made electricity by spinning a motor.
- ☐ I found that faster spinning made more light.
- ☐ I can trace electricity from a power plant to an outlet and name two safety rules.

ENGINEER'S NOTEBOOK

1. Draw the path of electricity from a power plant to your lamp. Label the generator, transformers, power lines, meter and outlet.
2. Make a table of pulling speed and LED brightness.
3. Write a thank-you note to a lineworker or a power plant operator.

From history. Lineworkers are some of the bravest workers in any city. After big storms, crews often travel from other states to help put the power back on. Many utility companies honor them each year, and families often leave thank-you notes and snacks for crews working in their neighborhood.

COMMON MISTAKES

- Thinking a power plant stores electricity in a big tank. Generators make it the moment it is used.
- Thinking a bird on a wire means wires are safe. Never touch or go near power lines.
- Forgetting that something must spin a generator: steam, falling water or wind.

Make it a game • Path of Power Chase. Race through the path of electricity with index cards: power plant, transformer, power line, meter and outlet. Shuffle the cards, and set a timer to put them in order. Say what each does. Then spin a toy generator and count the flashes. Beat your own time, and explain how magnets and coils make electricity.

5.4 ALEXANDER GRAHAM BELL AND THE TELEPHONE

OBJECTIVES

- Explain that sound is a vibration.
- Tell how Alexander Graham Bell made the first telephone.
- Build a string telephone and fairly test which string carries sound best.

Warm-up. Put your fingers gently on the front of your throat and hum. What do you feel? Now stretch a rubber band between your fingers and pluck it. What do you see and hear?

WATCH

The Science of the String Phone! - #sciencegoals

SciShow Kids · 4:38

<https://www.youtube.com/watch?v=3yqB2KFwJCo>

WHEN TO WATCH

Before the build.

KEY TERMS

sound

Vibrations that travel through air, water, string or solid things to our ears.

vibrate

To move back and forth very quickly.

telephone

A machine that turns the vibrations of a voice into electricity, sends it along a wire, and turns it back into sound.

diaphragm

A thin, flexible sheet that vibrates with sound, inside a telephone or a microphone.

CORE IDEAS

The story. Alexander Graham Bell grew up in Scotland in a family that studied speech. His mother was deaf, and later his wife was too. In America, he became a teacher of deaf students in Boston and studied how sounds are made. He dreamed of sending a voice along a wire. On March 10, 1876, in his workshop, he spoke into his new machine, and his assistant Thomas Watson heard his words come out of a receiver in another room: “Mr. Watson, come here, I want to see you.”

How they figured it out. Bell knew that a voice makes the air vibrate, and that the vibrations shake a thin sheet, like the skin of a drum. He also knew about the telegraph, which sent pulses of electricity. His idea was to make the electricity in a wire change smoothly, just as the air shakes when we speak. Bell and Watson worked for months, trying many designs. Some carried only a hum or a twang. Finally a design with a thin vibrating sheet, a **diaphragm**, carried clear words. Bell kept careful notebooks of every try.

The physics. Sound is vibration. When you speak, your vocal cords vibrate and shake the air, and the shaking travels to someone's ear. Sound can travel through solid things too, often better than through air. In a string phone, your voice shakes the bottom of the cup, the cup shakes the string, the string shakes the other cup, and the other cup shakes the air in your friend's ear. In a real telephone, the vibrations are turned into changes in electricity, which rush along the wire and are turned back into vibrations at the other end.

The engineering. After Bell's invention, engineers had to build a whole system: wires on poles, switchboards where operators connected calls, and later automatic switches and cables under the sea. Today, your voice is turned into a code of numbers and sent by radio waves, wires and glass fibers that carry light. But the first step is still the same: a tiny diaphragm in the phone's microphone that vibrates when you speak.

PICTURE STUDY



Bell Opens the Long-Distance Line from New York to Chicago, Unknown photographer, 1892 ·
Photograph · Library of Congress, Prints and Photographs Division
Image: [Wikimedia Commons](#), public domain

Sixteen years after his first telephone call, Bell made the first call on a new line from New York to Chicago, hundreds of miles away. In this photograph, he is speaking into the mouthpiece while officials watch.

Look closely

- Find Bell. What is he holding to his mouth? What is at his ear?
- Look at the faces of the men behind him. How do they seem to feel?
- Find the telephone box on the wall or table.
- Look for wires. Where do you think they go?

Talk about it

1. How did Bell's voice travel all the way from New York to Chicago?
2. Why was a long-distance line such a big event in 1892?
3. How is this telephone different from the phones we use today? How is it the same?

BUILD

The String Telephone Test

You will build string telephones and run a fair test to find which kind of string carries sound best, and whether the string must be tight.

You will need

- Four paper or plastic cups
- Three kinds of string, each about 5 meters long: cotton string, yarn and fishing line (or dental floss)
- Two paper clips and a pushpin or sharp pencil (adult help)
- A tape measure
- Engineer's notebook

Steps

1. Ask an adult to poke a small hole in the bottom of each cup.
2. Thread one string through two cups and tie each end around a paper clip inside the cup so it cannot pull through.
3. Stand 5 meters apart and pull the string tight. One person whispers a secret word into a cup; the other listens.
4. **Predict:** which string will carry the whisper best?
5. **Fair test.** Test each string with the same cups, the same distance, the same tightness and the same whisper. Rate how well you heard it: 0 (nothing), 1 (faint), 2 (clear), 3 (very clear). Have the listener try three times.
6. Test one string loose instead of tight. What happens?
7. Test with a finger pinching the middle of the string. What happens? Why?
8. **Improve it.** Try different cups (paper, plastic, a can with smooth edges) or a longer string. Record the best design.

Tips

- Keep the string from touching anything; touching stops the vibrations.
- Use the same secret word for each trial, but do not tell the listener which string is being tested.

- Speak into the cup, then quickly move it to your ear to listen for the answer.

Check your work

- ☐ I can explain that sound is vibration.
- ☐ I found which string carried sound best and recorded my scores.
- ☐ I can explain why a loose or pinched string does not work.

ENGINEER'S NOTEBOOK

1. Draw your string phone and use wavy lines to show the vibrations traveling from mouth to cup to string to cup to ear.
2. Make a table: string type, tight or loose, score.
3. Draw Bell's first telephone call: Bell in one room, Watson in the other, and the wire between them.

From history. Bell spent much of his life helping deaf people learn to communicate. He also invented a device to find metal inside the body, worked on airplanes and boats with hydrofoils, and helped lead a society for exploring the world. He said that the telephone was only one of many things he loved to study.

COMMON MISTAKES

- Thinking the sound goes inside the string like water in a pipe. The string itself shakes.
- Letting the string sag or touch furniture.
- Changing the string and the distance in the same test.

Make it a game • String Phone Vibration. Make a string telephone and speak through it with a tight string and a loose one. Rate the sound from one to five. Say vibrate, sound and diaphragm. Touch your throat while you hum, and describe what you feel. Tell your parent how Bell made the first telephone, and what vibrates in it.

UNIT 5

WATER, POWER AND TELEPHONES

Turn on a faucet, flush a toilet, flip a light switch or make a phone call, and you are using a great hidden machine that engineers built and that workers keep running day and night. These systems are called **public utilities**, because they serve everyone. In this unit you will follow water from a river to your faucet, as New York did when it built the Croton Aqueduct, and test your own sand filter.

Then you will see how Chicago lifted whole streets and buildings to make room for its sewers, follow electricity from the power plant to the outlet in your wall, and learn how Alexander Graham Bell taught a wire to carry a voice. Engineering is service: clean water, safe sewers and light in the dark are ways of loving our neighbors.

PREREQUISITES

- Knows how to build a complete circuit (Unit 4)
- Knows that conductors carry electricity and insulators block it (Unit 4)
- Can run a fair test and record three trials

MASTERY CHECKLIST

- ☐ I can describe the path of water from a river or well to my faucet, and the main steps that clean it.
- ☐ I can explain why sewers must slope downhill and how Chicago solved its sewer problem.
- ☐ I can describe the path of electricity from a generator to an outlet, and name the safety rules for power lines.
- ☐ I can explain that sound is vibration and how a telephone carries it.
- ☐ I can build and fairly test a water filter, a model sewer and a string telephone.

OPTIONAL KITS FOR THIS UNIT

- **Snap Circuits Jr.**: Ages 8 and up. Includes a motor and lamps for exploring how electricity is made and used, with battery power only. Fits Lesson 5.3.
- **Thames & Kosmos science kits**: Ages vary by kit. Several kits explore water, hydropower and renewable energy with small working models. Fits Lessons 5.1 and 5.3.

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

5.1	Clean Water: The Croton Aqueduct and the Sand Filter	2 sessions of 45 minutes
5.2	Sewers: Chicago Lifts Its Streets	2 sessions of 45 minutes
5.3	From the Power Plant to Your Outlet	2 sessions of 45 minutes
5.4	Alexander Graham Bell and the Telephone	2 sessions of 45 minutes

UNIT 5 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**
What force moved the water of the Croton Aqueduct 41 miles to New York City?
2. **5 pts**
Name three steps that clean drinking water at a treatment plant.
3. **5 pts**
Predict: you build a filter with gravel on top and fine sand on the bottom, and another with fine sand on top. Which will clog faster?
4. **5 pts**
Why must a sewer pipe slope downhill?

5. (5 pts)

Why did Chicago raise its streets and buildings in the 1850s and 1860s?

6. (5 pts)

How can 600 men with jackscrews lift a whole row of brick buildings?

7. (5 pts)

What does a generator do? Name two things that can spin a generator.

8. (5 pts)

Name two safety rules about power lines.

9. (5 pts)

What is sound?

10. (5 pts)

Why does a string telephone stop working if you pinch the string?

ANSWER KEY

1. Gravity. The tunnel sloped gently downhill the whole way.
2. Any three: clumping the dirt, settling, filtering through sand and gravel, disinfecting with chlorine, testing.
3. The one with fine sand on top, because the big dirt fills the tiny spaces right away. Gravel on top catches big pieces first.
4. Wastewater moves by gravity. Without a steady slope, it stops and the waste settles and clogs the pipe.
5. The city was too flat and low to dig sewers deep enough, so the pipes were laid on the old streets and covered, and the streets and buildings were raised.
6. A jackscrew is a screw (an inclined plane wrapped around a pole). Each turn lifts a little with a small force, and many screws turned together share the load.
7. It turns spinning motion into electricity. Steam (from coal, gas or nuclear), falling water or wind can spin it.
8. Any two: never touch them; stay far away from fallen lines; never fly kites or drones near them; stay out of substations; call 811 before digging.
9. Vibration that travels through air, water or solid things to our ears.
10. Pinching stops the string from vibrating, so the vibrations cannot travel to the other cup.

PORTFOLIO PIECE: A TESTED WATER FILTER AND REPORT

Design the best water filter you can from household materials (sand, gravel, cotton, coffee filters, cloth). Test at least two designs with the same muddy water, measuring the drip time and the clarity with your clarity card. Choose the best design and write a short report for a pretend town council: what you built, what you measured, which design won and why. Remember to warn the council that real drinking water must also be disinfected and tested.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the layers and the reason for their order.
Fair test	At least two designs were tested with the same amount of the same muddy water.
Data	Drip time and clarity are recorded in a table for each design.
Report	The report explains which design won and why, and includes the safety warning about disinfecting and never drinking filter water.

UNIT 6

BOATS AND SHIPS

How can a ship made of iron, heavier than a whole town of houses, float on top of the water? In this unit you will learn about density and buoyancy and see how Isambard Kingdom Brunel built one of the first great iron ships. You will learn how sails turn wind into motion, with the clipper ship *Flying Cloud*, and how paddle wheels and propellers push a boat forward, with a famous tug-of-war between two ships.

Finally, you will meet John Smeaton, who built a lighthouse on a rock in the sea that waves had swept clean twice before, and learn how lighthouse lenses send their beams far across the water. “They that go down to the sea in ships” (Psalm 107:23) have always depended on good engineering to bring them safely home.

PREREQUISITES

- Knows Newton’s first law and how to run a fair test (Unit 1)
- Can count pennies and use a kitchen scale
- Knows that light travels from a source to our eyes

MASTERY CHECKLIST

- ☐ I can explain why some things float and others sink, using the words density and buoyancy.
- ☐ I can explain why a heavy iron ship floats.
- ☐ I can explain how a sail and a keel work together to move a boat.
- ☐ I can explain how a paddle wheel or propeller pushes a boat forward (Newton’s third law).
- ☐ I can explain how a lighthouse reflector or lens makes a strong beam, and test it fairly.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Tinker Crate**: Ages 9 and up, with a parent. Some crates build water-powered or floating machines; check the crate list. A fun extra for Lessons 6.1–6.3.

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

6.1 Density and Buoyancy: Brunel's Iron Ship

2 sessions of 45 minutes

6.2 Sails and the Clipper Ship *Flying Cloud*

2 sessions of 45 minutes

6.3 Paddle Wheels, Propellers and Newton's Third Law

2 sessions of 45 minutes

6.4 John Smeaton's Lighthouse and the Light That Guides Ships

2 sessions of 45 minutes

UNIT 6 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What is density? Why does a ball of clay sink?

2. **5 pts**

Why does a huge iron ship like the *Great Britain* float?

3. **5 pts**

Predict: you load more pennies into a floating foil boat. What happens to how deep it sits in the water?

4. **5 pts**

What does the keel of a sailboat do?

5. **5 pts**

Can a sailboat sail straight into the wind? How do sailors get where the wind is coming from?

6. **5 pts**

State Newton's third law and use it to explain how a paddle wheel moves a boat.

7. **5 pts**

What happened in the tug-of-war between the *Rattler* and the *Alecto*?

8. 5 pts

How did John Smeaton make his lighthouse strong against the waves?

9. 5 pts

How does a reflector make a flashlight's beam brighter?

10. 5 pts

Why does each lighthouse have its own pattern of flashes?

ANSWER KEY

1. Density is how heavy something is for its size. The clay ball is denser than water, so it sinks.
2. Its big hollow hull pushes aside (displaces) so much water that the water's upward push (buoyancy) equals the ship's weight. Iron and air together are less dense than water.
3. It sinks lower, pushing aside more water, until the water comes over the sides.
4. It keeps the boat from sliding sideways and helps keep it upright, so the wind on the sail moves it forward.
5. No. They zigzag (tack) back and forth across the wind.
6. For every action there is an equal and opposite reaction. The paddle pushes the water backward, so the water pushes the boat forward.
7. The *Rattler*, with a propeller, pulled the paddle-wheel ship *Alecto* backward, showing that the propeller worked better.
8. He made it wide at the bottom like an oak tree, dovetailed the stones together so they locked like puzzle pieces, and used a mortar that hardened underwater.
9. It bounces light that would go sideways or backward forward in one direction.
10. So sailors can tell which lighthouse they are seeing and know where they are.

PORTFOLIO PIECE: A CARGO BOAT WITH A MEASURED CAPACITY

Design and build a boat from one 30-by-30-centimeter sheet of foil (or a mix of foil, straws and tape) that carries as many pennies as possible. Before you load it, mark the waterline. Load it one penny at a time and record the count every 10 pennies, with a sketch of how low it sits. Then add a sail or a rubber-band paddle and test whether your loaded boat can travel across the tub. Present your capacity and your best design.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the hull shape and explains why it should carry many pennies.
Capacity test	Pennies were added one at a time and the final count was recorded honestly.
Waterline record	Sketches or marks show the boat sinking lower as the load grew.
Moving boat	A sail or paddle was added and the boat's trip was tested and recorded.
Explanation	The student uses the words density, buoyancy or displace to explain why the boat floats.

6.1 DENSITY AND BUOYANCY: BRUNEL'S IRON SHIP

OBJECTIVES

- Explain density by comparing objects that sink and float.
- Explain buoyancy: water pushes up on a boat as hard as the weight of the water it pushes aside.
- Shape clay and foil into boats and test how many pennies each can carry.

Warm-up. Fill a tub or sink with water. Before you drop each object in, predict whether it will sink or float: a coin, a cork, an apple, a spoon, a crayon, a ball of foil and a flat sheet of foil. Record your guesses and the results.

WATCH

Why Do Ships Float?

SciShow Kids · 3:52

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

WHEN TO WATCH

After the warm-up.

BACKUP VIDEO

Why do big ships float? [Buoyancy and flotation explained]

Casual Navigation · 4:20

<https://www.youtube.com/watch?v=Z3vgsp4vKQs>

After the physics paragraph, for a closer look at displacement with a parent.

KEY TERMS

float

To stay on top of the water.

density

How much stuff is packed into a space. A rock is denser than a cork of the same size.

buoyancy

The upward push of water on an object in it.

displace

To push something aside. A boat displaces water when it floats.

hull

The body of a ship, the part that sits in the water.

CORE IDEAS

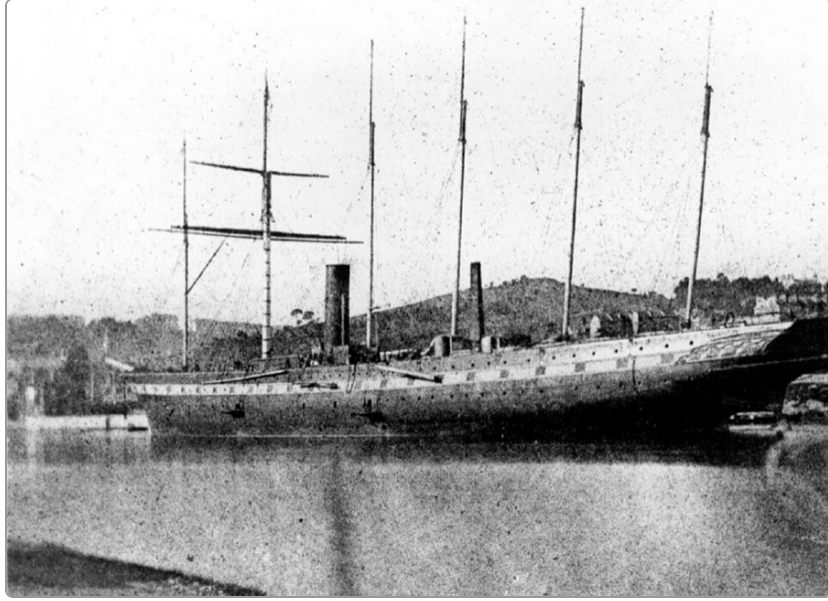
The story. For thousands of years, ships were made of wood. Many people thought a ship of iron would sink like a stone. But in Bristol, England, the engineer Isambard Kingdom Brunel built a huge ship with an iron hull and a screw propeller. When the *Great Britain* was launched in 1843, it was the largest ship in the world, more than 300 feet long. In 1845, it became the first iron, propeller-driven ship to cross the Atlantic Ocean. You can still visit it in Bristol today.

How they figured it out. Brunel knew the answer was not in the iron but in the shape. Long before, Archimedes had learned that anything put in water is pushed up by a force equal to the weight of the water it pushes aside. A solid lump of iron pushes aside only a little water, so it sinks. But a wide, hollow hull full of air pushes aside a great deal of water before it is in very deep. Iron was also stronger than wood for its weight, so the hull could be bigger and lighter for its size than any wooden ship.

The physics. **Density** is how heavy something is for its size. Things denser than water sink; things less dense than water float. A boat floats because the whole boat, iron and air together, is less dense than water. When the boat sits in water, it pushes some water aside, or **displaces** it. The water pushes back up with a force called **buoyancy**. The boat sinks lower and lower until the water it displaces weighs as much as the boat. Then it floats. Load it with cargo, and it sinks lower to push aside more water.

The engineering. Ship designers calculate how heavy a ship will be with all its cargo, and how deep it will sit in the water. They paint marks on the side of the hull so the crew can see if it is loaded too heavily. They divide the hull into watertight sections, so that if one section leaks, the others keep the ship afloat. Today almost every big ship is made of steel, from cargo ships carrying thousands of containers to ferries and cruise ships.

PICTURE STUDY



The Great Britain in Bristol Harbor, William Henry Fox Talbot, 1844 · Salted paper print from a paper negative · Talbot's photographs are held by several museums, including the National Science and Media Museum, England

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

William Henry Fox Talbot was one of the inventors of photography. In 1844 he took this picture of Brunel's new ship in Bristol. It is one of the very first photographs of a ship ever made.

Look closely

- Find the masts and the ropes of the rigging. The ship could use sails as well as its engine.
- Find the funnels, where smoke from the steam engine came out.
- Find the long, dark hull. What is it made of?
- Find the edge of the water along the hull. How deep do you think the ship sits?

Talk about it

1. Why did many people think an iron ship would sink?
2. What would happen to the waterline if the ship were loaded with heavy cargo?
3. Why do you think this early photograph looks so faded and soft?

Safety first. An adult stays close whenever water is in a tub or sink. Wipe up spills so no one slips.

BUILD

From Sinker to Floater: The Clay and Foil Boat Test

You will drop a ball of clay in water and watch it sink. Then you will shape the same clay into a boat and see how many pennies it can carry. Finally, you will test foil boats of different shapes made from the same size sheet.

You will need

- A tub or sink of water
- A lump of modeling clay about the size of a golf ball
- Several sheets of aluminum foil, all cut to the same size (15 by 15 centimeters)
- About 200 pennies
- A ruler and the engineer's notebook

Steps

1. Roll the clay into a ball and drop it in the water. It sinks. Write down why you think it sank.
2. Dry the clay and shape it into a boat with thin walls and a flat bottom. Float it. **Predict:** how many pennies will it hold?
3. Add pennies one at a time, spread out evenly, until water comes over the edge. Record the number.
4. **Fair test.** Make three foil boats from the same size foil: a flat raft with low edges, a tall narrow boat and a wide boat with medium sides. Load each one the same way, one penny at a time. Do two trials each with fresh foil.
5. Record your results in a table: shape, pennies held, trial 1 and trial 2.
6. **Improve it.** Use what you learned to make a new foil boat that holds even more. Before you load it, mark the waterline with a marker. Then watch it sink lower as you add pennies.

Tips

- Spread the pennies out evenly; piling them on one side tips the boat.
- Do not crumple the foil; wrinkles can leak.

- Wide boats usually hold more, because they push aside more water before the edges go under.

Check your work

- ☐ I can explain why a ball of clay sinks and a clay boat floats.
- ☐ I tested three foil boats fairly and found the best shape.
- ☐ I can explain why Brunel's iron ship floated.

ENGINEER'S NOTEBOOK

1. Draw your best boat floating, with arrows for its weight pushing down and buoyancy pushing up.
2. Make a bar graph of pennies held by each boat shape.
3. List five things that float and five that sink from the warm-up. Write one sentence about what each group has in common.

From history. After years of service, the *Great Britain* was left in the Falkland Islands near the bottom of South America. In 1970, it was floated on a raft, towed all the way back to Bristol, and returned to the very dock where it was built. Today it is a museum ship.

COMMON MISTAKES

- Thinking heavy things always sink. Shape matters: a heavy ship with a big hollow hull floats.
- Thinking air “holds up” the boat. The water pushes up on the hull; the air just makes the whole boat less dense.
- Testing boats made from different sizes of foil and calling it fair.

Make it a game • Density Sort and Predict. Gather eight small things and write down sink or float for each before testing them in water. Check your guesses. Give yourself a point per match. Then sink a clay ball and make a clay boat float. Say density, buoyancy and displace. Explain why a heavy iron ship floats, like Brunel's.

6.2 SAILS AND THE CLIPPER SHIP *FLYING CLOUD*

OBJECTIVES

- Explain how a sail catches the wind and how a curved sail can work like a wing.
- Explain what the keel and the rudder do.
- Build a sailboat and test how sail size and shape change its speed.

Warm-up. Hold a sheet of paper by two corners in front of a fan, flat and then curved. Can you feel the push? Then hold it at an angle. Which way does it want to move?

WATCH

How Sails Work or How Sailboats Sail into the Wind

Stick Science • 2:59

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

WHEN TO WATCH

After the physics paragraph.

KEY TERMS

sail

A large sheet of cloth that catches the wind to move a boat.

mast

The tall pole that holds up a ship's sails.

keel

The long fin along the bottom of a boat that keeps it from sliding sideways and helps keep it upright.

rudder

A flat board at the back of a boat that turns to steer it.

clipper

A fast sailing ship of the 1800s with a sharp, narrow hull and many sails.

CORE IDEAS

The story. In 1849, gold was found in California, and thousands of people wanted to get there fast. There was no railroad across America yet, so ships sailed from New York all the way around the tip of South America to San Francisco, a voyage of about 16,000 miles. In 1851, the clipper ship *Flying Cloud*, built by Donald McKay in Boston,

made the trip in 89 days and 21 hours, faster than any ship before. Her navigator was Eleanor Creesy, the captain's wife, who had learned to navigate by the sun and stars and plotted a daring course on the ocean winds.

How they figured it out. Shipbuilders learned that a long, narrow hull with a sharp bow slices through the water with less drag than a wide, round one. Clippers carried towering masts with many sails, so they could catch more wind. Navigators like Eleanor Creesy studied new charts made by Matthew Fontaine Maury, a naval officer who collected the logbooks of many captains and mapped where the winds and currents usually blew. With the right route, a clipper could ride the strongest winds.

The physics. When the wind blows from behind, it simply pushes on the sails. But a sail can do more. When it is set at an angle and curved like a wing, the wind flowing around it is turned aside, and the sail is pushed sideways and forward. The **keel** under the boat resists the sideways slide, so the boat moves forward instead. That is how a sailboat can sail across the wind and even zigzag toward it. No sailboat can sail straight into the wind; it must zigzag, which sailors call tacking. The **rudder** at the back steers.

The engineering. A ship designer balances speed against how much cargo a ship can carry. Clippers were fast but carried less than wider ships, so when steamships and railroads came, the clippers disappeared. But sail engineering never stopped. Today's racing sailboats have sails shaped by computers and tested in wind tunnels, and some new cargo ships are adding tall, stiff sails to help their engines and save fuel.

PICTURE STUDY



Clipper Ship Southern Cross Leaving Boston Harbor, Fitz Henry Lane, 1851 · Oil on canvas · Peabody Essex Museum, Salem, Massachusetts
Image: [Wikimedia Commons](#), public domain

Fitz Henry Lane painted the ships of New England with great care, rope by rope. This clipper sailed from Boston in the same year that the *Flying Cloud* set her record.

Look closely

- Count the masts. How many sails can you count on one mast?
- Look at the flags. Which way is the wind blowing?
- Find the bow (the front). Is it sharp or round?
- Look at the smaller ships behind. How are their sails set?

Talk about it

1. Why would a clipper carry so many sails?
2. Is the wind blowing from behind the ship or from the side? How can you tell?
3. What part of the ship, under the water, keeps it from sliding sideways?

Safety first. Keep the fan on low and away from the water. Never plug a fan in near a tub; set it on the floor or a table at a safe distance and have an adult handle it.

BUILD

Sail Power: A Fan-Driven Boat Test

You will build small sailboats from foam trays or plastic bottles, with masts and paper sails, and test how sail size, shape and angle change how fast they cross a tub.

You will need

- A foam tray, a plastic bottle cut in half the long way by an adult, or a small block of wood for a hull
- A straw or skewer for a mast, and modeling clay to hold it
- Paper or card stock for sails, scissors and tape
- A craft stick or a piece of plastic for a keel
- A long tub or bathtub with water, a box fan and a stopwatch
- Engineer's notebook

Steps

1. Stand the mast in a lump of clay in the middle of the hull. Tape a square paper sail, 10 by 10 centimeters, to the mast.
2. Put the boat at one end of the tub and the fan at the same end, about 1 meter away, on low. Time how long the boat takes to reach the far end.
3. **Predict:** will a bigger sail make the boat faster?
4. **Fair test.** Try sails 5, 10 and 15 centimeters square on the same hull with the fan in the same place. Time three trips each.
5. Record your times in a table and find the middle time for each sail.
6. **Keel test.** Set the fan to blow from the side. Try the boat with and without a craft-stick keel taped under the hull. Which one slides sideways less?
7. **Improve it.** Try a triangle sail, a curved sail or two sails. Can you beat your fastest time?

Tips

- Start the boat in the same spot every time, and let go without pushing.

- If the boat tips over, use a lower sail or add a little clay to the bottom of the hull.
- Watch the boat's path: does it go straight or turn? A small rudder may help.

Check your work

- ☐ I tested three sail sizes fairly and recorded the times.
- ☐ I showed that a keel helps a boat resist the wind from the side.
- ☐ I can explain how the

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ENGINEER'S NOTEBOOK

1. Draw a sailboat from above with the wind coming from the side. Show the sail, the keel and an arrow for the way the boat moves.
2. Make a table of sail size and time, and a bar graph.
3. Draw the route from New York around South America to San Francisco on a simple map.

From history. The *Flying Cloud* later sailed the route even a little faster, and her record stood until 1989, when a modern racing sailboat finally beat it. Eleanor Creesy learned navigation from her father, a ship's captain, and became one of the most famous navigators of her time.

COMMON MISTAKES

- Thinking a sailboat can only go where the wind blows. With a keel and a well-set sail, it can sail across the wind and zigzag toward it.
- Changing the sail and the fan distance at the same time.
- Thinking a bigger sail is always better. A sail that is too big can tip the boat over.

Make it a game • Sail Power Boat Race. Race a foil boat across a tub, one with a paper sail and a straw mast and one without, and use a fan or a breath for wind. Time each run, and note which wins. Say sail, mast, keel and rudder. Then explain how a curved sail works like a wing. Tell about Flying Cloud.

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 helm is the ship’s steering gear, and the governor is the person steering. A small rudder can turn a great ship, just as James says our small words can steer our whole lives.

6.3 PADDLE WHEELS, PROPELLERS AND NEWTON'S THIRD LAW

OBJECTIVES

- State Newton's third law and use it to explain how boats move.
- Compare paddle wheels and propellers.
- Build a rubber-band paddle boat and test how the number of winds changes how far it goes.

Warm-up. Sit on a rolling chair or stand on a skateboard on carpet (with a parent holding it steady) and push gently against a wall. Which way do you move? Then, in the tub, push water backward with your hand. Which way does your hand feel pushed?

WATCH

DIY Rubber Band Paddle Boat | STEM Activity

Science Buddies • 2:08

<https://www.youtube.com/watch?v=POt4gDIKTkc>

WHEN TO WATCH

Before the build.

Note: The video uses balsa wood and a craft knife; an adult should do any cutting, or use a foam tray instead.

BACKUP VIDEO

How Do Propellers Work? (Mr. Wizard)

Official Mr.Wizard's World Channel • 3:37

https://www.youtube.com/watch?v=CKDb1c-i_yc

After the physics paragraph. “Mr. Wizard” is the name of an old science television show; there is nothing magical in it, just a scientist and a student testing propellers.

KEY TERMS

Newton's third law

For every action, there is an equal and opposite reaction. If you push on something, it pushes back on you.

paddle wheel

A large wheel with flat boards around it that turns and pushes water backward to move a boat.

propeller

A spinning set of twisted blades that pushes water (or air) backward.

thrust

The force that pushes a boat or plane forward.

steamboat

A boat moved by a steam engine.

CORE IDEAS

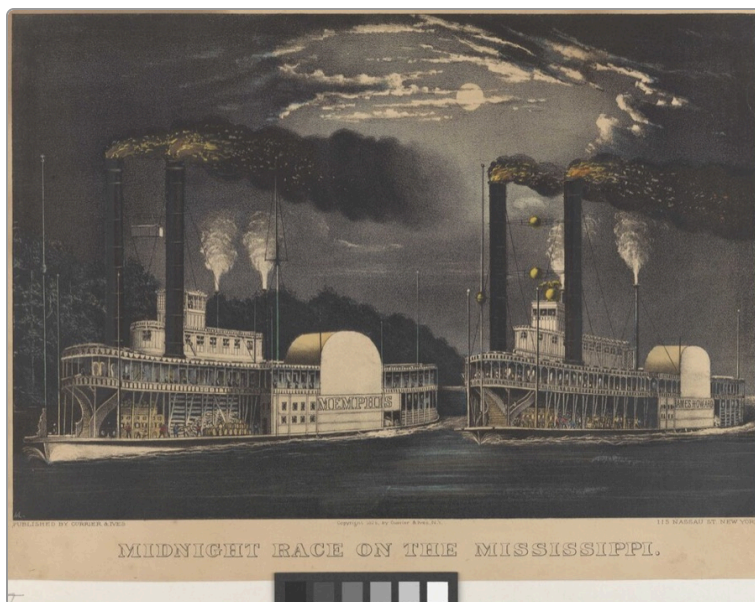
The story. By the 1840s, steamboats with big paddle wheels splashed up and down the rivers of America, racing each other on the Mississippi. But inventors like Francis Pettit Smith in England and John Ericsson, a Swedish engineer, were trying something new: a **propeller** under the water at the back of the ship. Which was better? In 1845, the British navy held a test. Two ships of the same size with engines of the same power, the *Rattler* with a propeller and the *Alecto* with paddle wheels, were tied stern to stern and set to pull against each other in a tug-of-war.

How they figured it out. The *Rattler* won, towing the *Alecto* backward. But the propeller had been improved by accident first. In 1837, Francis Smith was testing a long wooden screw shaped like an Archimedes screw on a small boat, when half of it broke off. The boat went faster! Smith realized that a shorter screw with fewer turns worked better. Engineers kept testing different shapes, and the propeller became the short, twisted blades we know today. A propeller also stays underwater, safe from waves that could lift a paddle wheel out of the water.

The physics. Newton's **third law** says that for every action there is an equal and opposite reaction. A paddle wheel pushes water backward, and the water pushes the boat forward. A propeller's twisted blades push water backward too, as they spin. That forward push is called **thrust**. When you swim, you do the same thing: push water back, and you move forward. The harder and faster the water is pushed back, the stronger the thrust.

The engineering. Almost every big ship today uses propellers, turned by diesel engines, steam turbines or electric motors. Engineers choose the size of the propeller, the number of blades and how much they twist, to push the most water with the least wasted energy. Paddle wheels are still used on some river boats, where the water is shallow and the boats are slow, and many people enjoy riding them.

PICTURE STUDY



A Midnight Race on the Mississippi, Currier & Ives, after Frances Flora Bond Palmer, 1860 · Hand-colored lithograph · Royal Museums Greenwich, London (copies in many collections)

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

Steamboat races on the Mississippi River were famous, and printmakers loved to show them. Here two paddle steamers speed side by side at night, their smokestacks glowing.

Look closely

- Find the big round boxes on the sides of the boats. The paddle wheels are inside them.
- Find the tall smokestacks. What do they tell you about the engines?
- Look at the water near the boats. Can you see where the paddles are churning it?
- Find the moon and the lights on the boats.

Talk about it

1. Which way do the paddle wheels push the water to move the boats forward?
2. Why might a paddle wheel be a good choice for a wide, shallow river?
3. What problems might a paddle wheel have on a stormy ocean?

Safety first. An adult does any cutting. Wind the rubber band carefully; it can snap. An adult stays near the water.

BUILD

The Rubber-Band Paddle Boat Test

You will build a boat with a rubber-band-powered paddle and test how the number of times you wind the band changes how far the boat travels. Then you will compare different paddle sizes.

You will need

- A foam tray, a juice carton or a small plastic bottle for the hull
- Two craft sticks or skewers for the paddle arms
- A rubber band and a small rectangle of plastic (from a lid) or foam for the paddle
- Waterproof tape or hot glue (adult)
- A tub or bathtub of water, a tape measure and the engineer's notebook

Steps

1. Tape the two craft sticks to the back of the hull so they stick out behind it, parallel, about 6 centimeters apart.
2. Stretch the rubber band across the ends of the sticks. Slip the paddle through the middle of the rubber band.
3. Wind the paddle 10 times. Hold it, set the boat in the water and let go. Which way does it go? If it goes backward, wind the other way.
4. **Predict:** how far will it go with 10, 20 and 30 winds?
5. **Fair test.** Measure how far the boat travels with 10, 20 and 30 winds. Start from the same place each time. Do three trials each.
6. Record the distances in a table.
7. **Improve it.** Make a bigger paddle and a smaller paddle. Test them with 20 winds. Which goes farther? Which goes faster? Explain why using Newton's third law.

Tips

- Count the winds out loud so you do not lose track.
- If the paddle hits the hull, make the sticks a little longer.

- Measure from the starting line to where the boat stops.

Check your work

- ☐ I can explain how the paddle pushes the water back and the water pushes the boat forward.
- ☐ I tested 10, 20 and 30 winds fairly and recorded the distances.
- ☐ I can tell the story of the

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ENGINEER'S NOTEBOOK

1. Draw your paddle boat with two arrows: one for the paddle pushing the water back, and one for the water pushing the boat forward.
2. Make a line graph: number of winds and distance traveled.
3. Draw the *Rattler* and the *Alecto* in their tug-of-war. Which way is each one trying to go?

From history. The *Rattler*'s victory convinced navies and shipbuilders around the world to use propellers. In 1843, John Ericsson's propeller ship *Princeton* joined the United States Navy, and Brunel's *Great Britain* from Lesson 6.1 was changed from paddle wheels to a propeller while it was being built.

COMMON MISTAKES

- Thinking the paddle pushes the boat directly. It pushes the water; the water pushes the boat.
- Winding the band so tightly it breaks. Find the most it can take safely.
- Starting from different places for each trial.

Make it a game • Push Back Newton Three. Sit on a rolling chair or skateboard with a parent nearby, and push a wall gently to roll backward. Say Newton's third law out loud. Then launch your rubber-band paddle boat and measure how far it goes. Explain how paddle wheels and propellers both push water backward. Compare which pushes better.

6.4 JOHN SMEATON'S LIGHTHOUSE AND THE LIGHT THAT GUIDES SHIPS

OBJECTIVES

- Tell how John Smeaton built a lighthouse that stood against the sea.
- Explain how a reflector or a lens gathers light into a strong beam.
- Test reflectors of different shapes on a flashlight and measure the beam.

Warm-up. In a dark room, shine a flashlight at a wall from 2 meters away. Then hold your hand around the bulb so no light comes out the sides. Then point it at the ceiling. Notice: light goes in straight lines and spreads out. How could you make all of it go one way?

WATCH

How Do Lighthouses Work?

Ticket To Know • 10:50

<https://www.youtube.com/watch?v=072wpvM7aS8>

WHEN TO WATCH

After the story. Watch the part about the Fresnel lens closely.

BACKUP VIDEO

How A Lighthouse Works | The Secret Life of Lighthouses | Channel 5

Channel 5 • 7:32

https://www.youtube.com/watch?v=0eU3Xeo_2c4

After the engineering paragraph, to see real lighthouse lenses and how they turn.

KEY TERMS

lighthouse

A tower with a bright light that warns ships of rocks and guides them to safe harbor.

reflector

A shiny, curved surface that bounces light in one direction.

lens

A curved piece of glass that bends light.

Fresnel lens

A lighthouse lens made of many rings of glass that bend light into a strong beam. (Say “fray-NEL.”)

dovetail

A joint shaped like a bird’s tail that locks two pieces together.

mortar

A paste that hardens to hold stones or bricks together.

CORE IDEAS

The story. About twelve miles out to sea from Plymouth, England, lie the Eddystone Rocks, hidden under the waves at high tide. Many ships had been wrecked on them. Two lighthouses had already been built there, and both were lost: a great storm swept the first one away in 1703, and the second, made of wood, burned in 1755. A young engineer named John Smeaton was asked to try again. He decided to build it of stone so heavy and so well locked together that the sea could not move it. His lighthouse was lit on October 16, 1759.

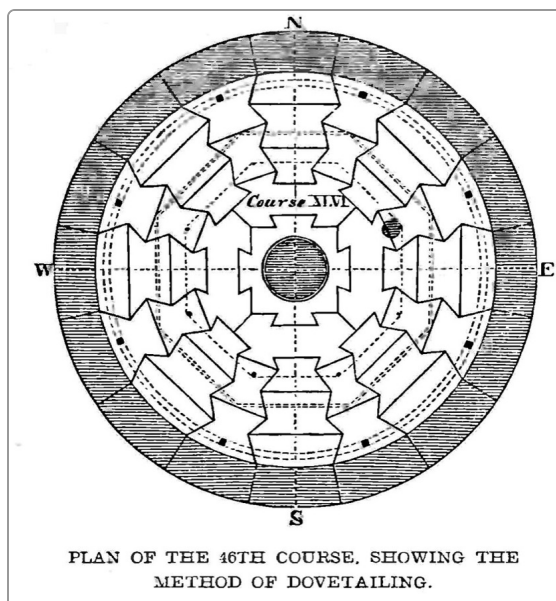
How they figured it out. Smeaton studied the trunk of an oak tree, which is wide at the bottom and curves up to a narrower top, and stands against storms. He shaped his tower the same way. He cut every stone so it fit its neighbors with **dovetail** joints, like the pieces of a puzzle, and locked each layer to the one below with stone pins, so that the whole tower acted like one solid rock. Ordinary mortar washed away in seawater, so Smeaton tested many kinds of lime and found one made with clay that hardened even underwater. His careful experiments helped lead to modern cement.

The physics. Light travels in straight lines and spreads out in every direction from a flame or a bulb. Most of it would be wasted going up, down or back toward land. A curved, shiny **reflector** behind the light bounces the light that hits it forward, making a brighter beam. A **lens** in front bends light into a beam too. In 1822, the French scientist Augustin Fresnel designed a lens made of many rings of glass, which was thinner and lighter than one big lens but gathered the light just as well. Lighthouses with Fresnel lenses could be seen more than 20 miles away.

The engineering. Each lighthouse has its own pattern of flashes, so sailors at night can tell which light they are looking at. Lighthouse keepers once lived in the towers to trim the wicks and wind the clockwork that turned the lenses. Today most

lighthouses are automatic, and ships also use radar and GPS. But lighthouses are still kept lit as a backup, because one wrong turn near rocks can sink a ship.

PICTURE STUDY



*Plan of the 46th Course, Showing the Method of Dovetailing, After John Smeaton, 1791 (lighthouse built 1756–1759) · Engraving · From Smeaton's book *A Narrative of the Building ... of the Edystone Lighthouse with Stone**

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

Smeaton wrote a whole book about how he built his lighthouse, with careful drawings. This one shows one layer of stones from above. Every stone locks into its neighbors.

Look closely

- Find the circle in the middle. Can you find how the center stone is locked in?
- Trace the outline of one stone with your finger. What shape is it?
- Find where two stones fit together like puzzle pieces. That is a dovetail joint.
- Find the letters N, S, E and W. Why might Smeaton mark the directions?

Talk about it

1. Why would dovetailed stones stand up to waves better than stones just stacked?
2. Why did Smeaton make the bottom of the tower wide, like an oak tree?
3. How is this like the arches and pyramids you studied earlier?

Safety first. Use a battery flashlight only. Do not shine flashlights into anyone's eyes.

BUILD

Make a Better Beam: The Reflector Test

You will make reflectors of different shapes from foil and card stock, put them around a small flashlight, and measure how bright and how narrow the beam is on a wall.

You will need

- A small flashlight or a battery-powered LED tea light
- Aluminum foil, card stock and tape
- A wall, a tape measure, and a book or newspaper with small print
- A dark room
- Engineer's notebook

Steps

1. **No reflector.** Take any reflector off the flashlight if you can, or use the tea light. Stand it 2 meters from the wall. Measure how wide the spot of light is.
2. **Reading test.** Hold the book in the light at the wall. Walk the light backward until you can no longer read the print by its light. Measure that distance.
3. **Predict:** which reflector shape will make the brightest, narrowest beam?
4. **Fair test.** Make three reflectors of the same size of foil-covered card: a flat sheet behind the light, a tube around it, and a cone (like a funnel) around it. Test each one the same way: spot width at 2 meters, and reading distance.
5. Record the results in a table.
6. **Improve it.** Try a curved, bowl-shaped reflector made from the inside of a foil-lined cup or a smooth ladle. Can you beat your best result?

Tips

- Keep the foil as smooth as you can; wrinkles scatter the light.
- Use the same flashlight and the same battery for every test.
- A narrow spot that is very bright can be seen from farther away.

Check your work

- ☐ I can explain how a reflector makes a beam.

- ☐ I tested three reflectors fairly and measured the spot and the reading distance.
- ☐ I can tell how Smeaton made his lighthouse strong.

ENGINEER'S NOTEBOOK

1. Draw a light with and without a reflector. Use arrows to show where the light goes.
2. Make a table: reflector shape, spot width, reading distance.
3. Design a flash pattern for your own lighthouse, such as two short flashes and one long, and draw a chart for sailors.

From history. Smeaton's tower stood for more than 120 years. In the 1870s, the sea wore away the rock under it, so a new lighthouse was built on a rock nearby. The top part of Smeaton's tower was taken apart, carried to Plymouth and rebuilt on a hill by the sea, where visitors can climb it today. Smeaton called himself a "civil engineer," and he is often remembered as the first to use that name.

COMMON MISTAKES

- Thinking a reflector makes more light. It does not make more; it sends the light that was already there in one direction.
- Changing the distance to the wall between tests.
- Thinking lighthouses are no longer needed. They are still important backups for ships.

Make it a game • Beacon Beam Aim. In a dim room, aim a flashlight through a paper cup lens or a cardboard reflector to hit a target on the wall. Count your hits out of ten. Say lighthouse, reflector and lens. Explain how a Fresnel lens gathers light into a beam. Tell the story of John Smeaton's lighthouse and the dovetail joints. Beat your score.

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

A lighthouse shines so that others can find their way safely. Jesus calls His people to shine like that, so others can see the way.

UNIT 6

BOATS AND SHIPS

How can a ship made of iron, heavier than a whole town of houses, float on top of the water? In this unit you will learn about density and buoyancy and see how Isambard Kingdom Brunel built one of the first great iron ships. You will learn how sails turn wind into motion, with the clipper ship *Flying Cloud*, and how paddle wheels and propellers push a boat forward, with a famous tug-of-war between two ships.

Finally, you will meet John Smeaton, who built a lighthouse on a rock in the sea that waves had swept clean twice before, and learn how lighthouse lenses send their beams far across the water. “They that go down to the sea in ships” (Psalm 107:23) have always depended on good engineering to bring them safely home.

PREREQUISITES

- Knows Newton’s first law and how to run a fair test (Unit 1)
- Can count pennies and use a kitchen scale
- Knows that light travels from a source to our eyes

MASTERY CHECKLIST

- ☐ I can explain why some things float and others sink, using the words density and buoyancy.
- ☐ I can explain why a heavy iron ship floats.
- ☐ I can explain how a sail and a keel work together to move a boat.
- ☐ I can explain how a paddle wheel or propeller pushes a boat forward (Newton’s third law).
- ☐ I can explain how a lighthouse reflector or lens makes a strong beam, and test it fairly.

OPTIONAL KITS FOR THIS UNIT

- **KiwiCo Tinker Crate**: Ages 9 and up, with a parent. Some crates build water-powered or floating machines; check the crate list. A fun extra for Lessons 6.1–6.3.

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

6.1 Density and Buoyancy: Brunel's Iron Ship

2 sessions of 45 minutes

6.2 Sails and the Clipper Ship *Flying Cloud*

2 sessions of 45 minutes

6.3 Paddle Wheels, Propellers and Newton's Third Law

2 sessions of 45 minutes

6.4 John Smeaton's Lighthouse and the Light That Guides Ships

2 sessions of 45 minutes

UNIT 6 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What is density? Why does a ball of clay sink?

2. **5 pts**

Why does a huge iron ship like the *Great Britain* float?

3. **5 pts**

Predict: you load more pennies into a floating foil boat. What happens to how deep it sits in the water?

4. **5 pts**

What does the keel of a sailboat do?

5. **5 pts**

Can a sailboat sail straight into the wind? How do sailors get where the wind is coming from?

6. **5 pts**

State Newton's third law and use it to explain how a paddle wheel moves a boat.

7. **5 pts**

What happened in the tug-of-war between the *Rattler* and the *Alecto*?

8. 5 pts

How did John Smeaton make his lighthouse strong against the waves?

9. 5 pts

How does a reflector make a flashlight's beam brighter?

10. 5 pts

Why does each lighthouse have its own pattern of flashes?

ANSWER KEY

1. Density is how heavy something is for its size. The clay ball is denser than water, so it sinks.
2. Its big hollow hull pushes aside (displaces) so much water that the water's upward push (buoyancy) equals the ship's weight. Iron and air together are less dense than water.
3. It sinks lower, pushing aside more water, until the water comes over the sides.
4. It keeps the boat from sliding sideways and helps keep it upright, so the wind on the sail moves it forward.
5. No. They zigzag (tack) back and forth across the wind.
6. For every action there is an equal and opposite reaction. The paddle pushes the water backward, so the water pushes the boat forward.
7. The *Rattler*, with a propeller, pulled the paddle-wheel ship *Alecto* backward, showing that the propeller worked better.
8. He made it wide at the bottom like an oak tree, dovetailed the stones together so they locked like puzzle pieces, and used a mortar that hardened underwater.
9. It bounces light that would go sideways or backward forward in one direction.
10. So sailors can tell which lighthouse they are seeing and know where they are.

PORTFOLIO PIECE: A CARGO BOAT WITH A MEASURED CAPACITY

Design and build a boat from one 30-by-30-centimeter sheet of foil (or a mix of foil, straws and tape) that carries as many pennies as possible. Before you load it, mark the waterline. Load it one penny at a time and record the count every 10 pennies, with a sketch of how low it sits. Then add a sail or a rubber-band paddle and test whether your loaded boat can travel across the tub. Present your capacity and your best design.

LOOK FOR	WHAT IT MEANS
Design	A labeled drawing shows the hull shape and explains why it should carry many pennies.
Capacity test	Pennies were added one at a time and the final count was recorded honestly.
Waterline record	Sketches or marks show the boat sinking lower as the load grew.
Moving boat	A sail or paddle was added and the boat's trip was tested and recorded.
Explanation	The student uses the words density, buoyancy or displace to explain why the boat floats.

UNIT 7

FLIGHT

For thousands of years, people watched birds and wished they could fly. “The way of an eagle in the air” was one of the wonders King Solomon could not understand (Proverbs 30:19). In this unit you will learn that air is real stuff that pushes hard, as Otto von Guericke showed with two copper bowls and sixteen horses, and you will launch a stomp rocket with a puff of squeezed air.

Then you will learn how a wing makes lift from George Cayley, the first person to draw an airplane the way we build them today, fly gliders that balance the way Otto Lilienthal’s did, and steer a paper plane with the Wright brothers’ great idea: twisting the wings. Every build is a flight test with a tape measure and a notebook.

PREREQUISITES

- Knows Newton’s first and third laws (Units 1 and 6)
- Can measure distances with a tape measure and record three trials
- Can fold paper neatly and evenly

MASTERY CHECKLIST

- ☐ I can explain that air presses on everything and show it with an experiment.
- ☐ I can explain how a stomp rocket uses air pressure.
- ☐ I can explain how a wing makes lift by turning air downward, and name the four forces of flight.
- ☐ I can explain why a glider needs the right balance, as Lilienthal learned.
- ☐ I can explain how the Wrights’ wing warping steered an airplane, and steer a paper plane with flaps.

OPTIONAL KITS FOR THIS UNIT

- **Stomp Rocket:** Ages vary by set (most are for ages 5 and up with an adult). A ready-made air-pressure launcher and foam rockets, for families who would rather not build one in Lesson 7.1. Always fly in an open field and never aim at people.
- **KiwiCo Tinker Crate:** Ages 9 and up, with a parent. Some crates build gliders, launchers or flying machines; check the crate list. Fits Lessons 7.1–7.4.

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 Air Pressure: The Magdeburg Hemispheres and a Stomp Rocket

2 sessions of 45 minutes

7.2 George Cayley and How a Wing Makes Lift

2 sessions of 45 minutes

7.3 Otto Lilienthal's Gliders and the Secret of Balance

2 sessions of 45 minutes

7.4 The Wright Brothers Twist Their Wings

2 sessions of 45 minutes

UNIT 7 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What held Guericke's two copper bowls together so tightly that horses could not pull them apart?

2. **5 pts**

How does stomping on a bottle launch a stomp rocket?

3. **5 pts**

Name the four forces of flight.

4. (5 pts)

How does a wing make lift?

5. (5 pts)

Predict: you tilt a wing's front edge up more and more. What happens to lift at first, and what happens if you tilt it too much?

6. (5 pts)

What was George Cayley's big idea about how to build a flying machine?

7. (5 pts)

What is the center of gravity? What happens to a glider if it is too far back?

8. (5 pts)

How did Otto Lilienthal steer his gliders?

9. (5 pts)

What gave Wilbur Wright the idea of wing warping?

10. (5 pts)

What happened on December 17, 1903?

ANSWER KEY

1. The air pressure outside pushing them together, because the air inside had been pumped out.
2. Stomping squeezes the air, raising its pressure, and the air rushes out through the tube and pushes the rocket off.
3. Lift, weight, thrust and drag.
4. The curved, tilted wing turns the air downward, and the air pushes the wing up (Newton's third law). The pressure on top of the wing is also lower than underneath.
5. At first lift increases. Too much tilt makes the air stop flowing smoothly and the wing stalls; lift drops.
6. Use a fixed wing for lift and a separate way to push it forward (thrust), with a tail for balance, instead of flapping wings.
7. The balance point. If it is too far back, the nose goes up, the glider slows down and stalls.
8. By shifting his body weight, swinging his legs and hips forward, back or to the side.
9. Twisting a long, empty cardboard box and seeing one end tilt up and the other tilt down.
10. Orville Wright made the first powered, controlled airplane flight at Kitty Hawk: 12 seconds and 120 feet. The brothers made four flights that day.

PORTFOLIO PIECE: A TESTED AND STEERABLE GLIDER

Design and build a paper glider that flies at least 5 meters and can be steered to land on a target. First, test the balance with a paper clip to find the best position. Then add flaps and test steering left and right. Record every flight in a table. In your final test, try to land three flights within 1 meter of a target placed off to one side. Explain which ideas came from Cayley, Lilienthal and the Wrights.

LOOK FOR	WHAT IT MEANS
Balance test	The clip was tested in at least three positions with three flights each, and the best was chosen.
Steering test	Flaps were bent in opposite directions and the results were measured and recorded.
Target flights	Three final flights were measured from the target and recorded honestly.
Explanation	The student connects the design to lift, balance and control, and names at least two of the three pioneers.

7.1 AIR PRESSURE: THE MAGDEBURG HEMISPHERES AND A STOMP ROCKET

OBJECTIVES

- Explain that air has weight and presses on everything.
- Tell how Otto von Guericke showed the power of air pressure.
- Build a stomp rocket and fairly test how launch angle changes how far it flies.

Warm-up. Fill a cup to the very top with water. Lay an index card flat on top, hold the card in place and turn the cup upside down over a sink. Slowly let go of the card. What holds the water in? Then push the open end of an empty plastic bottle under water. Why won't the water fill it?

WATCH

Pulling Apart The Magdeburg Hemispheres

The Action Lab · 4:33

<https://www.youtube.com/watch?v=x7Tbj2ee7t4>

WHEN TO WATCH

After the story.

Note: The video ends with a sponsor message; stop when the demonstration is over.

BACKUP VIDEO

DIY Space: Stomp Rockets - Make the Rocket (Part 1)

NASAJPL Edu · 5:36

<https://www.youtube.com/watch?v=5bO8dpPuG4E>

Before the build, to see how NASA educators make a paper rocket.

KEY TERMS

air pressure

The push of the air on everything it touches.

hemisphere

Half of a ball.

vacuum

A space with almost no air in it.

compress

To squeeze into a smaller space.

launch angle

The tilt of a launcher, measured from the ground.

CORE IDEAS

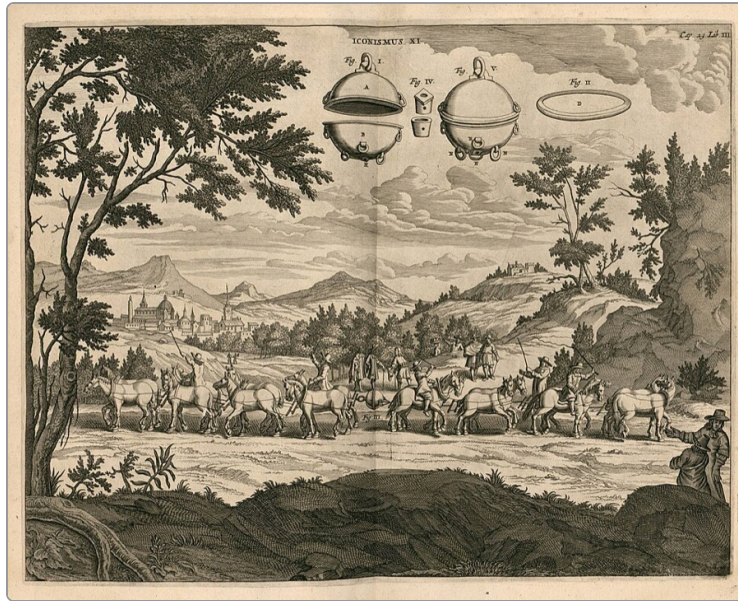
The story. Otto von Guericke was the mayor of the German city of Magdeburg in the 1600s, and he loved to experiment. He invented a pump that could suck the air out of a container. Then he had two copper bowls made that fit together to form a hollow ball about as wide as a car tire. He put them together and pumped out the air from inside. Then, in a famous show, he hitched teams of horses to each bowl, eight on each side, and drove them apart. The horses strained and pulled, but they could not separate the bowls. When Guericke opened a small valve to let the air back in, the bowls fell apart by themselves.

How they figured it out. Many people in Guericke's time believed that a truly empty space, a **vacuum**, could not exist, or that “nature hates a vacuum” and somehow sucks things into it. Guericke tested this. He showed that the bowls were not held together by anything inside them; there was almost nothing inside. They were pushed together from the outside by the air all around. He wrote about his experiments in a book in 1672, with a picture of the horses.

The physics. We live at the bottom of an ocean of air many miles deep. All that air has weight, and it presses on everything, in every direction, with a force called **air pressure**. At sea level, it pushes on every square inch with about as much force as a bowling ball weighs. We do not feel it because air is pushing equally on every side of us, and inside us too. But take the air out of one side, as Guericke did, and the push on the other side is huge. Squeeze air into a smaller space, and its pressure rises; that is how a stomp rocket works.

The engineering. Engineers use air pressure everywhere. Tires are filled with compressed air to hold up a car. Air brakes stop trucks and trains. Vacuum cleaners lower the pressure inside so the outside air rushes in, carrying dirt. Airplanes are pressurized so passengers can breathe high in the sky. When you stomp on a bottle, the squeezed air rushes out the only way it can, through the tube, and pushes the rocket up and away.

PICTURE STUDY



Guericke's Magdeburg Hemispheres, Engraving from Otto von Guericke's book, 1672 · Engraving · From Guericke's *Experimenta Nova (ut vocantur) Magdeburgica*
Image: [Wikimedia Commons](#), public domain

This picture from Guericke's own book shows the famous experiment. Two teams of horses pull against each other on a copper ball made of two halves, with the air pumped out.

Look closely

- Count the horses on each side.
- Find the ball between them. Can you see where the two halves meet?
- Find the men driving the horses. Are the horses pulling hard?
- Look for people watching. How do you think they felt?

Talk about it

1. What is really holding the two halves of the ball together?
2. Why did the bowls fall apart when Guericke let the air back in?
3. Could one team of horses tied to a tree have done the same job as two teams?
(Hint: a tree pulls back as hard as a team of horses.)

Safety first. Everyone wears safety glasses. Launch only outdoors in an open area, far from power lines, with no one in front of the launcher. Never aim a rocket at a person, an animal or a window. Use paper rockets only, never anything hard or pointed.

BUILD

Build a Stomp Rocket and Test the Launch Angle

You will make a launcher from a 2-liter bottle and a tube, roll paper rockets, and launch them with a stomp. Then you will run a fair test to find which launch angle sends a rocket the farthest.

You will need

- An empty 2-liter plastic bottle with its cap off
- About 60 centimeters of $\frac{1}{2}$ -inch PVC pipe or stiff vinyl tubing that fits snugly into the bottle neck
- Duct tape
- Paper, clear tape and a pencil or a piece of the same pipe to roll the rockets around
- A tape measure, a protractor (or a phone level app) and a few books to prop the tube
- Safety glasses and the engineer's notebook

Steps

1. Push the end of the pipe into the bottle neck and seal it tightly with duct tape. No air should leak out.
2. Roll a strip of paper around a spare piece of pipe (or a fat marker) to make a tube about 20 centimeters long, and tape it. Fold and tape the top end shut, or tape on a paper cone. Add three paper fins at the bottom. Slide it off.
3. Outside, lay the bottle on the ground and prop the pipe up on books. Slide the rocket onto the pipe. Make sure everyone is behind the launcher.
4. Stomp hard on the bottle. Measure how far the rocket flew, from the launcher to where it landed. Blow into the pipe to puff the bottle back up between launches.
5. **Predict:** which angle will fly farthest: 30, 45 or 60 degrees?
6. **Fair test.** Launch the same rocket three times at each angle, with the same person stomping as evenly as possible. Record the distances.

7. **Improve it.** Change only one thing about the rocket, such as fewer fins, a heavier nose (a bit of clay) or a longer body. Test it at your best angle and compare.

Tips

- If the rocket fits too loosely, air escapes around it. Make it snug but able to slide.
- Stomping evenly is hard. That is why you do three trials and look at the middle result.
- Write the angle on a piece of tape on the pipe so you can set it the same way each time.

Check your work

- ☐ I can explain how squeezed air launches the rocket.
- ☐ I tested three angles fairly, with three trials each.
- ☐ I can tell how Guericke showed that air pushes hard.

ENGINEER'S NOTEBOOK

1. Draw the Magdeburg hemispheres with arrows showing the air pushing in from all sides.
2. Make a table of launch angle and distance, and circle the best angle.
3. Draw your stomp rocket and label the nose, body and fins.

From history. Guericke's air pump helped other scientists study air. In England, Robert Boyle, a believing Christian and one of the founders of modern chemistry, built a better pump and discovered that when you squeeze air into half the space, its pressure doubles. We still call this Boyle's law.

COMMON MISTAKES

- Thinking the empty space inside the bowls "sucks" them together. The air outside pushes them together.
- Thinking air weighs nothing. Air has weight; there is just a lot of space between its tiny particles.
- Launching at different angles and changing the rocket at the same time.

Make it a game · Stomp Rocket Launch Angle. Launch your stomp rocket at three angles, and estimate the distance in steps before each. Then measure with footsteps. Closest estimate scores a point. Say air pressure, compress and launch angle. Explain how air pressure pushes the rocket. Tell your parent how Otto von Guericke's hemispheres showed that air presses on everything.

7.2 GEORGE CAYLEY AND HOW A WING MAKES LIFT

OBJECTIVES

- Name the four forces of flight: lift, weight, thrust and drag.
- Explain how a wing makes lift by turning air downward.
- Test paper wings in front of a fan and find how their curve and tilt change the lift.

Warm-up. With a parent driving slowly on a quiet road, or with a fan, hold your flat hand out in the moving air. Tilt the front edge of your hand up a little. What does your hand want to do? Tilt it down. What happens now?

WATCH

How Wings Work and Create Lift - Newton's 3rd Law of Motion

Stick Science · 2:42

<https://www.youtube.com/watch?v=6RoBo3fue4Q>

WHEN TO WATCH

After the physics paragraph. Watch where the air goes after it passes the wing.

KEY TERMS

lift

The upward force on a wing that holds a plane or a bird up in the air.

weight

The downward pull of gravity on an aircraft.

thrust

The forward push from a propeller, a jet engine or a flapping wing.

drag

The backward push of the air that slows a moving object.

airfoil

The curved shape of a wing, seen from the side.

angle of attack

How much the front edge of a wing is tilted up into the oncoming air.

CORE IDEAS

The story. In 1799, an English country gentleman named George Cayley scratched a little drawing on a silver disc. It showed a flying machine with a fixed wing, a tail, a seat for a pilot, and arrows for the forces of flight. People had always tried to fly by flapping like birds. Cayley's great idea was to separate the jobs: a fixed wing to hold

the machine up, and something else to push it forward. That is exactly how airplanes work today. In 1804, he built a model glider a few feet long, with a kite for a wing and a tail at the back, and it flew.

How they figured it out. Cayley did not just guess. He built a **whirling arm**, a long pole that spun around, carrying a small test wing at the end through the air, and he measured how much the wing was pushed up at different speeds and tilts. He studied the wings of birds and the seeds that glide from trees. He wrote down the four forces of flight, and he noticed that a slightly curved wing lifted better than a flat one. Many years later, in 1853, his full-size glider carried his coachman across a small valley near his home.

The physics. Four forces act on a flying machine. **Weight** pulls it down; **lift** pushes it up; **thrust** pushes it forward; **drag** holds it back. A wing makes lift by turning the moving air downward. A wing that is curved and tilted up a little, called its **angle of attack**, bends the air that flows over and under it down toward the ground behind it. By Newton's third law, if the wing pushes the air down, the air pushes the wing up. At the same time, the air pressure on top of the wing becomes lower than the pressure underneath, and that difference pushes the wing up too. These are two ways of describing the same lift.

The engineering. Airplane designers choose the size, curve and tilt of the wing to make enough lift for the plane's weight, without making too much drag. A bigger wing gives more lift but more drag. Too much tilt, and the air stops flowing smoothly over the wing, and the lift suddenly drops; pilots call that a stall. Engineers test wing shapes in wind tunnels, and they add flaps that slide out for slow, safe landings.

PICTURE STUDY



Cayley's Glider of 1804, Sir George Cayley, 1804 · Pen sketch from Cayley's notebook · Cayley's notebooks (Royal Aeronautical Society, London)

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

George Cayley drew this sketch of his model glider in his notebook. It looks simple, but it has the main parts of every airplane since: a fixed wing, a body and a tail.

Look closely

- Find the wing. Where is it on the pole: front, middle or back?
- Find the tail at the other end. What shape is it?
- Look closely at the wing. Is it flat with the pole or tilted?
- Find where a small weight might go to balance it.

Talk about it

1. Why do you think Cayley tilted the wing up a little at the front?
2. What job does the tail do?
3. How is this glider like a paper airplane? How is it different?

Safety first. Keep fingers away from the fan blades and run the fan on low or medium. An adult handles the fan.

BUILD

The Lift Tester

You will make paper wings that slide up and down a string in front of a fan. The higher a wing rises, the more lift it makes. You will test flat and curved wings at different tilts.

You will need

- Printer paper, tape and a ruler
- Drinking straws cut into 3-centimeter pieces
- About 1 meter of thread or fishing line, tied between the floor (taped to a heavy book) and the edge of a table above
- A box fan
- Engineer's notebook

Steps

1. Cut a piece of paper 10 by 20 centimeters. Fold it in half so the two short ends meet, but do not crease the fold; let the top bulge a little in a curve. Tape the ends together, with the top layer slid back about 1 centimeter so the top is curved. This is an airfoil.
2. Poke the straw piece straight up through both layers, about one-third of the way back from the curved front edge, and tape it in place.
3. Thread the string through the straw so the wing can slide up and down. Stretch the string straight up from the floor.
4. Turn on the fan, aimed at the curved front edge. Measure how high the wing rises up the string.
5. **Predict:** will a flat wing rise as high as a curved one?
6. **Fair test.** Make a flat wing from the same size of paper, with no curve. Test both wings at the same fan speed and distance, three trials each.
7. Record the heights in a table.
8. **Improve it.** Tilt the curved wing's front edge up a little more by moving the straw. Does it rise higher? What happens if you tilt it too much?

Tips

- Keep the string straight and vertical so the wing slides freely.
- Put the fan at the same distance for every test.
- A wing that flutters or flips may be tilted too much; that is like a stall.

Check your work

- ☐ I can name the four forces of flight.
- ☐ I can explain that a wing pushes air down and the air pushes the wing up.
- ☐ I compared flat and curved wings fairly and recorded the heights.

ENGINEER'S NOTEBOOK

1. Draw an airplane with four arrows for lift, weight, thrust and drag. Label each one.
2. Draw a wing from the side with air flowing past it and turning down behind it.
3. Make a table: wing type, tilt, height reached.

From history. Cayley wrote a famous paper called “On Aerial Navigation” in 1809 and 1810, which explained the science of flight. The Wright brothers studied his work, and he is often called the father of the airplane. He also invented a light wheel with wire spokes for his gliders, much like a bicycle wheel.

COMMON MISTAKES

- Thinking the air on top of the wing must hurry to “catch up” with the air underneath. That is a myth. The wing makes lift by turning air downward, and the pressure on top drops.
- Thinking wings need engines to make lift. Any wing moving through air makes lift; the engine just keeps it moving.
- Thinking more tilt always means more lift. Too much tilt causes a stall.

Make it a game • Lift Tester Wing Duel. Hold a paper wing in front of a fan or a strong blow, and tilt it to different angles. Predict which angle lifts the most, then test it with a paper clip load. Say lift, weight, thrust and drag. Name each force in turn, as fast as you can in ten seconds. Tell how George Cayley studied wings.

7.3 OTTO LILIENTHAL'S GLIDERS AND THE SECRET OF BALANCE

OBJECTIVES

- Tell how Otto Lilienthal learned to glide by studying birds and testing.
- Explain the center of gravity and why a glider must be balanced.
- Build a paper glider and fairly test how moving a paper clip forward or back changes its flight.

Warm-up. Balance a pencil on your finger. Where is the balance point? Now tape a coin to one end and find the new balance point. What changed? Then drop a flat sheet of paper and a crumpled one. Which falls more slowly?

WATCH

World's First Aircraft - Lilienthal's Glider Flight

Markus Raffel · 3:09

https://www.youtube.com/watch?v=_AZjozlvY4

WHEN TO WATCH

After the story. A scientist flies an exact copy of Lilienthal's glider. Watch how he swings his legs to steer.

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>

Before the story, as a short introduction.

KEY TERMS

glider

An aircraft with wings but no engine, which glides slowly down through the air.

center of gravity

The balance point of an object, where its weight seems to be centered.

stable

In flight, able to stay steady and come back to level after a bump.

weight shift

Steering a glider by moving the pilot's body to change the balance.

CORE IDEAS

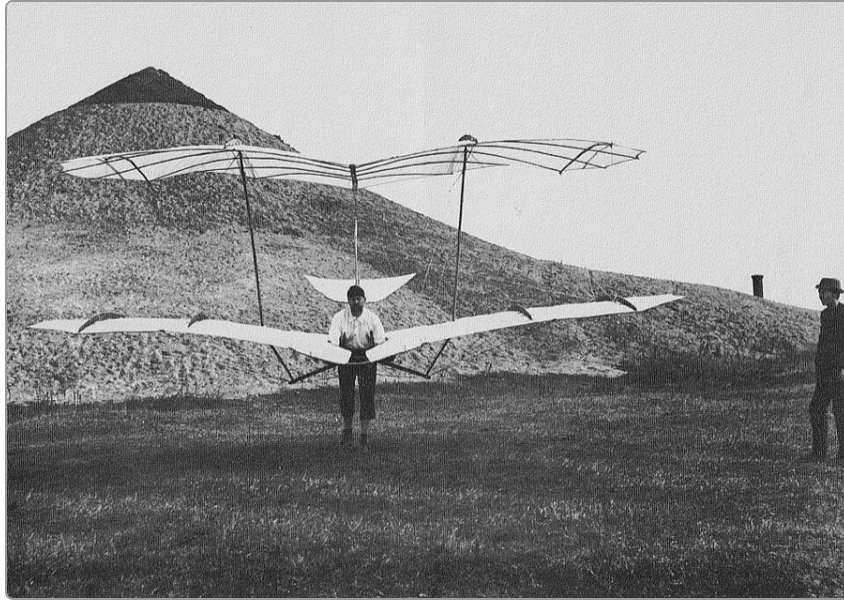
The story. As boys in Germany, Otto Lilienthal and his brother Gustav watched storks soar over the fields and dreamed of flying. As a grown man and an engineer, Otto studied birds for years and wrote a book about how they fly. Starting in 1891, he built gliders of willow wood and cotton cloth, shaped like the wings of a bird. He held on with his arms, ran down a hill into the wind, and lifted off. He even built his own hill near Berlin so he could launch into the wind from any direction. In all, he made about two thousand flights, some of them hundreds of feet long.

How they figured it out. Lilienthal measured the lift on curved wings with careful tests and wrote the numbers in tables, which other inventors used. He learned the most important lesson by flying: a glider must be balanced. If the weight is too far back, the nose goes up and the glider slows and drops; if it is too far forward, the nose dives. Lilienthal steered by swinging his legs and body to shift his weight, forward, back or to the side. It worked, but it took great strength and skill. In 1896, a gust of wind tipped his glider, and he fell and did not survive. His work inspired the Wright brothers to look for a better way to control a flying machine.

The physics. Every object has a **center of gravity**, the point where it balances. A glider's wing pushes up near a spot called the center of lift. If the center of gravity is a little in front of the center of lift, the glider flies nose-slightly-down and steady, gliding forward. If it is behind, the glider pitches up, slows down and stalls. A glider has no engine, so it is always gliding gently downhill through the air, trading height for forward speed.

The engineering. Every aircraft must be balanced before it flies. Airline crews weigh the passengers' bags and plan where cargo goes so the plane's center of gravity stays in a safe range. Hang gliders today still steer by weight shift, as Lilienthal did, but they are much safer, with strong frames, tested sails and trained pilots. Lilienthal showed what every designer learns: you can calculate a great deal, but real flight tests teach what calculations miss.

PICTURE STUDY



Otto Lilienthal with His Biplane Glider, Unknown photographer, About 1895 · Photograph · Otto Lilienthal Museum, Anklam, Germany (prints in many collections)

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

Lilienthal often had friends photograph his gliders so he could study them later. Here he stands inside one of his biplane gliders, with two wings stacked one above the other, below the hill he built near Berlin.

Look closely

- Find Lilienthal. Where does he hold on, and where would his legs hang in flight?
- Count the wings. How are they stacked?
- Look at the shape of the wings. How are they like a bird's wings?
- Find the hill behind him. Why did he build it shaped like a cone?

Talk about it

1. How did Lilienthal steer a glider like this one?
2. Why did he always take off into the wind?
3. What would you want to change to make this glider safer?

Safety first. Fly gliders indoors in an open room or outdoors on a calm day, away from people's faces. Never stand on chairs or tables to launch.

BUILD

The Balance Test Glider

You will fold a paper glider and fly it with a paper clip at three different spots along its body. You will measure how far it flies each time to find the best balance point, just as Lilienthal learned by flying.

You will need

- Printer paper
- Two or three paper clips
- A tape measure and masking tape for a launch line
- Engineer's notebook

Steps

1. Fold a simple glider with wide wings (a parent can help; a dart is not a good glider). Make the folds sharp and the two wings the same.
2. Mark a launch line on the floor with tape. Throw the glider gently and level from the line. Measure how far it flies. Watch: does it dive, glide or climb and drop?
3. Slide a paper clip onto the nose. **Predict:** farther or shorter?
4. **Fair test.** Fly the glider with the clip at the very front, in the middle of the body, and at the back. Use the same gentle throw each time. Fly three times at each spot.
5. Record the distances and describe each flight (dive, glide, stall).
6. **Improve it.** Find the clip position that gives the longest, smoothest glide. Then bend the back edges of both wings up slightly and test again. What changed?

Tips

- The same person should throw every time, with the same gentle push.
- Throw it level, not upward.
- If it turns to one side, check that both wings are the same shape.

Check your work

- ☐ I can explain what the center of gravity is.
- ☐ I tested three clip positions fairly and found the best one.
- ☐ I can explain how Lilienthal steered by shifting his weight.

ENGINEER'S NOTEBOOK

1. Draw your glider from the side three times, with the clip in the front, middle and back. Draw the flight path for each.
2. Make a table: clip position, three distances, kind of flight.
3. Draw a stork in flight and a Lilienthal glider. List three things that are alike.

From history. Photographs of Lilienthal flying were printed in newspapers and magazines around the world. In America, an engineer named Octave Chanute collected everything that had been learned about flight and shared it freely. The Wright brothers wrote to Chanute for advice, and he became their friend.

COMMON MISTAKES

- Thinking a heavier nose always makes a better glider. Too much weight in front makes it dive.
- Throwing the glider hard or upward, which makes every design look like it stalls.
- Changing the clip and the wing folds in the same test.

Make it a game • Balance the Glider. Add paper clips to the nose and tail of your glider and fly it ten times. Count the smooth glides. Say center of gravity and stable. Predict where to put a clip before each toss. Explain why a glider must be balanced. Tell how Otto Lilienthal studied birds, and beat your best number of smooth glides.

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)

Lilienthal studied soaring birds for years before he could glide. Isaiah uses the picture of an eagle rising on the wind to show the strength God gives to those who trust Him.

7.4 THE WRIGHT BROTHERS TWIST THEIR WINGS

OBJECTIVES

- Tell how the Wright brothers discovered wing warping.
- Explain how twisting the wings rolls an airplane so it can turn.
- Add flaps to a paper airplane and test how bending them steers it.

Warm-up. Take a long, empty cardboard box (like a cracker box) with both ends open. Hold the ends and twist them gently in opposite directions. Watch the top and bottom faces. What happens to the corners on the left side compared with the right?

WATCH

Wing Warping the Wright Way

Smithsonian National Air and Space Museum • 2:11

<https://www.youtube.com/watch?v=CiCJTR-hZnY>

WHEN TO WATCH

After the story. A museum curator shows wing warping with a box and a model.

KEY TERMS

wing warping

Twisting the ends of the wings in opposite directions to make an airplane roll and turn.

roll

When an airplane tips one wing down and the other up.

aileron

A hinged flap on the back edge of a wing that moves up or down to roll an airplane.

rudder

A flap on the tail that swings left or right to point the nose.

control

The pilot's ability to steer and balance an aircraft in the air.

CORE IDEAS

The story. Wilbur and Orville Wright ran a bicycle shop in Dayton, Ohio. They were the sons of a bishop, and they grew up in a home full of books and encouraged to be

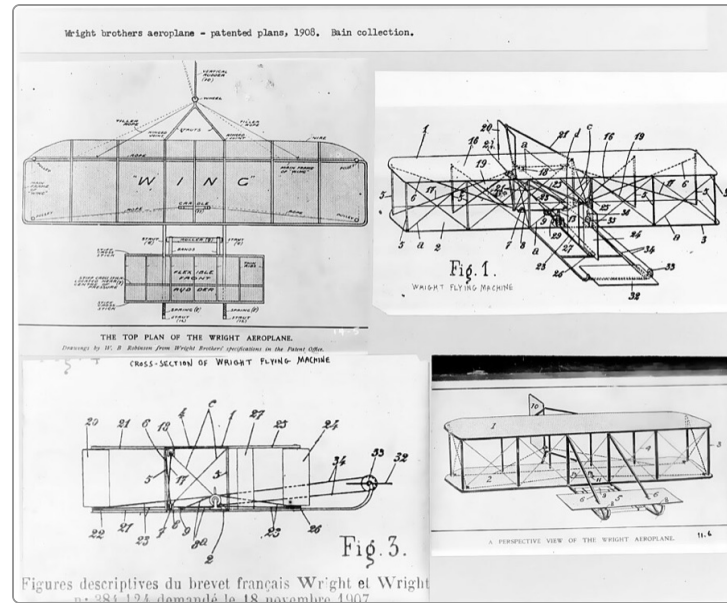
curious. When they read about Lilienthal, they decided that the hardest problem in flying was not lift or engines but **control**: how a pilot could balance and steer in the gusty air. One day in 1899, Wilbur was talking with a customer and absent-mindedly twisting a long, empty cardboard box in his hands. He saw that the twist made one end tilt up and the other end tilt down. That was the answer.

How they figured it out. Wilbur reasoned that if the wingtips of a flying machine were twisted like the box, the air would push one wing up and the other down, just as birds tilt their wingtips. The brothers built a kite with a five-foot wingspan, worked by strings, and the twist made it roll just as they hoped. Then, from 1900 to 1902, they built three gliders and flew them on the windy sand dunes of Kitty Hawk, North Carolina, making hundreds of flights and changing the design each time. They added a movable rudder to the tail when they found the glider could slip and spin. On December 17, 1903, Orville flew their engine-powered Flyer for 12 seconds and 120 feet, and the brothers made three more flights that day.

The physics. When one wing is twisted so its front edge tilts up, it meets the air at a steeper angle and makes more lift. The other wing, twisted the opposite way, makes less lift. So the airplane **rolls**, tipping to one side. A tilted wing pulls the plane around in a curve, the way a bicycle leans into a turn. The **rudder** on the tail helps the nose follow. Up and down movement of the nose is controlled by a separate flap, called the elevator.

The engineering. Wing warping worked for the Wrights' light wooden wings, but bigger, stronger metal wings cannot twist easily. So engineers soon used **ailerons**, small hinged flaps near the wingtips, which do the same job: one goes up and the other goes down. Every airplane today, from a small trainer to a jumbo jet, is controlled the same three ways the Wrights worked out: roll, pitch and turn. The Wrights received a patent for their control system in 1906.

PICTURE STUDY



The Wright Aeroplane: Plans from the Patent, W. B. Robinson, from the Wright brothers' patent specification, 1908 · Engineering drawing · Published in 1908 from the Wrights' patent drawings

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

Patent drawings show exactly how an invention works, so that no one else can claim it. These plans were drawn from the Wright brothers' patent to show their aeroplane from several sides.

Look closely

- Find the two wings stacked one above the other. What holds them apart?
- Find the elevator in front, which moves the nose up and down.
- Find the rudder at the back.
- Look closely at the wingtips. Where would they twist?

Talk about it

1. Why did the Wrights want a patent for their control system, not for wings?
2. If the left wingtip is twisted to make more lift, which way will the plane roll?
3. Why do engineers draw an invention from several views: the top, the front and the side?

Safety first. Fly paper airplanes away from people's faces, and never throw them at anyone.

BUILD

Steer with Flaps: The Aileron Test

You will add small cut flaps to the back of a paper airplane's wings, bend them up and down, and test how they make the plane roll and turn. You will measure how far left or right it lands.

You will need

- Printer paper and scissors
- Masking tape for a launch line and a straight “runway” line on the floor
- A tape measure
- Engineer's notebook

Steps

1. Fold a wide-winged paper airplane. On the back edge of each wing, near the tip, cut two short slits 2 centimeters apart and 2 centimeters deep to make a flap. These are your ailerons.
2. Lay a straight line of tape on the floor from the launch line. Fly the plane with both flaps flat along the line. Measure how far it lands to the left or right of the line. Do three trials.
3. **Predict:** if you bend the right flap up and the left flap down, which way will the plane roll and turn?
4. **Test.** Bend the flaps that way and fly three times. Measure how far off the line each flight lands, and which side.
5. **Fair test.** Try a small bend and a big bend. Then switch: left up, right down. Record all results in a table.
6. **Improve it.** Add a small rudder by cutting a flap in the back of the plane's body and bending it. Can you make the plane fly in a gentle curve and land on a target?

Tips

- Bend both flaps the same amount in opposite directions for a fair test.
- The same person should throw every time.

- Watch the wings in the air: you should see the plane tip toward one side before it turns.

Check your work

- ☐ I can explain how twisting the wings (or bending flaps) rolls an airplane.
- ☐ I measured how flap bends steered my plane left and right.
- ☐ I can tell the story of the Wrights' box and their first flight.

ENGINEER'S NOTEBOOK

1. Draw the Wrights' twisted box and show which corners go up and which go down.
2. Draw your plane from behind, with the flaps bent, and an arrow showing which way it rolls.
3. Make a table: flap setting, three landing spots, average side.

From history. The 1903 Wright Flyer now hangs in the Smithsonian National Air and Space Museum in Washington, D.C. A small piece of its wing cloth went to the moon with the Apollo 11 astronauts in 1969, and a tiny piece flew on Mars in 2021 aboard the helicopter Ingenuity.

COMMON MISTAKES

- Thinking a plane turns only with its rudder. It rolls first with its ailerons (or warped wings), and the rudder helps.
- Bending only one flap and calling it a fair comparison.
- Thinking the Wrights succeeded on the first try. They tested and changed their gliders for three years.

Make it a game • Aileron Steering Target. Fly a paper glider with flaps toward a target hoop on the floor. Bend the flaps to steer. Predict left or right before each toss, and count how many hits you make out of ten. Say aileron, roll and wing warping. Explain how the Wright brothers twisted their wings to turn.

UNIT 7

FLIGHT

For thousands of years, people watched birds and wished they could fly. “The way of an eagle in the air” was one of the wonders King Solomon could not understand (Proverbs 30:19). In this unit you will learn that air is real stuff that pushes hard, as Otto von Guericke showed with two copper bowls and sixteen horses, and you will launch a stomp rocket with a puff of squeezed air.

Then you will learn how a wing makes lift from George Cayley, the first person to draw an airplane the way we build them today, fly gliders that balance the way Otto Lilienthal’s did, and steer a paper plane with the Wright brothers’ great idea: twisting the wings. Every build is a flight test with a tape measure and a notebook.

PREREQUISITES

- Knows Newton’s first and third laws (Units 1 and 6)
- Can measure distances with a tape measure and record three trials
- Can fold paper neatly and evenly

MASTERY CHECKLIST

- ☐ I can explain that air presses on everything and show it with an experiment.
- ☐ I can explain how a stomp rocket uses air pressure.
- ☐ I can explain how a wing makes lift by turning air downward, and name the four forces of flight.
- ☐ I can explain why a glider needs the right balance, as Lilienthal learned.
- ☐ I can explain how the Wrights’ wing warping steered an airplane, and steer a paper plane with flaps.

OPTIONAL KITS FOR THIS UNIT

- **Stomp Rocket:** Ages vary by set (most are for ages 5 and up with an adult). A ready-made air-pressure launcher and foam rockets, for families who would rather not build one in Lesson 7.1. Always fly in an open field and never aim at people.
- **KiwiCo Tinker Crate:** Ages 9 and up, with a parent. Some crates build gliders, launchers or flying machines; check the crate list. Fits Lessons 7.1–7.4.

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 Air Pressure: The Magdeburg Hemispheres and a Stomp Rocket

2 sessions of 45 minutes

7.2 George Cayley and How a Wing Makes Lift

2 sessions of 45 minutes

7.3 Otto Lilienthal's Gliders and the Secret of Balance

2 sessions of 45 minutes

7.4 The Wright Brothers Twist Their Wings

2 sessions of 45 minutes

UNIT 7 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What held Guericke's two copper bowls together so tightly that horses could not pull them apart?

2. **5 pts**

How does stomping on a bottle launch a stomp rocket?

3. **5 pts**

Name the four forces of flight.

4. (5 pts)

How does a wing make lift?

5. (5 pts)

Predict: you tilt a wing's front edge up more and more. What happens to lift at first, and what happens if you tilt it too much?

6. (5 pts)

What was George Cayley's big idea about how to build a flying machine?

7. (5 pts)

What is the center of gravity? What happens to a glider if it is too far back?

8. (5 pts)

How did Otto Lilienthal steer his gliders?

9. (5 pts)

What gave Wilbur Wright the idea of wing warping?

10. (5 pts)

What happened on December 17, 1903?

ANSWER KEY

1. The air pressure outside pushing them together, because the air inside had been pumped out.
2. Stomping squeezes the air, raising its pressure, and the air rushes out through the tube and pushes the rocket off.
3. Lift, weight, thrust and drag.
4. The curved, tilted wing turns the air downward, and the air pushes the wing up (Newton's third law). The pressure on top of the wing is also lower than underneath.
5. At first lift increases. Too much tilt makes the air stop flowing smoothly and the wing stalls; lift drops.
6. Use a fixed wing for lift and a separate way to push it forward (thrust), with a tail for balance, instead of flapping wings.
7. The balance point. If it is too far back, the nose goes up, the glider slows down and stalls.
8. By shifting his body weight, swinging his legs and hips forward, back or to the side.
9. Twisting a long, empty cardboard box and seeing one end tilt up and the other tilt down.
10. Orville Wright made the first powered, controlled airplane flight at Kitty Hawk: 12 seconds and 120 feet. The brothers made four flights that day.

PORTFOLIO PIECE: A TESTED AND STEERABLE GLIDER

Design and build a paper glider that flies at least 5 meters and can be steered to land on a target. First, test the balance with a paper clip to find the best position. Then add flaps and test steering left and right. Record every flight in a table. In your final test, try to land three flights within 1 meter of a target placed off to one side. Explain which ideas came from Cayley, Lilienthal and the Wrights.

LOOK FOR	WHAT IT MEANS
Balance test	The clip was tested in at least three positions with three flights each, and the best was chosen.
Steering test	Flaps were bent in opposite directions and the results were measured and recorded.
Target flights	Three final flights were measured from the target and recorded honestly.
Explanation	The student connects the design to lift, balance and control, and names at least two of the three pioneers.

ROBOTS AND INVENTIONS

A robot is a machine that can **sense** the world around it, **think** about what to do, and **act**. In this unit you will meet Sojourner, a little rover that drove itself around rocks on Mars in 1997 because messages from Earth took too long to arrive. You will learn how Ada Lovelace, almost two hundred years ago, imagined a machine following a list of instructions with steps that repeat, and you will write your own loops.

Then you will build a cardboard hand that bends its fingers with string tendons, the way engineers design helping hands for people who need them. Finally, you will follow Abraham Lincoln from a stuck riverboat to his patent office drawing, and hold your own family invention fair to show off the best work of your whole year.

PREREQUISITES

- Can build a simple circuit and switch (Unit 4)
- Knows levers and pulleys (Unit 1)
- Can follow and write step-by-step instructions

MASTERY CHECKLIST

- ☐ I can explain sense, think and act, and give an example from a robot.
- ☐ I can write a program with a loop, on paper or in ScratchJr, and explain why loops are useful.
- ☐ I can explain how strings and joints work like tendons and levers in a robot hand.
- ☐ I can follow the steps of inventing: find a problem, imagine, plan, build, test and improve.
- ☐ I can present an invention and explain how I tested it.

OPTIONAL KITS FOR THIS UNIT

- **Makeblock mBot**: Ages 8 and up with an adult. A small wheeled robot with line and distance sensors, programmed with free block coding. A great extra for Lessons 8.1 and 8.2.
- **Sphero robots**: Ages vary by model. Rolling robots programmed with free block-coding apps on a tablet. Fits Lessons 8.1 and 8.2.
- **LEGO Education**: Ages vary by set. Beginner robotics sets with motors and sensors and simple coding. 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: Sojourner on Mars	2 sessions of 45 minutes
8.2	Ada Lovelace and Loops	2 sessions of 45 minutes
8.3	Levers and Tendons: Building a Helping Hand	2 sessions of 45 minutes
8.4	Abraham Lincoln's Patent and Our Invention Fair	2 sessions of 45 minutes

UNIT 8 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What are the three jobs every robot does? Give an example of each.

2. **5 pts**

Why did the rover Sojourner have to steer around rocks by itself?

3. **5 pts**

Predict: your bumper sensor's foil strips are taped so they always touch. What will the light do?

4. (5 pts)

What is a loop in a program? Why is it useful?

5. (5 pts)

Write a short program with a loop to draw a square.

6. (5 pts)

Who was Ada Lovelace, and what did she do?

7. (5 pts)

Where are the muscles that bend your fingers, and how do they move them?

8. (5 pts)

In your cardboard hand, what are the levers, the pivots and the tendons?

9. (5 pts)

How was Abraham Lincoln's invention supposed to work?

10. (5 pts)

Name the six steps of the engineering design process.

ANSWER KEY

1. Sense (a camera or touch sensor notices a rock), think (the program decides to turn), act (motors turn the wheels).
2. Mars is so far away that radio messages took about ten minutes each way, too slow for people on Earth to steer it in time.
3. It will stay on all the time, so the robot cannot tell when it bumps something.
4. A loop repeats a set of steps. It makes programs shorter, easier to read and easier to fix.
5. Repeat 4 times: move forward, turn right. (Other correct versions accepted.)
6. A mathematician who, in 1843, wrote step-by-step instructions for Charles Babbage's Analytical Engine, often called the first computer program, and described repeating steps (loops).
7. Mostly in the forearm. They pull on tendons, which pull the finger bones so the fingers bend at the joints.
8. The finger sections are levers, the folds are pivots (joints), and the strings are tendons.
9. Air chambers on the sides of a stuck boat would be filled with air, pushing aside more water so the boat rose and floated over the sandbar.
10. Ask, imagine, plan, build, test, improve.

PORTFOLIO PIECE: MY INVENTION AND FAMILY ENGINEERING FAIR

Present your invention from Lesson 8.4 with its patent-style drawing, your test results and your improvement. Alongside it, display the best build from each unit with its notebook page. Explain at least three builds to your guests: what you built, what you tested, what failed and how you made it better.

LOOK FOR	WHAT IT MEANS
Design process	The notebook shows the problem, three ideas, a labeled plan, tests and an improvement.
Working prototype	The invention does what it was designed to do, with test results recorded.
Year in review	At least one build from each unit is displayed with its notebook page.
Presentation	The student explains at least three builds clearly, using words such as force, test, measure and improve, and answers questions.

8.1 SENSE, THINK, ACT: SOJOURNER ON MARS

OBJECTIVES

- Explain the three jobs of a robot: sense, think and act.
- Explain why the Sojourner rover had to make some decisions by itself.
- Build a bumper sensor that lights a light when it touches something, and test it.

Warm-up. Play “human robot.” One person is the robot and may only follow exact instructions: step forward, turn left, stop. Another person gives instructions to guide the robot across the room to a chair. What happens when the instructions are not exact? Afterward, talk about how the robot could “sense” the chair.

WATCH

How Robots Sense, Plan, and Act

World Science Festival · 2:06

<https://www.youtube.com/watch?v=tUs2nyDcls8>

WHEN TO WATCH

After the physics paragraph. A robot scientist uses the word “plan” for what we call “think.”

KEY TERMS

robot

A machine that can sense, think and act by itself, following a program.

sensor

A part that lets a machine notice something, such as light, touch, distance or temperature.

program

A list of instructions that a computer or robot follows.

rover

A robot vehicle that drives across the surface of a moon or planet.

autonomous

Able to do a job and make some decisions without a person controlling every move.

CORE IDEAS

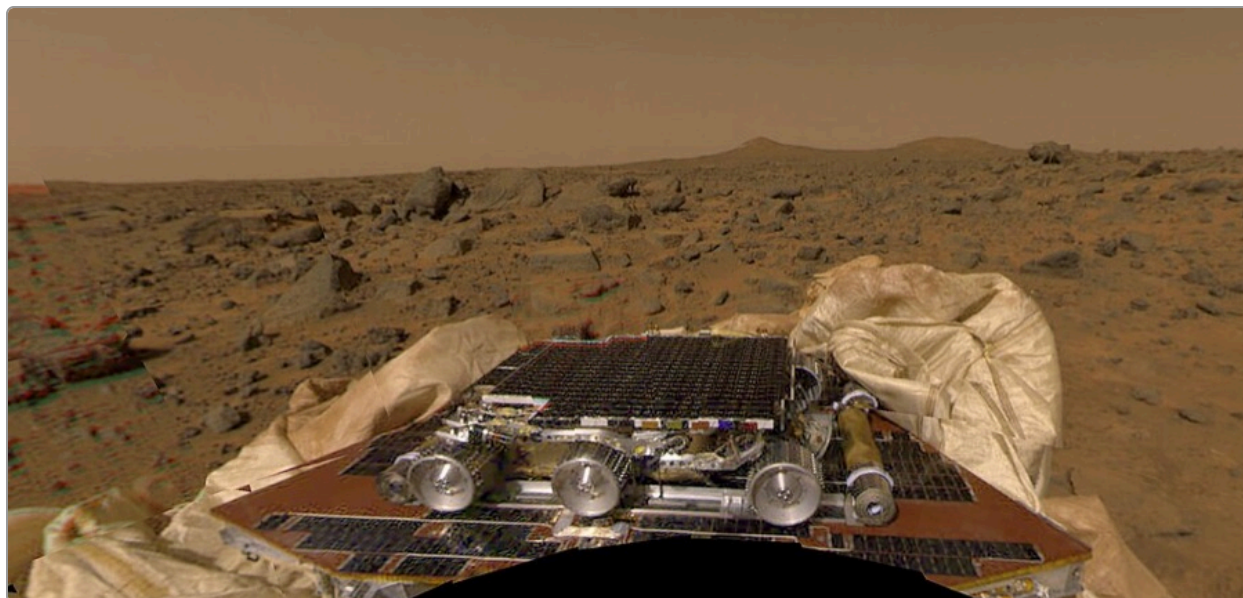
The story. On July 4, 1997, a spacecraft called Mars Pathfinder bounced onto Mars, wrapped in giant airbags. When the airbags were pulled in and the petals of the lander opened, a little six-wheeled rover rolled down a ramp onto the red dust. It was named Sojourner. It weighed about as much as a big bag of dog food and was about the size of a microwave oven. It was the first rover ever to drive on another planet.

How they figured it out. The engineers at NASA's Jet Propulsion Laboratory in California had a big problem. Mars is so far away that a radio message took about ten minutes to get there, and ten more for the answer to come back. If people on Earth tried to steer Sojourner like a remote-control car, it might bump into a rock long before they saw it. So they gave Sojourner its own senses and a small computer brain. Each day, the team sent a list of places to go. Sojourner used cameras and laser beams to look for rocks and holes in front of it, decided for itself how to steer around them, and drove on. It was built to work for one week, but it kept working for almost three months.

The physics. Every robot does three jobs. It **senses**: sensors measure light, touch, distance, tilt or heat and turn them into electrical signals. It **thinks**: a computer follows a **program**, a list of rules such as "if there is a rock ahead, turn right." It **acts**: motors turn wheels, arms or grippers. A simple touch sensor can be just a switch that closes when it bumps into something, completing a circuit, like the switches you built in Unit 4.

The engineering. Robot engineers decide which sensors a robot needs for its job, how its program should decide, and how strong its motors must be. Robots today vacuum floors, sort packages, help surgeons, explore the deep ocean and drive on Mars. Sojourner's great-grandchildren, the rovers Curiosity and Perseverance, are as big as cars and can drive much farther on their own. But they still sense, think and act.

PICTURE STUDY



Sojourner Beside the Pathfinder Lander, NASA / Jet Propulsion Laboratory, July 1997 · Photograph taken by the Mars Pathfinder lander's camera · NASA Jet Propulsion Laboratory, Pasadena, California

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

This picture was taken by a camera on the Pathfinder lander just after landing, before Sojourner rolled down its ramp onto Mars. Every picture came across millions of miles of space by radio.

Look closely

- Find Sojourner. How many wheels can you see?
- Find the flat panel on top. It is a solar panel that turned sunlight into electricity.
- Find the crumpled airbags that cushioned the landing.
- Look at the rocks beyond. Which ones would Sojourner need to steer around?

Talk about it

1. What did Sojourner use to sense the rocks in front of it?
2. Why couldn't people on Earth just steer it like a toy car?
3. If you could add one more sensor to Sojourner, what would it be and why?

Safety first. Use only batteries. Play the human-robot game slowly, in a clear space, with no stairs nearby.

BUILD

The Bumper Sensor

You will build a bumper from cardboard and foil that closes a circuit and lights a bulb or LED when it bumps into something. Then you will mount it on a toy car or a box and test how well it senses obstacles.

You will need

- A battery in a holder, a small bulb or LED, and three alligator clip leads
- Two strips of cardboard about 15 centimeters long, aluminum foil, tape and a small piece of sponge or folded paper (a spring)
- A toy car, a shoebox on wheels or a small box to push
- A few “rocks”: blocks, books and boxes
- Engineer’s notebook

Steps

1. Wrap each cardboard strip in foil. Tape the sponge between them at one end, so the strips are held a little apart but can be squeezed together.
2. Clip one lead from the battery to the front strip and one from the back strip to the bulb. Connect the bulb back to the battery. Squeeze the strips: the bulb should light. This is your touch sensor.
3. Tape the bumper to the front of the car or box with the front strip facing forward.
4. **Predict:** will the bumper sense a big flat book, a small block and a soft pillow?
5. **Test.** Roll the car slowly into each obstacle three times. Record whether the light came on: yes or no.
6. **Think and act.** Play robot: one person pushes the car with eyes closed and must stop and turn whenever the light shines (a helper calls out “light!”). Can the “robot” get across the room without crashing?
7. **Improve it.** Make the bumper wider, or the spring softer, and test again with the obstacles that were missed.

Tips

- If the light is always on, the strips are touching; add more sponge.
- If it never lights, check that the foil is touching the clips.
- A softer spring senses gentle bumps; a stiffer one ignores small ones. That is a trade-off.

Check your work

- ☐ I built a touch sensor and tested it on three obstacles.
- ☐ I can explain sense, think and act with my bumper car.
- ☐ I can explain why Sojourner had to steer itself around rocks.

ENGINEER'S NOTEBOOK

1. Draw your bumper sensor and its circuit. Label the sensor, the light and the battery.
2. Make a table: obstacle, trial 1, trial 2, trial 3 (light on or off).
3. Design a robot for a job at home. Draw it and label one sensor, one way it thinks and one way it acts.

From history. The name Sojourner was chosen in a naming contest for students, won by a twelve-year-old girl. A *sojourner* is a traveler, a good name for a rover. Sojourner's wheels left the first tracks ever made on another planet.

COMMON MISTAKES

- Thinking any machine is a robot. A toaster acts, but it does not sense and decide.
- Thinking robots understand like people. They only follow their programs.
- Forgetting that a sensor must be tested on many kinds of objects.

Make it a game • Sense Think Act Drill. Turn your family into a robot. One person senses, such as touching a wall, one thinks, calling the next step, and one acts. Run the robot through a path of shoes with no talking except the commands. Say sensor, program and autonomous. Explain why Sojourner had to decide some things by itself. Time your run.

8.2 ADA LOVELACE AND LOOPS

OBJECTIVES

- Tell how Ada Lovelace wrote instructions for a machine that had not yet been built.
- Explain what a loop is and why it makes programs shorter.
- Write a program with a loop, on paper and in ScratchJr or Scratch, and compare it with one without.

Warm-up. Write down the exact instructions to draw a square: “Draw a line 5 centimeters. Turn right. Draw a line 5 centimeters. Turn right...” How many steps did it take? Can you think of a shorter way to say it?

WATCH

Ada Lovelace for Kids | Bedtime History

Bedtime History · 6:14

<https://www.youtube.com/watch?v=QTCW2UyaRno>

WHEN TO WATCH

Before the story.

BACKUP VIDEO

Video 3 Using the Repeat block (ScratchJr Coding Video Tutorial series for beginners)

Mr Vullo · 2:45

https://www.youtube.com/watch?v=p-rb_nE6onc

Before the build, if you are using ScratchJr.

KEY TERMS

algorithm

A set of exact steps for doing a job.

code

Instructions written so that a computer can follow them.

loop

A part of a program that repeats a set of steps, a certain number of times or forever.

bug

A mistake in a program that makes it do the wrong thing.

debug

To find and fix the mistakes in a program.

CORE IDEAS

The story. Ada Lovelace was born in London in 1815. Her mother made sure she studied mathematics and science, and Ada loved them. At seventeen she met Charles Babbage, an inventor who was designing a giant calculating machine of brass gears, the Analytical Engine. It would be given its instructions on punched cards, like the cards that told weaving looms what pattern to weave. In 1843 Ada wrote a long set of notes explaining how the machine would work, and in them she wrote out, step by step, how it could calculate a difficult set of numbers. Many people call this the first computer program.

How they figured it out. The Analytical Engine was never finished; it was too costly and complicated to build in those days. So Ada had to work everything out on paper, imagining the gears turning. She noticed something important: many steps in her plan were the same steps done again and again. Instead of writing them out over and over, the machine could be told to go back and repeat them. She called this a “cycle.” Today we call it a **loop**. She also imagined that a machine like this might one day work with music and pictures, not just numbers.

The physics. A computer is a machine that follows instructions exactly, very fast. It does not guess what you mean. An **algorithm** is a list of exact steps. A **loop** tells the computer to repeat some steps: “Repeat 4 times: move forward, turn right” draws a square in two lines instead of eight. Loops make programs shorter, easier to read and easier to fix. If there is a **bug**, you only have to fix it in one place.

The engineering. Every robot, game, phone and washing machine runs on programs full of loops. A robot vacuum repeats “move forward until you bump, then turn” over and over. A traffic light repeats green, yellow, red all day. Programmers test their

code, find bugs and fix them, which is called **debugging**, just as you test and improve your builds.

PICTURE STUDY



Ada Lovelace, Alfred Edward Chalon, About 1840 · Watercolor
Image: [Wikimedia Commons](#), public domain

This portrait was painted a few years before Ada wrote her famous notes. Painters of the time often showed ladies in their best evening dress. You cannot see her mathematics in the picture, but it was in her notebooks.

Look closely

- Look at her face. What kind of person do you think she was?
- Look at her gown, her lace shawl and the fan in her hand. What do they tell you about her life?
- Look at the background. Is it plain or detailed?
- Notice how the painter used light and shadow on the gown.

Talk about it

1. Ada wrote a program for a machine that did not exist yet. How could she know if her program would work?
2. Why do you think she was excited about the idea of repeating steps?
3. What do you think she would say if she could see a computer today?

BUILD

Loop It! Unplugged and in ScratchJr

You will write programs to draw shapes and dance steps, first without loops and then with loops, and count how many instructions each one needs. Then you will try the same programs in ScratchJr or Scratch.

You will need

- Index cards or sticky notes, and a marker
- Graph paper and a pencil
- A tablet with the free ScratchJr app, or a computer with Scratch (scratch.mit.edu), if available
- Engineer's notebook

Steps

1. **Unplugged.** Make instruction cards: FORWARD 1, TURN RIGHT, TURN LEFT and a card that says REPEAT ___ TIMES with a bracket.
2. Write a program to draw a square on graph paper, moving one square at a time, without using REPEAT. Count the cards.
3. Now write it with REPEAT. Count the cards again. **Predict** first: how many cards will you save?
4. Have a family member be the “computer” and follow your cards exactly with a pencil on graph paper. Did it work? If not, find the bug and fix it.
5. **Fair test.** Write programs for a square, a rectangle and a staircase of 5 steps, each with and without loops. Record the number of cards in a table.
6. **On screen.** In ScratchJr, make the cat move and turn to walk in a square, first without a repeat block, then with one. Change the repeat number. What happens?
7. **Improve it.** Write a short “dance” with a loop inside a loop: for example, repeat 3 times (jump, repeat 2 times (spin)). Perform it or program it.

Tips

- Computers follow exactly what you say, not what you meant. Check every step.

- If the cat goes off the screen, check your turns.
- Bugs are normal. Every programmer finds and fixes them.

Check your work

- ☐ I wrote a program with a loop and one without, and counted the steps.
- ☐ I found and fixed at least one bug.
- ☐ I can explain why Ada Lovelace's idea of repeating steps was important.

ENGINEER'S NOTEBOOK

1. Copy your square program with a loop and without a loop side by side.
2. Make a table: shape, cards without a loop, cards with a loop.
3. List three things at home that repeat steps over and over, like a washing machine or a clock.

From history. Charles Babbage also designed a Difference Engine, a calculating machine. In 1991, more than 150 years later, engineers at the Science Museum in London built one from his drawings, and it worked. A modern programming language used for airplanes and trains is named Ada in her honor.

COMMON MISTAKES

- Putting the wrong steps inside the loop, so the shape comes out wrong.
- Forgetting to say how many times to repeat.
- Thinking a computer understands what you mean. It only does what you say.

Make it a game · Loop It Unplugged. Write a dance program for your parent with eight steps, then shorten it using a loop, such as repeat jump three times. Your parent follows it exactly. If it fails, find the bug and debug. Say algorithm and loop. Tell how Ada Lovelace wrote instructions for a machine not yet built. Fewest lines wins.

8.3 LEVERS AND TENDONS: BUILDING A HELPING HAND

OBJECTIVES

- Explain how your fingers work as levers moved by tendons.
- Describe how engineers have designed artificial hands, from iron hands of the 1500s to 3D-printed hands today.
- Build a cardboard hand with string tendons and test what it can grip.

Warm-up. Hold your hand flat on the table, palm up. Slowly curl your fingers. Watch the inside of your wrist and forearm. Can you see or feel anything moving? Now, with your other hand, feel the back of your hand as you open and close your fist.

WATCH

Make a Robotic Hand with Straws | Science Project

Science Buddies • 5:16

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

WHEN TO WATCH

Before the build.

BACKUP VIDEO

How To Make Your Own Robot Hand | Cardboard Crafts

TheDadLab • 2:51

<https://www.youtube.com/watch?v=uPS4SdQRPQk>

Before the build, to see a cardboard version.

KEY TERMS

tendon

A strong cord in your body that connects a muscle to a bone and pulls it.

joint

A place where two bones (or two parts of a machine) meet and can bend.

lever

A bar that turns on a pivot to move a load.

pivot

The point a lever turns around.

prosthesis

An artificial body part, such as a hand or a leg, made for someone who needs one.

linkage

Parts joined together so that moving one moves the others.

CORE IDEAS

The story. Long ago, people who lost a hand in an accident or in battle had few choices. In the 1500s, a French surgeon named Ambroise Paré, who spent his life caring for the wounded, described in his books mechanical hands made of iron, with fingers that could be bent and locked by springs and catches. Skilled metalworkers made such hands, and a few still survive in museums. One of them, from the late 1500s, is kept in an old house in Cornwall, England.

How they figured it out. The makers of iron hands studied the real hand. Each finger has joints, like hinges, so it can bend in three places. The early iron hands used a little ratchet in each joint so the fingers stayed bent once they were pushed closed, and a button to release them. Much later, engineers learned to copy the way a real hand moves, with cords that pull the fingers closed. Today, volunteers around the world 3D-print simple plastic hands for children, using strings for tendons, and give them away.

The physics. Each part of your finger is a **lever**, and each joint is a **pivot**. The muscles that close your hand are mostly in your forearm, not your fingers. They pull on long **tendons**, like strings, that run through your wrist and fasten to your finger bones. When a muscle pulls its tendon, the finger bends at its joints. Other tendons on the back of your hand pull the fingers straight again. A string pulled through straws on a cardboard finger works the same way.

The engineering. Robot hands in factories, on space stations and in hospitals use the same ideas: levers, joints and cables or motors that pull. Engineers designing a **prosthesis** must think about the person who will use it: is it light, strong, comfortable, easy to clean, and able to hold a cup or a pencil? They test their designs again and again with real users. Making a helping hand for someone who needs one is a way of loving your neighbor with engineering.

PICTURE STUDY



An Iron Hand from the 1500s, Photograph by Martinvl, Hand made about 1550–1600; photographed 2016 · Wrought iron (photograph) · Cotehele House, Cornwall, England

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

This iron hand was probably made in France or Germany more than four hundred years ago for someone who had lost a hand. It is on display in an old house in Cornwall. Look at how the fingers are made.

Look closely

- Count the fingers. Is there a thumb?
- Look for joints in the fingers. Are they in the same places as yours?
- Find the hollow forearm part, which fit over the person's arm.
- Look closely for rivets and bands where the pieces join. Some of those are pivots.

Talk about it

1. How do you think the person closed the fingers without tendons or motors?
2. What could this hand hold? What would be hard for it?
3. How is a modern helping hand different from this one?

Safety first. An adult cuts thick cardboard and handles any hot glue. Use scissors carefully when cutting straws.

BUILD

The String-Tendon Hand

You will trace your hand on cardboard, cut it out, add straw segments for “bones” and string for “tendons,” and make the fingers bend by pulling the strings. Then you will test what your hand can pick up.

You will need

- Thin cardboard (a cereal box) and a pencil
- Plastic drinking straws, cut into short pieces
- String or yarn (5 pieces about 40 centimeters long)
- Tape or glue, scissors and a ruler
- Objects to grip: a paper cup, a ball of yarn, a pencil, a small stuffed animal
- Engineer’s notebook

Steps

1. Trace your hand and wrist on the cardboard. Cut it out (an adult can help).
2. On each finger, draw lines where your own finger bends. Fold the cardboard gently along each line so the fingers can bend.
3. Tape short pieces of straw between the folds on each finger, and one long piece on the palm for each finger, all in a line toward the wrist. These are the guides for the tendons.
4. Thread a string through the straws of each finger and tape the end to the fingertip.
5. **Predict:** what will happen when you pull a string? Pull it gently and watch.
6. **Fair test.** Try to pick up each object three times by pulling all the strings together. Record how many times you held it for 5 seconds.
7. **Improve it.** Change one thing: add rubber bands to the back of the fingers to pull them open, add a second fold on the thumb, or add tape “grip pads” to the fingertips. Test the same objects again.

Tips

- Leave small gaps between the straw pieces at each fold, or the finger cannot bend.
- Tie the strings together at the wrist, or tie them to a ring, so you can pull them all at once.
- Pulling slowly gives more control.

Check your work

- ☐ I built a hand whose fingers bend when I pull the strings.
- ☐ I tested four objects fairly and recorded the results.
- ☐ I can explain how tendons and joints work as levers and pivots.

ENGINEER'S NOTEBOOK

1. Draw one of your fingers from the side. Label the joints, the tendon and the muscle in the forearm.
2. Make a table: object, trial 1, trial 2, trial 3, after improvement.
3. Design a helping hand for a special job, such as picking up litter or holding a paintbrush. Draw and label it.

From history. Ambroise Paré is remembered as one of the fathers of modern surgery. He was known for his gentle care of the wounded, and he is often quoted as saying of a patient, “I dressed him, and God healed him.”

COMMON MISTAKES

- Thinking the muscles that bend your fingers are in your fingers. They are mostly in your forearm.
- Forgetting a way to straighten the fingers again. Real hands use tendons on the back; you can use rubber bands.
- Cutting the straw pieces so long that they cover the folds.

Make it a game • Finger Lever Hunt. Bend your fingers and feel the tendons moving in your wrist. Point out the joints and the levers in your own hand. Build a cardboard hand with strings, then pick up a cup, a coin and a pencil, counting the grabs in a minute. Say tendon, pivot and prosthesis. Beat your count.

Scripture. “I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well.” (Psalm 139:14, KJV)

The best robot hands engineers can build are still far simpler than the hands God made. Studying your own hand is a good way to see how wonderfully you are made.

8.4 ABRAHAM LINCOLN'S PATENT AND OUR INVENTION FAIR

OBJECTIVES

- Tell how Abraham Lincoln invented a way to lift boats over sandbars, and what a patent is.
- Use the engineering design process to invent something that solves a real problem.
- Build, test, improve and present an invention at a family engineering fair.

Warm-up. Look around your home for a small problem: a cord that tangles, a door that slams, a sock that always gets lost, a plant that is hard to water. Make a list of five problems. Choose one you would like to solve.

WATCH

Little Inventors: How to think up invention ideas!

Little Inventors • 2:25

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

WHEN TO WATCH

After the warm-up, before you choose your invention.

KEY TERMS

invention

A new device or way of doing something.

patent

A government paper that says an inventor owns an idea for a certain number of years, so others cannot copy it without permission.

prototype

A first model of an invention, built to test the idea.

engineering design process

The steps engineers follow: ask, imagine, plan, build, test and improve.

shoal

A shallow place in a river or sea, such as a sandbar, where boats can get stuck.

CORE IDEAS

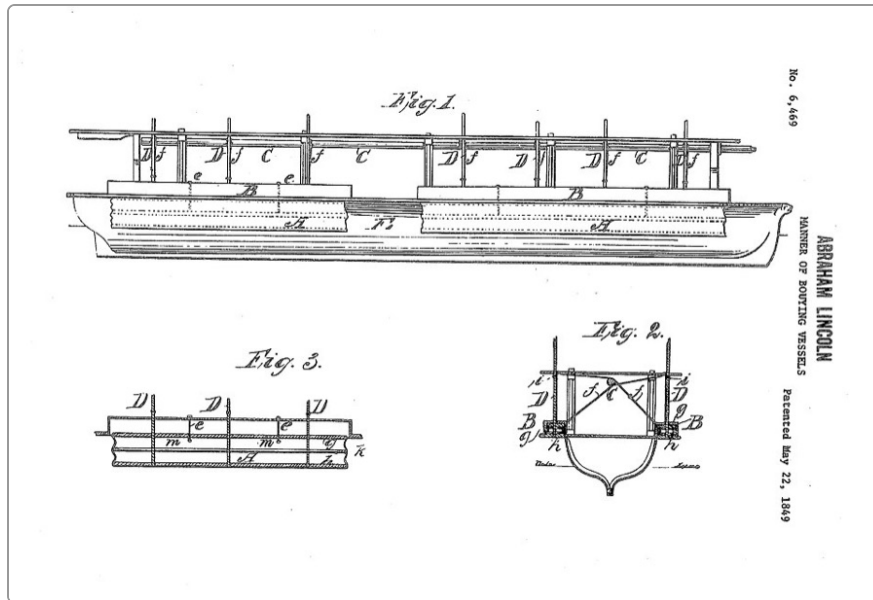
The story. As a young man, Abraham Lincoln worked on riverboats and took a flatboat of goods down the Mississippi to New Orleans. In 1831, his boat got stuck on a mill dam near New Salem, Illinois, and he and the crew had to work hard to free it. Years later, in 1848, he watched another boat stuck on a sandbar. He wondered: what if a boat could lift itself? He worked out a plan, whittled a wooden model, and on May 22, 1849, he received Patent No. 6,469 for a way of “buoying vessels over shoals.” He is the only President of the United States who ever held a patent.

How they figured it out. Lincoln’s idea was to fasten large air chambers, like folded bellows made of rubber cloth, along the sides of a boat below the waterline. When the boat got stuck, the crew would pump air into them. The air chambers would push aside more water, the buoyancy would increase, and the boat would rise a little and float over the sandbar. You learned this physics in Unit 6! He built a model to show the patent office how it worked. His invention was never built for real boats, but the idea was sound.

The physics. Every invention uses physics you have learned this year: forces and machines, structures, circuits, buoyancy, air pressure and flight. Inventors combine these ideas in new ways to solve problems. The most important tool is the **engineering design process**: ask what the problem is, imagine many solutions, plan one, build a **prototype**, test it fairly, and improve it. Then test again.

The engineering. A **patent** protects an inventor’s idea for a number of years, so the inventor can be rewarded for the work. In return, the patent drawings and description are published for everyone to learn from. Lincoln admired the patent system. In a lecture in 1859, he said that it “added the fuel of interest to the fire of genius.” Today, engineers and inventors still keep careful notebooks, sketch their ideas, build prototypes, and share what they learn, just as you have done all year.

PICTURE STUDY



Lincoln's Patent Drawings: Buoying Vessels over Shoals, Abraham Lincoln (inventor), drawn for the United States Patent Office, 1849 · Patent drawing · National Archives and the United States Patent and Trademark Office

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

These are the drawings that came with Lincoln's patent. They show his riverboat with air chambers along its sides, folded up when not needed and filled with air to lift the boat.

Look closely

- Find the boat. Which drawing shows it from the side, and which from the end?
- Find the folded air chambers along the bottom of the boat.
- Find the poles and ropes that would push the chambers down into the water.
- Find the waterline. Where would it be when the chambers are full of air?

Talk about it

1. How would filling the chambers with air help the boat float over a sandbar?
2. Why does a patent need such careful drawings?
3. What problems might this invention have on a real river?

Safety first. An adult handles any hot glue, craft knives or tools. Inventions must not use outlets in the wall; batteries only.

BUILD

Invent, Test, Improve and Present

You will invent something to solve a real problem from your warm-up list, using the engineering design process. You will build a prototype, test it, improve it, and present it at a family engineering fair, along with the best build from each unit of the year.

You will need

- Any safe household and craft materials: cardboard, tape, string, straws, rubber bands, cups, foil, paper clips, batteries and bulbs
- Your engineer's notebook from the whole year
- Your best builds or photographs from Units 1–7
- A table or space for the fair, and paper for signs

Steps

1. **Ask.** Write your problem in one sentence: “People in my house need a way to...”
2. **Imagine.** Sketch three different ideas. Do not stop at the first one!
3. **Plan.** Choose the best idea. Draw it carefully with labels, like Lincoln's patent drawing, and list the materials.
4. **Build** a prototype.
5. **Test.** Decide how to measure whether it works (how many times it works out of ten, how much it holds, how long it lasts). Test it at least three times and record the results.
6. **Improve.** Change one thing to make it better, and test it again.
7. **Fair.** Set out your invention with its drawing and test results. Also set out the best build from each unit with its notebook page. Invite family or friends, and explain each one: what you built, what you tested and what you learned.

Tips

- A simple invention that works well is better than a complicated one that does not.
- Write down every test, even the ones that fail; they show how you learned.

- Practice explaining your invention in one minute before the fair.

Check your work

- ☐ I followed all six steps of the engineering design process.
- ☐ I tested my prototype at least three times and improved it.
- ☐ I presented my invention and my year's work and answered questions.

ENGINEER'S NOTEBOOK

1. Draw your three invention ideas on one page, and circle the one you chose.
2. Make a "patent drawing" of your invention with a title, a side view and labels.
3. Write a short list: the three things I learned this year that I am most proud of.

From history. Lincoln's wooden model of his invention is kept at the Smithsonian's National Museum of American History in Washington, D.C. Over the years, the United States Patent Office has granted more than ten million patents, and every one began with someone noticing a problem and asking, "What if?"

COMMON MISTAKES

- Stopping at the first idea instead of imagining several.
- Skipping the test and calling an invention finished.
- Changing many things at once when improving, so you cannot tell what helped.

Make it a game • Lincoln's Patent Pitch. Pitch an invention to your parent in 60 seconds, the way Abraham Lincoln pitched his boat lifter. State the problem, the six steps of the design process and what makes the invention yours. Say patent and prototype. Your parent asks three questions, and you answer. Score points for each clear answer.

ROBOTS AND INVENTIONS

A robot is a machine that can **sense** the world around it, **think** about what to do, and **act**. In this unit you will meet Sojourner, a little rover that drove itself around rocks on Mars in 1997 because messages from Earth took too long to arrive. You will learn how Ada Lovelace, almost two hundred years ago, imagined a machine following a list of instructions with steps that repeat, and you will write your own loops.

Then you will build a cardboard hand that bends its fingers with string tendons, the way engineers design helping hands for people who need them. Finally, you will follow Abraham Lincoln from a stuck riverboat to his patent office drawing, and hold your own family invention fair to show off the best work of your whole year.

PREREQUISITES

- Can build a simple circuit and switch (Unit 4)
- Knows levers and pulleys (Unit 1)
- Can follow and write step-by-step instructions

MASTERY CHECKLIST

- ☐ I can explain sense, think and act, and give an example from a robot.
- ☐ I can write a program with a loop, on paper or in ScratchJr, and explain why loops are useful.
- ☐ I can explain how strings and joints work like tendons and levers in a robot hand.
- ☐ I can follow the steps of inventing: find a problem, imagine, plan, build, test and improve.
- ☐ I can present an invention and explain how I tested it.

OPTIONAL KITS FOR THIS UNIT

- **Makeblock mBot**: Ages 8 and up with an adult. A small wheeled robot with line and distance sensors, programmed with free block coding. A great extra for Lessons 8.1 and 8.2.
- **Sphero robots**: Ages vary by model. Rolling robots programmed with free block-coding apps on a tablet. Fits Lessons 8.1 and 8.2.
- **LEGO Education**: Ages vary by set. Beginner robotics sets with motors and sensors and simple coding. 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: Sojourner on Mars	2 sessions of 45 minutes
8.2	Ada Lovelace and Loops	2 sessions of 45 minutes
8.3	Levers and Tendons: Building a Helping Hand	2 sessions of 45 minutes
8.4	Abraham Lincoln's Patent and Our Invention Fair	2 sessions of 45 minutes

UNIT 8 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What are the three jobs every robot does? Give an example of each.

2. **5 pts**

Why did the rover Sojourner have to steer around rocks by itself?

3. **5 pts**

Predict: your bumper sensor's foil strips are taped so they always touch. What will the light do?

4. (5 pts)

What is a loop in a program? Why is it useful?

5. (5 pts)

Write a short program with a loop to draw a square.

6. (5 pts)

Who was Ada Lovelace, and what did she do?

7. (5 pts)

Where are the muscles that bend your fingers, and how do they move them?

8. (5 pts)

In your cardboard hand, what are the levers, the pivots and the tendons?

9. (5 pts)

How was Abraham Lincoln's invention supposed to work?

10. (5 pts)

Name the six steps of the engineering design process.

ANSWER KEY

1. Sense (a camera or touch sensor notices a rock), think (the program decides to turn), act (motors turn the wheels).
2. Mars is so far away that radio messages took about ten minutes each way, too slow for people on Earth to steer it in time.
3. It will stay on all the time, so the robot cannot tell when it bumps something.
4. A loop repeats a set of steps. It makes programs shorter, easier to read and easier to fix.
5. Repeat 4 times: move forward, turn right. (Other correct versions accepted.)
6. A mathematician who, in 1843, wrote step-by-step instructions for Charles Babbage's Analytical Engine, often called the first computer program, and described repeating steps (loops).
7. Mostly in the forearm. They pull on tendons, which pull the finger bones so the fingers bend at the joints.
8. The finger sections are levers, the folds are pivots (joints), and the strings are tendons.
9. Air chambers on the sides of a stuck boat would be filled with air, pushing aside more water so the boat rose and floated over the sandbar.
10. Ask, imagine, plan, build, test, improve.

PORTFOLIO PIECE: MY INVENTION AND FAMILY ENGINEERING FAIR

Present your invention from Lesson 8.4 with its patent-style drawing, your test results and your improvement. Alongside it, display the best build from each unit with its notebook page. Explain at least three builds to your guests: what you built, what you tested, what failed and how you made it better.

LOOK FOR	WHAT IT MEANS
Design process	The notebook shows the problem, three ideas, a labeled plan, tests and an improvement.
Working prototype	The invention does what it was designed to do, with test results recorded.
Year in review	At least one build from each unit is displayed with its notebook page.
Presentation	The student explains at least three builds clearly, using words such as force, test, measure and improve, and answers questions.

TOY LAB: THE PHYSICS OF PLAY

Toys are machines too, and many were invented by engineers. In this optional bonus unit, you will look inside four favorite toys. You will learn how strings and pulleys move the hidden stylus of an Etch A Sketch, why the steel balls of Newton’s cradle pass their motion down the line, why a spinning gyroscope top refuses to fall over, and how A. C. Gilbert’s Erector set taught generations of children to build with girders, nuts and bolts.

Use this unit after the family engineering fair, over the summer, or any week that needs something fun. Every lesson still has a story, the physics, a build and a fair test. And every lesson talks about toy safety, because engineers who design toys must think about the youngest children who might play with them.

PREREQUISITES

- Knows pulleys, gears and levers (Unit 1)
- Knows why triangles are strong (Units 2 and 3)
- Can run a fair test and record three trials

MASTERY CHECKLIST

- ☐ I can explain how two knobs, strings and pulleys can move a point anywhere on a screen.
- ☐ I can explain how Newton’s cradle passes motion and energy through the balls, and why it slowly stops.
- ☐ I can explain why a spinning top or gyroscope stays upright, and test what makes it spin longer.
- ☐ I can build a sturdy structure with girders and bolts and explain why bracing matters.
- ☐ I can name toy-safety rules, such as small parts, magnets and button batteries, and explain why they matter.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box:** Ages 8 and up. Monthly toys to build, each with a video by engineer Mark Rober explaining the physics inside. A great fit for this whole unit.
- **Meccano (Erector) construction sets:** Ages vary by set (usually 8 and up). Metal and plastic girders, nuts, bolts and tools, the modern version of the Erector set in Lesson 9.4.
- **KiwiCo Tinker Crate:** Ages 9 and up, with a parent. Many crates are working toys with gears, springs and spinning parts.

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 Inside the Etch A Sketch: Strings, Pulleys and Two Knobs 2 sessions of 45 minutes

9.2 Newton's Cradle: Passing the Push 2 sessions of 45 minutes

9.3 The Gyroscope Top: Why Spinning Things Stay Up 2 sessions of 45 minutes

9.4 A. C. Gilbert's Erector Set: Building with Girders and Bolts

2 sessions of 45 minutes

UNIT 9 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What do the two knobs on an Etch A Sketch do?

2. **5 pts**

How does the Etch A Sketch draw a line, and how does shaking erase it?

3. **5 pts**

Why should you never break open an Etch A Sketch?

4. (5 pts)

Predict: you swing two balls of a Newton's cradle into the row. What happens at the other end?

5. (5 pts)

Why does a Newton's cradle slowly stop?

6. (5 pts)

Why does a spinning top stay up but a still top falls over?

7. (5 pts)

Predict: two tops weigh the same, but one has its weight near the rim. Which spins longer?

8. (5 pts)

Name one way gyroscopes are used today.

9. (5 pts)

What gave A. C. Gilbert the idea for the Erector set?

10. (5 pts)

Why does a square frame of bolted girders lean, and how do you fix it?

ANSWER KEY

1. One moves the stylus left and right; the other moves it up and down.
2. The stylus scrapes the powder off the inside of the screen, leaving a dark line. Shaking tumbles the powder and beads back over the screen.
3. It may contain glass, and the fine metal powder should not be breathed in or touched.
4. Two balls swing out.
5. A little energy is lost in each click as sound and heat, and the air slows the balls.
6. Spinning makes it resist tipping; instead of falling, its axle slowly circles (precesses). When it slows down, it falls.
7. The one with weight near the rim.
8. Any one: ship gyrocompasses, airplane instruments, spacecraft and telescopes pointing, phone and game-controller sensors.
9. Watching workers put up steel girders for electric railroad lines from a train window.
10. The bolts let the corners turn, so the square folds into a diamond. Add a diagonal brace to make triangles.

PORTFOLIO PIECE: MY OWN TOY: DESIGNED, BUILT AND TESTED

Invent a toy that uses one of the ideas from this unit: strings and pulleys, passing a push, spinning or girders and bolts. Draw a plan, build a prototype from household materials, and test it at least three times with a measurement (how long it spins, how far it rolls, how much it lifts). Make one improvement. Then write a short “toy safety label” listing who the toy is for and any warnings, such as small parts.

LOOK FOR	WHAT IT MEANS
Physics idea	The toy clearly uses one idea from the unit, and the student explains it.
Test and data	At least three trials were measured and recorded with units.
Improvement	One change was made because of the tests, and the new result was recorded.
Safety label	The label names an age range and sensible warnings, such as small parts or sharp points.

9.1 INSIDE THE ETCH A SKETCH: STRINGS, PULLEYS AND TWO KNOBS

OBJECTIVES

- Explain how two knobs can move a point left and right and up and down.
- Explain how strings and pulleys inside the Etch A Sketch move the stylus.
- Build a two-string drawing machine and test how well you can draw straight lines with it.

Warm-up. If you have an Etch A Sketch, draw a square, then a diagonal line, then a circle. Which is hardest? Why? If you do not have one, make a grid on paper and give a partner directions using only “right 3” and “up 2” to draw a shape.

WATCH

What's inside an Etch A Sketch?

What's Inside? • 8:11

<https://www.youtube.com/watch?v=Oloj5W9yFaE>

WHEN TO WATCH

After the story, to see the strings, pulleys and powder.

Note: In this video adults cut an Etch A Sketch open with power tools while wearing masks. Children must never open one: it may contain glass, and the fine metal powder should not be breathed in or touched.

KEY TERMS

stylus

A small pointed tool used to draw or write.

pulley

A wheel with a groove that a string or rope runs over (you met it in Unit 1).

coordinates

Two numbers that tell exactly where a point is: how far across and how far up.

static cling

The way tiny bits of material stick to a surface because of static electricity.

prototype

An early test model of a new product.

CORE IDEAS

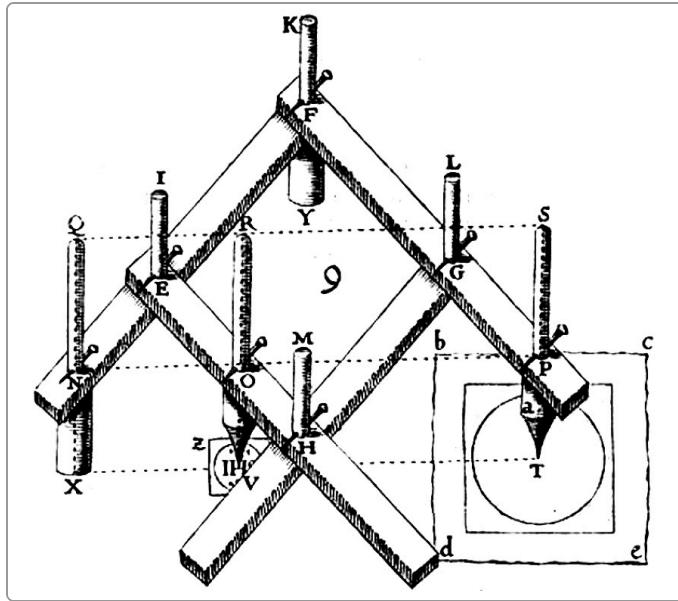
The story. In the late 1950s, a French electrician named André Cassagnes was putting up a light-switch plate when he noticed something odd. Pencil marks he had made on a protective film showed up as clear lines on the other side, where a fine powder had stuck. He realized that a screen coated on the inside with powder could be drawn on by scraping it away from behind. With a partner, Arthur Granjean, he built a drawing toy and showed it at a toy fair in Germany in 1959. The Ohio Art Company bought the idea and began selling it in 1960 as the Etch A Sketch. It became one of the most popular toys ever made.

How they figured it out. The first version moved the stylus with a single joystick. The toy company's engineers changed it to two knobs: one moves the stylus left and right, the other moves it up and down. They had to make it cheap enough to sell, sealed tight so the powder could never leak out, and tough enough to be shaken hard by children. They tested how the strings ran over the pulleys so that the stylus moved smoothly and did not slip.

The physics. Inside the screen, a coating of very fine aluminum powder mixed with tiny plastic beads sticks to the back of the window by **static cling**. A small metal **stylus** under the screen scrapes the powder away, leaving a dark line. The stylus hangs on a set of strings that run over little **pulleys**. Turning the left knob winds the strings to pull the stylus left or right. Turning the right knob pulls it up or down. Any point on the screen can be reached with two numbers, how far across and how far up, called its **coordinates**. A diagonal line needs both knobs at once. Shaking the toy tumbles the beads and powder back over the screen.

The engineering. Toy engineers must think about safety first. The Etch A Sketch is sealed so the powder and beads stay inside, and its frame protects the screen. The same idea of moving a tool across and up and down with motors is used in 3D printers, laser cutters and the machines that carve parts in factories. Engineers call these machines X-Y plotters, after the two directions they move.

PICTURE STUDY



Scheiner's Pantograph, a Drawing Machine, Christoph Scheiner, 1631 · Engraving · From Scheiner's book on the pantograph, printed in Rome

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

Long before the Etch A Sketch, people built machines to help them draw. In 1631, Christoph Scheiner wrote a book about the pantograph, a frame of hinged rods. Trace a picture with one end, and a pen at the other end copies it, larger or smaller.

Look closely

- Find the rods and the pins that join them. Those pins are pivots.
- Find the zigzag shape the rods make. How many diamond shapes can you count?
- Find the end that traces the picture and the end that holds the pen.
- Find where the machine is pinned to the board so it can swing.

Talk about it

1. How is the pantograph like the Etch A Sketch? How is it different?
2. If you move the tracing point to the right, which way does the pen move?
3. What jobs might a machine that copies drawings be useful for?

Safety first. Never break open an Etch A Sketch; it may contain glass, and the metal powder should not be breathed in. Keep markers and small parts away from children under 3.

BUILD

The Two-String Drawing Machine

You will hang a marker from two strings that wind onto two spools at the top corners of a board. By winding one spool or the other, you move the marker, just as the Etch A Sketch knobs pull its stylus. Then you will test how well you can draw straight lines.

You will need

- A large piece of cardboard (at least 50 by 50 centimeters) with a sheet of paper taped to it, propped up against a wall
- Two empty thread spools and two pencils for axles, taped to the top corners
- String, tape and a washable marker
- A small weight, such as a few washers or a lump of clay, taped to the marker so it hangs down
- A ruler and the engineer's notebook

Steps

1. Tape one pencil through a spool at each top corner of the board so the spools can turn. These are your knobs.
2. Tie a string to each spool and wind a little on. Tie both free ends to the marker, so it hangs between them, touching the paper. Add the weight to the marker.
3. Turn the left spool only. Which way does the marker move? Then turn only the right spool. Draw arrows on the paper to record what each one does.
4. **Predict:** what must you do to draw a straight line across the page?
5. **Fair test.** Try to draw three straight lines: one across, one up and down, and one diagonal. Measure how far each line wanders from a ruler laid along it, at its worst spot.
6. Record the results in a table.
7. **Improve it.** Ask a partner to turn one spool while you turn the other. Does working together make straighter lines? Try drawing a simple house.

Tips

- Turn the spools slowly, a little at a time.
- Mark each spool with a line so you can count quarter turns.
- If the marker skips, add more weight or tilt the board back a little.

Check your work

- ☐ I can explain how two strings and two knobs move the marker anywhere on the page.
- ☐ I measured how straight my lines were.
- ☐ I can explain why you should never open an Etch A Sketch.

ENGINEER'S NOTEBOOK

1. Draw how the strings and pulleys inside an Etch A Sketch might look, with arrows for each knob.
2. Draw a picture on graph paper using only across and up moves, and write the coordinates of each corner.
3. Make a table of your three test lines and how far each one wandered.

From history. Some artists have made amazing pictures on an Etch A Sketch, one line at a time, without ever lifting the stylus. To keep a picture, some even carefully remove the knobs and seal the toy so no one can shake it.

COMMON MISTAKES

- Thinking each knob moves the stylus in a circle. Each one pulls it in a straight line.
- Thinking the drawing is ink. It is a path scraped through powder.
- Turning both spools at once when you meant to test only one.

Make it a game • Two Knobs Coordinates. Move a pencil point across a sheet using only two strings, one for left and right and one for up and down. Draw a square in thirty seconds. Say stylus, pulley and coordinates. Explain how the two knobs inside an Etch A Sketch move the stylus. Draw a house and see whose lines are neatest.

9.2 NEWTON'S CRADLE: PASSING THE PUSH

OBJECTIVES

- Describe what happens when one, two or three balls of a Newton's cradle are swung.
- Explain that motion and energy pass through the balls, and why the cradle slowly stops.
- Build a marble "cradle" in a ruler track and fairly test how the number of marbles in and out matches.

Warm-up. Line up five coins touching each other on a smooth table. Slide a sixth coin into the end of the line. What happens? Try sliding two coins at once. Watch closely.

WATCH

The physics behind Newton's cradle!

Sabins · 3:01

<https://www.youtube.com/watch?v=DMRulHySH3c>

WHEN TO WATCH

After the warm-up.

KEY TERMS

Newton's cradle

A desk toy with a row of steel balls hanging on strings; when one ball hits the row, one ball swings out the other end.

collision

When two moving objects bump into each other.

momentum

The push a moving object carries, which depends on how heavy it is and how fast it moves.

energy

The ability to make things move or change.

pendulum

A weight hanging on a string or rod that swings back and forth.

CORE IDEAS

The story. More than three hundred years ago, scientists such as Christiaan Huygens in Holland and Edme Mariotte in France hung balls on strings and let them crash into each other, to learn the rules of collisions. Isaac Newton wrote about these experiments in his book of laws of motion. Hundreds of years later, in 1967, an English actor named Simon Prebble began selling a wooden desk toy with five hanging balls, and he named it Newton's cradle. It became a favorite on desks all over the world.

How they figured it out. The early scientists noticed that when a ball hits an identical ball sitting still, the moving ball stops and the other ball moves off at the same speed. It is as if the push has been handed from one to the other. With a whole row of balls, the push passes through the middle balls, which barely move, and out the far end. The toy makers learned that the balls must be very hard (usually steel), all the same size, and lined up exactly, or the trick does not work well. The strings are hung in a V shape so each ball swings only in one line.

The physics. A moving ball carries **momentum** and **energy**. When it hits the row, it passes them along to the next ball, and that ball passes them on, faster than you can see, until they reach the last ball. That ball has nothing to pass them to, so it swings out. Swing one ball, and one swings out; swing two, and two swing out. The momentum and energy coming in match what goes out. But every click makes a sound and a tiny bit of heat, and the air slows the balls, so a little energy is lost each time. That is why the cradle slowly stops.

The engineering. Toy engineers must make every ball the same size and weight and line them up within a fraction of a millimeter. Steel is used because it is very hard and bounces with little energy lost. Engineers who design cars use the opposite idea: car bumpers and crumple zones are made to squash slowly in a crash, so the energy is soaked up instead of passed on to the people inside. Small balls and marbles are choking hazards, so toys with them carry warnings for children under 3.

PICTURE STUDY



A Newton's Cradle, Photograph by Nysam1 (released to the public domain), 2007 · Photograph
Image: [Wikimedia Commons](#), public domain

This is the familiar desk toy. Look closely at how it is built: each part has a job in making the balls swing straight and hit squarely.

Look closely

- Count the balls. Are they all the same size?
- Follow the strings of one ball. How many strings hold it? What shape do they make?
- Look at where the balls touch. Are there gaps between them?
- Look at the frame. Why does it need to be stiff and heavy?

Talk about it

1. Why does each ball hang from two strings in a V instead of one string?
2. If one ball were bigger than the others, what might happen?
3. Why does the cradle eventually stop?

Safety first. Marbles and small balls are choking hazards. Keep them away from children under 3, and pick them all up when you finish.

BUILD

The Marble Cradle

You will line up marbles in the groove of a ruler (or between two rulers), roll other marbles into the line, and count how many roll out the other end. Then you will try a hanging version.

You will need

- A ruler with a groove down the middle, or two rulers taped side by side with a small gap
- Six or more marbles of the same size, and one larger marble
- Books to make a gentle ramp at one end
- For the hanging version (optional): string, tape, a stick or ruler across two chairs and five equal wooden beads or ping-pong balls
- Engineer's notebook

Steps

1. Lay the ruler flat. Put four marbles in the groove, touching, in the middle.
2. Roll one marble down a short ramp (a book under one end of a second ruler) into the line. Count how many marbles roll off the far end. Do three trials.
3. **Predict:** what will happen if you roll two marbles together? Three?
4. **Fair test.** Roll one, two and three marbles from the same ramp height, three times each. Count how many leave the far end each time. Record the results in a table.
5. **Change one thing.** Roll the larger marble into the line. What happens now?
6. **Improve it (optional).** Build a hanging cradle: hang five beads or ping-pong balls from a stick so they just touch in a straight line. Swing one. Compare how well it works with a real Newton's cradle, and explain what you would change.

Tips

- Make sure the line of marbles is touching, with no gaps.
- Roll from the same spot on the ramp every time for a fair test.
- Ping-pong balls lose more energy than steel balls, so expect a weaker result.

Check your work

- ☐ I found that the number of marbles rolling in matched the number rolling out.
- ☐ I tested what happens with a larger marble.
- ☐ I can explain why Newton's cradle slowly stops.

ENGINEER'S NOTEBOOK

1. Draw a Newton's cradle before and after one ball hits. Use arrows to show the push passing through.
2. Make a table: marbles in, marbles out, for each trial.
3. List three ways energy is lost each time the balls click.

From history. Simon Prebble made his first cradles of wood, and later versions used shiny steel balls. Newton's cradles are now made in every size, from tiny desk toys to giant ones with bowling balls in science museums.

COMMON MISTAKES

- Thinking the middle balls do nothing. They pass the push along; they just barely move.
- Thinking the cradle should go on forever. Sound, heat and air slowly use up its energy.
- Rolling from different heights and calling it a fair test.

Make it a game • Cradle Prediction Duel. Swing one, two and three balls in your Newton's cradle or a row of marbles in a groove. Before each swing, predict how many balls pop out on the other side. Score a point per correct guess. Say collision, momentum and energy. Explain why the cradle slowly stops.

9.3 THE GYROSCOPE TOP: WHY SPINNING THINGS STAY UP

OBJECTIVES

- Explain why a spinning top or gyroscope stays upright while it spins fast.
- Tell how Léon Foucault used a gyroscope and how gyroscopes help ships and airplanes.
- Build a top and fairly test how weight near the rim or near the center changes the spin time.

Warm-up. Try to balance a coin on its edge. Now spin it on its edge. Which is easier? Then roll a coin across the floor. Why doesn't it fall over until it slows down?

WATCH

Gyroscope

ScienceOnline • 5:01

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

WHEN TO WATCH

After the story. Watch the gyroscope balance on a string and on a pencil point.

BACKUP VIDEO

How do gyroscopes really work?

CrunchLabs • 0:52

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

After the build. A one-minute clip with an astronaut spinning a gyroscope in space.

KEY TERMS

gyroscope

A spinning wheel mounted so that its axle can point in any direction; while it spins fast, it holds its direction.

axle

The rod that a wheel or top spins around.

spin

To turn around and around quickly.

precession

The slow, circling wobble of a spinning top's axle as it tilts.

friction

The rubbing force that slows a top where its point touches the floor.

CORE IDEAS

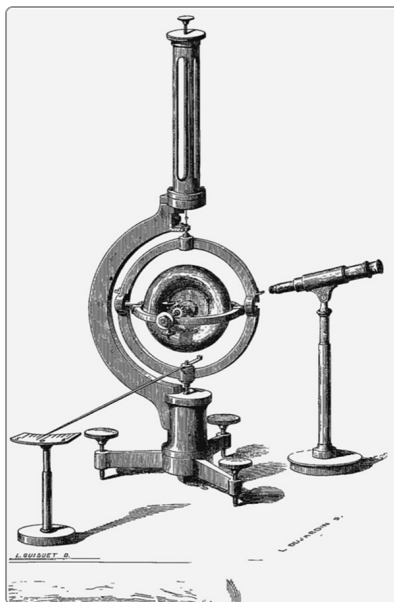
The story. Children have spun tops for thousands of years. In 1852, a French scientist named Léon Foucault built a heavy brass wheel that could spin very fast inside rings that let it tilt any way. He wanted to show that the earth itself is turning. While the wheel spun, its axle kept pointing the same way in space, and the earth slowly turned underneath it. Foucault named his invention the gyroscope, from Greek words meaning “to see the turning.” By the early 1900s, toy gyroscope tops were sold everywhere, and they still amaze people today.

How they figured it out. Foucault knew from Newton’s first law that things keep doing what they are doing unless a force changes them. A spinning wheel keeps spinning in the same direction, and it resists being tipped. The faster it spins and the more of its weight is near its rim, the more stubborn it is. Foucault made his wheel heavy at the rim and spun it fast with a crank and gears. Toy makers do the same: a toy gyroscope has a heavy metal ring and is spun hard with a pull string.

The physics. A spinning top stays up because the spin makes it resist tipping over. When gravity tries to pull it down, instead of falling, the top slowly swings its axle around in a circle. This circling is called **precession**. As **friction** at the point and the air slow the top down, it wobbles more and more, and finally falls. A wheel with its weight near the rim stores more spin than a wheel the same weight with its weight near the middle, so it spins longer.

The engineering. Engineers use gyroscopes to keep track of direction. Ships use gyrocompasses that point north without using magnets. Airplanes have gyroscope instruments that show the pilot which way is level, even inside a cloud. Spacecraft and the Hubble Space Telescope use spinning wheels to turn and to point steadily. Phones and game controllers have tiny sensors also called gyroscopes, which measure turning in a different way, without a spinning wheel. Toy tops must be designed with rounded points and no sharp edges, and pull strings must be short enough to be safe.

PICTURE STUDY



Foucault's Gyroscope, From Camille Flammarion's *Astronomie populaire*, 1880 · Engraving · From Flammarion's book *Astronomie populaire* (Paris)

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

This engraving shows the gyroscope Foucault built in 1852. The heavy wheel in the middle spun very fast, and the rings around it let it tilt any way it wanted.

Look closely

- Find the wheel in the center. Where is most of its metal: at the rim or the middle?
- Find the rings around the wheel. How many are there?
- Find the pivots where each ring can turn.
- Find the stand. Why must it be heavy and steady?

Talk about it

1. Why did Foucault make the wheel heavy at the rim?
2. While the wheel spins, which way does its axle point?
3. How could a gyroscope help a ship or an airplane know which way it is going?

Safety first. Spin tops on the floor, away from faces. A pushed-through pencil point can be sharp; an adult can blunt it with tape or use a short dowel.

BUILD

Spin It Longer: The Rim Weight Test

You will make a top from a paper plate or an old CD and a pencil, then run a fair test: does it spin longer with coins taped near the rim or near the center?

You will need

- Sturdy paper plates or old CDs (all the same), and a short pencil or dowel for each
- Modeling clay to hold the pencil in the hole
- Four pennies and tape
- A stopwatch and a smooth floor
- Engineer's notebook

Steps

1. Push the pencil through the center of the plate (or the CD hole), with about 2 centimeters sticking out below. Hold it in place with clay. Make sure it is straight.
2. Spin the top on the floor by twisting the pencil with your fingers. Time how long it spins until it touches the floor. Do three trials.
3. **Predict:** will coins near the rim or near the center make it spin longer?
4. **Fair test.** Tape four pennies evenly spaced near the center. Spin and time it three times. Then move the same four pennies to near the rim, evenly spaced, and test three more times. Spin the same way each time.
5. Record all the times in a table and find the middle time for each.
6. **Improve it.** Try a lower plate (less pencil below) or a bigger plate. Can you beat your best time? Watch for precession: does the top wobble in a circle as it slows?

Tips

- The same person should spin every time, with the same twist.
- Pennies must be evenly spaced, or the top will wobble and fall quickly.
- A smooth floor works better than a carpet.

Check your work

- ☐ I tested coins near the rim and near the center, three times each.
- ☐ I can explain why weight near the rim helps a top spin longer.
- ☐ I can name two ways gyroscopes help people today.

ENGINEER'S NOTEBOOK

1. Draw your top from above, with the pennies near the rim and near the center.
2. Make a table: penny position, three times, middle time.
3. Draw the path of the pencil's top as the spinning top slows and precesses.

From history. In 1851, a year before his gyroscope, Foucault hung a heavy ball on a very long wire in a great building in Paris. As it swung back and forth for hours, the floor slowly turned beneath it, showing that the earth rotates. Foucault pendulums now swing in science museums around the world.

COMMON MISTAKES

- Thinking a heavier top always spins longer. Where the weight sits matters.
- Spinning harder in one test than another.
- Putting the pennies unevenly, so the top is out of balance.

Make it a game • Spin It Longer. Spin your top and time how long it spins in seconds. Change one thing, like the weight or the axle, and spin again. Beat your best time. Say gyroscope, spin and friction. Explain why a spinning top stays upright and a still one falls. Tell your parent how Foucault used a gyroscope.

9.4 A. C. GILBERT'S ERECTOR SET: BUILDING WITH GIRDERS AND BOLTS

OBJECTIVES

- Tell how A. C. Gilbert invented the Erector set after watching steel girders go up.
- Explain why bolted joints need triangles to make a structure stiff.
- Build cardboard girders with brass-fastener “bolts” and test a square frame, a braced frame and a small crane.

Warm-up. Look for steel girders: on a bridge, a power-line tower, a crane or a playground. What shapes do the holes and the braces make? Sketch one from memory or from a picture.

WATCH

The Story of The A. C. Gilbert Company

Thomas B. Barker • 29:58

<https://www.youtube.com/watch?v=ryokl-gS9mM>

WHEN TO WATCH

Watch the first part, about Gilbert's early life and the invention of the Erector set.

Note: This is a long history film for adults. Watch only the first section, which tells the Erector story with old photographs. The film also mentions Gilbert's first company, which sold trick sets for stage shows; you can skip past that part.

KEY TERMS

girder

A long, strong beam of steel used in buildings, bridges and towers.

bolt and nut

A threaded metal pin and the piece that screws onto it, used to fasten parts together so they can be taken apart again.

modular

Made of standard parts that fit together in many ways.

bracing

Diagonal parts added to a frame to make triangles and keep it from leaning.

crane

A machine with a long arm, ropes and pulleys for lifting heavy loads.

CORE IDEAS

The story. Alfred Carlton Gilbert grew up in Oregon, studied to be a doctor at Yale, and won an Olympic gold medal in the pole vault in 1908. But he loved to make things. In 1911, riding a train between New Haven and New York, he watched workers putting up steel girders to carry the new electric lines for the railroad. He thought: what if boys and girls could build with little steel girders too? In 1913, his company began selling the Erector set, with small steel strips full of holes, nuts, bolts, pulleys and wheels. Children could build bridges, cranes, towers and even Ferris wheels.

How they figured it out. Gilbert built his first models himself out of cardboard, then made metal parts. He wanted the girders to fold into a square box shape so models would look and work like real steel structures. He made the holes evenly spaced so any part could bolt to any other. Later sets added gears and a small electric motor, so children could build machines that really moved. He also wrote instruction books full of ideas and held contests for the best models children invented themselves.

The physics. A frame of four girders bolted at the corners is a square, and a square can lean over into a diamond, because one bolt at each corner lets the girders turn. Add one diagonal girder, and the square becomes two triangles, which cannot change shape. This is the same reason bridges and the Eiffel Tower are made of triangles. Bolts also hold parts together by squeezing them tight, so friction keeps them from slipping.

The engineering. Erector sets are **modular**: a few kinds of standard parts can build thousands of different things. Engineers use the same idea in real buildings, bridges and machines, because standard parts are cheaper to make and easier to fix. Many engineers have said they first learned to build with Erector or Meccano sets. Toy

engineers today make sure the metal edges are smooth and rounded, the small nuts and bolts come with warnings for children under 3, and the tools are easy for small hands to use.

PICTURE STUDY



An Erector Set Advertisement, The A. C. Gilbert Company, 1922 · Printed magazine advertisement · Published in American magazines

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

The A. C. Gilbert Company advertised the Erector set in magazines that children read. Advertisements like this one showed the amazing models that could be built, to make children want to try.

Look closely

- Find the bridge the boys are building. What kind of bridge is it?
- Count the triangles in one side of the bridge.
- Find the man helping the boys. What is he showing them?
- Read the big words of the advertisement with a parent. What does it promise?

Talk about it

1. Why do you think the advertisement shows so many different models?
2. Which model would you want to build first, and why?
3. How is building with an Erector set like being a real engineer?

Safety first. Brass fasteners have points; handle them carefully and keep them, and all small parts, away from children under 3. An adult punches holes in thick cardboard.

BUILD

Cardboard Girders: Square, Brace and Crane

You will make your own girders from strips of cardboard with evenly spaced holes, join them with brass fasteners like nuts and bolts, and test how bracing changes a frame. Then you will build a small crane with a pulley and test how much it can lift.

You will need

- Cereal-box or thin corrugated cardboard cut into strips 2 centimeters wide and 15 and 21 centimeters long
- A hole punch (or an adult with a pencil to poke holes), a ruler and a marker
- Brass paper fasteners
- A thread spool and a pencil for a pulley, string and a paper cup with pennies
- Engineer's notebook

Steps

1. Mark holes along each strip every 2 centimeters, the same on every strip, and punch them. These are your girders.
2. Fasten four 15-centimeter girders into a square with brass fasteners at the corners. Push gently on one corner. What happens?
3. **Predict:** how much stiffer will it be with one diagonal brace?
4. **Fair test.** Lay the square flat with one side taped to the table. Hang the cup from the opposite top corner over the table edge (or press with a rubber-band force meter) and add pennies until the square leans by 2 centimeters. Then add a diagonal brace (a 21-centimeter girder) and test again. Record both.
5. **Build a crane.** Make a tower of braced squares, then bolt on an arm. Put a spool on a pencil at the end of the arm as a pulley, run a string over it, and tie on the cup.

6. Lift pennies by pulling the string. Add pennies 5 at a time until the crane tips or bends. Record the number.
7. **Improve it.** Add more bracing, a wider base or a counterweight on the back of the crane (a few pennies taped there). Test again and record.

Tips

- Evenly spaced holes let any girder fit any other, just like Gilbert's.
- Press the fastener legs flat so the joints stay tight.
- A crane usually tips before it breaks. A counterweight behind the tower helps balance the load.

Check your work

- ☐ I showed that a square frame leans and a braced frame does not.
- ☐ I built a crane with a pulley and measured how much it lifted.
- ☐ I can tell how A. C. Gilbert invented the Erector set.

ENGINEER'S NOTEBOOK

1. Draw your square and your braced frame. Color the triangles.
2. Make a table: frame, pennies to lean 2 centimeters; crane version, pennies lifted.
3. Design a new Erector-style model, such as a bridge, a Ferris wheel or a tower, and draw it with every girder and bolt shown.

From history. Gilbert also made toy trains, chemistry sets and microscope sets, and he believed children learn best by doing. In 1998, the Erector set was in the first group of toys chosen for the National Toy Hall of Fame. Today Erector and Meccano sets are still sold, and engineers often say they started with one.

COMMON MISTAKES

- Thinking more bolts alone make a frame stiff. Without a diagonal, a square still leans.
- Making holes at uneven spacing, so the parts do not line up.
- Forgetting the counterweight, so the crane tips forward.

Make it a game • Girder Bracing Challenge. Build a square from cardboard strips and paper fasteners. Push on it, and see it fold. Add a diagonal and push again. Say girder, bracing and modular. Race the clock to build the tallest braced crane in three minutes, and measure it with a ruler. Tell how A. C. Gilbert invented the Erector set.

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

Toy testing, like all engineering, depends on honest measurement. Record the real number of pennies your crane held, even if it is fewer than you hoped.

TOY LAB: THE PHYSICS OF PLAY

Toys are machines too, and many were invented by engineers. In this optional bonus unit, you will look inside four favorite toys. You will learn how strings and pulleys move the hidden stylus of an Etch A Sketch, why the steel balls of Newton’s cradle pass their motion down the line, why a spinning gyroscope top refuses to fall over, and how A. C. Gilbert’s Erector set taught generations of children to build with girders, nuts and bolts.

Use this unit after the family engineering fair, over the summer, or any week that needs something fun. Every lesson still has a story, the physics, a build and a fair test. And every lesson talks about toy safety, because engineers who design toys must think about the youngest children who might play with them.

PREREQUISITES

- Knows pulleys, gears and levers (Unit 1)
- Knows why triangles are strong (Units 2 and 3)
- Can run a fair test and record three trials

MASTERY CHECKLIST

- ☐ I can explain how two knobs, strings and pulleys can move a point anywhere on a screen.
- ☐ I can explain how Newton’s cradle passes motion and energy through the balls, and why it slowly stops.
- ☐ I can explain why a spinning top or gyroscope stays upright, and test what makes it spin longer.
- ☐ I can build a sturdy structure with girders and bolts and explain why bracing matters.
- ☐ I can name toy-safety rules, such as small parts, magnets and button batteries, and explain why they matter.

OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box:** Ages 8 and up. Monthly toys to build, each with a video by engineer Mark Rober explaining the physics inside. A great fit for this whole unit.
- **Meccano (Erector) construction sets:** Ages vary by set (usually 8 and up). Metal and plastic girders, nuts, bolts and tools, the modern version of the Erector set in Lesson 9.4.
- **KiwiCo Tinker Crate:** Ages 9 and up, with a parent. Many crates are working toys with gears, springs and spinning parts.

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 Inside the Etch A Sketch: Strings, Pulleys and Two Knobs 2 sessions of 45 minutes

9.2 Newton's Cradle: Passing the Push 2 sessions of 45 minutes

9.3 The Gyroscope Top: Why Spinning Things Stay Up 2 sessions of 45 minutes

9.4 A. C. Gilbert's Erector Set: Building with Girders and Bolts

2 sessions of 45 minutes

UNIT 9 REVIEW

Answer each question in a sentence or two, or draw and label a picture. Your teacher may read the questions aloud. The review is worth 50 points.

1. **5 pts**

What do the two knobs on an Etch A Sketch do?

2. **5 pts**

How does the Etch A Sketch draw a line, and how does shaking erase it?

3. **5 pts**

Why should you never break open an Etch A Sketch?

4. (5 pts)

Predict: you swing two balls of a Newton's cradle into the row. What happens at the other end?

5. (5 pts)

Why does a Newton's cradle slowly stop?

6. (5 pts)

Why does a spinning top stay up but a still top falls over?

7. (5 pts)

Predict: two tops weigh the same, but one has its weight near the rim. Which spins longer?

8. (5 pts)

Name one way gyroscopes are used today.

9. (5 pts)

What gave A. C. Gilbert the idea for the Erector set?

10. (5 pts)

Why does a square frame of bolted girders lean, and how do you fix it?

ANSWER KEY

1. One moves the stylus left and right; the other moves it up and down.
2. The stylus scrapes the powder off the inside of the screen, leaving a dark line. Shaking tumbles the powder and beads back over the screen.
3. It may contain glass, and the fine metal powder should not be breathed in or touched.
4. Two balls swing out.
5. A little energy is lost in each click as sound and heat, and the air slows the balls.
6. Spinning makes it resist tipping; instead of falling, its axle slowly circles (precesses). When it slows down, it falls.
7. The one with weight near the rim.
8. Any one: ship gyrocompasses, airplane instruments, spacecraft and telescopes pointing, phone and game-controller sensors.
9. Watching workers put up steel girders for electric railroad lines from a train window.
10. The bolts let the corners turn, so the square folds into a diamond. Add a diagonal brace to make triangles.

PORTFOLIO PIECE: MY OWN TOY: DESIGNED, BUILT AND TESTED

Invent a toy that uses one of the ideas from this unit: strings and pulleys, passing a push, spinning or girders and bolts. Draw a plan, build a prototype from household materials, and test it at least three times with a measurement (how long it spins, how far it rolls, how much it lifts). Make one improvement. Then write a short “toy safety label” listing who the toy is for and any warnings, such as small parts.

LOOK FOR	WHAT IT MEANS
Physics idea	The toy clearly uses one idea from the unit, and the student explains it.
Test and data	At least three trials were measured and recorded with units.
Improvement	One change was made because of the tests, and the new result was recorded.
Safety label	The label names an age range and sensible warnings, such as small parts or sharp points.