

# GRADE 6 ENGINEERING & PHYSICS

**First edition**

8 units

32 lessons + Toy Lab

A video for every lesson

FIRST EDITION

## COURSE GUIDE

This course follows the same eight strands of engineering as the earlier grades, forces and motion, bridges, architecture, electricity, public utilities, boats and ships, flight, and robots, but now the student begins to work with real equations. Speed is distance divided by time. Force equals mass times acceleration. Density is mass divided by volume. Voltage equals current times resistance. Each formula is introduced through the person who needed it, worked once with real numbers and units, and then used in the build.

Every lesson follows the same path. First comes **the story**: Galileo timing balls on a ramp, Robert Stephenson testing model tubes for the Britannia Bridge, Christopher Wren and Robert Hooke shaping the dome of St Paul's, Georg Ohm measuring current, Samuel Plimsoll fighting for a line on the side of every ship, Charles Lindbergh crossing the Atlantic by compass and clock, Robert Goddard launching the first liquid-fueled rocket. Then **how they figured it out, the physics** underneath, and **the engineering** that turns the idea into something safe and useful. Last, the student repeats the discovery in miniature, measures it, calculates from the data, and improves the design in a second round.

God made an orderly world that can be measured and described with numbers, and He made people in His image to be makers. Engineering, rightly done, is a way of loving our neighbors: a bridge that is inspected and kept safe, water that is clean, a light in a dark room. The old Latin saying *Fabricando fit faber*, “by making, one becomes a maker,” is the whole method of this course.

Most videos come from museums and trusted teaching channels: NASA, the Smithsonian, Practical Engineering, The Engineering Mindset, Jared Owen, Lesics, Steve Mould and a few others chosen lesson by lesson. Every video was checked in preview for content and accuracy. Some channels end with a short sponsor message or an

invitation to subscribe; you can stop the video when the teaching ends, and the lesson's note says so where it matters. Watch together when you can, and pause when the lesson tells you to predict or to work a number before the video does.

**Start with Lesson 1.1 →**

## WHO IT IS FOR

Written for students in grade 6 (about ages 11–12) who read independently and can multiply and divide decimals, work with fractions and simple ratios, and measure in metric units. 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, plus an inexpensive digital multimeter for Unit 4. 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 50 minutes) is the warm-up, the video, the teaching and the picture study. Session 2 (about 50 minutes) is the build and the engineer's notebook. In the last week of each unit, add a third session for the unit review and the portfolio build.
2. **Story, then physics, then engineering.** The core ideas are written for the student to read, with a parent reading along. The paragraphs marked *The story* and *How they figured it out* tell what happened; *The physics* explains why it works, usually with one equation worked out with real numbers; *The engineering* explains how people turn that idea into a real, safe thing. After each paragraph, ask the student to tell it back in his or her own words, and to rework the number with a different value.
3. **Equations and units.** Every calculation in this course is written with its units: meters, seconds, newtons, kilograms, watts, ohms. Insist on the units in the notebook. Most mistakes in real engineering come from mixed-up units, not from bad arithmetic. A calculator is fine once the student can set up the problem.
4. **Picture study.** Each lesson has one historic photograph, drawing, patent or painting. Look at it quietly for two minutes. Then put it away and have the student tell everything he or she remembers. Bring it back and work through the “look

for” items and questions, which point to the physics and engineering in the picture.

5. **The engineer’s notebook.** Use a graph-paper composition book for the whole year. For every build, write a prediction first, then record measurements in a table with units, then calculate, graph where it helps, and write what happened and what you would change. Date every page. Honest records matter more than perfect results: “a just weight is his delight” (Proverbs 11:1).
6. **Fair tests and improvement.** Most builds change only one variable at a time and repeat each trial at least three times, then average. Every build ends with an “improve it” round. A design that fails and is then improved has taught more than one that worked the first time.
7. **Optional kits.** Some units list kits such as a BBC micro:bit, an Arduino starter kit, a Pitsco balsa bridge kit or an Estes model rocket. They are extras for families who enjoy them. Every lesson can be completed without them.
8. **Unit review and portfolio.** Each unit ends with a review worth 100 points, with two or three short calculations and one or two written explanations, and a portfolio build that pulls the unit together. Keep the portfolio pages and photographs in a folder for the year.
9. **Safety.** Read the safety box before each build. Electricity in this course comes only from AA, C, D or 9-volt batteries and USB-powered boards, never from the outlets in the wall. An adult handles hot glue guns, craft knives and drills. Wear safety glasses for anything that flies, snaps or is under tension, including water rockets and load tests.
10. **The Toy Lab (optional).** Unit 9 is a bonus unit on the physics and design of toys: pull-back cars, the drinking bird, radio-controlled cars and toy safety testing. Use it after the family engineering fair, over the summer, or in any week that needs something fun. It has the same lessons, review and portfolio as the other units.
11. **The family engineering fair.** In the last week, set out the best build from each unit with its notebook pages and let the student explain them to family and guests, including one calculation from the data. Explaining your work clearly is part of being an engineer.

# SCOPE AND SEQUENCE

## UNIT 1 • WEEKS 1–4

### Motion

Speed, velocity and acceleration with Stephenson's *Rocket*; Newton's laws with numbers ( $F = ma$ ); friction and Galileo's inclined plane; and work, power and James Watt's horsepower.

- 1.1 Speed, Velocity and Acceleration: Stephenson's Rocket
- 1.2 Newton's Laws with Numbers:  $F = ma$
- 1.3 Friction and Galileo's Inclined Plane
- 1.4 Work, Power and Watt's Horsepower

## UNIT 3 • WEEKS 9–12

### Architecture

Architectural drawing in plan, elevation and scale; Vitruvius's firmness, commodity and delight; the great domes of the Pantheon, Hagia Sophia and St Paul's; and the hidden systems inside a skyscraper.

- 3.1 Architectural Drawing: Plan, Elevation and Scale
- 3.2 Vitruvius: Firmness, Commodity and Delight
- 3.3 Great Domes: The Pantheon, Hagia Sophia and Wren's St Paul's
- 3.4 The Systems Inside a Skyscraper: Elevators, Water and Air

## UNIT 2 • WEEKS 5–8

### Bridges

Bending and the I-beam, learned from the Britannia Bridge tests; arch bridges from Rome to James Eads's steel arches at St. Louis; cable-stayed versus suspension bridges; and how inspectors keep old bridges safe.

- 2.1 Bending and the I-Beam: Stephenson's Britannia Bridge
- 2.2 Arch Bridges from Rome to Eads
- 2.3 Cable-Stayed versus Suspension: Telford's Menai Bridge
- 2.4 Bridge Inspection and Maintenance: The Silver Bridge

## UNIT 4 • WEEKS 13–16

### Electricity

Ohm's law measured with a multimeter; series and parallel circuits calculated and tested; Faraday, motors and generators; and first programs on a micro:bit or Arduino.

- 4.1 Ohm's Law with a Multimeter
- 4.2 Series and Parallel: Edison's Pearl Street Station
- 4.3 Faraday, Motors and Generators
- 4.4 First Steps with a Microcontroller: Making an LED Blink



## UNIT 5 • WEEKS 17–20

### Public Utilities

Water treatment by coagulation, filtration and disinfection; pumps, pressure and water towers; how power plants make electricity, compared as engineering trade-offs; and communication from the telegraph to fiber optics.

- 5.1 Water Treatment: Coagulation, Filtration and Disinfection
- 5.2 Pumps, Pressure and Water Towers: The Fairmount Water Works
- 5.3 How Power Plants Make Electricity: Parsons’s Turbine and the Trade-offs
- 5.4 From Telegraph to Telephone to Fiber Optics: Colladon’s Light Fountain

## UNIT 7 • WEEKS 25–28

### Flight

Lift as pressure difference and turned air, measured on a kitchen-scale wind tunnel; control surfaces; Lindbergh’s flight and dead-reckoning navigation; and Robert Goddard and the physics of rockets.

- 7.1 Lift: Pressure and Turning the Air
- 7.2 Control Surfaces: Ailerons, Elevator and Rudder
- 7.3 Lindbergh and Navigation: Dead Reckoning Across the Atlantic
- 7.4 Goddard and Rockets: The First Liquid-Fueled Flight

## UNIT 6 • WEEKS 21–24

### Boats and Ships

Density and displacement with numbers; stability and the Plimsoll line; propulsion by oar, sail, paddle, screw and jet; and submarines, ballast and the bathyscaphe *Trieste*, with a Cartesian diver.

- 6.1 Density and Displacement with Numbers: Why an Iron Ship Floats
- 6.2 Stability and the Plimsoll Line
- 6.3 Propulsion: Oar, Sail, Paddle, Screw and Jet
- 6.4 Submarines and Ballast: The Trieste and a Cartesian Diver

## UNIT 8 • WEEKS 29–32

### Robots, Coding and Invention

Motors and gear ratios in robots; loops and conditionals from Ada Lovelace to MakeCode; distance sensors and the speed of sound; and drone basics with the FAA’s rules, ending with the family engineering fair.

- 8.1 Motors and Gears: The Lunar Roving Vehicle
- 8.2 Loops and Conditionals: From Ada Lovelace to MakeCode
- 8.3 Distance Sensors: Echoes and the Speed of Sound
- 8.4 Drone Basics and the FAA’s Rules: Ingenuity on Mars

## UNIT 9 • WEEKS 33–36

### Toy Lab: The Physics of Play

Optional bonus unit, the Toy Lab: stored energy and gear trains in rubber-band and pull-back cars; the drinking bird as a heat engine; radio control from Tesla's 1898 boat to the RC car; and toy safety engineering with the small-parts cylinder and drop tests.

**9.1** Rubber-Band and Pull-Back Cars: Stored Energy and Gear Trains

**9.2** The Drinking Bird: A Toy Heat Engine

**9.3** Radio-Controlled Cars: From Tesla's Boat to Your Floor

**9.4** Toy Safety Engineering: The Small-Parts Cylinder and the Drop Test

## WEEKLY PACING CALENDAR

| WEEK | PLAN                                                                                                                                                                                                                                                                                                                                                                                                         |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1    | <ul style="list-style-type: none"><li>• Session 1: Lesson 1.1 Speed, Velocity and Acceleration: Stephenson's Rocket: warm-up, video, teaching and picture study</li><li>• Session 2: Lesson 1.1 build project and engineer's notebook</li></ul> <p><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></p> |
| 2    | <ul style="list-style-type: none"><li>• Session 1: Lesson 1.2 Newton's Laws with Numbers: <math>F = ma</math>: warm-up, video, teaching and picture study</li><li>• Session 2: Lesson 1.2 build project and engineer's notebook</li></ul>                                                                                                                                                                    |
| 3    | <ul style="list-style-type: none"><li>• Session 1: Lesson 1.3 Friction and Galileo's Inclined Plane: warm-up, video, teaching and picture study</li><li>• Session 2: Lesson 1.3 build project and engineer's notebook</li></ul>                                                                                                                                                                              |
| 4    | <ul style="list-style-type: none"><li>• Session 1: Lesson 1.4 Work, Power and Watt's Horsepower: warm-up, video, teaching and picture study</li><li>• Session 2: Lesson 1.4 build project and engineer's notebook</li><li>• Session 3: Unit 1 review and portfolio project</li></ul>                                                                                                                         |

| WEEK | PLAN                                                                                                                                                                                                                                                                                                             |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 5    | <ul style="list-style-type: none"> <li>• Session 1: Lesson 2.1 Bending and the I-Beam: Stephenson's Britannia Bridge: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 2.1 build project and engineer's notebook</li> </ul>                                                               |
| 6    | <ul style="list-style-type: none"> <li>• Session 1: Lesson 2.2 Arch Bridges from Rome to Eads: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 2.2 build project and engineer's notebook</li> </ul>                                                                                      |
| 7    | <ul style="list-style-type: none"> <li>• Session 1: Lesson 2.3 Cable-Stayed versus Suspension: Telford's Menai Bridge: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 2.3 build project and engineer's notebook</li> </ul>                                                              |
| 8    | <ul style="list-style-type: none"> <li>• Session 1: Lesson 2.4 Bridge Inspection and Maintenance: The Silver Bridge: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 2.4 build project and engineer's notebook</li> <li>• Session 3: Unit 2 review and portfolio project</li> </ul>      |
| 9    | <ul style="list-style-type: none"> <li>• Session 1: Lesson 3.1 Architectural Drawing: Plan, Elevation and Scale: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 3.1 build project and engineer's notebook</li> </ul>                                                                    |
| 10   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 3.2 Vitruvius: Firmness, Commodity and Delight: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 3.2 build project and engineer's notebook</li> </ul>                                                                          |
| 11   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 3.3 Great Domes: The Pantheon, Hagia Sophia and Wren's St Paul's: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 3.3 build project and engineer's notebook</li> </ul>                                                        |
| 12   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 3.4 The Systems Inside a Skyscraper: Elevators, Water and Air: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 3.4 build project and engineer's notebook</li> <li>• Session 3: Unit 3 review and portfolio project</li> </ul> |
| 13   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 4.1 Ohm's Law with a Multimeter: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 4.1 build project and engineer's notebook</li> </ul>                                                                                         |
|      |                                                                                                                                                                                                                                                                                                                  |

| WEEK | PLAN                                                                                                                                                                                                                                                                                                                          |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 14   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 4.2 Series and Parallel: Edison's Pearl Street Station: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 4.2 build project and engineer's notebook</li> </ul>                                                                               |
| 15   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 4.3 Faraday, Motors and Generators: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 4.3 build project and engineer's notebook</li> </ul>                                                                                                   |
| 16   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 4.4 First Steps with a Microcontroller: Making an LED Blink: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 4.4 build project and engineer's notebook</li> <li>• Session 3: Unit 4 review and portfolio project</li> </ul>                |
| 17   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 5.1 Water Treatment: Coagulation, Filtration and Disinfection: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 5.1 build project and engineer's notebook</li> </ul>                                                                        |
| 18   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 5.2 Pumps, Pressure and Water Towers: The Fairmount Water Works: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 5.2 build project and engineer's notebook</li> </ul>                                                                      |
| 19   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 5.3 How Power Plants Make Electricity: Parsons's Turbine and the Trade-offs: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 5.3 build project and engineer's notebook</li> </ul>                                                          |
| 20   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 5.4 From Telegraph to Telephone to Fiber Optics: Colladon's Light Fountain: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 5.4 build project and engineer's notebook</li> <li>• Session 3: Unit 5 review and portfolio project</li> </ul> |
| 21   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 6.1 Density and Displacement with Numbers: Why an Iron Ship Floats: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 6.1 build project and engineer's notebook</li> </ul>                                                                   |
| 22   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 6.2 Stability and the Plimsoll Line: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 6.2 build project and engineer's notebook</li> </ul>                                                                                                  |

| WEEK | PLAN                                                                                                                                                                                                                                                                                                             |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 23   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 6.3 Propulsion: Oar, Sail, Paddle, Screw and Jet: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 6.3 build project and engineer's notebook</li> </ul>                                                                        |
| 24   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 6.4 Submarines and Ballast: The Trieste and a Cartesian Diver: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 6.4 build project and engineer's notebook</li> <li>• Session 3: Unit 6 review and portfolio project</li> </ul> |
| 25   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 7.1 Lift: Pressure and Turning the Air: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 7.1 build project and engineer's notebook</li> </ul>                                                                                  |
| 26   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 7.2 Control Surfaces: Ailerons, Elevator and Rudder: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 7.2 build project and engineer's notebook</li> </ul>                                                                     |
| 27   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 7.3 Lindbergh and Navigation: Dead Reckoning Across the Atlantic: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 7.3 build project and engineer's notebook</li> </ul>                                                        |
| 28   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 7.4 Goddard and Rockets: The First Liquid-Fueled Flight: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 7.4 build project and engineer's notebook</li> <li>• Session 3: Unit 7 review and portfolio project</li> </ul>       |
| 29   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 8.1 Motors and Gears: The Lunar Roving Vehicle: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 8.1 build project and engineer's notebook</li> </ul>                                                                          |
| 30   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 8.2 Loops and Conditionals: From Ada Lovelace to MakeCode: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 8.2 build project and engineer's notebook</li> </ul>                                                               |
| 31   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 8.3 Distance Sensors: Echoes and the Speed of Sound: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 8.3 build project and engineer's notebook</li> </ul>                                                                     |
|      |                                                                                                                                                                                                                                                                                                                  |

| WEEK | PLAN                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 32   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 8.4 Drone Basics and the FAA's Rules: Ingenuity on Mars: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 8.4 build project and engineer's notebook</li> <li>• Session 3: Unit 8 review and portfolio project</li> </ul> <p><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></p> |
| 33   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 9.1 Rubber-Band and Pull-Back Cars: Stored Energy and Gear Trains: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 9.1 build project and engineer's notebook</li> </ul> <p><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></p>                                                                                    |
| 34   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 9.2 The Drinking Bird: A Toy Heat Engine: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 9.2 build project and engineer's notebook</li> </ul>                                                                                                                                                                                                                                                         |
| 35   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 9.3 Radio-Controlled Cars: From Tesla's Boat to Your Floor: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 9.3 build project and engineer's notebook</li> </ul>                                                                                                                                                                                                                                       |
| 36   | <ul style="list-style-type: none"> <li>• Session 1: Lesson 9.4 Toy Safety Engineering: The Small-Parts Cylinder and the Drop Test: warm-up, video, teaching and picture study</li> <li>• Session 2: Lesson 9.4 build project and engineer's notebook</li> <li>• Session 3: Unit 9 review and portfolio project</li> </ul>                                                                                                                                                                 |

## MATERIALS

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

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

### **Meter stick or tape measure, ruler, protractor and a kitchen scale that reads in grams**

Measuring is the heart of every build.

### **Smartphone stopwatch (a slow-motion camera mode helps)**

For timing carts, ramps, stair climbs, rockets and echoes.

### **Cardboard, card stock, file folders, paper, masking tape, clear tape and white glue**

The main building materials all year.

**Craft sticks (about 200), straws, wooden skewers, string, rubber bands and a toy car or small cart**

For beams, arches, cable models and motion tests.

**About 200 pennies, paper cups, metal washers and a small bucket or zip-top bag**

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

**An inexpensive digital multimeter**

For measuring voltage, current and resistance in Unit 4 and the generator test.

About the price of a book at a hardware store.

**AA and 9-volt batteries with holders or snaps, alligator clip leads, red LEDs, resistors (100, 220, 470 and 1,000 ohms) and a small hobby motor with a propeller**

For Unit 4 and the turbine, motor and thrust tests. Batteries only; never the outlets in the wall.

**Magnet wire (about 22–26 gauge), strong ceramic or neodymium magnets, a compass and fine sandpaper**

For the generator build. Keep strong magnets away from small children.

**Clear plastic bottles, a plastic tub or sink, a measuring cup, aluminum foil, modeling clay and table salt**

For the water, pressure, boat, Plimsoll-line and Cartesian-diver builds.

**Alum (from the spice aisle), coffee filters, sand and gravel**

For the water-treatment jar test in Unit 5. Never drink the treated water.

**A box fan**

The “wind tunnel” for the lift and turbine tests.

**A 2-liter soda bottle, a cork or rubber stopper, a needle inflation adapter and a bicycle pump**

For the water-rocket build in Unit 7, outdoors with an adult and safety glasses.

**Free software: Microsoft MakeCode ([makecode.microbit.org](https://makecode.microbit.org)) or Scratch ([scratch.mit.edu](https://scratch.mit.edu))**

For the coding lessons in Units 4 and 8. MakeCode’s on-screen simulator works without a board.

**Safety glasses**

For load tests, rubber bands, rockets and anything else that can snap or fly.

**Optional: one kit, such as a BBC micro:bit, an Arduino starter kit or a balsa bridge kit**

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, measuring and recording. In grade 6 the notebook also counts the calculations: a correct number with its units, worked from the student's own data. A build that fails but is honestly recorded and then improved earns full credit.

| PART                                                                                 | %  |
|--------------------------------------------------------------------------------------|----|
| Builds (effort, fair testing and the improve round)                                  | 35 |
| Engineer's notebook (predictions, data tables, calculations with units, conclusions) | 25 |
| Unit reviews                                                                         | 15 |
| Portfolio builds                                                                     | 25 |

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

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

## A NOTE TO PARENTS

You do not need to be an engineer to teach this course. Read the story together, watch the video, and then be the student's assistant at the build: hold the meter



stick, run the stopwatch, 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. When an equation appears, ask the student to explain what each letter stands for and what units it carries before doing any arithmetic.

Expect things to fail. Beams will sag, gliders will dive, circuits will refuse to light and rockets will veer. Robert Goddard’s first liquid-fueled rocket flew for two and a half seconds; Georg Ohm’s first measurements did not fit his idea. The course is built to show that failure, carefully studied, is how engineers learn. Praise careful testing and honest records more than a winning result. *Fabricando fit faber*: by making, one becomes a maker.

Some lessons tell of disasters, such as the collapse of the Silver Bridge and the overloaded ships that led to the Plimsoll line. They are told plainly and briefly, with the focus on what engineers learned and changed so that others would be safe.

## UNIT 1

# MOTION

Every machine, bridge, ship and airplane in this course obeys the same few rules of motion. In this unit you will learn to describe motion with numbers: speed, velocity and acceleration, measured the way the judges measured Stephenson's *Rocket* in 1829. You will meet Isaac Newton's three laws and use the most useful equation in engineering,  $F = ma$ , to predict how hard something must be pushed to speed it up.

Then you will roll balls down a ramp as Galileo did, discovering that a falling object gains speed in a steady pattern, and measure the friction that fights every moving part. Last, you will learn how James Watt measured the work of a horse so that he could sell steam engines, and you will measure your own horsepower on a flight of stairs. Throughout the unit, every number you write will carry its units.

### PREREQUISITES

- Can multiply and divide decimals and round sensibly
- Can measure in centimeters and meters and time with a stopwatch
- Knows that a force is a push or a pull, and keeps a dated engineer's notebook

### MASTERY CHECKLIST

- ☐ I can calculate speed, velocity and acceleration from measured distances and times, with units.
- ☐ I can state Newton's three laws and use  $F = ma$  to find a force, a mass or an acceleration.
- ☐ I can describe Galileo's inclined-plane experiment and measure a coefficient of friction.
- ☐ I can calculate work and power in joules and watts and convert watts to horsepower.
- ☐ I can run a fair test with repeated trials, average the results and graph them.

## OPTIONAL KITS FOR THIS UNIT

- **LEGO Education:** Ages vary by set. LEGO Education's science and engineering sets include carts, gears and motors that can replace the toy car and winch in Lessons 1.1, 1.2 and 1.4. Check the age range of each set.
- **K'NEX building sets:** Ages vary by set. Rods, wheels and pulleys for building carts and winches to measure speed, force and power. Fits Lessons 1.1–1.4.

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

## LESSONS IN THIS UNIT

|     |                                                       |                          |
|-----|-------------------------------------------------------|--------------------------|
| 1.1 | Speed, Velocity and Acceleration: Stephenson's Rocket | 2 sessions of 50 minutes |
| 1.2 | Newton's Laws with Numbers: $F = ma$                  | 2 sessions of 50 minutes |
| 1.3 | Friction and Galileo's Inclined Plane                 | 2 sessions of 50 minutes |
| 1.4 | Work, Power and Watt's Horsepower                     | 2 sessions of 50 minutes |

## UNIT 1 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

What is the difference between speed and velocity? Give an example of two objects with the same speed but different velocities.

2. 10 pts

Calculate: a train travels 4,800 meters in 400 seconds. What is its average speed in m/s?

3. 10 pts

Calculate: a bicycle speeds up from 2 m/s to 8 m/s in 3 seconds. What is its acceleration?

4. **8 pts**

State Newton's first law and give one example of it from a car or a train.

5. **10 pts**

Calculate: what net force is needed to accelerate a 1,500-kilogram car at  $2 \text{ m/s}^2$ ?

6. **8 pts**

A rocket pushes hot gas downward out of its nozzle. Which of Newton's laws explains why the rocket goes up? Explain.

7. **8 pts**

How did Galileo measure time when he rolled balls down his ramp, and why did he use a ramp instead of dropping the ball?

8. **8 pts**

Predict: a ball rolls from rest down a ramp and travels 5 cm in the first second. How far from the start will it be after 3 seconds?

9. **6 pts**

A block begins to slide when a board is raised 20 cm over a run of 80 cm. What is the coefficient of friction?

10. **10 pts**

Calculate: a 40-kilogram student climbs stairs 3 meters high in 5 seconds. Find the work done and the power. (Use  $9.8 \text{ m/s}^2$  for gravity.)

11. **6 pts**

Why did James Watt invent the horsepower?

12. **8 pts**

Explain in two or three sentences why engineers always write units with their numbers.

## ANSWER KEY

1. Speed is how fast something moves (distance  $\div$  time). Velocity is speed in a particular direction. Two cars each going 20 m/s, one north and one south, have the same speed but different velocities.
2. Speed = distance  $\div$  time = 4,800 m  $\div$  400 s = 12 m/s.
3. Acceleration = change in velocity  $\div$  time = (8 – 2) m/s  $\div$  3 s = 2 m/s<sup>2</sup>.
4. An object stays at rest or keeps moving at the same velocity unless a net force acts on it. Example: passengers lurch forward when a train brakes, because their bodies keep moving.
5.  $F = ma = 1,500 \text{ kg} \times 2 \text{ m/s}^2 = 3,000 \text{ N}$ .
6. The third law. The rocket pushes the gas down, and the gas pushes the rocket up with an equal and opposite force.
7. He let water flow from a vessel into a cup while the ball rolled and weighed the water. He used a gentle ramp to slow the motion down so it could be timed; a dropped ball falls too fast.
8. Distance grows with the square of time:  $3^2 = 9$ , so  $9 \times 5 \text{ cm} = 45 \text{ cm}$ .
9.  $\mu = \text{rise} \div \text{run} = 20 \div 80 = 0.25$ .
10. Weight =  $40 \times 9.8 = 392 \text{ N}$ . Work =  $392 \text{ N} \times 3 \text{ m} = 1,176 \text{ J}$ . Power =  $1,176 \text{ J} \div 5 \text{ s} \approx 235 \text{ W}$  (about 0.3 horsepower).
11. To tell customers who used horses how many horses one of his steam engines could replace, so they could compare and buy.
12. A number without units can be read wrongly (meters or centimeters, kilograms or pounds), and a mix-up can make a part too weak or a calculation badly wrong. Units also let you check that an equation makes sense.

## PORTFOLIO PIECE: A MEASURED MOTION REPORT

Choose one moving thing you can test safely, such as a toy car on a ramp, a rubber-band cart or a bicycle coasting down a gentle driveway with an adult watching. Measure its speed in two places and its acceleration, with at least three trials at each setting, and change one variable (height, mass or pulling force). Write a one-page engineer's report with a labeled sketch, a data table with units, at least two worked calculations, a graph, and a paragraph explaining your results with Newton's laws.

| LOOK FOR                     | WHAT IT MEANS                                                                              |
|------------------------------|--------------------------------------------------------------------------------------------|
| <b>Fair test</b>             | Only one variable changed; at least three trials at each setting, averaged.                |
| <b>Measurement and units</b> | Distances and times measured carefully; every number in the table has its units.           |
| <b>Calculations</b>          | Speed and acceleration calculated correctly from the data, with the work shown.            |
| <b>Explanation</b>           | Results explained using at least one of Newton's laws and the word acceleration correctly. |
| <b>Improvement</b>           | One source of error identified and a specific way to reduce it proposed or tested.         |

# 1.1 SPEED, VELOCITY AND ACCELERATION: STEPHENSON'S ROCKET

## OBJECTIVES

- Calculate average speed from a measured distance and time, in meters per second.
- Explain the difference between speed and velocity, and calculate acceleration.
- Measure the speed of a toy car in two parts of a ramp run and calculate its acceleration.

**Warm-up.** Walk 10 meters at an ordinary pace while someone times you. Then walk it again as fast as you safely can. Before you calculate anything, guess your speed in meters per second for each walk and write the guesses down.

## WATCH

### What Are Speed and Velocity? | Physics in Motion

GPB Education • 8:23

<https://www.youtube.com/watch?v=R8m9VJfwYrc>

## WHEN TO WATCH

After the physics paragraph. Pause when the presenter shows the distance and time for the car, and work out the speed yourself before she does.

## BACKUP VIDEO

### Sans Pareil: Rocket's Rainhill Rival | Curator with a Camera

National Railway Museum • 11:03

<https://www.youtube.com/watch?v=ACPqym3islw>

After the story, to see Rocket's rival Sans Pareil up close with a museum curator.

## KEY TERMS

### speed

How far something travels in a unit of time: distance ÷ time. Measured in meters per second (m/s), kilometers per hour or miles per hour.

### velocity

Speed in a particular direction, such as 8 m/s east.

**acceleration**

How quickly velocity changes: change in velocity  $\div$  time. Measured in meters per second per second ( $\text{m/s}^2$ ).

**average speed**

The total distance divided by the total time, even if the object sped up and slowed down along the way.

**locomotive**

An engine on wheels that pulls a train; in 1829, a steam engine on rails.

**CORE IDEAS**

**The story.** In 1829 the directors of the new Liverpool and Manchester Railway had a problem. Their line was nearly built, but they could not agree whether trains should be pulled by locomotives or by ropes wound in by steam engines standing beside the track. So they held a contest: the Rainhill Trials, in October 1829. A prize of £500 would go to the locomotive that could pull a load three times its own weight at an average of at least 10 miles per hour, back and forth over a level stretch of track, again and again, without breaking down. Five engines entered. Only one finished: *Rocket*, built by George Stephenson and his son Robert at their works in Newcastle.

**How they figured it out.** The judges did not trust anyone's boasting. They marked a measured course on the track, timed each run with watches, and divided distance by time to find each engine's speed. *Rocket* averaged about 12 miles per hour pulling its load, and running on its own it reached about 30 miles per hour, faster than anyone had traveled on land. Its rivals failed for reasons engineers could study: *Sans Pareil* cracked a cylinder and *Novelty* kept breaking pipes in its boiler. Robert Stephenson had won with two improvements: a boiler with 25 copper tubes carrying hot gas through the water, which made steam much faster, and a blast pipe that sent used steam up the chimney to draw the fire hotter. Measurement, not opinion, settled the question, and nearly every steam locomotive built afterward used the same ideas.

**The physics.** **Speed** is distance divided by time. If a train covers 2,400 meters in 300 seconds, its average speed is  $2,400 \text{ m} \div 300 \text{ s} = 8 \text{ m/s}$ , about 18 miles per hour.

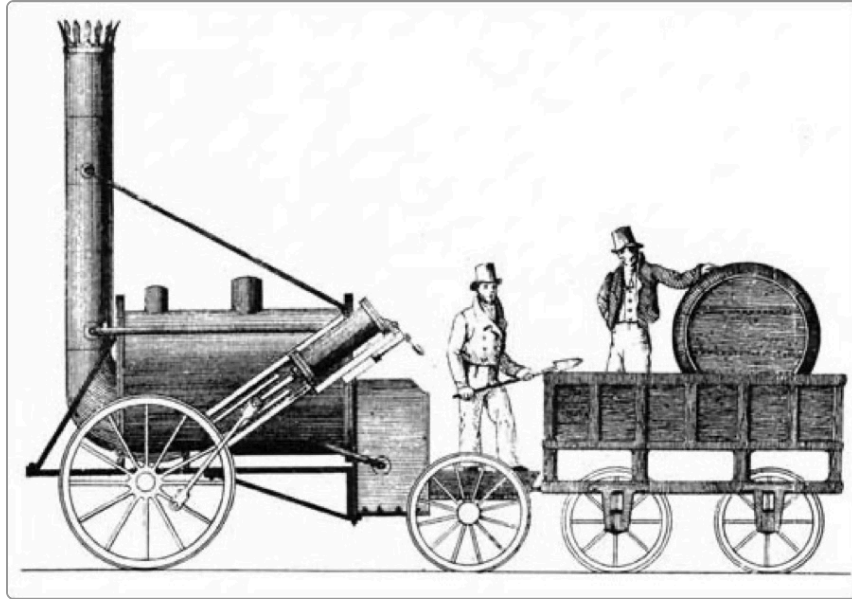
**Velocity** is speed with a direction: 8 m/s toward Manchester. Two trains can have the same speed but different velocities if they are going opposite ways. **Acceleration** is how fast velocity changes: change in velocity  $\div$  time. A train that goes from 0 to 12 m/s in 60 seconds has an acceleration of  $12 \text{ m/s} \div 60 \text{ s} = 0.2 \text{ m/s}^2$ , which means it



gains 0.2 meters per second of speed every second. Slowing down is acceleration too, just in the opposite direction, and turning a corner at a steady speed is acceleration because the direction changes.

**The engineering.** Railway engineers still live by these numbers. They need the speed to draw up a timetable, the acceleration to know how quickly a train can leave a station, and the slowing-down rate to know where to put signals so that a train can stop in time. A heavy freight train might take more than a kilometer to stop. Engineers also design curves and hills around acceleration, so that passengers are not thrown about. Every one of those decisions starts with someone measuring a distance and a time carefully, as the Rainhill judges did.

## PICTURE STUDY



*Stephenson's Rocket*, Unknown draftsman, About 1829 · Engraving

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

This drawing shows *Rocket* as it ran at Rainhill. It is small next to a modern engine, about 4 tons, but almost every steam locomotive for the next 130 years followed its pattern.

### Look closely

- Find the boiler, the long barrel lying along the engine. Inside it were the 25 copper tubes that made steam quickly.
- Find the tall chimney. The used steam was blown up it to make the fire burn hotter.
- Find the cylinder and the rod that turns the big wheel. Which way does the rod push and pull?
- Compare the size of the front and rear wheels.

### Talk about it

1. Why would a bigger driving wheel let the engine go farther with each turn?
2. The judges needed a distance and a time to find speed. Which of those two would have been harder to measure accurately in 1829?
3. Why did the directors want to see the engines run many trips, not just one fast run?

**Safety first.** Keep the ramp on the floor or a low table, and keep the test lane clear so no one trips over the car or the meter stick.

## BUILD

### Speed Traps on a Ramp

You will be the Rainhill judge. You will roll a toy car down a ramp and along the floor, time it through two measured “speed traps,” calculate its speed in each, and find its acceleration. Then you will change one thing, the height of the ramp, and test again.

#### You will need

- A toy car that rolls straight
- A board, shelf or stiff cardboard about 1 meter long, and books to prop it up
- Masking tape and a meter stick or tape measure
- A smartphone that can record slow-motion video, or two stopwatches and a helper
- Calculator and engineer’s notebook

#### Steps

1. **Set up.** Prop one end of the board on books so it is 10 centimeters high. Mark a starting line near the top. On the board, put tape marks at 20, 40, 60 and 80 centimeters from the start.
2. **Predict.** Will the car cover the last 20 centimeters faster or slower than the first 20? Write your prediction.
3. **Measure.** Release the car from the start line without pushing. Record it in slow motion from the side, with the tape marks in view. Play the video back frame by frame and write down the time when the front of the car passes each mark.
4. Repeat for three runs. Make a table: mark, time for run 1, run 2, run 3, average time.
5. **Calculate speed.** For the first trap (0 to 20 cm) and the last trap (60 to 80 cm), divide 0.20 m by the time the car took to cross it. Write each speed in m/s.
6. **Calculate acceleration.** Find the change in speed between the two traps and divide by the time between the middle of the first trap and the middle of the

last trap. Write the answer in  $\text{m/s}^2$ .

7. **Fair test.** Change only the height: raise the ramp to 20 centimeters and repeat steps 3–6.
8. **Improve.** Look at your three runs. Were they close? If not, find out why (a crooked release, a bumpy board, a car that drifts) and fix it. Run again and see whether your results agree better.

#### Tips

- Most phones record slow motion at 120 or 240 frames per second. At 240 frames per second, each frame is about 0.004 seconds.
- Release the car by lifting a ruler held in front of it, not with your fingers, so you never push it.
- If your times differ a lot between runs, that is useful information. Engineers call it scatter, and they reduce it by improving the test, not by choosing the run they like.

#### Check your work

- ☐ I can calculate speed from distance and time, with units.
- ☐ I can calculate acceleration from two speeds and a time.
- ☐ I can explain how the height of the ramp changed the acceleration.

#### ENGINEER'S NOTEBOOK

1. Draw your ramp from the side, label the tape marks and the two speed traps, and write the measured speeds beside them.
2. Make a table of mark distance and average time for both ramp heights. Graph distance (up) against time (across) for both on the same axes. Which line curves more steeply?
3. Work this Rainhill problem: *Rocket* ran 1.5 miles in 7.5 minutes. What was its average speed in miles per hour? (Answer:  $1.5 \text{ miles} \div 0.125 \text{ hour} = 12 \text{ miles per hour}$ .)

**From history.** The Liverpool and Manchester Railway opened on September 15, 1830, the first intercity railway in the world worked entirely by steam locomotives and carrying passengers on a timetable. *Rocket* itself survives in the Science Museum Group's collection in Britain, worn and altered by years of service.

## COMMON MISTAKES

- Forgetting the units, or mixing centimeters and meters in one calculation. Change 20 cm to 0.20 m first.
- Thinking that steady speed around a curve means no acceleration. A change in direction is acceleration.
- Using a single run. One run can be spoiled by a bump; average at least three.

**Make it a game • Speed Trap Showdown.** Mark a 5-meter course with tape. Take turns walking, jogging and crawling it while your parent times you. Calculate each average speed in meters per second before the stopwatch answer is revealed. Then say how velocity differs from speed. Closest calculation wins the round. Add one fact about Stephenson's Rocket.

# 1.2 NEWTON'S LAWS WITH NUMBERS: $F = ma$

## OBJECTIVES

- State Newton's three laws of motion and give an engineering example of each.
- Use  $F = ma$  to calculate force, mass or acceleration, with newtons, kilograms and  $m/s^2$ .
- Measure how a cart's acceleration changes when the pulling force and the mass change.

**Warm-up.** Push an empty shopping basket or an empty laundry basket across a smooth floor, then the same basket filled with books, using about the same push. What happened differently? Write one sentence explaining it before you read on.

## WATCH

### STEMonstrations: Newton's 2nd Law of Motion

NASA Johnson · 2:39

<https://www.youtube.com/watch?v=sPZ2bjW53c8>

## WHEN TO WATCH

After the physics paragraph. Predict which object will speed up more before each push on the space station.

## KEY TERMS

### **inertia**

The tendency of an object to keep doing what it is doing: to stay still, or to keep moving at the same velocity.

### **net force**

The total of all the forces on an object after the pushes and pulls that cancel are taken away.

### **newton (N)**

The unit of force. One newton accelerates a 1-kilogram mass at  $1 m/s^2$ . An apple weighs about 1 newton.

### **mass**

How much matter is in an object, measured in kilograms. It does not change from place to place.

## weight

The pull of gravity on a mass: weight = mass  $\times$  9.8 m/s<sup>2</sup> on Earth, measured in newtons.

### CORE IDEAS

**The story.** In August 1684 the astronomer Edmond Halley rode to Cambridge to ask Isaac Newton a question that he and his friends in London could not answer: if the Sun pulls on a planet more weakly the farther away it is, what path will the planet follow? Newton answered at once: an ellipse. He had worked it out years before. Halley asked to see the proof, and Newton could not find his papers, so he promised to write it out again. That promise grew into the *Principia*, published in July 1687, with Halley checking the proofs and paying for the printing himself. In it Newton set down three laws of motion that engineers still use every day.

**How they figured it out.** Newton built on the work of Galileo, who had measured rolling balls (Lesson 1.3), and on careful observations of the planets and the Moon by many astronomers. His great step was to say that the same laws rule a falling apple, a cannonball and the Moon, and then to test that claim with numbers: he calculated how fast the Moon must fall toward the Earth to stay in its orbit and showed that it matched the pull of gravity at that distance. Newton, a devout believer, wrote that such an orderly system could only come from the counsel and rule of an intelligent and powerful Being.

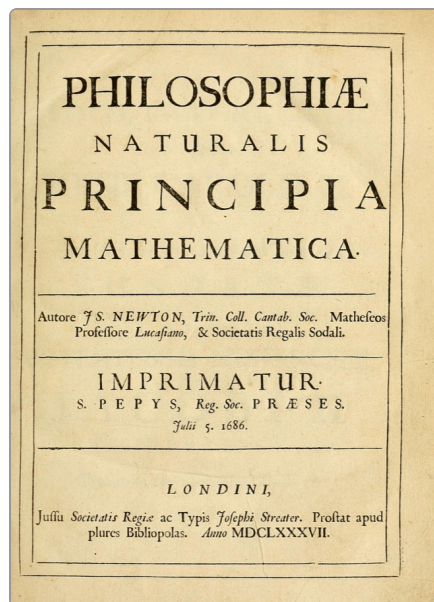
**The physics. First law:** an object stays at rest, or keeps moving at the same velocity, unless a net force acts on it. This is why you lurch forward when a car stops. **Second law:** the net force on an object equals its mass times its acceleration,  $F = ma$ . Force is measured in newtons, mass in kilograms and acceleration in m/s<sup>2</sup>. To speed a 1,200-kilogram car up at 2 m/s<sup>2</sup>, the road must push it forward with  $F = 1,200 \text{ kg} \times 2 \text{ m/s}^2 = 2,400 \text{ N}$ . Turn the equation around and  $a = F \div m$ : the same 2,400 N push on a 2,400-kilogram truck gives only 1 m/s<sup>2</sup>. **Third law:** when one object pushes on another, the second pushes back just as hard in the opposite direction. The tire pushes back on the road; the road pushes forward on the tire.

**The engineering.**  $F = ma$  is the first equation an engineer reaches for. Elevator designers use it to find how strong the cable must be when the car speeds up: a 1,000-kilogram car accelerating upward at 1 m/s<sup>2</sup> needs a cable pulling with its



weight (about 9,800 N) plus another 1,000 N, about 10,800 N in all, and then they multiply by a safety factor. Car makers use it to design brakes and seat belts, rocket engineers to size engines, and bridge engineers to work out what happens when a heavy truck brakes hard on a deck. Every one of those calculations depends on careful units: kilograms, not grams; newtons, not pounds.

## PICTURE STUDY



A Page of Newton's *Principia*, Isaac Newton (author); printed for the Royal Society, 1687 · Printed book ·  
Many libraries, including Cambridge University Library

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

This is the title page of the first edition of Newton's *Principia*, printed in London in 1687. Inside it are the three laws of motion you are using in this unit.

### Look closely

- Find the title. *Philosophiæ Naturalis Principia Mathematica* means “Mathematical Principles of Natural Philosophy.” Why do you think Newton chose the word “mathematical”?
- Find Newton's name. The Latin says he was the Lucasian Professor of Mathematics at Cambridge.
- Find the word IMPRIMATUR and the name S. Pepys. Samuel Pepys, president of the Royal Society, approved the book for printing on July 5, 1686.
- Find the year in Roman numerals at the bottom: MDCLXXXVII. Work out what year it is.

### Talk about it

1. Why might it matter that a whole society of scientists, not just one man, approved the book?
2. Newton wrote in Latin. Why would that help scientists in other countries read it?

3. Which of Newton's three laws do you think is most useful to an engineer, and why?

**Safety first.** Keep feet clear of the falling washers, and put a folded towel on the floor where they land.

## BUILD

### Testing $F = ma$ with a Pulled Cart

A string over the edge of a table, with washers hanging on its end, pulls a toy car across the table with a steady force. You will time the car over one meter, calculate its acceleration, and see what happens when you double the pulling force and when you double the mass.

#### You will need

- A toy car or small cart that rolls freely (a heavier die-cast car works well)
- Thin string about 1.5 meters long and a paper clip hook
- Metal washers or coins, all the same size, and a kitchen scale
- A smooth table, a meter stick, masking tape and a stopwatch or slow-motion phone
- Modeling clay to add mass to the car
- A folded towel for the floor

#### Steps

1. Weigh the car and the washers on the kitchen scale and record their masses in grams. Then change each to kilograms (divide by 1,000).
2. Tie the string to the car, run it over the edge of the table, and hang a paper clip hook on the end. Mark a start line on the table 1.00 meter from the edge.
3. **Predict.** If you double the number of washers, what will happen to the time to cross 1 meter? Write a prediction.
4. **Test 1.** Hang 2 washers. Hold the car at the start line, let go, and time how long it takes to travel 1.00 meter. Do three runs and average them.
5. Calculate the acceleration with  $a = 2 \times \text{distance} \div \text{time}^2$ . (This works for anything that starts from rest and speeds up steadily.) For example, 1.00 m in 1.25 s gives  $a = 2 \times 1.00 \div 1.5625 = 1.28 \text{ m/s}^2$ .
6. **Test 2 (change the force).** Hang 4 washers and repeat. **Test 3 (change the mass).** Go back to 2 washers but press clay onto the car until its mass is doubled, and repeat.

7. Make a table: test, hanging mass, car mass, average time, acceleration. Did doubling the force about double the acceleration? Did doubling the mass about halve it?
8. **Improve.** Friction and the mass of the washers themselves make the numbers imperfect. Choose one source of error, reduce it (oil the axles, use a smoother table, use a lighter hook) and test again.

#### Tips

- The hanging washers provide the force. Their weight in newtons is their mass in kilograms  $\times 9.8$ .
- Catch the car before it flies off the table edge, or put a book there as a stop.
- If the car is too fast to time, use fewer washers or a heavier car.

#### Check your work

- ☐ I can state Newton's three laws and give an example of each.
- ☐ I can calculate a force, mass or acceleration with  $F = ma$ .
- ☐ I can explain what my data showed about force, mass and acceleration.

#### ENGINEER'S NOTEBOOK

1. Draw a free-body sketch of your car: arrows for the string's pull, friction, gravity and the table pushing up. Make the arrow lengths show which forces are bigger.
2. Graph acceleration (up) against number of washers (across) for your force tests. Is it close to a straight line?
3. Work it: a 60-kilogram skateboarder is pushed with a net force of 120 N. What is the acceleration? ( $120 \text{ N} \div 60 \text{ kg} = 2 \text{ m/s}^2$ .)

**From history.** Newton wrote the *Principia* in Latin. The first English translation, by Andrew Motte, appeared in 1729. The unit of force was named the newton in 1948, and engineers and scientists around the world now use it every day.

#### COMMON MISTAKES

- Using grams instead of kilograms in  $F = ma$ . 500 g is 0.5 kg.
- Thinking a moving object needs a force to keep it moving. It needs a force only to change its motion; on Earth, the extra push just cancels friction.
- Thinking the third-law pair cancels out. The two forces act on different objects, so they do not cancel.

**Make it a game • Force Duel.** Your parent calls out two of three values in  $F = ma$ , such as a 2 kg cart accelerating at 3 m/s squared. Calculate the missing force, mass or acceleration in your head or on paper, in thirty seconds. Five rounds. Then give an engineering example for each of Newton's three laws. Score points for correct units.

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

Newton’s laws work the same today as in 1687, on Earth and in the heavens. That steady order is what makes engineering possible.

# 1.3 FRICTION AND GALILEO'S INCLINED PLANE

## OBJECTIVES

- Describe how Galileo used a ramp and a water clock to study falling motion.
- Show that a ball rolling from rest covers distances in the ratio 1 : 4 : 9 in equal times.
- Measure the coefficient of friction of several surfaces with a tilting board.

**Warm-up.** Hold a sheet of paper and a book at the same height and drop them together. Then put the paper flat on top of the book and drop them again. What changed? Write what you think was slowing the paper the first time.

## WATCH

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

Spark · 5:01

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

## WHEN TO WATCH

After the story and before the physics. Watch how the water clock is used to time the rolling ball.

## BACKUP VIDEO

### Introduction to the Coefficient of Friction

Flipping Physics · 4:58

<https://www.youtube.com/watch?v=QwuldyEP9Jk>

Before Part B of the build, for a clear explanation of the coefficient of friction ( $\mu$ ). Older students.

## KEY TERMS

### **inclined plane**

A flat surface tilted at an angle; a ramp.

### **friction**

A force between two surfaces that resists sliding.

**normal force**

The push of a surface straight out against an object resting on it.

**coefficient of friction ( $\mu$ )**

A number that tells how “grippy” two surfaces are: friction force  $\div$  normal force. It has no units.

**uniform acceleration**

Gaining the same amount of speed every second.

**CORE IDEAS**

**The story.** Around 1600, Galileo Galilei, a professor in Padua, Italy, wanted to know how falling objects speed up. The problem was that a dropped ball falls too fast to time. There were no stopwatches, and his best clocks could not measure fractions of a second. So he slowed the fall down. In his book *Two New Sciences* (1638), he described a wooden beam about 12 cubits long (roughly 7 meters) with a straight, smooth groove cut along it and lined with polished parchment. He tilted the beam and rolled a hard, smooth bronze ball down the groove.

**How they figured it out.** To time the ball, Galileo let water run from a large vessel through a thin pipe into a cup while the ball rolled, then weighed the water on a fine balance. The weight of the water measured the time. He wrote that he repeated the test a full hundred times, at different tilts and over different lengths of the groove, and the results always agreed. The distance traveled was always proportional to the square of the time: in 2 units of time the ball went 4 times as far as in 1, and in 3 units of time 9 times as far. Galileo reasoned that a steeper and steeper ramp becomes a free fall, so falling objects must speed up in the same steady way.

**The physics.** A ball rolling from rest with **uniform acceleration** covers distances in equal times in the ratio 1 : 3 : 5 : 7, so the total distances go 1, 4, 9, 16. In the language of Lesson 1.2, distance =  $\frac{1}{2} \times a \times t^2$ . **Friction** is the force that works against sliding. It depends on how hard the surfaces press together (the **normal force**) and on how rough or grippy they are. In 1699 Guillaume Amontons found that friction is about proportional to that pressing force and does not depend much on how large the contact area is. We write friction =  $\mu \times$  normal force. You can measure  $\mu$  with a tilting board: raise one end slowly until a block just starts to slide, then measure the rise



and the run. At that moment,  $\mu = \text{rise} \div \text{run}$ . If a block starts to slide when the board rises 30 cm over a run of 60 cm,  $\mu = 30 \div 60 = 0.5$ .

**The engineering.** Engineers fight friction in some places and need it in others. Bearings, oil and smooth rails reduce it, so that a train's steel wheels on steel rails ( $\mu$  about 0.002 for rolling) take far less force to pull than a cart on a dirt road. Brakes, tires, shoe soles and the bolts that hold a bridge together depend on friction. Road engineers measure the grip of pavement and cut grooves in it on curves so that tires will hold in the rain. Knowing  $\mu$  lets an engineer calculate whether a car can stop in time or whether a crate will slide off a tilted truck bed.

## PICTURE STUDY



*A Reconstruction of Galileo's Workroom, Deutsches Museum (reconstruction; photograph 2022), Workroom of about 1600; photographed 2022 · Photograph · Deutsches Museum, Munich*  
Image: [Wikimedia Commons](#), public domain

The Deutsches Museum in Munich has rebuilt a workroom like Galileo's. The long wooden beam slanting across the floor is a model of his inclined plane. Look for the other instruments he used to measure motion and time.

### Look closely

- Follow the long beam from its high end to its low end. Where would the ball start, and which way would it roll?
- Find the balance on the table at the right. How did Galileo use a balance to measure time?
- Find the tall stand near the back wall. What might hang from it? (Galileo also studied pendulums.)
- Look at how gently the beam slopes. Why would a gentle slope help Galileo measure?

### Talk about it

1. Why couldn't Galileo simply drop a ball and time it?
2. If the ball rolls 10 cm in the first beat of time, how far from the start will it be after three beats?

3. What would you need to add to the beam to measure friction instead of falling?

## BUILD

### Galileo's Ramp and the Friction Board

In part A you will repeat Galileo's experiment with a marble and a long grooved ramp, using your ears as he may have done: marks placed at 1, 4, 9 and 16 units of distance should be passed at equal beats of time. In part B you will measure the coefficient of friction of several surfaces with a tilting board.

#### You will need

- A long grooved track: a 2-meter piece of wooden cove molding, a curtain track, or a pool noodle cut in half lengthwise
- A marble or steel ball, books to prop up the track, masking tape and a meter stick
- A metronome app set to about 120 beats per minute, or a helper clapping steadily
- A smooth board about 60 cm long, a small wooden block, and pieces of sandpaper, felt, foil and rubber (cut from a glove) to tape on the block
- Engineer's notebook

#### Steps

1. **Part A, set up.** Tilt the track gently (raise one end only 4–6 cm). Choose a unit length, such as 10 cm, and put tape marks at 1, 4, 9 and 16 units from the start: 10, 40, 90 and 160 cm.
2. **Predict.** If the ball speeds up steadily, it will reach each mark one beat after the last. Write whether you think it will.
3. Start the metronome. Release the ball exactly on a beat. Watch and listen: does it cross the marks on the next beats? Adjust the tilt until the first mark falls on the first beat, then judge the others. Repeat five times and record what you see.
4. Now move the marks to equal spacing (40, 80, 120, 160 cm) and run it again. Does the ball reach them on equal beats? Record what is different.
5. **Part B, set up.** Lay the board flat with the block on one end. Slowly raise that end until the block just begins to slide. Hold the board there and measure the

rise (height of the raised end) and the run (horizontal distance along the floor).

6. Calculate  $\mu = \text{rise} \div \text{run}$ . Do three trials and average them.
7. **Fair test.** Tape a different material to the bottom of the block (sandpaper, felt, foil, rubber) and repeat. Change only the material each time.
8. **Improve.** Add a second block on top (double the normal force). Does  $\mu$  change? Amontons said it should not. Test it and record what you find.

#### Tips

- Tilt the ramp only a little. A steep ramp makes the ball too fast to judge.
- Raise the friction board slowly and smoothly; a sudden jerk starts the block sliding too early.
- A shallow groove keeps the marble from wandering off the track.

#### Check your work

- ☐ I can explain how Galileo slowed down falling motion so he could measure it.
- ☐ I can calculate a coefficient of friction from a rise and a run.
- ☐ I can say which surface had the most friction and why that might be useful.

#### ENGINEER'S NOTEBOOK

1. Draw the ramp with its tape marks at 1, 4, 9 and 16 units and write what you heard at each beat.
2. Make a table of  $\mu$  for each surface, with three trials and an average. Draw a bar graph from highest to lowest.
3. Work it: a crate on a truck bed starts to slide when the bed is raised 45 cm over a run of 150 cm. What is  $\mu$ ? ( $45 \div 150 = 0.3$ .)

**From history.** Galileo's ramp experiments were long doubted by some historians, until in 1961 the physicist Thomas Settle rebuilt the apparatus from Galileo's description, timed it with a water clock and got results as good as Galileo claimed. Galileo's notebooks, now in Florence, also show the measurements he made.

#### COMMON MISTAKES

- Releasing the ball late or with a push. Hold it with a ruler and lift the ruler on the beat.

- Thinking friction depends mostly on how big the touching area is. For most dry surfaces, it depends on the pressing force and the materials.
- Measuring the length of the sloping board instead of the horizontal run.

**Make it a game · One Four Nine.** Roll a marble down a ramp and mark where it is at equal beats of a steady count. Predict where it will be at beat three by using 1 : 4 : 9. Check against the marks. Then explain how Galileo used a water clock. Closest prediction takes the point, and friction explanations earn a bonus.

# 1.4 WORK, POWER AND WATT'S HORSEPOWER

## OBJECTIVES

- Calculate work (force  $\times$  distance) in joules and power (work  $\div$  time) in watts.
- Explain why James Watt invented the horsepower and convert between horsepower and watts.
- Measure your own power climbing stairs and the power of a hand-cranked winch.

**Warm-up.** Carry a backpack with a few books up a flight of stairs once slowly and once briskly (walking, holding the rail). Which trip took more work? Which took more power? Write your guesses, then read on to see whether you were right.

## WATCH

### Horsepower: James Watt and the Transition from Horse to Steam

The History Guy: History Deserves to Be Remembered • 12:05

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

## WHEN TO WATCH

After the story, before the physics.

## BACKUP VIDEO

### What Is Horsepower? | Earth Science

BBC Earth Science • 7:49

<https://www.youtube.com/watch?v=Xym2XNezZ-w>

After the physics paragraph, for another explanation of work, power and horsepower.

## KEY TERMS

### work

Force  $\times$  the distance moved in the direction of the force. Measured in joules (J): 1 J = 1 newton  $\times$  1 meter.

### horsepower

A unit of power set by James Watt: 33,000 foot-pounds of work per minute, about 746 watts.

### power

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

### separate condenser

Watt's 1765 improvement: a chamber where steam is cooled back to water outside the hot cylinder, saving fuel.

## efficiency

Useful work out  $\div$  energy put in, often given as a percent.

### CORE IDEAS

**The story.** In 1763 a young instrument maker at the University of Glasgow, James Watt, was asked to repair a small model of a Newcomen steam engine. These engines pumped water from mines, but they burned enormous amounts of coal, because the same cylinder was heated by steam and then cooled with a spray of cold water on every stroke. In 1765, walking on Glasgow Green on a Sunday afternoon, Watt saw the answer: cool the steam in a separate chamber, a **condenser**, and keep the cylinder hot all the time. With his business partner Matthew Boulton he built engines that used about a quarter of the coal of the old ones.

**How they figured it out.** Watt now had to sell his engines to mill and mine owners who used horses to turn their machinery. They asked a fair question: how many horses will your engine replace? Watt needed a unit. Watching horses turning mill wheels, he estimated that a horse could lift 33,000 pounds one foot in one minute (or 330 pounds 100 feet in a minute), and he called that a **horsepower**. He was generous to the horse; most horses cannot keep that pace all day. That made his engines look modest, and customers were pleased. The unit stuck: car engines are still rated in horsepower. In 1882 engineers honored Watt by naming the metric unit of power the **watt**.

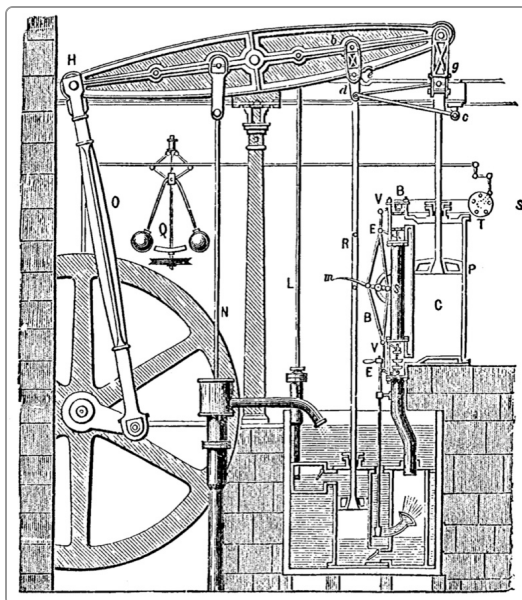
**The physics.** **Work** is force times distance:  $W = F \times d$ . Lifting a 10-newton bag 2 meters takes  $10 \text{ N} \times 2 \text{ m} = 20 \text{ joules}$ . **Power** is work divided by time:  $P = W \div t$ . Do that 20 joules in 4 seconds and your power is 5 watts; do it in 1 second and it is 20 watts. Here is a full example. A 50-kilogram student weighs about  $50 \times 9.8 = 490 \text{ N}$ . Climbing stairs 3.0 meters high, she does  $490 \text{ N} \times 3.0 \text{ m} = 1,470 \text{ J}$  of work. If she takes 4.0 seconds, her power is  $1,470 \text{ J} \div 4.0 \text{ s} \approx 370 \text{ W}$ , about half a horsepower ( $370 \div 746 \approx 0.49 \text{ hp}$ ). A strong person can manage that for a few seconds; a horse can keep up much more for hours.

**The engineering.** Power is how engineers size machines. An elevator motor must lift the car and its passengers at a set speed; a pump must lift so many liters of water so many meters every minute; a locomotive must pull so many tons up a hill at a set speed. Each of those is work divided by time. Engineers then divide the useful power



out by the power put in to find the **efficiency**. Watt's condenser raised the efficiency of steam engines several times over, and that, more than anything else, is why steam power spread through the mines, mills and railways of the world.

## PICTURE STUDY



*A Boulton and Watt Steam Engine*, Unknown engraver, Engine of 1784; engraving published 1878 · Engraving

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

This engraving shows a Boulton and Watt engine of 1784, the kind Watt rated in horsepower. Each letter labels a part; the engraving was published in a book in 1878 to teach how it worked.

## Look closely

- Find the great rocking beam at the top. One end is pulled down by the piston; what does the other end turn?
- Find the large flywheel at the lower left. Why would an engine need a heavy wheel that keeps turning?
- Find the two balls hanging from arms (the governor). As the engine speeds up, they swing outward and close a valve.
- Find the cylinder (C) and the condenser below it, Watt's great improvement.

## Talk about it

1. Where in this engine is work being done, force times distance?
2. How would you measure this engine's power in horsepower?
3. Why did keeping the cylinder hot save so much coal?

**Safety first.** Walk briskly on the stairs, never run, and keep one hand on the rail. Use a staircase with a rail and an adult watching. Stop if you feel dizzy.

## BUILD

### How Many Horsepower Are You?

You will measure your own power by timing yourself climbing stairs, then build a simple winch from a spool and a pencil and measure the power of your hand lifting a cup of pennies. You will compare both with Watt's horse.

#### You will need

- A flight of stairs with a rail, a tape measure and a stopwatch
- A bathroom scale (or your mass from a recent check-up)
- An empty thread spool or paper-towel tube, a pencil or dowel for an axle, string and a paper cup
- Pennies (2.5 grams each) or washers, and a kitchen scale
- Two chairs or a table edge to hold the winch, tape, and the engineer's notebook

#### Steps

1. **Measure the stairs.** Measure the height of one step in meters and count the steps. Multiply to find the total height (for example,  $14 \text{ steps} \times 0.18 \text{ m} = 2.52 \text{ m}$ ).
2. Find your mass in kilograms and calculate your weight:  $\text{mass} \times 9.8 = \text{weight}$  in newtons.
3. **Predict.** Guess your power in watts and in horsepower before you test.
4. **Test.** Walk up the stairs briskly while someone times you, holding the rail. Do three trials with a rest between them and average the times.
5. Calculate  $\text{work} = \text{weight} \times \text{height}$  and  $\text{power} = \text{work} \div \text{time}$ . Convert to horsepower by dividing by 746.
6. **Build the winch.** Push the pencil through the spool, tape the spool to the pencil so they turn together, and rest the pencil ends on two chair backs. Tie the string to the spool and the cup to the string. Put 100 pennies (250 g) in the cup.
7. Wind the cup up 1.0 meter by turning the pencil, and time it. Calculate work ( $0.25 \text{ kg} \times 9.8 \times 1.0 \text{ m} \approx 2.5 \text{ J}$ ) and power. Do three trials.

8. **Fair test and improve.** Change one thing: use a fatter spool, or tape a crank (a craft stick) to the pencil end. Does the lift get faster or easier? Record the new power and explain the change.

#### Tips

- Measure height straight up, not along the slope of the stairs. Only the vertical height counts as work against gravity.
- Your power will be highest for a short burst. Watt's horse had to keep its pace for hours.
- A crank makes the winch easier to turn because your hand moves in a bigger circle, a wheel and axle at work.

#### Check your work

- ☐ I can calculate work in joules and power in watts.
- ☐ I can convert watts to horsepower.
- ☐ I can explain why Watt needed a unit like the horsepower to sell his engines.

#### ENGINEER'S NOTEBOOK

1. Make a table for your stair climbs: trial, time, work, power in watts, power in horsepower.
2. Draw your winch with arrows for the force of your hand, the pull of the string and the weight of the cup. Write its measured power.
3. Work it: a pump lifts 600 kg of water 10 m in 60 s. What is its power? ( $600 \times 9.8 \times 10 = 58,800 \text{ J}$ ;  $58,800 \text{ J} \div 60 \text{ s} = 980 \text{ W}$ , about 1.3 hp.)

**From history.** Watt and Boulton often sold engines on a shared-savings plan: the customer paid a yearly sum equal to one third of the money saved on coal compared with a Newcomen engine. Engineers still use the same idea today, measuring efficiency carefully so that a better machine can prove its worth.

#### COMMON MISTAKES

- Using mass (kilograms) where weight (newtons) is needed. Multiply by 9.8 first.
- Thinking a slow climb does less work than a fast one. The work is the same; only the power is different.
- Measuring the length of the staircase along the slope instead of its height.

**Make it a game • Horsepower Stairs.** Carry a 2 kg bag of rice up a flight of stairs while your parent times you. Measure the height in meters, then calculate work in joules (force in newtons times height) and power in watts. Convert to horsepower. Guess first; closest guess wins. Say why James Watt invented the horsepower, then try to beat your time.

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

Power is work done with might. Watt spent years improving one engine, and the patient, careful work of an engineer is a good way to serve God and neighbor.

## UNIT 1

# MOTION

Every machine, bridge, ship and airplane in this course obeys the same few rules of motion. In this unit you will learn to describe motion with numbers: speed, velocity and acceleration, measured the way the judges measured Stephenson's *Rocket* in 1829. You will meet Isaac Newton's three laws and use the most useful equation in engineering,  $F = ma$ , to predict how hard something must be pushed to speed it up.

Then you will roll balls down a ramp as Galileo did, discovering that a falling object gains speed in a steady pattern, and measure the friction that fights every moving part. Last, you will learn how James Watt measured the work of a horse so that he could sell steam engines, and you will measure your own horsepower on a flight of stairs. Throughout the unit, every number you write will carry its units.

### PREREQUISITES

- Can multiply and divide decimals and round sensibly
- Can measure in centimeters and meters and time with a stopwatch
- Knows that a force is a push or a pull, and keeps a dated engineer's notebook

### MASTERY CHECKLIST

- ☐ I can calculate speed, velocity and acceleration from measured distances and times, with units.
- ☐ I can state Newton's three laws and use  $F = ma$  to find a force, a mass or an acceleration.
- ☐ I can describe Galileo's inclined-plane experiment and measure a coefficient of friction.
- ☐ I can calculate work and power in joules and watts and convert watts to horsepower.
- ☐ I can run a fair test with repeated trials, average the results and graph them.

## OPTIONAL KITS FOR THIS UNIT

- **LEGO Education:** Ages vary by set. LEGO Education's science and engineering sets include carts, gears and motors that can replace the toy car and winch in Lessons 1.1, 1.2 and 1.4. Check the age range of each set.
- **K'NEX building sets:** Ages vary by set. Rods, wheels and pulleys for building carts and winches to measure speed, force and power. Fits Lessons 1.1–1.4.

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

## LESSONS IN THIS UNIT

|     |                                                       |                          |
|-----|-------------------------------------------------------|--------------------------|
| 1.1 | Speed, Velocity and Acceleration: Stephenson's Rocket | 2 sessions of 50 minutes |
| 1.2 | Newton's Laws with Numbers: $F = ma$                  | 2 sessions of 50 minutes |
| 1.3 | Friction and Galileo's Inclined Plane                 | 2 sessions of 50 minutes |
| 1.4 | Work, Power and Watt's Horsepower                     | 2 sessions of 50 minutes |

## UNIT 1 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

What is the difference between speed and velocity? Give an example of two objects with the same speed but different velocities.

2. 10 pts

Calculate: a train travels 4,800 meters in 400 seconds. What is its average speed in m/s?

3. 10 pts

Calculate: a bicycle speeds up from 2 m/s to 8 m/s in 3 seconds. What is its acceleration?



4. **8 pts**

State Newton's first law and give one example of it from a car or a train.

5. **10 pts**

Calculate: what net force is needed to accelerate a 1,500-kilogram car at  $2 \text{ m/s}^2$ ?

6. **8 pts**

A rocket pushes hot gas downward out of its nozzle. Which of Newton's laws explains why the rocket goes up? Explain.

7. **8 pts**

How did Galileo measure time when he rolled balls down his ramp, and why did he use a ramp instead of dropping the ball?

8. **8 pts**

Predict: a ball rolls from rest down a ramp and travels 5 cm in the first second. How far from the start will it be after 3 seconds?

9. **6 pts**

A block begins to slide when a board is raised 20 cm over a run of 80 cm. What is the coefficient of friction?

10. **10 pts**

Calculate: a 40-kilogram student climbs stairs 3 meters high in 5 seconds. Find the work done and the power. (Use  $9.8 \text{ m/s}^2$  for gravity.)

11. **6 pts**

Why did James Watt invent the horsepower?

12. **8 pts**

Explain in two or three sentences why engineers always write units with their numbers.

## ANSWER KEY

1. Speed is how fast something moves (distance  $\div$  time). Velocity is speed in a particular direction. Two cars each going 20 m/s, one north and one south, have the same speed but different velocities.
2. Speed = distance  $\div$  time = 4,800 m  $\div$  400 s = 12 m/s.
3. Acceleration = change in velocity  $\div$  time = (8 – 2) m/s  $\div$  3 s = 2 m/s<sup>2</sup>.
4. An object stays at rest or keeps moving at the same velocity unless a net force acts on it. Example: passengers lurch forward when a train brakes, because their bodies keep moving.
5.  $F = ma = 1,500 \text{ kg} \times 2 \text{ m/s}^2 = 3,000 \text{ N}$ .
6. The third law. The rocket pushes the gas down, and the gas pushes the rocket up with an equal and opposite force.
7. He let water flow from a vessel into a cup while the ball rolled and weighed the water. He used a gentle ramp to slow the motion down so it could be timed; a dropped ball falls too fast.
8. Distance grows with the square of time:  $3^2 = 9$ , so  $9 \times 5 \text{ cm} = 45 \text{ cm}$ .
9.  $\mu = \text{rise} \div \text{run} = 20 \div 80 = 0.25$ .
10. Weight =  $40 \times 9.8 = 392 \text{ N}$ . Work =  $392 \text{ N} \times 3 \text{ m} = 1,176 \text{ J}$ . Power =  $1,176 \text{ J} \div 5 \text{ s} \approx 235 \text{ W}$  (about 0.3 horsepower).
11. To tell customers who used horses how many horses one of his steam engines could replace, so they could compare and buy.
12. A number without units can be read wrongly (meters or centimeters, kilograms or pounds), and a mix-up can make a part too weak or a calculation badly wrong. Units also let you check that an equation makes sense.

## PORTFOLIO PIECE: A MEASURED MOTION REPORT

Choose one moving thing you can test safely, such as a toy car on a ramp, a rubber-band cart or a bicycle coasting down a gentle driveway with an adult watching. Measure its speed in two places and its acceleration, with at least three trials at each setting, and change one variable (height, mass or pulling force). Write a one-page engineer's report with a labeled sketch, a data table with units, at least two worked calculations, a graph, and a paragraph explaining your results with Newton's laws.

| LOOK FOR                     | WHAT IT MEANS                                                                              |
|------------------------------|--------------------------------------------------------------------------------------------|
| <b>Fair test</b>             | Only one variable changed; at least three trials at each setting, averaged.                |
| <b>Measurement and units</b> | Distances and times measured carefully; every number in the table has its units.           |
| <b>Calculations</b>          | Speed and acceleration calculated correctly from the data, with the work shown.            |
| <b>Explanation</b>           | Results explained using at least one of Newton's laws and the word acceleration correctly. |
| <b>Improvement</b>           | One source of error identified and a specific way to reduce it proposed or tested.         |

## BRIDGES

In Grade 5 you learned the forces inside a structure and built a truss. This year you will go a step deeper and ask the questions a bridge engineer asks with a pencil and a calculator. Why is a steel beam shaped like the letter I? How much does an arch push outward on its foundations, and why does a flatter arch push harder? Why are some long bridges hung from great curved cables and others from straight cables fanned out from a tower?

You will follow Robert Stephenson as he tested model iron tubes until they buckled, James Eads as he insisted on testing every piece of steel for his arches at St. Louis, and Thomas Telford as he hung the first great suspension bridge over the Menai Strait. Last, you will learn what happened at the Silver Bridge in 1967, and how it led to the inspection program that keeps hundreds of thousands of bridges safe today. A bridge is not finished when it opens; someone must keep watching it.

### PREREQUISITES

- Knows compression, tension, shear and torsion and can find them in a truss (Grade 5 or Unit 1)
- Can calculate with  $F = ma$  and  $\text{weight} = \text{mass} \times 9.8$  (Lesson 1.2)
- Can find an average and make a line graph

### MASTERY CHECKLIST

- ☐ I can explain why an I-beam or box girder is stiff for its weight, and show that a beam's depth matters more than its width.
- ☐ I can explain how an arch carries load in compression and calculate how its outward thrust grows as it gets flatter.
- ☐ I can compare suspension and cable-stayed bridges and calculate the tension in a sloping cable.
- ☐ I can explain fatigue, corrosion and redundancy, and describe how and why bridges are inspected.
- ☐ I can load-test a model, measure its deflection and failure load, and improve it.

## OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits:** Ages 11 and up with an adult. Balsa sticks, plans and gussets for a truss bridge that can be weighed and load-tested to failure; a good portfolio option for this unit.
- **KEVA planks:** Ages 6 and up. Identical maple planks with no connectors; good for building block arches and testing why abutments matter in Lesson 2.2.

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

## LESSONS IN THIS UNIT

|     |                                                               |                          |
|-----|---------------------------------------------------------------|--------------------------|
| 2.1 | <b>Bending and the I-Beam: Stephenson's Britannia Bridge</b>  | 2 sessions of 50 minutes |
| 2.2 | <b>Arch Bridges from Rome to Eads</b>                         | 2 sessions of 50 minutes |
| 2.3 | <b>Cable-Stayed versus Suspension: Telford's Menai Bridge</b> | 2 sessions of 50 minutes |
| 2.4 | <b>Bridge Inspection and Maintenance: The Silver Bridge</b>   | 2 sessions of 50 minutes |

## UNIT 2 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

When a beam bends under a load in the middle, which part is in compression, which is in tension, and where is the neutral axis?

2. **10 pts**

Calculate: a board is 10 cm wide and 2 cm thick. Find its stiffness number (width  $\times$  depth<sup>3</sup>) lying flat and standing on edge. How many times stiffer is it on edge?

3. **8 pts**

Explain in two or three sentences why an I-beam is shaped like the letter I.

4. (7 pts)

What did Fairbairn's model-tube tests for the Britannia Bridge show about how the tubes failed, and what did he change?

5. (8 pts)

What is an abutment, and what happens to an arch whose abutments slide apart?

6. (10 pts)

Calculate: a load of 2,000 N sits on the middle of an arch that spans 8 m with a rise of 2 m. Using  $H = P \times \text{span} \div (4 \times \text{rise})$ , find the thrust. Then find it again if the rise is only 1 m.

7. (7 pts)

Why did James Eads insist on testing the steel for his bridge?

8. (8 pts)

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

9. (10 pts)

Calculate: a straight stay 60 m long climbs 30 m up its tower and holds up 40 kN of deck. What is the tension in the stay?

10. (8 pts)

Give two differences between a suspension bridge and a cable-stayed bridge.

11. (8 pts)

What is metal fatigue, and how did it lead to the Silver Bridge collapse?

12. (8 pts)

Explain what redundancy means for a bridge and why inspectors pay special attention to fracture-critical members.

## ANSWER KEY

1. The top is in compression, the bottom is in tension, and the neutral axis runs through the middle, where there is neither.
2. Flat:  $10 \times 2^3 = 80$ . On edge:  $2 \times 10^3 = 2,000$ . It is  $2,000 \div 80 = 25$  times stiffer on edge.
3. When a beam bends, the top and bottom do most of the work and the middle near the neutral axis does little. An I-beam puts thick flanges at the top and bottom and only a thin web between them, so it is stiff and strong for its weight.
4. The tubes failed when the thin top plate, in compression, buckled. He stiffened the top (and bottom) with rows of small square cells.
5. An abutment is the solid support at each end of an arch that resists its outward thrust. If the abutments slide apart, the arch spreads, flattens and collapses.
6. Rise 2 m:  $H = 2,000 \times 8 \div (4 \times 2) = 2,000$  N. Rise 1 m:  $H = 2,000 \times 8 \div (4 \times 1) = 4,000$  N. The flatter arch pushes twice as hard.
7. Steel was new for large structures and its quality varied from batch to batch, so he tested every piece for strength and stretch and rejected bad batches to be sure the arches were safe.
8. Deck  $\rightarrow$  vertical hangers (tension)  $\rightarrow$  main cables (tension)  $\rightarrow$  over the towers (compression) down to the foundations, with the cable ends held by the anchorages.
9. Tension = load  $\times$  (length  $\div$  rise) =  $40 \text{ kN} \times (60 \div 30) = 80 \text{ kN}$ .
10. Any two: suspension main cables sag in a curve and need anchorages, while cable-stayed stays are straight and need none; suspension decks hang from vertical hangers, cable-stayed decks are held directly by sloping stays; suspension bridges reach longer spans; cable-stayed bridges are stiffer and can be built out from the tower segment by segment.
11. Fatigue is weakening by many repeated loads, which grows small cracks. A tiny crack (helped by corrosion) grew in one eyebar until it broke, and because the chain had no other load path, the bridge fell.
12. Redundancy means there is more than one load path, so the bridge survives if one part fails. Fracture-critical members have no backup: if one breaks, the bridge can collapse, so they are inspected closely at arm's length.

## PORTFOLIO PIECE: A DESIGNED, TESTED AND INSPECTED BRIDGE

Design and build a model bridge of any type from this unit (beam, arch, suspension or cable-stayed) to span 40 centimeters using card stock, craft sticks, string and glue. Before building, draw it to scale and mark every part in tension or compression. Measure its mass, its deflection under a 200-gram load at the center, and finally its failure load. Then write a one-page engineer's report: design, calculations (at least one: efficiency, thrust or cable tension), test data, where and why it failed, an inspector's condition rating of the parts before the failure test, and what you would change.

| LOOK FOR                                | WHAT IT MEANS                                                                                                       |
|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| <b>Plan</b>                             | Scale drawing with tension and compression parts marked and the span and materials listed.                          |
| <b>Craftsmanship</b>                    | Straight, square, well-joined model; abutments, anchorages or supports built as designed.                           |
| <b>Testing and data</b>                 | Mass, deflection and failure load measured and recorded with units; tests done fairly.                              |
| <b>Calculation</b>                      | At least one correct calculation from the unit (efficiency, thrust or cable tension) using the model's own numbers. |
| <b>Failure analysis and improvement</b> | Report explains where and why the bridge failed using the unit's vocabulary and proposes a specific improvement.    |



## 2.1 BENDING AND THE I-BEAM: STEPHENSON'S BRITANNIA BRIDGE

### OBJECTIVES

- Explain where a bending beam is in compression and in tension, and what the neutral axis is.
- Show with numbers why a beam's depth makes it much stiffer, and why I-beams and box girders put material at the top and bottom.
- Build beams of different shapes from the same card stock, measure their deflection under load, and compare them fairly.

**Warm-up.** Take a plastic ruler and lay it flat across a gap between two books. Press the middle with one finger. Now stand the ruler on its edge across the same gap and press again. Before reading on, guess how many times stiffer the ruler is on edge.

### WATCH

#### Why Are I-Beams Shaped Like An I?

Real Engineering · 3:47

<https://www.youtube.com/watch?v=zSz0kV0BPDY>

#### WHEN TO WATCH

After the physics paragraph. Pause at the I-beam and find the neutral axis before the narrator does.

### BACKUP VIDEO

#### The History of the Britannia Bridge

Network Rail · 3:34

[https://www.youtube.com/watch?v=9sQJoD\\_a0pM](https://www.youtube.com/watch?v=9sQJoD_a0pM)

After the story, to see the Britannia Bridge and Stephenson's original drawings.

### KEY TERMS

#### **beam**

A long structural member that carries loads across a span by bending.

#### **deflection**

How far a beam sags under load, measured at the middle.

**neutral axis**

The line through the middle of a bending beam that is neither squeezed nor stretched.

**flange**

The top or bottom plate of an I-beam or box girder, which carries most of the compression or tension.

**web**

The thin vertical plate joining the flanges of an I-beam.

**buckling**

A sudden sideways crumpling of a thin part under compression.

**CORE IDEAS**

**The story.** In the 1840s Robert Stephenson, the son who had built *Rocket*, was asked to carry the railway from London to Holyhead across the Menai Strait in Wales, where the Admiralty insisted on 100 feet of clear headroom for tall-masted ships and would not allow scaffolding in the channel during construction. The spans would be about 460 feet (140 m), far longer than any iron railway bridge then built. Stephenson's daring idea was a giant hollow beam: a rectangular tube of wrought-iron plates, riveted together, big enough for trains to run through the inside.

**How they figured it out.** No one knew how such a tube would behave, so Stephenson asked the shipbuilder William Fairbairn and the mathematician Eaton Hodgkinson to find out by experiment. At Fairbairn's works in London they built and broke dozens of model tubes, round, oval and rectangular, and finally a model one-sixth full size, 75 feet long. Again and again the tubes did not fail by tearing at the bottom. They failed when the thin top plate, squeezed in compression, rippled and buckled. So Fairbairn stiffened the top and bottom with rows of small square cells, like a honeycomb, and the model then carried far more. The full tubes, each weighing about 1,500 tons, were built on the shore, floated out on pontoons and lifted by hydraulic jacks. The Britannia Bridge opened in 1850 and carried trains for 120 years.

**The physics.** When a beam bends, its top is squeezed (compression) and its bottom is stretched (tension). Halfway between is the **neutral axis**, which is neither squeezed nor stretched and does little work. So material near the middle is mostly wasted, and material far from the middle does the most good. That is why an **I-beam** puts thick **flanges** at the top and bottom, joined by a thin **web**. Depth matters enormously: for a rectangular beam, stiffness grows with the width times the depth cubed (depth  $\times$  depth  $\times$  depth). Take a board 20 cm wide and 2 cm thick. Lying flat, its stiffness

number is  $20 \times 2^3 = 20 \times 8 = 160$ . Standing on edge, it is  $2 \times 20^3 = 2 \times 8,000 = 16,000$ . Same board, same weight, 100 times stiffer, just by turning it.

**The engineering.** Engineers choose beam shapes to get the most stiffness and strength from the least material. Steel I-beams and wide-flange beams hold up floors and short bridges everywhere. Box girders, the descendants of Stephenson's tubes, carry many highway bridges because they also resist twisting. But the Britannia tests also taught the hard lesson of **buckling**: a thin plate in compression can crumple long before the steel itself is overstressed. Modern steel beams have stiffeners welded to their webs for this reason, and engineers still check every compression part for buckling.

## PICTURE STUDY



*The Britannia Tubular Bridge*, Unknown engraver, About 1860 · Print

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

This print shows the Britannia Bridge soon after it opened. The trains ran inside the long iron tubes, which rest on three tall stone towers and two abutments. The caption gives the total length of the tubes, 1,380 feet, and the weight of the ironwork, 10,000 tons.

### Look closely

- Find the long rectangular tubes. Where would the top flange and bottom flange be?
- Find the towers. Why are they so tall?
- Find the ships. What rule did the Admiralty make about them, and how did it shape the bridge?
- Look at the tops of the towers. Stephenson first planned to hang the tubes from chains as well, but the tests showed the tubes could carry themselves.

### Talk about it

1. Where in the tube would the iron be squeezed hardest when a train is in the middle of a span?
2. Why did Fairbairn's honeycomb cells at the top make the tube stronger?
3. Why did Stephenson test models before building the full bridge?

**Safety first.** Wear safety glasses when loading beams to failure; a card beam can snap and flick pennies.

## BUILD

### Flat, Channel, I or Box? A Beam Deflection Test

You will make four beams from identical strips of card stock, each with the same mass, folded into different shapes: flat, U-channel, I-beam and box. You will hang the same load from each, measure how far it sags, and then load each to failure. Like Fairbairn, you will watch closely for how each one fails.

#### You will need

- Card stock or file folders cut into strips 30 cm long and 10 cm wide (about 8 strips)
- Glue stick or white glue, clear tape, a ruler and a pencil for scoring folds
- Two equal stacks of books to make a 25 cm gap
- A paper cup with a string or paper-clip hanger, about 200 pennies, and a kitchen scale
- A second ruler held upright to measure sag, and the engineer's notebook

#### Steps

1. **Make the beams.** Use one 30 × 10 cm strip for each. Flat: leave it flat. Channel: fold up 3 cm along each long edge to make a U. Box: fold it into a long square tube 2.5 cm on each side and tape the seam. I-beam: fold the strip into a Z and glue as shown in the tips. Weigh each beam; they should be nearly the same.
2. **Predict.** Rank the beams from stiffest to floppiest and write down your reasons.
3. Set the first beam across the 25 cm gap. Stand the second ruler upright on the table under the middle of the beam and note the height of the beam's bottom edge.
4. **Deflection test.** Hang the cup from the middle and add 20 pennies (50 g). Measure the new height. The difference is the deflection in millimeters. Remove the load and test each beam the same way. Do each test twice.
5. **Failure test.** Put safety glasses on. Add pennies to each beam, 10 at a time, until it collapses. Record the load and watch how it fails: does the top crumple, does a side buckle, or does it twist?

6. Make a table: beam shape, mass, deflection under 50 g, failure load, how it failed.
7. **Improve.** Take your best beam and change one thing to fix the way it failed, such as adding a strip to stiffen the top or a few cross-pieces inside the box (like Fairbairn's cells). Test it again.

#### Tips

- For the I-beam, fold the strip into thirds lengthwise like a Z, then fold the outer thirds over again to make flanges, and glue. Or glue two narrow strips as flanges onto a third as the web.
- Measure deflection to the nearest millimeter, and look straight across, not from above.
- Hang the load from the bottom of the beam at exactly the middle every time.

#### Check your work

- ☐ I can explain where a beam is in compression and tension and what the neutral axis is.
- ☐ I can show with numbers why depth makes a beam stiffer.
- ☐ I can describe how my beams failed and why buckling matters.

#### ENGINEER'S NOTEBOOK

1. Draw the cross-section (end view) of each beam you tested. Shade where the material is, and draw a dashed line for the neutral axis.
2. Graph deflection under 50 g for each beam as a bar graph. Which shape had the smallest sag?
3. Work it: a plank 30 cm wide and 3 cm thick. Find its stiffness number lying flat ( $30 \times 3^3$ ) and on edge ( $3 \times 30^3$ ). How many times stiffer on edge? (810 and 81,000: 100 times.)

**From history.** In 1970 a fire started by two boys exploring inside the Britannia tubes burned the tar-coated timber roof, and the heat cracked the iron tubes. The bridge was rebuilt with steel arches under the original towers and now carries both a railway and a road deck. Fairbairn and Hodgkinson's test results were published and used by engineers for decades.

## COMMON MISTAKES

- Thinking the strongest beam is the one with the most material. Shape and depth matter more.
- Measuring deflection from different starting points. Always subtract the unloaded height from the loaded height.
- Forgetting that a deep, thin beam can buckle or twist sideways. Depth needs bracing.

**Make it a game · Neutral Axis Quiz.** Bend a sponge or a rolled paper beam. Your parent points to a spot and you call out compression, tension or neutral axis. Then rank flat, channel, I and box shapes from stiffest to weakest and give a reason. Teach it back in a minute, with one planted wrong fact for your parent to catch.



## 2.2 ARCH BRIDGES FROM ROME TO EADS

### OBJECTIVES

- Explain how an arch turns a downward load into compression and an outward thrust on its abutments.
- Calculate how the outward thrust of an arch grows as the arch gets flatter.
- Build and load-test paper arches with and without firm abutments and with different rises.

**Warm-up.** Bend a strip of card into an arch between two books on a smooth table, without taping it. Press down gently on the top. What do the books do? Now push the books tight against two heavy objects and press again.

### WATCH

#### The Eads Bridge

Missouri Historical Society · 9:46

[https://www.youtube.com/watch?v=Pwrhept8G\\_Q](https://www.youtube.com/watch?v=Pwrhept8G_Q)

### WHEN TO WATCH

After the story, before how they figured it out.

### BACKUP VIDEO

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

Paul Kassabian · 5:34

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

Before the build, for a hands-on demonstration of arch thrust.

### KEY TERMS

#### **arch**

A curved structure that carries load across an opening mainly in compression.

#### **voussoir**

One of the wedge-shaped stones of a masonry arch.

#### **keystone**

The top center voussoir, placed last, which locks the arch together.

#### **abutment**

The solid support at each end of an arch that resists its outward push.

**thrust**

The sideways push an arch makes on its abutments.

**rise**

The height of an arch from its springing points to its crown.

**CORE IDEAS**

**The story.** Roman engineers built stone arch bridges so well that some still carry traffic. The Pons Fabricius in Rome, finished in 62 BC, has stood over the Tiber for more than 2,000 years. Eighteen centuries later, the arch faced its greatest test yet. In 1867 James B. Eads began a bridge over the Mississippi at St. Louis. Eads was not a trained engineer. As a young man he had walked the river bottom in a diving bell of his own design, salvaging sunken steamboats, so he knew the river's scouring currents, ice and shifting sand better than anyone. He chose three great arches, the middle one 520 feet (158 m) long, made not of stone or iron but of a new material: steel.

**How they figured it out.** In 1867 hardly anyone had used steel in a large structure, and its quality varied from batch to batch. Eads wrote strict rules: every piece had to be tested for strength and stretch before it went into the bridge, and many batches were rejected. To reach solid rock under the riverbed, his men worked inside pneumatic caissons pressed down through as much as 100 feet of water and sand. The high air pressure caused caisson disease, and fifteen workers died before Eads's physician, Alphonse Jaminet, worked out that slower changes in pressure and shorter shifts reduced the danger. Because the river could not be blocked with scaffolding, the arches were built out from each pier like reaching arms until they met in the middle. In July 1874, before the bridge opened, fourteen locomotives were driven onto it at once as a load test. The Eads Bridge still stands and now carries St. Louis light-rail trains.

**The physics.** An arch turns a downward load into compression that runs around the curve and down into the ground. But an arch also pushes **outward** at its feet. That outward push, the **thrust**, must be resisted by the **abutments**, or the arch will spread and fall. The flatter the arch, the bigger the thrust. For a single load  $P$  at the middle of a simple arch, the thrust is about  $H = P \times \text{span} \div (4 \times \text{rise})$ . Put 1,000 N on an arch that spans 4 m with a rise of 1 m:  $H = 1,000 \times 4 \div (4 \times 1) = 1,000$  N pushing outward on each abutment. Halve the rise to 0.5 m and the thrust doubles to 2,000 N. Stone is

very strong in compression but weak in tension, which is why the shape must keep the whole arch squeezed.

**The engineering.** Arch engineers choose the shape and rise to keep every part in compression and design abutments that will not slide or settle. Where the ground is soft, they may tie the two ends of the arch together with a steel deck in tension (a **tied arch**) so the thrust never reaches the ground. Eads's bridge proved that steel could be trusted if it was tested and specified carefully, and his written specification for steel helped open the way for steel bridges and buildings across America.

## PICTURE STUDY



*Building the Eads Bridge*, Unknown photographer, September 1873 · Photograph · Missouri Historical Society

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

This photograph was taken in 1873, while the arches were being built out from the piers. There is no scaffolding in the river. Instead, the half-arches are held up by cables from temporary towers on top of the piers until the two halves meet.

### Look closely

- Find a stone pier. How far down do you think it goes below the water?
- Find the steel arch ribs reaching out from the pier. Is the gap in the middle closed yet?
- Find the temporary towers and cables. What are they holding up?
- Look for the river below. Why could Eads not fill it with scaffolding?

### Talk about it

1. Before the two halves of an arch meet, is it an arch yet? What is holding it up?
2. Why would Eads want every batch of steel tested before it went into the bridge?
3. Where does the outward thrust of these arches go?

**Safety first.** Wear safety glasses when loading arches to failure.

## BUILD

### Thrust and Abutments: A Paper Arch Test

You will build arches from card stock, load them with pennies, and find out how much the abutments matter and how the rise changes the arch's strength and push.

#### You will need

- Card stock or file folders cut into strips 40 cm long and 8 cm wide
- Two heavy books for abutments, and two more heavy objects (a brick, a full jar) to block them
- A stiff piece of cardboard 10 cm square to spread the load at the top
- About 200 pennies in a paper cup, a kitchen scale and a ruler
- Masking tape and the engineer's notebook

#### Steps

1. **Set up.** Stand two books on a smooth table with their spines facing each other 30 cm apart. Bend a strip into an arch and set its ends against the book spines so the arch rises about 10 cm.
2. **Predict.** Will the arch hold more pennies with free books or blocked books? Will a high arch or a low arch hold more?
3. **Test 1 (free abutments).** Set the cardboard square on the crown and add pennies, five at a time, until the arch collapses or the books slide apart. Record the load and measure how far the books slid.
4. **Test 2 (firm abutments).** Block the outside of each book with a heavy object so it cannot slide. Repeat with a new strip.
5. **Test 3 (change the rise).** With firm abutments, move the books closer so the arch rises 15 cm, then farther apart so it rises 5 cm. Test each with a new strip. Keep the strip size the same.
6. Make a table: rise, abutments free or firm, load at failure, how it failed.
7. Use  $H = P \times \text{span} \div (4 \times \text{rise})$  to calculate the thrust for your 10 cm and 5 cm arches with the same load. Does your data agree that the flatter arch pushes harder?

8. **Improve.** Design a “tied arch”: tape a string tightly between the two ends of the arch and test it with free books. Does the tie do the job of the abutments?

**Tips**

- Use a fresh strip for each test; a creased arch is weaker.
- Watch where the arch fails. Often one side bends up while the other bends down.
- Spreading the load with the cardboard square keeps the pennies from pinching the crown.

**Check your work**

- ☐ I can explain why an arch needs abutments.
- ☐ I can calculate the outward thrust of an arch and explain why a flatter arch pushes harder.
- ☐ I can explain how a tied arch works.

**ENGINEER’S NOTEBOOK**

1. Draw an arch with arrows: the load at the top, compression running down the curve, and the thrust and downward push at each abutment.
2. Make a bar graph of the load held in each of your tests.
3. Work it: a load of 3,000 N sits at the middle of an arch that spans 12 m with a rise of 3 m. What is the thrust? ( $3,000 \times 12 \div (4 \times 3) = 3,000$  N.) What if the rise is 2 m? (4,500 N.)

**From history.** On June 14, 1874, an elephant from a visiting menagerie was led across the Eads Bridge, because many people believed an elephant would refuse to step onto an unsafe structure. The elephant’s walk proved nothing, but the locomotive test that followed did. Eads also designed jetties at the mouth of the Mississippi that scoured a deep channel for ships.

**COMMON MISTAKES**

- Thinking an arch only pushes down. It also pushes outward, and that push must go somewhere.
- Changing two things at once, such as the rise and the strip width.
- Calling every curved bridge an arch. A suspension bridge’s cable hangs in tension; an arch stands in compression.

**Make it a game • Flatter Arch, More Thrust.** Your parent draws three arches on paper: tall, medium and flat. Rank them by outward thrust on the abutments, and explain why the order holds. Then take turns naming parts: voussoir, keystone, abutment, rise. One point for each part with a correct role. Add one fact about Eads and his bridge.

**Scripture.** “Behold, I lay in Zion for a foundation a stone, a tried stone, a precious corner stone, a sure foundation” (Isaiah 28:16, KJV)

Eads would not use a piece of steel that had not been tried. A sure foundation, tested and trusted, is what every arch and every life needs.

## 2.3 CABLE-STAYED VERSUS SUSPENSION: TELFORD'S MENAI BRIDGE

### OBJECTIVES

- Trace the load path of a suspension bridge and a cable-stayed bridge from deck to ground.
- Calculate the tension in a sloping cable from its load and its shape.
- Build both kinds of model bridge and compare their deflection under the same load.

**Warm-up.** Hold a string between your two hands with a little sag and have someone hang a key ring on the middle. Pull your hands apart to make the string straighter. What happens to how hard you have to pull? Write it down.

### WATCH

#### A Love Letter to Cable-Stayed Bridges

Practical Engineering · 20:19

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

#### WHEN TO WATCH

After the physics paragraph. Longer; watch the first 14 minutes in session 1 and the rest before the build.

**Note:** The last minute is a sponsor message; you can stop when the teaching ends.

---

### BACKUP VIDEO

#### 4. Suspension Bridges

Engineering Models · 7:02

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

Before the build, for a model demonstration of how a suspension bridge carries its load.



## KEY TERMS

### **suspension bridge**

A bridge whose deck hangs from vertical hangers attached to main cables draped over towers and anchored in the ground at each end.

### **anchorage**

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

### **sag**

How far a cable droops below the line between its supports.

### **cable-stayed bridge**

A bridge whose deck is held up by straight cables running directly from one or more towers to points along the deck.

### **stay**

A straight cable in a cable-stayed bridge.

## CORE IDEAS

**The story.** In 1819 Thomas Telford, a Scottish stonemason who had become Britain's leading road engineer, began a bridge for the London-to-Holyhead road across the Menai Strait, the same water Stephenson would later cross by rail. To leave room for tall ships, Telford chose a suspension bridge with a main span of 577 feet (176 m), longer than any bridge in the world at the time. Its deck hung from chains made of flat wrought-iron bars linked end to end and draped over two stone towers. The bridge opened on January 30, 1826.

**How they figured it out.** Telford did not trust iron he had not tested. Every bar for the chains was stretched in a testing machine to well above its working load before it was used, and any bar that failed was thrown out. The sixteen chains were lifted into place one at a time, each hauled up by teams of men on capstans while crowds watched. But Telford had not foreseen how much the wind would move a light, flexible deck. Gales damaged it in the years after it opened, and engineers stiffened and replaced the deck more than once. Those lessons in wind and stiffness were learned the hard way again at Tacoma Narrows a century later.

**The physics.** In a **suspension bridge**, the deck hangs from vertical hangers, the hangers hang from the main cables, the cables carry the load over the towers in tension, and huge **anchorage**s hold the cable ends to the ground. In a **cable-stayed**

**bridge**, straight **stays** run directly from the tower to the deck, and the deck itself is squeezed lengthwise like a long column. A sloping cable must pull harder than the weight it holds up, because only part of its pull is upward. For a straight cable,  $\text{tension} = \text{load} \times (\text{cable length} \div \text{height it climbs})$ . A stay 40 m long that climbs 20 m up the tower and holds up 50 kN of deck pulls with  $50 \times (40 \div 20) = 100$  kN. A flatter cable, say 40 m long climbing only 10 m, would need 200 kN. The same is true of a sagging cable: a nearly straight cable must be pulled very hard.

**The engineering.** Suspension bridges can span farther than any other kind, more than 2,000 m today, but they need massive anchorages and a stiff deck to resist wind. Cable-stayed bridges, developed after 1950 by German engineers such as Franz Dischinger and Fritz Leonhardt, need no anchorages, are stiffer, and can be built out from the tower one segment and one stay at a time. For spans from about 200 m to 1,000 m, engineers now often choose cable-stayed. The choice depends on span, ground, wind, cost and how the bridge will be built, which is the kind of trade-off engineers weigh every day.

## PICTURE STUDY



*The Menai Suspension Bridge, Unknown artist, About 1840 · Print*

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

This view shows Telford's bridge some years after it opened. The curved lines are the iron chains; the thin vertical lines hanging from them are the rods that carry the deck.

### Look closely

- Follow one chain from one end of the bridge to the other. Where does it go at each end?
- Find the towers. Are they being pulled, or pushed down?
- Find the vertical hangers. Are they in tension or compression?
- Look at the ships. How much room did Telford leave for them?

### Talk about it

1. Where does the weight of a coach on the deck finally go into the ground?
2. Why would a light deck like this one move in strong wind?
3. If Telford had built a cable-stayed bridge instead, what would the cables look like?

## BUILD

### Hang It or Stay It? Two Model Bridges

You will build a model suspension bridge and a model cable-stayed bridge with the same span, the same deck and the same towers, then measure how much each deck sags under the same load, and test how the angle of the stays changes things.

#### You will need

- Two strips of thin cardboard 60 cm long and 8 cm wide for decks
- Four towers: paper-towel tubes or rolled card, about 25 cm tall, taped to a base board
- String or strong thread, paper clips and masking tape
- Two heavy books to anchor the suspension cables
- Pennies, a paper cup and a ruler held upright for measuring sag

#### Steps

1. **Suspension model.** Tape two towers to the base 40 cm apart. Drape two strings over the towers, tie their ends to heavy books beyond each tower (the anchorages), and let them sag about 10 cm in the middle. Hang the deck from the strings with seven paper-clip hangers.
2. **Cable-stayed model.** On a second base, tape two towers at the same spacing. From the top of each tower, run four straight strings fanning down to points along the deck. Tape each string firmly.
3. **Predict.** Which deck will sag less under 30 pennies placed at the center? At a quarter-span?
4. **Test.** Measure the deck height at the center with no load. Place 30 pennies at the center and measure again. Then move them to a point halfway between the center and a tower. Do each test three times.
5. Record the sag for each bridge and each load position in a table.
6. **Change one thing.** On the cable-stayed model, lower the attachment points on the towers so the stays are flatter. Test again. Use  $\text{tension} = \text{load} \times (\text{cable length} \div \text{rise})$  to explain what you saw.

7. **Improve.** Choose the better design for a 40 cm span with a load that moves (like a car crossing). Change one detail to reduce sag, and test it.

**Tips**

- Tie the strings off tightly; a slipping knot ruins the test.
- A suspension model sags most when the load is off-center, because the cable changes shape. Watch for it.
- Keep the deck strips identical so the comparison is fair.

**Check your work**

- ☐ I can trace the load path of both kinds of cable bridge.
- ☐ I can calculate the tension in a sloping cable.
- ☐ I can explain which kind of bridge my test favored, and why.

**ENGINEER'S NOTEBOOK**

1. Draw both bridges side by side. Label tension (red) and compression (blue) in the cables, hangers, towers and deck.
2. Make a table of sag for each bridge and each load position, and write two sentences comparing them.
3. Work it: a stay is 50 m long and climbs 25 m up its tower. It holds up 80 kN of deck. What is its tension? ( $80 \times 50 \div 25 = 160$  kN.)

**From history.** Telford's original wrought-iron chains were replaced with steel chains in 1938–1940, and the bridge still carries road traffic today. Telford was the first president of the Institution of Civil Engineers, founded in London in 1818, which helped make engineering a profession with shared knowledge and standards.

**COMMON MISTAKES**

- Thinking the cables of a suspension bridge are in compression. All cables are in tension; they cannot push.
- Forgetting the anchorages. Without them, a suspension bridge's towers would be pulled over.
- Thinking a tighter, straighter cable is under less force. A straighter cable must pull harder to hold the same load.

**Make it a game • Load Path Race.** Draw a suspension bridge and a cable-stayed bridge. Trace the load path from deck to ground on each in fifteen seconds, naming cable, stay, tower and anchorage. Your parent times you. Then estimate how cable tension changes when the sag is smaller. Best of three tries beats your own record.

## 2.4 BRIDGE INSPECTION AND MAINTENANCE: THE SILVER BRIDGE

### OBJECTIVES

- Explain fatigue, corrosion and redundancy, and why they matter for old bridges.
- Describe what happened at the Silver Bridge and how it changed bridge inspection in the United States.
- Measure metal fatigue with a repeated-bending test and write an inspection report for a model or a real bridge.

**Warm-up.** Bend a paper clip open and closed at the same spot, counting each bend, until it breaks. Before you start, guess the number. Feel the bend after ten bends. What do you notice?

### WATCH

#### How Sensors Keep Bridges From Collapsing (and other structures too).

Practical Engineering · 17:07

<https://www.youtube.com/watch?v=DdbmTl0rhGw>

#### WHEN TO WATCH

After the engineering paragraph, to see how inspectors and sensors watch bridges today.

**Note:** The video ends with a short sponsor message; stop when the teaching ends.

---

### BACKUP VIDEO

#### Silver Bridge | The Tragedy That Changed Civil Engineering Forever

Sabin Civil Engineering · 10:25

[https://www.youtube.com/watch?v=\\_GoQmBhdr98](https://www.youtube.com/watch?v=_GoQmBhdr98)

After the story, for more on how the Silver Bridge eyebar failed. It tells of the 46 people lost plainly and without disturbing detail; preview it for sensitive students.

## KEY TERMS

### **fatigue**

Weakening of a material by many repeated loads, which can grow a small crack until a part breaks at a load it once carried easily.

### **redundancy**

Having more than one load path, so that if one part fails, others can carry the load.

### **eyebars**

A flat steel bar with a large hole (an “eye”) at each end, pinned to other eyebars to form a chain.

### **corrosion**

Damage to metal by chemical reaction, such as rust on iron and steel.

### **fracture-critical member**

A steel part in tension whose failure would cause the bridge to collapse.

### **condition rating**

An inspector’s score for a part of a bridge, from 9 (excellent) down to 0 (failed).

## CORE IDEAS

**The story.** At about 5 p.m. on December 15, 1967, the Silver Bridge between Point Pleasant, West Virginia, and Ohio was full of rush-hour traffic and Christmas shoppers when it fell into the Ohio River in less than a minute. Forty-six people died. The bridge had opened in 1928. It was a suspension bridge, but instead of wire cables it hung from chains of steel **eyebars**, two bars side by side in each link, pinned together.

**How they figured it out.** Investigators from the National Transportation Safety Board lifted the wreckage from the river and laid it out piece by piece in a field. They traced the failure to one eyebar in the north chain, where a crack only about one tenth of an inch (2.5 mm) deep had grown at the edge of the eye. Years of moisture and stress had slowly deepened it until the eye snapped. With only two bars in the link, the other bar could not carry the load alone, the chain came apart, and the whole bridge followed. The crack had been hidden where no inspector could see it without taking the joint apart. The bridge had almost no **redundancy**: one small part was carrying the whole structure.

**The physics.** Steel can carry a load safely once, a thousand times, a million times. But every time a truck crosses, every part of the bridge stretches a tiny bit and



relaxes again. If there is a tiny flaw, each cycle of stress can grow it a little. This is **fatigue**, the same thing that broke your paper clip. **Corrosion** makes it worse, eating metal away and starting new cracks. A crack grows slowly for years and then suddenly reaches a size where the part breaks all at once. A bridge with **redundancy** has other paths for the load, so one broken part does not bring it down.

**The engineering.** After the Silver Bridge fell, Congress required the National Bridge Inspection Standards, which took effect in 1971. Every public highway bridge in the United States, now more than 600,000 of them, must be inspected by a qualified inspector, usually at least once every two years. Inspectors look for cracks, rust, scour of the riverbed around piers, loose bolts and failed paint, and give each main part a **condition rating** from 9 down to 0. **Fracture-critical members** must be examined at arm's length. Inspectors use ultrasound and dye to find hidden cracks, and some bridges now carry sensors that report strain all day. Maintenance, such as painting steel, sealing concrete and replacing bearings, is far cheaper than replacing a bridge. Engineers also design new bridges with redundancy, so that no single crack can cause a collapse.

## PICTURE STUDY



*Eyebars in a Truss: The Washingtonville Bridge*, Historic American Engineering Record, Photograph of a bridge built in the 1800s · Photograph · Library of Congress, Prints and Photographs Division

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

The Historic American Engineering Record photographed this small Pennsylvania truss bridge. Its bottom chord is made of pairs of flat eyebars joined by pins, the same kind of part that failed at the Silver Bridge. Look at it the way an inspector would.

### Look closely

- Find the double eyebars in the lower chord. Are they in tension or compression?
- Find a pin where eyebars meet. Where would water collect, and where could a crack hide?
- Look for rust, bent members or missing pieces.
- Find the braced posts. How are they different from the flat eyebars?

### Talk about it

1. If one of the two eyebars in a link cracked, what would the other one have to do?
2. How would you inspect the inside of a pin joint without taking it apart?
3. What condition rating (9 to 0) would you give the parts you can see, and why?

**Safety first.** Bend paper clips with pliers if your fingers get sore, and wear safety glasses, because a breaking clip can flick. If you look at a real bridge, stay on the sidewalk or a safe public path; never climb on a bridge or go near traffic or the water's edge.

## BUILD

### Fatigue Test and an Inspector's Report

In part A you will measure fatigue: how many bends a paper clip survives at two different bend angles, with enough clips to see the pattern. In part B you will inspect a bridge, either a model from this unit or a real footbridge or road bridge seen from a safe place, and write a report like a real bridge inspector's.

#### You will need

- 20 identical paper clips and a pair of pliers
- A protractor drawn on card to guide the bend angle
- Safety glasses
- A model bridge from Lessons 2.1–2.3, or a real bridge you can see from a safe public place
- A camera or phone, a clipboard and the engineer's notebook

#### Steps

1. **Part A, predict.** Will a clip survive more cycles if you bend it  $90^\circ$  each time or  $45^\circ$  each time? How many more?
2. Straighten the outer loop of a clip. Mark a spot with a marker. Bend it to  $90^\circ$  and back to straight; that is one cycle. Count cycles until it breaks. Test 5 clips this way.
3. Test 5 more clips bending only  $45^\circ$  each time.
4. Make a table and find the average number of cycles for each angle. How much longer did the smaller bend last?
5. **Part B, inspect.** Choose your bridge. Photograph or sketch it from the side and label its main parts (deck, beams or truss, piers or towers, bearings, cables).
6. For each main part, look closely for cracks, rust, bending, loose joints and wear. Give each a condition rating from 9 (excellent) to 0 (failed), and write the reason for each rating.
7. Decide whether the bridge has redundancy: if one part failed, could another carry the load?

8. **Improve.** Write one maintenance recommendation, such as “repaint the rusty lower chord” or “add a second load path at the center joint,” and explain why it would make the bridge safer.

**Tips**

- Bend each clip at the same speed and the same spot so the test is fair.
- Your clip warms up as you bend it. That heat is energy going into changing the metal.
- Real inspectors photograph every defect with a ruler or coin beside it for scale. You can do the same.

**Check your work**

- ☐ I can explain fatigue, corrosion and redundancy.
- ☐ I can tell what happened at the Silver Bridge and what changed afterward.
- ☐ I can write an inspection report with condition ratings and a recommendation.

**ENGINEER’S NOTEBOOK**

1. Draw a bar graph of average cycles to failure for 90° and 45° bends.
2. Draw an eyebar chain link with its pin, and mark where the Silver Bridge crack began.
3. Copy your inspection table: part, what you saw, condition rating, reason.

**From history.** The Silver Bridge’s near twin, the St. Marys Bridge upstream, was soon closed to traffic and later torn down. A new bridge at Point Pleasant, the Silver Memorial Bridge, opened in 1969. The lessons of the Silver Bridge are taught to every bridge inspector in America.

**COMMON MISTAKES**

- Thinking a bridge that carried a load yesterday must be safe today. Fatigue and corrosion change a bridge slowly.
- Testing only one paper clip. Fatigue results scatter widely; you need several.
- Confusing a strong part with a redundant structure. Even a strong part can crack; redundancy means the bridge survives if it does.

**Make it a game • Inspector's Eye.** Play bridge inspector. Your parent describes a bridge with rust, one eyebar and tiny cracks. You say what fatigue, corrosion and redundancy mean, rate the condition, and decide whether to close the bridge. Then tell what happened at the Silver Bridge. Each sound judgment earns a point.

**Scripture.** “and viewed the walls of Jerusalem, which were broken down” (Nehemiah 2:13, KJV)

Before Nehemiah rebuilt, he went out by night and inspected every part of the wall himself. Careful inspection, even when it is dull, is how engineers keep people safe.

## BRIDGES

In Grade 5 you learned the forces inside a structure and built a truss. This year you will go a step deeper and ask the questions a bridge engineer asks with a pencil and a calculator. Why is a steel beam shaped like the letter I? How much does an arch push outward on its foundations, and why does a flatter arch push harder? Why are some long bridges hung from great curved cables and others from straight cables fanned out from a tower?

You will follow Robert Stephenson as he tested model iron tubes until they buckled, James Eads as he insisted on testing every piece of steel for his arches at St. Louis, and Thomas Telford as he hung the first great suspension bridge over the Menai Strait. Last, you will learn what happened at the Silver Bridge in 1967, and how it led to the inspection program that keeps hundreds of thousands of bridges safe today. A bridge is not finished when it opens; someone must keep watching it.

### PREREQUISITES

- Knows compression, tension, shear and torsion and can find them in a truss (Grade 5 or Unit 1)
- Can calculate with  $F = ma$  and  $\text{weight} = \text{mass} \times 9.8$  (Lesson 1.2)
- Can find an average and make a line graph

### MASTERY CHECKLIST

- ☐ I can explain why an I-beam or box girder is stiff for its weight, and show that a beam's depth matters more than its width.
- ☐ I can explain how an arch carries load in compression and calculate how its outward thrust grows as it gets flatter.
- ☐ I can compare suspension and cable-stayed bridges and calculate the tension in a sloping cable.
- ☐ I can explain fatigue, corrosion and redundancy, and describe how and why bridges are inspected.
- ☐ I can load-test a model, measure its deflection and failure load, and improve it.

## OPTIONAL KITS FOR THIS UNIT

- **Pitsco balsa bridge kits:** Ages 11 and up with an adult. Balsa sticks, plans and gussets for a truss bridge that can be weighed and load-tested to failure; a good portfolio option for this unit.
- **KEVA planks:** Ages 6 and up. Identical maple planks with no connectors; good for building block arches and testing why abutments matter in Lesson 2.2.

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

## LESSONS IN THIS UNIT

|     |                                                               |                          |
|-----|---------------------------------------------------------------|--------------------------|
| 2.1 | <b>Bending and the I-Beam: Stephenson's Britannia Bridge</b>  | 2 sessions of 50 minutes |
| 2.2 | <b>Arch Bridges from Rome to Eads</b>                         | 2 sessions of 50 minutes |
| 2.3 | <b>Cable-Stayed versus Suspension: Telford's Menai Bridge</b> | 2 sessions of 50 minutes |
| 2.4 | <b>Bridge Inspection and Maintenance: The Silver Bridge</b>   | 2 sessions of 50 minutes |

## UNIT 2 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

When a beam bends under a load in the middle, which part is in compression, which is in tension, and where is the neutral axis?

2. **10 pts**

Calculate: a board is 10 cm wide and 2 cm thick. Find its stiffness number (width  $\times$  depth<sup>3</sup>) lying flat and standing on edge. How many times stiffer is it on edge?

3. **8 pts**

Explain in two or three sentences why an I-beam is shaped like the letter I.



4. (7 pts)

What did Fairbairn's model-tube tests for the Britannia Bridge show about how the tubes failed, and what did he change?

5. (8 pts)

What is an abutment, and what happens to an arch whose abutments slide apart?

6. (10 pts)

Calculate: a load of 2,000 N sits on the middle of an arch that spans 8 m with a rise of 2 m. Using  $H = P \times \text{span} \div (4 \times \text{rise})$ , find the thrust. Then find it again if the rise is only 1 m.

7. (7 pts)

Why did James Eads insist on testing the steel for his bridge?

8. (8 pts)

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

9. (10 pts)

Calculate: a straight stay 60 m long climbs 30 m up its tower and holds up 40 kN of deck. What is the tension in the stay?

10. (8 pts)

Give two differences between a suspension bridge and a cable-stayed bridge.

11. (8 pts)

What is metal fatigue, and how did it lead to the Silver Bridge collapse?

12. (8 pts)

Explain what redundancy means for a bridge and why inspectors pay special attention to fracture-critical members.

## ANSWER KEY

1. The top is in compression, the bottom is in tension, and the neutral axis runs through the middle, where there is neither.
2. Flat:  $10 \times 2^3 = 80$ . On edge:  $2 \times 10^3 = 2,000$ . It is  $2,000 \div 80 = 25$  times stiffer on edge.
3. When a beam bends, the top and bottom do most of the work and the middle near the neutral axis does little. An I-beam puts thick flanges at the top and bottom and only a thin web between them, so it is stiff and strong for its weight.
4. The tubes failed when the thin top plate, in compression, buckled. He stiffened the top (and bottom) with rows of small square cells.
5. An abutment is the solid support at each end of an arch that resists its outward thrust. If the abutments slide apart, the arch spreads, flattens and collapses.
6. Rise 2 m:  $H = 2,000 \times 8 \div (4 \times 2) = 2,000$  N. Rise 1 m:  $H = 2,000 \times 8 \div (4 \times 1) = 4,000$  N. The flatter arch pushes twice as hard.
7. Steel was new for large structures and its quality varied from batch to batch, so he tested every piece for strength and stretch and rejected bad batches to be sure the arches were safe.
8. Deck  $\rightarrow$  vertical hangers (tension)  $\rightarrow$  main cables (tension)  $\rightarrow$  over the towers (compression) down to the foundations, with the cable ends held by the anchorages.
9. Tension = load  $\times$  (length  $\div$  rise) =  $40 \text{ kN} \times (60 \div 30) = 80 \text{ kN}$ .
10. Any two: suspension main cables sag in a curve and need anchorages, while cable-stayed stays are straight and need none; suspension decks hang from vertical hangers, cable-stayed decks are held directly by sloping stays; suspension bridges reach longer spans; cable-stayed bridges are stiffer and can be built out from the tower segment by segment.
11. Fatigue is weakening by many repeated loads, which grows small cracks. A tiny crack (helped by corrosion) grew in one eyebar until it broke, and because the chain had no other load path, the bridge fell.
12. Redundancy means there is more than one load path, so the bridge survives if one part fails. Fracture-critical members have no backup: if one breaks, the bridge can collapse, so they are inspected closely at arm's length.

## PORTFOLIO PIECE: A DESIGNED, TESTED AND INSPECTED BRIDGE

Design and build a model bridge of any type from this unit (beam, arch, suspension or cable-stayed) to span 40 centimeters using card stock, craft sticks, string and glue. Before building, draw it to scale and mark every part in tension or compression. Measure its mass, its deflection under a 200-gram load at the center, and finally its failure load. Then write a one-page engineer's report: design, calculations (at least one: efficiency, thrust or cable tension), test data, where and why it failed, an inspector's condition rating of the parts before the failure test, and what you would change.

| LOOK FOR                                | WHAT IT MEANS                                                                                                       |
|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| <b>Plan</b>                             | Scale drawing with tension and compression parts marked and the span and materials listed.                          |
| <b>Craftsmanship</b>                    | Straight, square, well-joined model; abutments, anchorages or supports built as designed.                           |
| <b>Testing and data</b>                 | Mass, deflection and failure load measured and recorded with units; tests done fairly.                              |
| <b>Calculation</b>                      | At least one correct calculation from the unit (efficiency, thrust or cable tension) using the model's own numbers. |
| <b>Failure analysis and improvement</b> | Report explains where and why the bridge failed using the unit's vocabulary and proposes a specific improvement.    |

### UNIT 3

## ARCHITECTURE

Architecture is where engineering meets beauty and daily life. In this unit you will learn the language architects and builders use to talk to each other, the measured drawing: plan, elevation, section and scale. You will meet Vitruvius, the Roman architect who said that every good building must have firmness, commodity and delight, and you will test columns the way builders have tested them ever since.

Then you will climb inside three of the greatest domes ever built, the Pantheon in Rome, Hagia Sophia in Constantinople and St Paul's Cathedral in London, and learn how Christopher Wren and Robert Hooke used a hanging chain to find the shape of an arch. Last, you will look at the hidden systems that make a tall building livable: elevators with counterweights, water that has to be pumped to the top floor, and air that has to be heated, cooled and moved.

#### PREREQUISITES

- Can measure in meters and centimeters and multiply and divide decimals
- Knows compression and tension, and how arches push outward (Unit 2)
- Can calculate weight from mass ( $\text{weight} = \text{mass} \times 9.8$ ) (Unit 1)

#### MASTERY CHECKLIST

- ☐ I can read and draw a floor plan and an elevation to scale, and convert between drawing and real sizes.
- ☐ I can explain Vitruvius's firmness, commodity and delight, and test how a column's shape and height change its strength.
- ☐ I can explain how a dome works, what hoop tension is, and how Wren and Hooke used the hanging chain.
- ☐ I can calculate water pressure from height and explain why tall buildings need pumps and tanks.
- ☐ I can explain how an elevator counterweight saves energy and calculate what the motor must lift.

## OPTIONAL KITS FOR THIS UNIT

- **KEVA planks:** Ages 6 and up. Identical maple planks for building columns, arches, towers and small domes without glue; good for trying Hooke's arch shapes in Lesson 3.3.
- **Tinkercad:** Free, browser-based 3D design from Autodesk, for ages 8 and up with a parent's account setup. Students can model the room they drew in Lesson 3.1 or the pavilion from Lesson 3.2.

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

## LESSONS IN THIS UNIT

|                                                                         |                          |
|-------------------------------------------------------------------------|--------------------------|
| <b>3.1 Architectural Drawing: Plan, Elevation and Scale</b>             | 2 sessions of 50 minutes |
| <b>3.2 Vitruvius: Firmness, Commodity and Delight</b>                   | 2 sessions of 50 minutes |
| <b>3.3 Great Domes: The Pantheon, Hagia Sophia and Wren's St Paul's</b> | 2 sessions of 50 minutes |
| <b>3.4 The Systems Inside a Skyscraper: Elevators, Water and Air</b>    | 2 sessions of 50 minutes |

## UNIT 3 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**  
What is the difference between a plan, an elevation and a section?
2. **10 pts**  
Calculate: on a 1 : 50 drawing, how long is a wall that is really 5.5 m long? On the same drawing, a window measures 2.4 cm. How wide is the real window?
3. **6 pts**  
Why did the Historic American Buildings Survey begin in 1933, and why are its drawings still valuable?

4. (8 pts)

Name Vitruvius's three qualities of good architecture and give an example of each from a building you know.

5. (10 pts)

Calculate: a column 25 cm tall buckles under a load of 12 kg. Using the rule that buckling load falls with the square of the height, about how much will the same column hold if it is 50 cm tall?

6. (8 pts)

Explain in two or three sentences what hoop tension is and how Wren dealt with it at St Paul's.

7. (8 pts)

What did Robert Hooke discover about a hanging chain, and why does it matter for arches?

8. (7 pts)

Name one way the builders of the Pantheon or Hagia Sophia made their domes safer.

9. (10 pts)

Calculate: how much water pressure, in pascals, is needed just to hold water at the top of a pipe 20 m high? (Use  $\text{pressure} = 1,000 \times 9.8 \times \text{height}$ .)

10. (9 pts)

Calculate: an elevator car has a mass of 900 kg and a rated load of 1,000 kg. The counterweight is the car plus 45% of the rated load. Find the counterweight's mass and the mass the motor must lift with a full car.

11. (8 pts)

Why do tall buildings pump water to tanks on upper floors instead of relying on city water pressure?

12. (8 pts)

What problem was Willis Carrier first asked to solve in 1902, and what idea from a foggy night helped him?

## ANSWER KEY

1. A plan is a horizontal slice seen from above showing walls, doors and windows; an elevation is a straight-on view of one side showing heights; a section is a vertical slice showing floors, ceilings and the inside of walls.
2.  $5.5 \text{ m} = 550 \text{ cm}$ ;  $550 \div 50 = 11 \text{ cm}$  on the drawing. Window:  $2.4 \times 50 = 120 \text{ cm} = 1.2 \text{ m}$ .
3. To give work to unemployed architects and to record historic buildings before they were lost. Its drawings are free to all and are the only record of many buildings that are now gone.
4. Firmness (it stands strong and lasts), commodity (it is useful), delight (it is beautiful). Examples will vary.
5. The height doubles, so the load falls by  $2^2 = 4$ :  $12 \div 4 = 3 \text{ kg}$ .
6. Hoop tension is the stretching around the lower part of a dome as it tries to spread outward, which can crack masonry in vertical lines. Wren laid an iron chain around the base of his brick cone to hold it together.
7. A hanging chain takes the shape where it is only in tension; turned upside down, that shape is an arch that is only in compression, which is ideal for masonry.
8. Pantheon: lighter concrete (pumice) toward the top, thinner dome near the oculus, heavy stepped rings at the base. Hagia Sophia: after the first dome partly fell, it was rebuilt higher so it pushed outward less.
9.  $1,000 \times 9.8 \times 20 = 196,000 \text{ Pa}$  (about 28 psi).
10. Counterweight =  $900 + 450 = 1,350 \text{ kg}$ . Full car =  $1,900 \text{ kg}$ . Motor lifts  $1,900 - 1,350 = 550 \text{ kg}$ .
11. City pressure can only lift water about five or six stories and still give enough pressure at the tap. Pumps lift water to tanks in each zone, and it flows down by gravity to the floors below.
12. A Brooklyn printing company's paper swelled and shrank with humidity, spoiling color printing. He realized that cooling air to a set dew point makes extra water condense out, so cooling can control how much moisture the air keeps.

## PORTFOLIO PIECE: A MEASURED MODEL PAVILION

Design a small building, such as a garden pavilion, a chapel or a bus shelter, and draw its plan, one elevation and one section at a stated scale. Then build a model from card stock and cardboard at the same scale and test its firmness with a measured load on the roof. Write a one-page report that explains how your design meets firmness, commodity and delight, gives at least one scale calculation and one load or column calculation, and says what you would change.

| LOOK FOR                               | WHAT IT MEANS                                                                                              |
|----------------------------------------|------------------------------------------------------------------------------------------------------------|
| <b>Drawings</b>                        | Plan, elevation and section drawn neatly to a stated scale, with a title box and dimensions.               |
| <b>Scale accuracy</b>                  | The model matches the drawings; at least three dimensions checked and recorded.                            |
| <b>Firmness test</b>                   | Roof load test done carefully with the load and the way the model failed recorded.                         |
| <b>Calculations</b>                    | At least one scale conversion and one load or column calculation, worked correctly with units.             |
| <b>Firmness, commodity and delight</b> | The report explains all three qualities with specific features of the design and proposes one improvement. |



## 3.1 ARCHITECTURAL DRAWING: PLAN, ELEVATION AND SCALE

### OBJECTIVES

- Explain what a plan, an elevation and a section show.
- Use a scale such as 1 : 50 to convert real measurements to drawing measurements and back.
- Measure a real room and draw its floor plan and one elevation to scale, then check the drawing against the room.

**Warm-up.** Without measuring, sketch the floor of the room you are in as if you were looking down from the ceiling. Mark the door and windows. Then pace out the length and width (one pace is about 0.7 meters for most sixth graders) and write them on your sketch.

### WATCH

#### How to Read and Draw a Scale Floor Plan – Scaled Floorplans Drawing Course for Architecture Students

Kyle Sinko · 8:57

<https://www.youtube.com/watch?v=YL4it90rMb8>

### WHEN TO WATCH

Before the build. Pause when he converts a real length to the drawing and do it yourself first.

### KEY TERMS

#### **plan**

A drawing of a building as if it were sliced horizontally about 1.2 meters above the floor and seen from above, showing walls, doors and windows.

#### **elevation**

A drawing of one side of a building seen straight on, with no perspective, showing heights.

**section**

A drawing of a building as if it were sliced vertically, showing floors, ceilings and the inside of walls.

**scale**

The ratio between a drawing and the real thing. At 1 : 50, 1 centimeter on paper stands for 50 centimeters in real life.

**measured drawing**

A drawing made by carefully measuring an existing building, rather than designing a new one.

**CORE IDEAS**

**The story.** In the winter of 1933, many American architects were out of work. Charles E. Peterson, a young architect with the National Park Service, proposed a plan that would put them to work and save something precious at the same time: send teams to measure and draw the nation's historic buildings, many of which were falling down or being torn down. The Historic American Buildings Survey (HABS) began that December. Within weeks about a thousand architects and draftsmen were measuring old farmhouses, churches, mills and mansions with tapes and rods and drawing them in ink. The program never stopped. Its drawings and photographs, now in the Library of Congress and free for anyone to use, record tens of thousands of buildings, and a companion program, the Historic American Engineering Record, does the same for bridges, dams and machines.

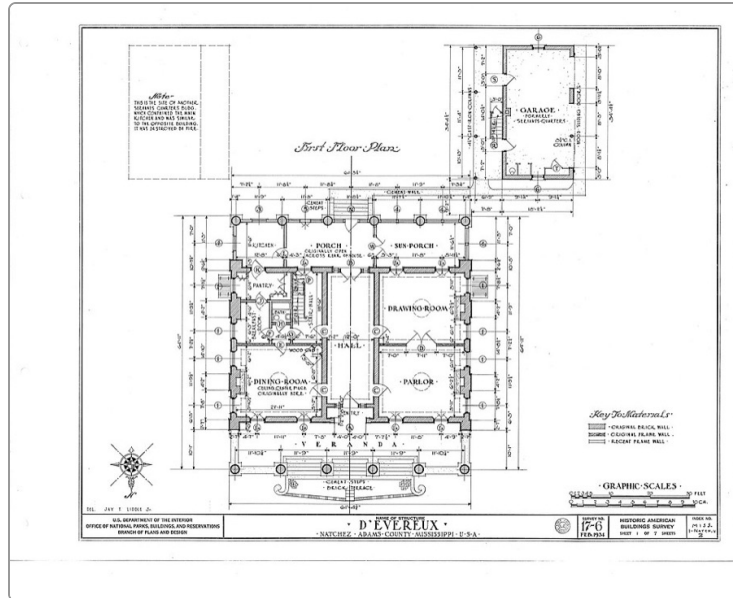
**How they figured it out.** The HABS teams followed rules that every architect still uses. First measure everything twice: every wall, door, window and step, in a sketch called a field book. Then draw it in standard views at a stated scale, so that anyone, anywhere, can read the drawings and even rebuild the building from them. When a measurement and the drawing did not agree, they went back and measured again. Many buildings recorded by HABS have since been lost, and its drawings are now the only way to know exactly what they were like.

**The physics.** Drawing to scale is geometry with ratios. At a scale of 1 : 50, every real length is divided by 50 to get the drawing length. A room 4.6 meters long is 460 cm;  $460 \div 50 = 9.2$  cm on paper. A door 0.8 m wide becomes  $80 \div 50 = 1.6$  cm. To go back, multiply: a wall 6.0 cm long on the drawing is  $6.0 \times 50 = 300$  cm, or 3 m, in real life. Areas do not shrink the same way: halving every length makes the area one quarter

as big, because area is length  $\times$  width. American drawings often use inch scales such as  $\frac{1}{4}$  inch = 1 foot, which is 1 : 48.

**The engineering.** Drawings are how a building gets from one mind to hundreds of hands. Architects draw the **plan**, **elevations** and **sections**; structural engineers add drawings of beams and columns; mechanical engineers add pipes and ducts; builders read them all and build to the dimensions written on them. Today most drawings are made on computers, but the views, the scales and the habits of careful measuring are the same as in 1933. A wrong number on a drawing can mean a beam that does not fit or a stair that is too steep, so engineers check drawings again and again before anything is built.

## PICTURE STUDY



*A HABS First-Floor Plan, Historic American Buildings Survey, 1934 · Measured drawing · Library of Congress*

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

This is a real HABS drawing, made in 1934, of the first floor of D'Evereux, a house in Natchez, Mississippi. Every number on it was measured by hand with tapes and rods.

### Look closely

- Find the title block at the bottom. What does it tell you about who drew it, when and where?
- Find the bar scale. How would you use it to measure the size of the parlor?
- Find the dimension lines with numbers along the outside walls.
- Find the north arrow and the key to materials, which shows which walls are brick and which are wood.

### Talk about it

1. Why did HABS draftsmen include a bar scale instead of only writing the scale in words?
2. If the house were destroyed, could a builder rebuild it from this drawing? What else would be needed?
3. How is this plan like the plan you will draw of your own room?

## BUILD

### A Measured Drawing of Your Room

You will be a HABS draftsman. You will measure a real room carefully, draw its floor plan and one elevation at a scale of 1 : 50 on graph paper, and then test your drawing: can someone else find things in the room using only your drawing?

#### You will need

- A tape measure (metric), a pencil, an eraser and a ruler
- Graph paper with 5 mm or 1 cm squares
- A clipboard for the field sketch
- A helper to hold the other end of the tape
- Engineer's notebook

#### Steps

1. **Field sketch.** Make a quick freehand plan of the room on the clipboard, not to scale. Mark every wall, door, window, closet and built-in shelf.
2. **Measure.** Measure each wall from corner to corner at about waist height. Measure where each door and window starts and stops along the wall, and how wide each one is. Write every number on the field sketch in centimeters. Measure the longest walls twice.
3. **Check.** Add up the measurements along each wall (corner to window, window width, window to door, and so on). Does the total match the wall length? If not, measure again.
4. **Convert.** Divide every measurement by 50 to get drawing lengths. Make a table: item, real length (cm), drawing length (cm).
5. **Draw the plan.** On graph paper, draw the walls with a ruler at 1 : 50. Show doors with a quarter-circle for their swing and windows with thin double lines. Write "Scale 1 : 50," a north arrow and your name and date in a title box.
6. **Draw an elevation.** Measure the height of the room and the heights of the window sill and top, door top and any shelves on one wall. Draw that wall as

an elevation at the same scale.

7. **Test it.** Give the drawing to a family member. Ask them to find a spot you marked on the plan with an X (for example, 1.5 m from the door wall and 0.5 m from the window wall) using only the drawing and a tape measure.
8. **Improve.** Where was your drawing hard to read or wrong? Fix it, and write one rule for yourself for next time.

#### Tips

- Hold the tape level and straight; a sagging tape reads long.
- Measure to the nearest half centimeter, and round drawing lengths to the nearest millimeter.
- Draw walls about 2–3 mm thick on the plan (about 10–15 cm real at 1 : 50).

#### Check your work

- ☐ I can explain the difference between a plan, an elevation and a section.
- ☐ I can convert between real and drawing sizes at 1 : 50.
- ☐ I can make a measured drawing that someone else can use.

#### ENGINEER'S NOTEBOOK

1. Paste in or copy your field sketch with all its numbers.
2. Make the conversion table: item, real length, drawing length at 1 : 50.
3. Work it: on a 1 : 100 drawing, a house is 12.5 cm long. How long is the real house? ( $12.5 \times 100 = 1,250 \text{ cm} = 12.5 \text{ m}$ .) How long would it be on a 1 : 50 drawing? (25 cm.)

**From history.** Measured drawing is much older than HABS. Renaissance architects such as Brunelleschi and Palladio measured the ruins of ancient Rome to learn how they were built, and Thomas Jefferson drew his own designs for Monticello and the University of Virginia on gridded paper, much like your notebook.

#### COMMON MISTAKES

- Mixing meters and centimeters. Change everything to centimeters before dividing by 50.
- Drawing an elevation in perspective. Elevations are flat and straight on, with no vanishing points.
- Measuring a wall in pieces and never checking that the pieces add up to the whole.

**Make it a game • Scale It Down.** Your parent calls a real measurement, such as a 3-meter wall, and a scale such as 1 : 50. Convert to the drawing length in centimeters, then reverse the process. Ten rounds in three minutes. Then sketch a quick plan, elevation and section of a box from memory, labeling each view. Beat your own score.

## 3.2 VITRUVIUS: FIRMNESS, COMMODITY AND DELIGHT

### OBJECTIVES

- Explain Vitruvius's three qualities of good architecture and find them in a real building.
- Explain why tall, slender columns buckle and how a column's height and shape change the load it can carry.
- Test paper columns of different shapes and heights fairly and use the results to design a small pavilion.

**Warm-up.** Roll a sheet of paper into a tube and tape it. Stand it on end and gently balance a light book on top. Now try a sheet folded into a square tube, and a short tube made from half a sheet. Which do you think will hold the most? Write a guess for each.

### WATCH

#### Understanding Buckling

The Efficient Engineer • 14:48

<https://www.youtube.com/watch?v=21G7LA2DcGQ>

#### WHEN TO WATCH

After the physics paragraph. A thorough engineering explanation; watch the first half in session 1 and pause to retell what buckling is.

**Note:** Written for older students; the second half adds equations you do not need yet. The video may end with a sponsor message.

### BACKUP VIDEO

#### Genius of the Villa Rotonda

National Building Museum • 1:31

<https://www.youtube.com/watch?v=bvq1cYDqd0U>

After the story, for a short look at Palladio's Villa Rotonda.



## KEY TERMS

### **firmness**

Vitruvius's *firmitas*: a building must stand strong and last.

### **delight**

Vitruvius's third quality: a building must be beautiful and well proportioned.

### **order**

A style of classical column and beam with its own proportions: Doric, Ionic or Corinthian.

### **commodity**

Vitruvius's *utilitas*: a building must be useful and serve the people in it.

### **column**

An upright member that carries load in compression.

### **slenderness**

How tall a column is compared with its thickness. Slender columns buckle more easily.

## CORE IDEAS

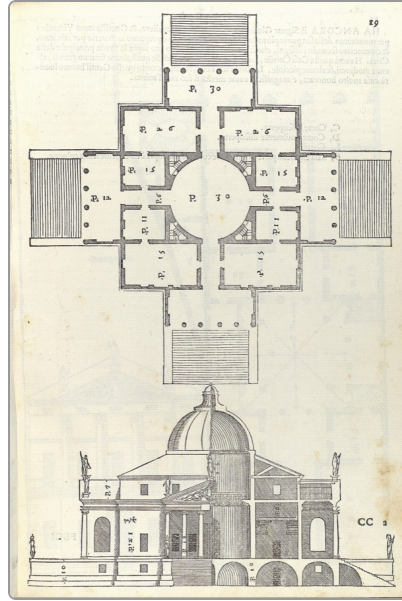
**The story.** About 2,000 years ago, a Roman architect and engineer named Marcus Vitruvius Pollio, who had served Julius Caesar as a builder of machines, wrote a book for the emperor Augustus: *De architectura*, “On Architecture,” in ten books. It covered almost everything: choosing a healthy site, making bricks and lime mortar, the proportions of temples, aqueducts and water wheels, cranes, sundials and town planning. It is the only complete book on architecture to survive from ancient times. For centuries it was copied by hand in monasteries, and in 1416 the scholar Poggio Bracciolini found a fine copy in the library of the abbey of St. Gall. Printed in 1486, it became the handbook of the Renaissance.

**How they figured it out.** Vitruvius wrote that all building should be done with regard to three things: firmness (*firmitas*), usefulness (*utilitas*) and beauty. An English writer, Sir Henry Wotton, put it in 1624 as “commodity, firmness and delight.” Vitruvius did not invent these from nothing; he gathered the experience of Greek and Roman builders, much of it learned from buildings that had cracked or fallen. Later architects tested his rules by measuring the ruins themselves. Andrea Palladio spent years measuring ancient Rome, and his *Four Books of Architecture* (1570) spread Vitruvius's ideas to England and America, where Thomas Jefferson studied them closely.

**The physics.** Firmness starts with columns. A column carries its load in compression. A short, thick column fails only when the material itself is crushed. But a tall, slender column fails long before that by **buckling**: it bows sideways and collapses. In 1757 the mathematician Leonhard Euler showed that the buckling load of a slender column falls with the square of its length. Double the height and the column can carry only one quarter as much: if a 20 cm paper tube holds 4 kg before buckling, a 40 cm tube of the same kind will hold about  $4 \div 2^2 = 1$  kg. A wider tube, with its material farther from the center, resists buckling much better, the same idea as the I-beam in Lesson 2.1.

**The engineering.** Vitruvius gave each order of column its own proportions: stocky Doric, slimmer Ionic and slender Corinthian. Those proportions were partly beauty and partly firmness, since a stone column too slender for its load would crack. Modern engineers use steel and concrete columns that can be far more slender, but they still check every column for buckling and brace tall ones. And they still weigh all three of Vitruvius's qualities. A building that is strong but useless, or useful but ugly, is not finished. Good engineering serves people well, lasts, and is worthy to be looked at.

## PICTURE STUDY



*Palladio's Villa Rotonda*, Andrea Palladio, 1570 · Woodcut · *I quattro libri dell'architettura*; Metropolitan Museum of Art

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

Andrea Palladio drew his Villa Rotonda for his *Four Books of Architecture* (1570). Above is the plan; below is a section, as if the house were sliced in half. Palladio studied Vitruvius closely, and this villa follows Vitruvius's ideas of order and proportion.

### Look closely

- In the plan, find the round hall in the center and the four porticoes, one on each side. Is the plan symmetrical?
- In the section, find the dome over the central hall. What holds it up?
- Find the columns of the porticoes. Are they slender or stocky?
- Find the numbers written in the rooms of the plan. They are measurements in Vicentine feet.

### Talk about it

1. Where can you see firmness, commodity and delight in this design?
2. Why would a builder need both a plan and a section?
3. Why do you think Palladio made all four sides the same?

**Safety first.** Stack books gently and keep fingers clear when a column is near buckling; it can collapse suddenly.

## BUILD

### Column Test and a Firm, Useful, Delightful Pavilion

In part A you will test paper columns, changing one thing at a time: first the shape, then the height. In part B you will use your best column in a small model pavilion and judge it by Vitruvius's three qualities.

#### You will need

- Sheets of copy paper (same size), tape and scissors
- A stiff square of cardboard to rest loads on
- Books or bags of rice and a bathroom or kitchen scale
- Card stock, cardboard and glue for the pavilion
- Ruler and engineer's notebook

#### Steps

1. **Part A, shape.** Make three columns from one full sheet each, all 28 cm tall: a round tube, a square tube and a triangular tube. Tape each seam with the same amount of tape.
2. **Predict.** Rank the shapes by how much load they will carry.
3. Stand a column on the table, put the cardboard square on top, and add books one at a time, gently and centered, until it buckles. Weigh the books that it held. Test two of each shape.
4. **Part A, height.** Using your best shape, make columns 28 cm, 21 cm and 14 cm tall (cut the paper so the tube size stays the same). Test two of each.
5. Make a table and a graph of load held against height. Compare your results with Euler's rule: does halving the height multiply the load by about four?
6. **Part B, design.** Design a small open pavilion (a garden shelter or porch) on paper, about 20 cm on each side, with four columns and a card roof. Write how it will meet firmness, commodity and delight.
7. Build it and test firmness by loading the roof with books until something fails. Test commodity by asking: could a small toy figure fit and stand inside? Test delight by asking two people to say what they like and what they would change.

8. **Improve.** Change one thing to fix the weakest of the three qualities, and test it again.

**Tips**

- Cut the ends of the columns square so they sit flat; a crooked end makes a column fail early.
- Add the load in the center of the cardboard. An off-center load bends the column.
- Short paper columns can hold surprising loads; have plenty of books ready.

**Check your work**

- ☐ I can explain firmness, commodity and delight with an example.
- ☐ I can explain why tall, slender columns buckle and use the rule that load falls with the square of the height.
- ☐ I can describe how my test results shaped my pavilion.

**ENGINEER'S NOTEBOOK**

1. Draw the cross-section of each column shape and record the load each held.
2. Graph load held (up) against column height (across). Draw a smooth curve through your points.
3. Work it: a column 30 cm tall buckles under 9 kg. About how much will the same column hold if it is 60 cm tall? ( $9 \div 4 = 2.25$  kg.) If it is 15 cm tall? (About 36 kg, unless the paper crushes first.)

**From history.** Vitruvius also told the story of Archimedes and King Hiero's crown, which you will meet again in Unit 6, and he described a water wheel turning a mill and the water screw that lifts water. Much of what we know about Roman engineering comes from his ten books.

**COMMON MISTAKES**

- Changing the shape and the height at the same time.
- Thinking a column can carry twice as much if it is half as tall. Buckling load grows with the square: about four times as much.
- Treating delight as unimportant. Vitruvius counted beauty as one of the three things a building must have.

**Make it a game • Three Qualities Hunt.** Walk through your home like Vitruvius and find one example of firmness, one of commodity and one of delight, explaining each in a sentence. Then stand a long paper column and a short one, press down gently with a book, and say which buckles first and why. Your parent scores your explanations.

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

Vitruvius’s three qualities are a kind of wisdom for builders. A house built with wisdom stands firm, serves its people and is good to look at.

## 3.3 GREAT DOMES: THE PANTHEON, HAGIA SOPHIA AND WREN'S ST PAUL'S

### OBJECTIVES

- Explain how a dome carries load, including compression along its curves and hoop tension near its base.
- Describe how the builders of the Pantheon, Hagia Sophia and St Paul's solved the problem of a great dome.
- Use Hooke's hanging chain to find an arch shape, and load-test a paper dome with and without a tension ring.

**Warm-up.** Hold a bead necklace or a light chain by its two ends so it hangs in a curve. Now imagine turning that curve upside down. Where have you seen that shape? Sketch it.

### WATCH

#### St Paul's Cathedral: Sir Christopher Wren's Engineering Masterpiece

IET - Institution of Engineering and Technology · 3:40

<https://www.youtube.com/watch?v=G9Yk0JgFo9E>

### WHEN TO WATCH

After the story, before how they figured it out.

### KEY TERMS

#### **dome**

A curved roof shaped like the top half of a ball, which works like an arch turned all the way around.

#### **catenary**

The curve a hanging chain makes. Turned upside down, it is the best shape for an arch carrying only its own weight.

#### **hoop tension**

The stretching force that pulls outward around the lower part of a dome, trying to split it like the staves of a barrel.

#### **oculus**

A round opening at the top of a dome, like the “eye” of the Pantheon.



**pendentive**

A curved triangle of masonry that lets a round dome sit on a square of four arches.

**lantern**

A small tower with windows on top of a dome.

**CORE IDEAS**

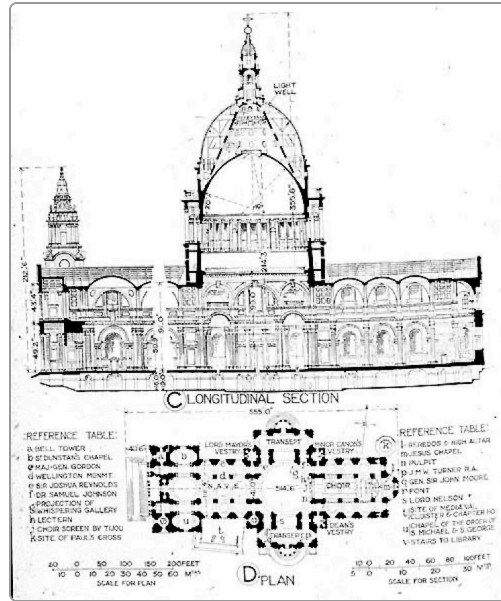
**The story.** Three domes tell the story. In Rome, the emperor Hadrian rebuilt the **Pantheon** around AD 125 with a concrete dome 43 meters across, still the largest unreinforced concrete dome in the world, open at the top to the sky through a round **oculus**. In Constantinople, the emperor Justinian's architects, Anthemius of Tralles and Isidore of Miletus, finished **Hagia Sophia** in AD 537, a church whose dome seemed to float on a ring of forty windows. And in London, after the Great Fire of 1666 destroyed the old cathedral, **Christopher Wren**, an astronomer turned architect, spent 35 years building a new **St Paul's Cathedral**, finished in 1710, with a dome that still rules the city's skyline.

**How they figured it out.** Each builder learned from trouble. The Roman engineers made the Pantheon's concrete lighter toward the top, using heavy stone at the bottom and light volcanic pumice near the oculus, and thinned the dome from about 6 meters thick at its base to about 1.2 meters at the top. Hagia Sophia's first dome was too flat; after earthquakes, part of it fell in 558, and Isidore the Younger rebuilt it about 6 meters higher, so it pushed outward less. Wren worked with his friend Robert Hooke, who discovered that a hanging chain, which is pulled only in tension, takes the perfect shape for an arch when turned upside down, so that the arch is pushed only in compression. Hooke published it as a Latin riddle in the 1670s: as hangs the flexible line, so but inverted will stand the rigid arch.

**The physics.** A dome is an arch turned all the way around its center. Along its curves, from the top down to the base, it is squeezed in compression, like an arch. But around its lower part, the dome tries to spread outward, and the rings of masonry are stretched in **hoop tension**, like the hoops around a barrel. Stone, brick and concrete are strong in compression but weak in tension, so old domes often crack in vertical lines near their base. Builders resisted this with heavy walls and buttresses around the base, with iron chains and rings buried in the masonry, or, as in the Pantheon, with stepped rings of heavy concrete that press the base down and inward.

**The engineering.** Wren's solution at St Paul's was three domes in one. The inner dome, made of brick, is shaped to look right from inside the cathedral. Above it, hidden from view, a **cone of brick** rises to carry the heavy stone **lantern** at the top; a cone is close to the shape of Hooke's inverted chain for that load. Over both is the outer dome, a light frame of timber covered with lead, shaped to look grand from the street. Around the base of the brick cone, Wren laid a great iron chain to resist hoop tension. Engineers today still use tension rings in domes and stadium roofs, and they still find shapes the way Hooke did, now with computers that "hang" a model and turn it upside down.

## PICTURE STUDY



*Plan and Section of St Paul's Cathedral, After Christopher Wren, 18th century · Engraving*

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

This drawing slices St Paul's Cathedral lengthwise (above) and shows its floor plan (below). Look closely at the dome: you can see that it is not one dome but three layers.

### Look closely

- Find the inner dome, the curved ceiling seen from inside the cathedral.
- Find the hidden cone of brick rising above the inner dome to hold up the lantern.
- Find the outer dome, the shape seen from the street.
- In the plan, find where the dome sits. What holds it up at the crossing of the nave and transepts?

### Talk about it

1. Why did Wren need a cone to carry the heavy stone lantern?
2. Where would hoop tension be greatest, and where did Wren put his iron chain?
3. Why might Wren have wanted the inside and outside of the dome to be different shapes?

## BUILD

### Hooke's Chain and a Paper Dome

In part A you will find the shape of an ideal arch the way Robert Hooke did, with a hanging chain, and compare it with a half-circle. In part B you will build paper domes and test whether a tension ring at the base, like Wren's iron chain, lets the dome hold more.

#### You will need

- A light chain or bead necklace about 60 cm long, two push pins and a large sheet of cardboard
- Card stock or file folders, scissors, a ruler, a protractor or compass, and tape
- Thin string or a strip of strong tape for the tension ring
- A paper plate or card square to spread the load, pennies and a kitchen scale
- Engineer's notebook

#### Steps

1. **Part A, hang the chain.** Stand the cardboard upright against a wall. Push in two pins 40 cm apart at the same height and hang the chain between them so it sags about 25 cm. Trace the curve carefully with a pencil.
2. Next to it, draw a half-circle with the same 40 cm span (its height will be 20 cm). Compare the two curves. Which is pointier at the top?
3. Change one thing: hang a few paper clips evenly along the chain to stand for a heavy deck, and trace the new shape. How does a load change the ideal arch?
4. **Part B, build domes.** Cut 8 identical strips of card stock, each 40 cm long and 2.5 cm wide. Cross them at their centers like the spokes of a wheel and tape them together. Bend the ends down to a circle 25 cm across on the table and tape each end to the table. This is your dome.
5. **Predict.** Will a tension ring around the base help the dome carry more?

6. **Test 1 (no ring).** Lift the tape from the table ends so the strip ends rest free on the table. Put the paper plate on top and add pennies until the strips spread and the dome collapses. Record the load and watch how it fails.
7. **Test 2 (with ring).** Build an identical dome and tie a string tightly around the strip ends at the base, like Wren's chain. Test it the same way.
8. **Improve.** Add a second ring partway up the dome, or more strips, and test again. Record which change helped the most per gram of material added.

#### Tips

- The strips will try to slide outward at the base. That outward spread is hoop tension at work.
- Use the same card stock and strip size for every dome so the test is fair.
- Photograph each dome just before it fails.

#### Check your work

- ☐ I can explain how a dome is like an arch and what hoop tension is.
- ☐ I can explain Hooke's hanging-chain rule.
- ☐ I can describe how Wren's three domes and his iron chain work.

#### ENGINEER'S NOTEBOOK

1. Draw a cross-section of St Paul's dome and label the inner dome, the brick cone, the outer dome, the lantern and the chain.
2. Trace or copy your chain curve and your half-circle on one page and label which is which.
3. Make a table of your dome tests: dome, ring or no ring, load held, how it failed.

**From history.** Wren is buried in the crypt of St Paul's. His son placed a Latin inscription over the tomb that is often translated, "Reader, if you seek his monument, look around you." Hooke and Wren were both founding members of the Royal Society, where Newton's *Principia* was later published.

#### COMMON MISTAKES

- Thinking a dome is only in compression. Near its base, it is stretched around its circumference.
- Thinking a half-circle is the best arch shape. For an arch carrying its own weight, the inverted chain (catenary) is better.

- Letting the base of a model dome be held by tape in one test and free in another without noticing.

**Make it a game • Dome Chain Duel.** Hang a string between two points and trace its catenary shape. Flip the picture upside down and you have the shape of a strong arch. Name the Pantheon, Hagia Sophia and St Paul's solutions to a great dome in turn, one fact each. Explain hoop tension near the base. Fewest hesitations wins.

**Scripture.** “And the house, when it was in building, was built of stone made ready before it was brought thither” (1 Kings 6:7, KJV)

Solomon's builders shaped every stone before it reached the temple, just as Wren planned every stone and timber of his dome before it rose. Careful planning is part of building well.

## 3.4 THE SYSTEMS INSIDE A SKYSCRAPER: ELEVATORS, WATER AND AIR

### OBJECTIVES

- Explain how an elevator's counterweight reduces the work its motor must do, and calculate the motor's load.
- Calculate water pressure from height and explain why tall buildings need pumps and tanks.
- Describe how Willis Carrier's air conditioning works and why tall buildings need it.

**Warm-up.** Turn on a tap on the ground floor and one on the highest floor of your home, or a garden hose held low and then held high. Which has the stronger stream? Write a guess about why.

### WATCH

#### Elevator Expert on How to Move 10,000 People Up a 118-Floor Skyscraper | WSJ Pro Perfected

The Wall Street Journal • 8:02

<https://www.youtube.com/watch?v=dK6XZvlt22w>

### WHEN TO WATCH

After the physics paragraph, to see how engineers plan elevators for a very tall tower.

### BACKUP VIDEO

#### Air Conditioning System Basics hvacr how does it work

The Engineering Mindset • 7:17

<https://www.youtube.com/watch?v=SfuSzBja8QA>

After the story of Willis Carrier, to see how an air-conditioning system moves heat.

### KEY TERMS

#### **counterweight**

A heavy weight on the other end of an elevator's cables that balances the car and part of its load.

#### **pressure**

Force per unit of area, measured in pascals (Pa) or pounds per square inch (psi).

**head**

The height of a column of water; each 10 meters of head gives about 98,000 pascals (about 14 psi) of pressure.

**HVAC**

Heating, ventilation and air conditioning: the systems that keep a building's air comfortable and fresh.

**humidity**

The amount of water vapor in the air.

**CORE IDEAS**

**The story.** Tall buildings became possible only when engineers solved three hidden problems: moving people up, moving water up and keeping the air fit to breathe. Elisha Otis's safety elevator (1853) solved the first, and in 1857 the first passenger safety elevator was installed in the E. V. Haughwout store in New York. In 1902 a young engineer named Willis Carrier, just out of Cornell University, was asked to help a printing company in Brooklyn whose paper swelled and shrank with the summer humidity, so that colored inks printed out of line. Carrier designed a machine that blew air over cold coils to control both its temperature and its moisture. That was the beginning of modern air conditioning.

**How they figured it out.** Carrier later said that the key idea came to him on a foggy night in 1902 while he waited on a train platform in Pittsburgh. Fog, he realized, is air holding all the water vapor it can at that temperature. If you cool air, it can hold less, and the extra water condenses out. So by cooling air to a chosen temperature, called the dew point, you could set exactly how much moisture it kept. He tested the idea, measured it, and in 1911 presented a chart and formulas that engineers used to design air-conditioning systems for decades. Meanwhile elevator engineers learned that a **counterweight** could balance most of the weight of a car, so that the motor only had to move the difference.

**The physics.** Water pressure grows with depth, or **head**:  $\text{pressure} = \text{density} \times g \times \text{height}$ . For water,  $1,000 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 10 \text{ m} = 98,000 \text{ pascals}$ , about 14 psi, for every 10 meters of height. City water mains usually push with about 350–550 kilopascals (50–80 psi). Lifting water 30 meters to the 10th floor uses up about 294,000 Pa of that, and the faucet still needs pressure to flow, so city pressure alone usually reaches only five or six stories. For the **counterweight**: suppose an elevator car has a mass of 1,000 kg and can carry 1,000 kg of passengers. Engineers often



make the counterweight equal the car plus about 45% of the full load:  $1,000 + 450 = 1,450$  kg. With a full car (2,000 kg), the motor lifts only the difference,  $2,000 - 1,450 = 550$  kg, instead of 2,000 kg.

**The engineering.** Tall buildings are divided into vertical zones. Pumps in the basement lift water to tanks on mechanical floors or the roof, and from each tank water flows down by gravity to the floors below it, with valves that reduce the pressure so taps on lower floors do not blast. Elevators are grouped too: express elevators carry people to “sky lobbies,” where they change to local elevators. Air-handling units on mechanical floors heat, cool, filter and dry the air and send it through ducts; tall buildings must also manage the stack effect, in which warm air rises through stairwells and shafts like a chimney. Most of a skyscraper’s floors look like offices, but whole floors are given over to machines that most visitors never see.

## PICTURE STUDY



*The E. V. Haughwout Building*, Unknown artist, 1859 • Engraving

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

The E. V. Haughwout Building in New York, a five-story store with a cast-iron front, was finished in 1857 and was the first building with a passenger safety elevator. This picture shows it two years later.

### Look closely

- Count the floors. Before elevators, why would the top floors be the hardest to rent or use?
- Look at the rows of identical arched windows. The cast-iron front was made from repeated molded pieces, like a kit.
- Look for where an elevator shaft could fit inside such a building.
- Find the people and carriages. How tall is the building compared with them?

### Talk about it

1. How did the safety elevator change which floors of a building were most valuable?
2. How would water reach the top floor of this building in 1857?
3. What systems would this building need if it were built today?

**Safety first.** Do the water test outdoors, in a bathtub or over a sink. Use a pushpin or nail held with pliers to poke the bottle holes, with an adult.

## BUILD

### A Counterweighted Elevator and a Water-Pressure Column

In part A you will build a model elevator with a car, a counterweight and a “motor” cup, and measure how much the counterweight reduces the force needed to lift a load. In part B you will measure how water pressure grows with depth by watching jets from holes at different heights in a tall bottle.

#### You will need

- A thread spool or smooth round pencil as a pulley, mounted between two chair backs or on a shelf edge
- String and three paper cups with string handles (car, counterweight and motor cups)
- About 200 pennies (2.5 g each) and a kitchen scale
- A tall 2-liter plastic bottle, a pushpin, masking tape, a ruler and a baking pan
- Engineer’s notebook

#### Steps

1. **Part A, set up.** Run a string over the pulley with the car cup on one end. Put 40 pennies in the car cup to stand for the empty car, and 40 pennies of passengers.
2. **Test 1 (no counterweight).** Tie the motor cup to the other end of the string. Add pennies to the motor cup until the car just rises. Record how many pennies it took.
3. **Test 2 (with counterweight).** Hang a counterweight cup beside the motor cup on the same string end, holding 40 pennies (car) plus 18 pennies (45% of the 40 passengers). Add pennies to the motor cup until the car rises. Record it.
4. Repeat both tests with 0 passengers and 20 passengers. Make a table. When did the counterweight help the most? Did the motor ever have to hold the car back instead of lifting it?
5. **Part B, predict.** Poke three holes in a line up the side of the bottle, at 5, 12 and 19 cm from the bottom. Which jet will reach farthest?

6. Cover the holes with tape, fill the bottle with water, set it at the edge of the baking pan in a tub or outdoors, and pull off all the tape at once. Measure how far each jet lands from the bottle while the bottle is full. Repeat twice, refilling each time.
7. Calculate the pressure at each hole from the depth of water above it:  
pressure (Pa) =  $1,000 \times 9.8 \times \text{depth in meters}$ . Compare with the jet distances.
8. **Improve.** Design a way to keep the jets steady as the bottle drains, like a water tower that is refilled by a pump, and test it.

#### **Tips**

- The pulley must turn freely, or friction will hide the counterweight's effect. A spool on a smooth pencil works well.
- Read the jets quickly, while the water level is still near the top.
- Real elevator counterweights are usually set to the car plus 40–50% of the rated load, because a car is seldom completely full.

#### **Check your work**

- ☐ I can explain how a counterweight reduces the motor's work, with numbers.
- ☐ I can calculate water pressure from depth.
- ☐ I can explain why tall buildings pump water to tanks and how Carrier controlled humidity.

#### **ENGINEER'S NOTEBOOK**

1. Draw your elevator model and label the car, counterweight, motor cup and pulley, with the penny counts for each test.
2. Draw the bottle with its three jets and write the depth and calculated pressure beside each hole.
3. Work it: an elevator car has a mass of 1,200 kg and a rated load of 800 kg. With a counterweight of the car plus 45% of the load, what is the counterweight's mass? ( $1,200 + 360 = 1,560$  kg.) What must the motor lift with a full car? ( $2,000 - 1,560 = 440$  kg.)

**From history.** Skyscrapers depend on all three systems at once. The Empire State Building (1931) opened with dozens of elevators and pumps that lifted water to tanks on several floors, and it was later fitted with air conditioning. Today, tall towers use computers to send elevators where they are needed and to save energy in their air systems.

#### COMMON MISTAKES

- Thinking the counterweight makes the elevator heavier to move. It balances the car, so the motor moves only the difference.
- Thinking water pressure depends on the width of the tank. It depends on the height of water above the point.
- Thinking air conditioning only cools. Carrier's first purpose was to control humidity.

**Make it a game • Counterweight Numbers.** Pose a puzzle: a 600 kg elevator car with a 500 kg counterweight. What load does the motor lift? Solve it aloud, then do three similar puzzles your parent makes up. Next, calculate the water pressure at the bottom of a 30 m tower. Score a point for correct units and the term head.

### UNIT 3

## ARCHITECTURE

Architecture is where engineering meets beauty and daily life. In this unit you will learn the language architects and builders use to talk to each other, the measured drawing: plan, elevation, section and scale. You will meet Vitruvius, the Roman architect who said that every good building must have firmness, commodity and delight, and you will test columns the way builders have tested them ever since.

Then you will climb inside three of the greatest domes ever built, the Pantheon in Rome, Hagia Sophia in Constantinople and St Paul's Cathedral in London, and learn how Christopher Wren and Robert Hooke used a hanging chain to find the shape of an arch. Last, you will look at the hidden systems that make a tall building livable: elevators with counterweights, water that has to be pumped to the top floor, and air that has to be heated, cooled and moved.

#### PREREQUISITES

- Can measure in meters and centimeters and multiply and divide decimals
- Knows compression and tension, and how arches push outward (Unit 2)
- Can calculate weight from mass ( $\text{weight} = \text{mass} \times 9.8$ ) (Unit 1)

#### MASTERY CHECKLIST

- ☐ I can read and draw a floor plan and an elevation to scale, and convert between drawing and real sizes.
- ☐ I can explain Vitruvius's firmness, commodity and delight, and test how a column's shape and height change its strength.
- ☐ I can explain how a dome works, what hoop tension is, and how Wren and Hooke used the hanging chain.
- ☐ I can calculate water pressure from height and explain why tall buildings need pumps and tanks.
- ☐ I can explain how an elevator counterweight saves energy and calculate what the motor must lift.

## OPTIONAL KITS FOR THIS UNIT

- **KEVA planks:** Ages 6 and up. Identical maple planks for building columns, arches, towers and small domes without glue; good for trying Hooke's arch shapes in Lesson 3.3.
- **Tinkercad:** Free, browser-based 3D design from Autodesk, for ages 8 and up with a parent's account setup. Students can model the room they drew in Lesson 3.1 or the pavilion from Lesson 3.2.

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

## LESSONS IN THIS UNIT

|                                                                         |                          |
|-------------------------------------------------------------------------|--------------------------|
| <b>3.1 Architectural Drawing: Plan, Elevation and Scale</b>             | 2 sessions of 50 minutes |
| <b>3.2 Vitruvius: Firmness, Commodity and Delight</b>                   | 2 sessions of 50 minutes |
| <b>3.3 Great Domes: The Pantheon, Hagia Sophia and Wren's St Paul's</b> | 2 sessions of 50 minutes |
| <b>3.4 The Systems Inside a Skyscraper: Elevators, Water and Air</b>    | 2 sessions of 50 minutes |

## UNIT 3 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**  
What is the difference between a plan, an elevation and a section?
2. **10 pts**  
Calculate: on a 1 : 50 drawing, how long is a wall that is really 5.5 m long? On the same drawing, a window measures 2.4 cm. How wide is the real window?
3. **6 pts**  
Why did the Historic American Buildings Survey begin in 1933, and why are its drawings still valuable?

4. (8 pts)

Name Vitruvius's three qualities of good architecture and give an example of each from a building you know.

5. (10 pts)

Calculate: a column 25 cm tall buckles under a load of 12 kg. Using the rule that buckling load falls with the square of the height, about how much will the same column hold if it is 50 cm tall?

6. (8 pts)

Explain in two or three sentences what hoop tension is and how Wren dealt with it at St Paul's.

7. (8 pts)

What did Robert Hooke discover about a hanging chain, and why does it matter for arches?

8. (7 pts)

Name one way the builders of the Pantheon or Hagia Sophia made their domes safer.

9. (10 pts)

Calculate: how much water pressure, in pascals, is needed just to hold water at the top of a pipe 20 m high? (Use  $\text{pressure} = 1,000 \times 9.8 \times \text{height}$ .)

10. (9 pts)

Calculate: an elevator car has a mass of 900 kg and a rated load of 1,000 kg. The counterweight is the car plus 45% of the rated load. Find the counterweight's mass and the mass the motor must lift with a full car.

11. (8 pts)

Why do tall buildings pump water to tanks on upper floors instead of relying on city water pressure?

12. (8 pts)

What problem was Willis Carrier first asked to solve in 1902, and what idea from a foggy night helped him?



## ANSWER KEY

1. A plan is a horizontal slice seen from above showing walls, doors and windows; an elevation is a straight-on view of one side showing heights; a section is a vertical slice showing floors, ceilings and the inside of walls.
2.  $5.5 \text{ m} = 550 \text{ cm}$ ;  $550 \div 50 = 11 \text{ cm}$  on the drawing. Window:  $2.4 \times 50 = 120 \text{ cm} = 1.2 \text{ m}$ .
3. To give work to unemployed architects and to record historic buildings before they were lost. Its drawings are free to all and are the only record of many buildings that are now gone.
4. Firmness (it stands strong and lasts), commodity (it is useful), delight (it is beautiful). Examples will vary.
5. The height doubles, so the load falls by  $2^2 = 4$ :  $12 \div 4 = 3 \text{ kg}$ .
6. Hoop tension is the stretching around the lower part of a dome as it tries to spread outward, which can crack masonry in vertical lines. Wren laid an iron chain around the base of his brick cone to hold it together.
7. A hanging chain takes the shape where it is only in tension; turned upside down, that shape is an arch that is only in compression, which is ideal for masonry.
8. Pantheon: lighter concrete (pumice) toward the top, thinner dome near the oculus, heavy stepped rings at the base. Hagia Sophia: after the first dome partly fell, it was rebuilt higher so it pushed outward less.
9.  $1,000 \times 9.8 \times 20 = 196,000 \text{ Pa}$  (about 28 psi).
10. Counterweight =  $900 + 450 = 1,350 \text{ kg}$ . Full car =  $1,900 \text{ kg}$ . Motor lifts  $1,900 - 1,350 = 550 \text{ kg}$ .
11. City pressure can only lift water about five or six stories and still give enough pressure at the tap. Pumps lift water to tanks in each zone, and it flows down by gravity to the floors below.
12. A Brooklyn printing company's paper swelled and shrank with humidity, spoiling color printing. He realized that cooling air to a set dew point makes extra water condense out, so cooling can control how much moisture the air keeps.

## PORTFOLIO PIECE: A MEASURED MODEL PAVILION

Design a small building, such as a garden pavilion, a chapel or a bus shelter, and draw its plan, one elevation and one section at a stated scale. Then build a model from card stock and cardboard at the same scale and test its firmness with a measured load on the roof. Write a one-page report that explains how your design meets firmness, commodity and delight, gives at least one scale calculation and one load or column calculation, and says what you would change.

| LOOK FOR                               | WHAT IT MEANS                                                                                              |
|----------------------------------------|------------------------------------------------------------------------------------------------------------|
| <b>Drawings</b>                        | Plan, elevation and section drawn neatly to a stated scale, with a title box and dimensions.               |
| <b>Scale accuracy</b>                  | The model matches the drawings; at least three dimensions checked and recorded.                            |
| <b>Firmness test</b>                   | Roof load test done carefully with the load and the way the model failed recorded.                         |
| <b>Calculations</b>                    | At least one scale conversion and one load or column calculation, worked correctly with units.             |
| <b>Firmness, commodity and delight</b> | The report explains all three qualities with specific features of the design and proposes one improvement. |

## UNIT 4

# ELECTRICITY

This year you will stop guessing about circuits and start measuring them. With an inexpensive multimeter you will measure voltage, current and resistance, and you will discover for yourself the rule Georg Ohm found in 1827:  $V = IR$ . Then you will calculate what happens when parts are joined in series and in parallel, and see why Thomas Edison wired every lamp in New York in parallel.

Next you will follow Michael Faraday into his laboratory in 1831, when he found that a moving magnet can make electricity, and you will build a generator and measure its voltage. Last, you will write your first program for a tiny computer, a micro:bit or an Arduino, and make it blink a light on command. Every circuit in this unit runs on batteries or a USB cable, never on the outlets in the wall.

### PREREQUISITES

- Can build a simple battery-and-bulb circuit and knows conductors and insulators (earlier grades)
- Can multiply, divide and use decimals and simple fractions
- Can record measurements in a table and make a line graph

### MASTERY CHECKLIST

- ☐ I can measure voltage, current and resistance safely with a multimeter.
- ☐ I can use  $V = IR$  to find voltage, current or resistance, with volts, amperes and ohms.
- ☐ I can calculate total resistance and current for resistors in series and in parallel, and explain why homes are wired in parallel.
- ☐ I can explain how Faraday's discovery of induction leads to generators and motors, and measure what makes a generator's voltage go up.
- ☐ I can write a program with an output and a delay to blink an LED on a micro:bit or Arduino, and choose a safe resistor for it.

## OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** Ages 8 and up. A small programmable board with lights, buttons and sensors, coded with the free Microsoft MakeCode editor; fits Lesson 4.4 and Unit 8. The MakeCode on-screen simulator works without a board.
- **Arduino Starter Kit:** Ages 12 and up with an adult. An Arduino Uno board with a breadboard, LEDs, resistors, a motor and sensors, plus a project book. Fits Lessons 4.1, 4.2 and 4.4 and the robotics unit.
- **Snap Circuits:** Ages 8 and up. Parts snap together on a grid with no soldering; useful for building series and parallel circuits quickly in Lesson 4.2.

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

## LESSONS IN THIS UNIT

|     |                                                         |                          |
|-----|---------------------------------------------------------|--------------------------|
| 4.1 | Ohm's Law with a Multimeter                             | 2 sessions of 50 minutes |
| 4.2 | Series and Parallel: Edison's Pearl Street Station      | 2 sessions of 50 minutes |
| 4.3 | Faraday, Motors and Generators                          | 2 sessions of 50 minutes |
| 4.4 | First Steps with a Microcontroller: Making an LED Blink | 2 sessions of 50 minutes |

## UNIT 4 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Name the units of voltage, current and resistance, and say in one sentence what each quantity means.

2. 10 pts

Calculate: a 6-volt battery is connected to a 300-ohm resistor. What current flows, in amps and in milliamps?

3. (8 pts)

How should a multimeter be connected to measure the current through a resistor, and how to measure the voltage across it?

4. (6 pts)

Why did Ohm switch from a battery to a thermocouple?

5. (10 pts)

Calculate: a  $220\ \Omega$  and a  $330\ \Omega$  resistor are connected in series to 11 V. Find the total resistance, the current, and the voltage across the  $220\ \Omega$  resistor.

6. (10 pts)

Calculate: two 60-ohm lamps are in parallel on a 12-volt battery. Find the current in each lamp and the total current.

7. (8 pts)

Explain in two or three sentences why Edison wired lamps in parallel and why he wanted high-resistance filaments.

8. (8 pts)

What did Faraday observe on August 29, 1831, with his iron ring, and what did it show?

9. (8 pts)

Predict: a coil of 100 turns gives 20 mV when a magnet is pushed through it. Name two changes that would give a larger voltage, and estimate the voltage with 300 turns.

10. (8 pts)

How are a motor and a generator related?

11. (8 pts)

Calculate: a red LED uses 2 V and should run at 20 mA from a 5 V output pin. What resistor is needed?

12. (8 pts)

What is a microcontroller? Give two examples of where one is used.

## ANSWER KEY

1. Voltage in volts (the push), current in amperes (the rate of flow of charge), resistance in ohms (how much a part opposes the flow).
2.  $I = V \div R = 6 \div 300 = 0.02 \text{ A} = 20 \text{ mA}$ .
3. Current: in line (in series), so the current flows through the meter. Voltage: across the resistor (in parallel), touching its two ends.
4. The batteries of his day gave a voltage that drooped and changed during use; the thermocouple gave a small but steady voltage, so his measurements could be compared.
5.  $R = 220 + 330 = 550 \text{ } \Omega$ .  $I = 11 \div 550 = 0.02 \text{ A}$ .  $V = 0.02 \times 220 = 4.4 \text{ V}$ .
6. Each:  $12 \div 60 = 0.2 \text{ A}$ . Total:  $0.4 \text{ A}$  (the pair acts like  $30 \text{ } \Omega$ ).
7. In parallel, each lamp gets the full voltage and can be switched on and off by itself, and one burned-out lamp does not darken the rest. But parallel currents add up, so he used high-resistance filaments to keep each lamp's current small and the copper mains affordable.
8. The galvanometer on the second coil jumped only when the battery on the first coil was connected or disconnected, not while the current was steady. It showed that a changing magnetic field induces a voltage.
9. Move the magnet faster, use a stronger magnet, or add turns. With 300 turns, about 60 mV.
10. They are the same kind of machine working in opposite directions: a motor turns electrical energy into motion; a generator turns motion into electrical energy. Spinning a motor's shaft makes it act as a generator.
11. The resistor has  $5 - 2 = 3 \text{ V}$  across it.  $R = 3 \div 0.020 = 150 \text{ } \Omega$  (use  $150 \text{ } \Omega$  or the next size up).
12. A tiny computer on one chip that runs one program to control a device.  
Examples: microwave oven, thermostat, washing machine, car, toy, traffic light.

## PORTFOLIO PIECE: A MEASURED AND PROGRAMMED SIGNAL LIGHT

Build a signal light that a microcontroller controls: two or more LEDs, each with a resistor you calculated, blinking in a pattern you program (a traffic light, a lighthouse code or a Morse message). Draw the circuit diagram, show your resistor calculations with Ohm's law, and measure the actual current through one LED with a multimeter. If you have no board, build the same circuit with batteries and a switch and work the program in the MakeCode simulator. Write a one-page report with your diagram, program, calculations, measurements and one improvement.

| LOOK FOR              | WHAT IT MEANS                                                                                     |
|-----------------------|---------------------------------------------------------------------------------------------------|
| <b>Circuit design</b> | A neat circuit diagram with standard symbols; every LED has a resistor.                           |
| <b>Calculations</b>   | Resistor values worked out correctly with Ohm's law and the units shown.                          |
| <b>Measurement</b>    | Current measured safely with the meter in line and compared with the calculation.                 |
| <b>Program</b>        | The program runs the planned pattern, uses a loop and delays, and is written out in the notebook. |
| <b>Improvement</b>    | One change is tested and explained, such as a button input or a new pattern.                      |

## 4.1 OHM'S LAW WITH A MULTIMETER

### OBJECTIVES

- Define voltage, current and resistance and give their units.
- Measure voltage, current and resistance safely with a digital multimeter.
- Discover from your own measurements that current is proportional to voltage, and use  $V = IR$ .

**Warm-up.** Look at the labels on three batteries (for example AA, 9 V and a phone power bank). What numbers and units do you see? Write down what you think a volt is before reading on.

### WATCH

#### How to Use a Multimeter

Science Buddies • 17:22

<https://www.youtube.com/watch?v=ts0EVc9vXcs>

#### WHEN TO WATCH

Before the build. Watch the sections on measuring voltage, current and resistance; pause and try each with your own meter.

### BACKUP VIDEO

#### Resistors Obey Ohm's Law (Experiment) - GCSE Physics Required Practical

vt.physics • 1:59

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

After the build, to compare your graph with this classroom experiment.

### KEY TERMS

#### **voltage (V)**

The electrical “push” that drives current around a circuit, measured in volts.

#### **current (I)**

The rate at which electric charge flows past a point, measured in amperes (amps, A). 1 milliamp (mA) = 0.001 A.



**resistance (R)**

How much a part opposes the flow of current, measured in ohms ( $\Omega$ ).

**Ohm's law**

$V = I \times R$ : the voltage across a resistor equals the current through it times its resistance.

**multimeter**

A meter that can measure voltage, current and resistance.

**CORE IDEAS**

**The story.** In the 1820s Georg Simon Ohm was a mathematics and physics teacher at a school in Cologne, in Germany. He had little money and no university laboratory, but he wanted to answer a simple question: how does the current in a wire depend on the wire and on the battery? He built his own apparatus, made his own wires of different lengths and thicknesses, and in 1827 published his results in a book, *Die galvanische Kette, mathematisch bearbeitet* ("The Galvanic Circuit Investigated Mathematically").

**How they figured it out.** Ohm's first experiments failed because the batteries of his day gave a voltage that drooped as they were used, so his measurements kept changing. On a friend's advice he switched to a thermocouple, a junction of two different metals kept with one end in boiling water and the other in ice, which gave a small but very steady voltage. To measure current he hung a magnetized needle on a thin wire above his circuit and measured how far the current twisted it. Changing the length of the test wire again and again, he found a simple rule: the current was proportional to the push of the source and inversely proportional to the resistance of the circuit. Many German scientists ignored or mocked his work at first, but in 1841 the Royal Society in London gave him its highest honor, the Copley Medal, and the unit of resistance was later named the ohm.

**The physics.** Voltage is the push, current is the flow and resistance is what holds the flow back. Ohm's law ties them together:  $V = I \times R$ . You can rearrange it as  $I = V \div R$  or  $R = V \div I$ . Connect a 9-volt battery across a 470-ohm resistor:  $I = 9 \text{ V} \div 470 \text{ } \Omega \approx 0.019 \text{ A}$ , or 19 milliamps. If you measure 3.0 V across a resistor and 0.0136 A through it, its resistance is  $3.0 \div 0.0136 \approx 220 \text{ } \Omega$ . Double the voltage across a resistor and the current doubles; a graph of current against voltage is a straight line.

**The engineering.** Ohm's law is the first tool of every electrical engineer. It tells how big a resistor must be to protect an LED, how thick a wire must be so it does not overheat, and how much current a motor will draw. Engineers check their calculations with a **multimeter**. A voltmeter is connected **across** a part (in parallel) to measure the push on it. An ammeter is connected **in line** (in series), so the current flows through the meter. Resistance is measured only with the power off. Getting these right protects both the circuit and the meter.

## PICTURE STUDY



*Georg Simon Ohm*, Unknown artist, 19th century · Engraving

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

This portrait shows Georg Simon Ohm, the schoolteacher whose careful measurements gave us  $V = IR$ . We look at the man today, and at what kind of patience it took to measure currents with a twisting needle.

### Look closely

- Look at his face and expression. What kind of person do you think he was?
- Look at his clothes. When do you think the portrait was made?
- Imagine his workbench: a thermocouple in boiling water and ice, wires of different lengths, a magnetized needle on a thread. Sketch what it might have looked like.

### Talk about it

1. Why did Ohm need a steady voltage source before his measurements made sense?
2. Why do you think other scientists were slow to accept his law?
3. What does it mean that a unit of measurement is named after him?

**Safety first.** Use only AA batteries in holders for this build. Never connect the multimeter on its current (A or mA) setting directly across a battery; that is a short circuit and can blow the meter's fuse or heat the battery. Measure resistance only with the battery disconnected.

## BUILD

### Finding Ohm's Law for Yourself

You will measure the resistance of several resistors, then connect one of them to 1, 2, 3 and 4 AA cells, measuring the voltage and current each time. You will graph your results and find Ohm's straight line.

#### You will need

- A digital multimeter
- A 4 × AA battery holder (or four single holders) and 4 AA batteries
- Resistors: 100, 220, 470 and 1,000 ohms
- Alligator clip leads (at least 5)
- Graph paper and the engineer's notebook

#### Steps

1. **Measure resistance.** Turn the meter to the  $\Omega$  setting. Touch the probes to each end of each resistor (not touching the metal with your fingers) and record the reading. Compare it with the value marked on the resistor.
2. **Measure voltage.** Set the meter to DC volts. Measure one AA cell, then 2, 3 and 4 in series. Record each.
3. **Build the circuit.** Clip the 220-ohm resistor to one cell. Put the meter on DC mA, and connect it **in line**: battery → meter → resistor → back to battery. Record the current.
4. **Predict.** If you use 2 cells, what will the current be? Use  $I = V \div R$  and write your prediction.
5. Measure the current with 2, 3 and 4 cells. Each time, also measure the voltage across the resistor with a second meter or by moving your one meter (set back to volts) across the resistor.
6. Make a table: cells, voltage across resistor, current (mA), and  $R = V \div I$  (change mA to A first).
7. Graph current (up) against voltage (across). Draw the best straight line through your points.

8. **Fair test and improve.** Repeat with the 470-ohm resistor and graph it on the same axes. Which line is steeper, and why? If any point is far off the line, find the cause (a loose clip, a tired battery) and measure again.

#### Tips

- A fresh AA cell reads a little above 1.5 V. That is normal.
- Clip leads can have a little resistance of their own; for tiny currents it does not matter.
- Disconnect the batteries as soon as you finish each reading so they do not run down.

#### Check your work

- ☐ I can measure voltage, current and resistance safely.
- ☐ I can use  $V = IR$  to predict a current and check it with a meter.
- ☐ I can explain what the slope of my graph tells me.

#### ENGINEER'S NOTEBOOK

1. Draw a circuit diagram of your test circuit with standard symbols, showing where the ammeter and voltmeter were connected.
2. Make your data table and your graph of current against voltage for both resistors.
3. Work it: an LED circuit runs on 6 V and needs 4 V across its resistor at 0.02 A. What resistor is needed? ( $4 \div 0.02 = 200 \Omega$ ; use the next standard size, 220  $\Omega$ .)

**From history.** The thermocouple Ohm used had been discovered only a few years before, in 1821, by Thomas Seebeck. Today thermocouples are used as temperature sensors in ovens, furnaces and jet engines, and you will meet sensors again in Unit 8.

#### COMMON MISTAKES

- Connecting the meter on a current setting across the battery. A current meter goes in line, never across.
- Forgetting to change milliamps to amps before using  $V = IR$ . 20 mA = 0.020 A.
- Measuring resistance with the circuit still powered.

**Make it a game • Ohm's Law Speed Round.** Use the triangle V, I and R. Your parent shouts two values with units and you solve for the third in twenty seconds. If you answer wrong, say what the units are. Ten rounds. Then explain how to measure voltage, current and resistance safely with a multimeter. Beat your own record.

## 4.2 SERIES AND PARALLEL: EDISON'S PEARL STREET STATION

### OBJECTIVES

- Calculate the total resistance and current for resistors in series and in parallel.
- Explain why Edison wired lamps in parallel and why homes are wired that way today.
- Predict, then measure, the currents and voltages in series and parallel circuits.

**Warm-up.** Think of a string of old holiday lights in which one dead bulb made the whole string go dark, and the lights in your house, where one burned-out bulb leaves the others lit. Draw how you think each is wired.

### WATCH

#### **Series and Parallel Circuits | Electricity | Physics | FuseSchool**

FuseSchool - Global Education • 4:56

<https://www.youtube.com/watch?v=8Z0jhQeYDUE>

### WHEN TO WATCH

After the physics paragraph. Pause at each question and work it out before the answer is shown.

### BACKUP VIDEO

#### **Series & Parallel Circuits**

Patrick Haney • 5:02

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

Before the build, for another look at series and parallel bulbs.

### KEY TERMS

#### **series circuit**

Parts joined end to end in one loop, so the same current flows through each.

#### **parallel circuit**

Parts joined across the same two points, so each has the same voltage and its own path for current.

**total resistance**

The single resistance that would draw the same current as a whole group of parts.

**branch**

One path in a parallel circuit.

**dynamo**

An early name for an electric generator, especially one making direct current.

**CORE IDEAS**

**The story.** On September 4, 1882, Thomas Edison’s Pearl Street Station in lower Manhattan began sending electricity through underground copper mains to customers in the surrounding square mile. Six huge steam-driven dynamos, nicknamed “Jumbos” after a famous circus elephant, made direct current at about 110 volts. On the first evening it lit about 400 lamps for 82 customers, including the offices of the *New York Times*. Within two years it served more than 500 customers and over 10,000 lamps.

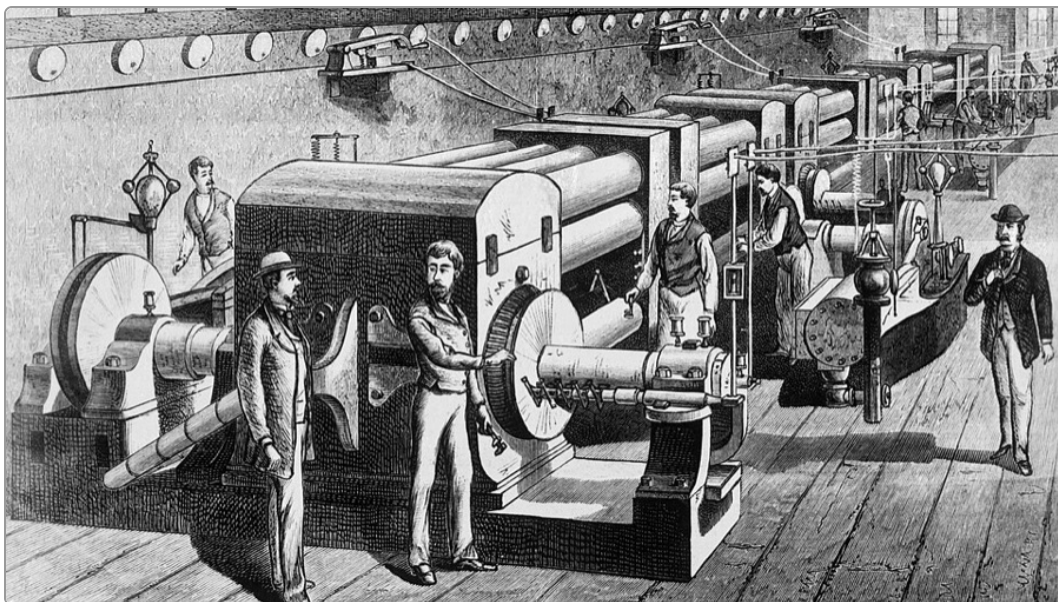
**How they figured it out.** Street arc lamps of the time were usually wired in **series**, one after another on a single loop. That worked for streetlights but would never do in a home: switch off one lamp, or let one burn out, and every lamp on the loop goes dark. Edison wanted each lamp to be turned on and off by itself, so he wired them in **parallel**, each across the same two mains. But parallel lamps each draw their own current, and the total current would need copper mains as thick as a man’s arm. Edison and his mathematician Francis Upton worked through Ohm’s law and found the answer: make each lamp’s filament of **high resistance**, so each drew only a small current. That calculation, as much as the bulb itself, is why Edison’s system worked.

**The physics.** In **series**, resistances add:  $R = R_1 + R_2$ . A 100  $\Omega$  and a 220  $\Omega$  resistor in series make 320  $\Omega$ , and on 6 V the current is  $6 \div 320 \approx 0.019$  A through both; the voltages across them add up to 6 V. In **parallel**, each branch gets the full voltage, and the currents add. Two 100  $\Omega$  resistors in parallel on 6 V each draw  $6 \div 100 = 0.06$  A, a total of 0.12 A, so together they act like  $6 \div 0.12 = 50$   $\Omega$ . Adding a branch in parallel always lowers the total resistance and raises the total current. The general rule is  $1/R = 1/R_1 + 1/R_2$ .



**The engineering.** Every house is wired in parallel, so each light and appliance gets the full voltage and can be switched by itself. But because currents add in parallel, too many appliances on one circuit can draw more current than its wires can safely carry. That is why each circuit has a fuse or circuit breaker sized for its wires. Engineers use series wiring where the same current must pass through everything, such as a switch in line with the lamp it controls, or a fuse in line with the whole circuit.

## PICTURE STUDY



*Edison's Pearl Street Station, Unknown artist, About 1882–1885 · Engraving*

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

This engraving shows the dynamo room at Pearl Street, where steam engines turned Edison's "Jumbo" dynamos. From here, current flowed through underground mains to lamps wired in parallel all over lower Manhattan.

### Look closely

- Find the long, round magnets of the dynamos. Which part spins?
- Find where the engines connect to the dynamos.
- Look at the men. How big are the machines compared with them?
- Look for wires or switches overhead. Where would the current leave the building?

### Talk about it

1. Why did Edison need such large machines to light only about 400 lamps at first?
2. If one lamp in a customer's office burned out, why did the others stay lit?
3. Why did each Pearl Street-style station serve only about a square mile?

**Safety first.** Batteries only. Small bulbs and resistors can get warm; disconnect the battery between tests and never leave a circuit connected unattended.

## BUILD

### Predict, Then Measure: Series and Parallel

You will calculate the currents and voltages in a series circuit and a parallel circuit before you build them, then build each and measure. A good engineer's predictions and measurements should agree within a few percent.

#### You will need

- A digital multimeter
- A 4 × AA battery holder (6 V) with batteries
- Resistors: two of 100  $\Omega$  and one each of 220  $\Omega$  and 470  $\Omega$
- Two small flashlight bulbs (2.5–6 V) in holders (optional, to see brightness)
- Alligator clip leads and the engineer's notebook

#### Steps

1. Measure the battery pack voltage and the exact resistance of each resistor. Use these real numbers in your calculations.
2. **Predict (series).** For 100  $\Omega$  and 220  $\Omega$  in series, calculate the total resistance, the current, and the voltage across each resistor ( $V = I \times R$  for each).
3. **Measure (series).** Build it. Measure the current in line, then the voltage across each resistor. Record predictions and measurements side by side.
4. **Predict (parallel).** For 100  $\Omega$  and 220  $\Omega$  in parallel, calculate the current in each branch and the total current.
5. **Measure (parallel).** Build it. Measure the current in each branch and the total current from the battery.
6. Calculate the percent difference for each pair:  $(\text{measured} - \text{predicted}) \div \text{predicted} \times 100$ .
7. **See it.** If you have two bulbs, wire them in series and then in parallel on the same battery. Which is brighter? Unscrew one bulb in each circuit. What happens to the other?
8. **Improve.** Design a circuit with three lamps (or resistors) in which one switch controls all three and each can also be removed without darkening the

others. Draw it, build it with resistors and the meter, and check your design.

#### Tips

- Draw the circuit diagram before you clip anything together, and check it against the diagram after.
- To measure a branch current, open that branch and put the meter in the gap.
- Small differences between prediction and measurement usually come from the resistors' tolerance (often  $\pm 5\%$ ) and the battery's voltage changing under load.

#### Check your work

- ☐ I can calculate series and parallel resistance and current.
- ☐ I can explain why Edison wired lamps in parallel and used high-resistance filaments.
- ☐ I can compare my predictions with my measurements and explain the difference.

#### ENGINEER'S NOTEBOOK

1. Draw circuit diagrams for your series and parallel circuits, labeled with predicted and measured values.
2. Make a table: quantity, predicted, measured, percent difference.
3. Work it: three  $300\ \Omega$  lamps are in parallel on 120 V. What is the current in each and the total? (0.4 A each; 1.2 A total.) If they were in series? ( $900\ \Omega$ ;  $120 \div 900 \approx 0.13\text{ A}$ .)

**From history.** Pearl Street used direct current, which could not be sent far without large losses, so every square mile needed its own station. Within a few years, alternating current, which can be stepped up to high voltage by transformers and sent many miles, began to win the contest for long-distance power, as you will see in later grades.

#### COMMON MISTAKES

- Adding parallel resistances like series ones. Parallel resistance is always smaller than the smallest branch.
- Thinking current is “used up” going around a series circuit. The same current flows through every part of a series loop.
- Putting the ammeter across a part instead of in line with it.

**Make it a game • Predict the Branch.** Your parent names two resistors, such as 4 ohms and 6 ohms. Predict the total resistance in series and in parallel, then the current from a 12 volt supply. Write the answers before checking. Explain why Edison wired lamps in parallel. Three correct predictions out of five win the match.

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

Edison’s parallel wiring was designed so that every room could have its own light. Jesus tells us to let our light shine for everyone in the house.

## 4.3 FARADAY, MOTORS AND GENERATORS

### OBJECTIVES

- Describe Faraday's 1831 experiments and explain electromagnetic induction.
- Explain how a generator and a motor are the same machine working in opposite directions.
- Build a coil-and-magnet generator, measure its voltage, and find what makes the voltage larger.

**Warm-up.** Connect a small hobby motor to a multimeter set to DC volts (no battery). Spin the motor's shaft between your fingers, slowly and then fast. What does the meter show? Write what you think is happening.

### WATCH

#### How a generator works, both AC and DC!

PhysicsHigh · 5:39

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

### WHEN TO WATCH

After the story and before the physics.

### BACKUP VIDEO

#### Faraday's Law of Induction Demonstration - Penn Physics

Penn Online Learning · 3:15

<https://www.youtube.com/watch?v=BZaTW6lnaEg>

Before the build, to see a magnet pushed through a coil and a meter respond.

### KEY TERMS

#### **electromagnetic induction**

Making a voltage in a wire or coil by changing the magnetic field through it.

#### **motor**

A machine that turns electrical energy into motion, using the push between a current and a magnet.

#### **generator**

A machine that turns motion into electrical energy by induction.

#### **coil**

Wire wound in many turns; more turns give more induced voltage.

## **galvanometer**

A sensitive meter for detecting small currents.

### **CORE IDEAS**

**The story.** Michael Faraday was the son of a London blacksmith and left school at 13 to work for a bookbinder. He read the science books he bound, attended lectures by Humphry Davy at the Royal Institution, and talked his way into a job as Davy's assistant. In 1821 he made the first electric motor, a wire that spun around a magnet when a current flowed. But he was sure that if electricity could make magnetism, magnetism should somehow make electricity. He tried for ten years and failed again and again.

**How they figured it out.** On August 29, 1831, Faraday wound two separate coils of wire on opposite sides of an iron ring. He connected one coil to a battery and the other to a galvanometer. A steady current in the first coil did nothing to the meter. But at the moment he connected or disconnected the battery, the needle jumped. The secret was **change**: a changing magnetic field makes a voltage. A few weeks later he pushed a bar magnet into a coil and pulled it out, and the needle swung each way. By the end of October he had spun a copper disk between the poles of a magnet and drawn a steady current from it, the first generator. Faraday was a devout Christian who saw his work as reading the laws God had written into nature, and he spent much of his life explaining science to ordinary people, including children at his Royal Institution Christmas lectures.

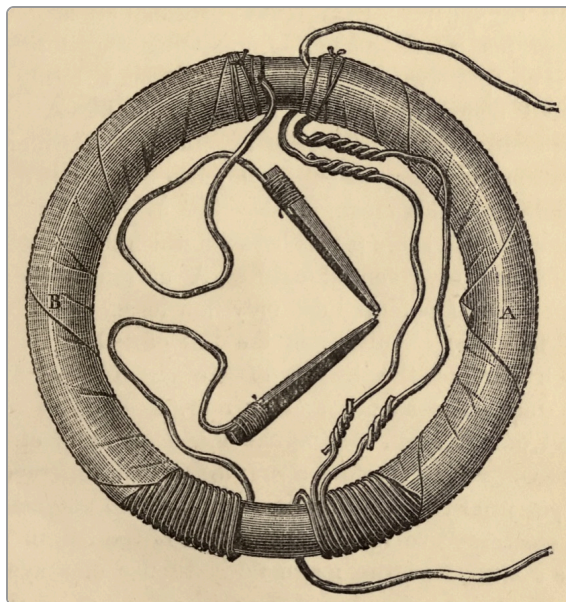
**The physics.** When the magnetic field through a coil changes, a voltage is induced in the coil. The voltage is bigger when the field changes **faster** (move the magnet quickly), when the magnet is **stronger**, and when the coil has **more turns** (each turn adds its share, so 200 turns give about twice the voltage of 100). A **motor** runs this the other way: a current in a coil inside a magnetic field feels a push that turns it. In fact, a small motor is also a generator. Spin its shaft and it makes a voltage. If your hobby motor gives 0.6 V when spun at 2 turns per second, you can expect about 1.2 V at 4 turns per second.

**The engineering.** Almost all the electricity in the world is made by Faraday's principle. In a power plant, steam, water or wind turns a shaft that spins huge magnets inside coils of copper, or coils inside magnets. Engineers design generators

to turn at a steady speed so the voltage and frequency stay constant. Electric motors, from the vibrator in a phone to the traction motors of a locomotive, use the same physics in reverse. Electric cars even run their motors as generators when braking, turning motion back into stored energy.



## PICTURE STUDY



*Faraday's Induction Ring*, Unknown illustrator, Published 1896 · Engraving

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

This drawing shows the iron ring Faraday made for his experiment of August 29, 1831. Coil A could be connected to a battery and coil B to a galvanometer. The two coils never touch.

### Look closely

- Find coil A and coil B. Are they connected to each other by any wire?
- Find the iron ring that links them. What does the iron carry from one coil to the other?
- Find the loose wire ends. Which pair would go to the battery, and which to the meter?
- Look at how many turns of wire are on each side.

### Talk about it

1. Why did the meter jump only when the battery was connected or disconnected?
2. How is this ring like the transformers that change the voltage on power lines today?
3. How could Faraday make the meter jump farther?

**Safety first.** Strong magnets can pinch fingers and must be kept away from small children (swallowed magnets are dangerous), phones, credit cards and pacemakers. Batteries only.

## BUILD

### A Coil-and-Magnet Generator

You will wind a coil of magnet wire, connect it to a multimeter, and move a strong magnet in and out. You will measure how the voltage changes when you move the magnet faster and when you double the number of turns, two fair tests of Faraday's law.

#### You will need

- Magnet wire (26–30 gauge), about 30 meters
- A cardboard tube (toilet-paper roll or a rolled index card) just wide enough for the magnet to slide through
- A strong cylinder or stack of disc magnets (neodymium or ceramic)
- Fine sandpaper, tape and a digital multimeter (DC millivolt setting)
- A small hobby motor (1.5–3 V) and string, for part B
- Engineer's notebook

#### Steps

1. **Wind the coil.** Tape the start of the wire to the tube, leaving 20 cm free. Wind 100 turns neatly around the middle of the tube, counting carefully. Tape it and leave another 20 cm free. Sand the enamel off the last 2 cm of each end.
2. Connect the ends to the multimeter on DC millivolts.
3. **Predict.** What will happen when you push the magnet in quickly? When you pull it out? When you hold it still inside?
4. **Test speed.** Push the magnet through the coil slowly, then at medium speed, then quickly. Record the largest reading each time. Do three trials of each.
5. **Test turns.** Wind another 100 turns on top (now 200 in all) and repeat the fast test. Does the voltage about double?
6. **Part B, motor as generator.** Wrap string around the hobby motor's shaft, connect the motor to the meter, and pull the string off with a slow pull and a fast pull. Record the voltages.
7. Make a table for both parts, with averages.

8. **Improve.** Change one more thing to get a bigger voltage: a stronger magnet, a narrower coil, or more turns. Predict, test and explain.

**Tips**

- The reading flicks up and back quickly; watch for the peak, or use the meter's "max hold" button if it has one.
- If you get no reading at all, check that the enamel is sanded off both wire ends.
- The meter swings positive one way and negative the other: the current changes direction when the magnet changes direction. That is alternating current in miniature.

**Check your work**

- ☐ I can explain what Faraday discovered in 1831.
- ☐ I can name three ways to make a generator's voltage bigger.
- ☐ I can explain how a motor and a generator are related.

**ENGINEER'S NOTEBOOK**

1. Draw Faraday's iron ring with its two coils, the battery and the galvanometer, and explain when the needle moved.
2. Graph peak voltage against magnet speed (slow, medium, fast) for 100 and 200 turns.
3. Work it: a coil of 150 turns gives 30 mV. About how much would 450 turns give, moving the magnet the same way? (90 mV.)

**From history.** Faraday kept careful laboratory notebooks and numbered every paragraph. His entry for August 29, 1831, begins by describing the soft-iron ring he had made for the experiment. The notebooks survive at the Royal Institution, and fifty years later Edison's dynamos, like every power station since, ran on the law they record.

**COMMON MISTAKES**

- Thinking a magnet sitting still in a coil makes electricity. Only a changing field induces a voltage.
- Forgetting to sand the enamel off magnet wire, so no current can flow.
- Thinking motors and generators are different kinds of machine. They are the same idea run in opposite directions.

**Make it a game • Same Machine Reversed.** Act out induction. Your parent holds a coil of cupped fingers while you move a fist magnet through. Whisper "current" when it moves and nothing when it stops. Then explain why a generator and a motor are the same machine running opposite ways. Add Faraday's 1831 experiment and the galvanometer needle.

## 4.4 FIRST STEPS WITH A MICROCONTROLLER: MAKING AN LED BLINK

### OBJECTIVES

- Explain what a microcontroller is and what inputs, outputs and programs are.
- Write a program that turns an output on and off with a delay to blink an LED, and change its timing.
- Choose a safe resistor for an LED with Ohm's law, and measure how fast a light can blink before it looks steady.

**Warm-up.** Watch the second hand of a clock for ten seconds and say “on, off, on, off” with each tick. Now write those instructions as a list a machine could follow, step by step, forever.

### WATCH

#### How to Blink an LED with Arduino (Lesson #2)

Science Buddies • 15:57

<https://www.youtube.com/watch?v=FKEkzzj5844>

### WHEN TO WATCH

Before the build if you use an Arduino. micro:bit users can watch the backup instead.

### BACKUP VIDEO

#### Micro:bit Flashing Heart Tutorial

Microsoft MakeCode • 4:35

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

Before the build if you use a micro:bit or the MakeCode simulator.

### KEY TERMS

#### **microcontroller**

A tiny computer on a single chip that runs one program to control a device, such as a microwave oven, a toy or a car's windshield wipers.

#### **program**

A list of instructions a computer follows in order.

**output**

Something a computer controls, such as a light, a motor or a speaker.

**input**

Something a computer reads, such as a button, a sensor or a dial.

**delay**

An instruction that makes the program wait, usually measured in milliseconds (ms). 1,000 ms = 1 second.

**loop**

Instructions that repeat over and over.

**CORE IDEAS**

**The story.** In 2005, teachers at the Interaction Design Institute in Ivrea, Italy, had a problem. Their design students wanted to build things that sensed and moved, but the control boards on the market were expensive and hard to use. So Massimo Banzi and a few colleagues designed their own small, cheap board, with free software anyone could use, and named it after a café in town, the Bar di Re Arduino. The Arduino spread around the world. In 2016 the BBC and its partners went further, giving about a million BBC micro:bit boards free to children in their first year of secondary school across Britain.

**How they figured it out.** The Arduino team's idea was to remove every obstacle between a beginner and a working project. The board plugged into a computer with a USB cable for both power and programming. The software was free. The design of the board itself was published openly, so anyone could make and improve it. And the very first program they suggested was the simplest that does something you can see: turn a light on, wait, turn it off, wait, and do it again. Engineers call it “Blink,” and nearly every engineer who works with microcontrollers has written it.

**The physics.** A microcontroller's output pin switches between 0 volts (off, or LOW) and its supply voltage (on, or HIGH), 5 V on an Arduino Uno and 3 V on a micro:bit. An LED must have a resistor in series to limit its current, or it will burn out. A red LED uses about 2 V, so on a 5 V pin the resistor has 3 V across it. For a safe 15 mA:  $R = V \div I = 3 \div 0.015 = 200 \, \Omega$ , so use the next standard size up, 220  $\Omega$ . Your eyes cannot see flicker faster than about 50 times a second, so a light blinking faster than that looks steady. Many dimmers and LED screens use that fact, switching on and off very fast.

**The engineering.** There are billions of microcontrollers in use: in washing machines, thermostats, cars (often dozens in one car), traffic lights and medical

devices. Engineers write their programs in steps: make one small thing work, test it, then add the next. A program to blink a light becomes a program to blink a warning light only when a sensor reads too hot. Testing small pieces one at a time, and keeping notes of what each change did, is how engineers keep big programs working.



## PICTURE STUDY



*The Apollo Computer's Keyboard in a Test Airplane, NASA, Photograph 1996; equipment from the early 1970s · Photograph · NASA Armstrong Flight Research Center*

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

This is the display and keyboard (called the DSKY) of the computer that guided the Apollo spacecraft. In 1972 NASA put an Apollo computer in a test airplane, the F-8 Digital Fly-By-Wire, which became the first airplane flown entirely by a digital computer. Inside, like your micro:bit, a program ran in a loop, reading inputs and setting outputs.

### Look closely

- Find the keys marked VERB and NOUN. Astronauts typed a verb (an action) and a noun (what to act on), like a tiny program command.
- Find the status lights at the upper left. Each is an output the computer could turn on.
- Find the number display at the upper right.
- Find the key marked PRO (proceed). Why would a computer stop and wait for a person to press it?

### Talk about it

1. What are the inputs and outputs of this computer?
2. Your micro:bit is far more powerful than this computer. Why do you think engineers still trusted it to fly to the Moon?

### 3. Why would engineers test a computer that flies an airplane so carefully?

**Safety first.** Power the board only from a computer's USB port or a battery pack made for it. Never connect anything on the board to a household electrical outlet or to more than the board's rated voltage.

## BUILD

### Blink, Signal and Flicker

You will program a micro:bit or an Arduino to blink an LED, change the timing, send “SOS” in Morse code, and then run a fair test to find the blink speed at which the light seems to stop blinking. No board? Use the free MakeCode micro:bit simulator on screen.

#### You will need

- A BBC micro:bit (or an Arduino Uno) and a USB cable, or a computer with the free MakeCode simulator ([makecode.microbit.org](https://makecode.microbit.org))
- For an Arduino: a red LED, a 220  $\Omega$  resistor, a breadboard and two jumper wires
- A stopwatch and the engineer’s notebook

#### Steps

1. **Blink.** In MakeCode, place a “forever” loop. Inside it: plot one LED, pause 500 ms, unplot it, pause 500 ms. (Arduino: `digitalWrite(13, HIGH); delay(500); digitalWrite(13, LOW); delay(500);` inside loop(.)) Download it and watch it run.
2. **Measure.** Count blinks for 30 seconds with a stopwatch. Calculate the blinks per second. Does it match what your program says (one blink per 1,000 ms)?
3. **Change one thing.** Change both pauses to 250 ms and measure again. Predict first.
4. **Signal.** Program “SOS” in Morse code: three short flashes (200 ms on), three long flashes (600 ms on), three short flashes, with 200 ms off between flashes and a 1,400 ms pause before it repeats.
5. **Predict.** At what pause length will the blinking seem to become a steady light?
6. **Fair test.** Set both pauses to 100, 50, 30, 20, 10 and 5 ms in turn. For each, record whether you see blinking, flicker or a steady light. Ask two other people to look too, without telling them the setting.

7. Make a table and work out the blinks per second at each setting:  $1,000 \div (\text{on time} + \text{off time})$ .
8. **Improve.** Add a button (button A on the micro:bit) so the light blinks only while the button is held, or so it switches between slow and fast. Test it and write down what you changed.

#### Tips

- On an Arduino, the long leg of the LED goes toward the output pin and the short leg toward ground, with the resistor in series.
- Change one number at a time and download again. If something stops working, undo your last change.
- Save each working version with a new name, such as “blink2,” so you can go back.

#### Check your work

- ☐ I can explain what a microcontroller, an input and an output are.
- ☐ I can write and change a blink program.
- ☐ I can calculate a safe LED resistor and explain why fast blinking looks steady.

#### ENGINEER'S NOTEBOOK

1. Write out your blink program and your SOS program, and draw a timing diagram (on and off against time) for the SOS.
2. Record your flicker test in a table: pause, blinks per second, what each viewer saw.
3. Work it: a blue LED uses 3.0 V and should run at 10 mA from a 5 V pin. What resistor is needed?  $((5 - 3) \div 0.010 = 200 \Omega$ ; use 220  $\Omega$ .)

**From history.** The first microcontrollers on a single chip appeared in the 1970s. Before that, the computer that guided Apollo spacecraft to the Moon filled a box about the size of a briefcase and was among the first computers built from integrated circuits. Today a micro:bit is far more powerful and fits in a pocket.

#### COMMON MISTAKES

- Leaving out the second pause, so the light turns off and instantly on again and looks always on.
- Connecting an external LED without a resistor.

- Changing several parts of a program at once, so when it fails you cannot tell why.

**Make it a game · Blink Code Challenge.** Write a program on paper that blinks an LED on for 500 milliseconds and off for 500. Your parent plays the microcontroller and follows your lines exactly, tapping the table. Then change the timing to blink twice as fast. Find any bug. Name input, output, delay and loop in your code.

**Scripture.** “Let all things be done decently and in order.” (1 Corinthians 14:40, KJV)

A computer does exactly what it is told, in exactly the order it is told. Writing a program is practice in doing things decently and in order.

## UNIT 4

# ELECTRICITY

This year you will stop guessing about circuits and start measuring them. With an inexpensive multimeter you will measure voltage, current and resistance, and you will discover for yourself the rule Georg Ohm found in 1827:  $V = IR$ . Then you will calculate what happens when parts are joined in series and in parallel, and see why Thomas Edison wired every lamp in New York in parallel.

Next you will follow Michael Faraday into his laboratory in 1831, when he found that a moving magnet can make electricity, and you will build a generator and measure its voltage. Last, you will write your first program for a tiny computer, a micro:bit or an Arduino, and make it blink a light on command. Every circuit in this unit runs on batteries or a USB cable, never on the outlets in the wall.

### PREREQUISITES

- Can build a simple battery-and-bulb circuit and knows conductors and insulators (earlier grades)
- Can multiply, divide and use decimals and simple fractions
- Can record measurements in a table and make a line graph

### MASTERY CHECKLIST

- ☐ I can measure voltage, current and resistance safely with a multimeter.
- ☐ I can use  $V = IR$  to find voltage, current or resistance, with volts, amperes and ohms.
- ☐ I can calculate total resistance and current for resistors in series and in parallel, and explain why homes are wired in parallel.
- ☐ I can explain how Faraday's discovery of induction leads to generators and motors, and measure what makes a generator's voltage go up.
- ☐ I can write a program with an output and a delay to blink an LED on a micro:bit or Arduino, and choose a safe resistor for it.

## OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** Ages 8 and up. A small programmable board with lights, buttons and sensors, coded with the free Microsoft MakeCode editor; fits Lesson 4.4 and Unit 8. The MakeCode on-screen simulator works without a board.
- **Arduino Starter Kit:** Ages 12 and up with an adult. An Arduino Uno board with a breadboard, LEDs, resistors, a motor and sensors, plus a project book. Fits Lessons 4.1, 4.2 and 4.4 and the robotics unit.
- **Snap Circuits:** Ages 8 and up. Parts snap together on a grid with no soldering; useful for building series and parallel circuits quickly in Lesson 4.2.

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

## LESSONS IN THIS UNIT

|     |                                                         |                          |
|-----|---------------------------------------------------------|--------------------------|
| 4.1 | Ohm's Law with a Multimeter                             | 2 sessions of 50 minutes |
| 4.2 | Series and Parallel: Edison's Pearl Street Station      | 2 sessions of 50 minutes |
| 4.3 | Faraday, Motors and Generators                          | 2 sessions of 50 minutes |
| 4.4 | First Steps with a Microcontroller: Making an LED Blink | 2 sessions of 50 minutes |

## UNIT 4 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. 8 pts

Name the units of voltage, current and resistance, and say in one sentence what each quantity means.

2. 10 pts

Calculate: a 6-volt battery is connected to a 300-ohm resistor. What current flows, in amps and in milliamps?

3. (8 pts)

How should a multimeter be connected to measure the current through a resistor, and how to measure the voltage across it?

4. (6 pts)

Why did Ohm switch from a battery to a thermocouple?

5. (10 pts)

Calculate: a  $220\ \Omega$  and a  $330\ \Omega$  resistor are connected in series to 11 V. Find the total resistance, the current, and the voltage across the  $220\ \Omega$  resistor.

6. (10 pts)

Calculate: two 60-ohm lamps are in parallel on a 12-volt battery. Find the current in each lamp and the total current.

7. (8 pts)

Explain in two or three sentences why Edison wired lamps in parallel and why he wanted high-resistance filaments.

8. (8 pts)

What did Faraday observe on August 29, 1831, with his iron ring, and what did it show?

9. (8 pts)

Predict: a coil of 100 turns gives 20 mV when a magnet is pushed through it. Name two changes that would give a larger voltage, and estimate the voltage with 300 turns.

10. (8 pts)

How are a motor and a generator related?

11. (8 pts)

Calculate: a red LED uses 2 V and should run at 20 mA from a 5 V output pin. What resistor is needed?

12. (8 pts)

What is a microcontroller? Give two examples of where one is used.



## ANSWER KEY

1. Voltage in volts (the push), current in amperes (the rate of flow of charge), resistance in ohms (how much a part opposes the flow).
2.  $I = V \div R = 6 \div 300 = 0.02 \text{ A} = 20 \text{ mA}$ .
3. Current: in line (in series), so the current flows through the meter. Voltage: across the resistor (in parallel), touching its two ends.
4. The batteries of his day gave a voltage that drooped and changed during use; the thermocouple gave a small but steady voltage, so his measurements could be compared.
5.  $R = 220 + 330 = 550 \text{ } \Omega$ .  $I = 11 \div 550 = 0.02 \text{ A}$ .  $V = 0.02 \times 220 = 4.4 \text{ V}$ .
6. Each:  $12 \div 60 = 0.2 \text{ A}$ . Total:  $0.4 \text{ A}$  (the pair acts like  $30 \text{ } \Omega$ ).
7. In parallel, each lamp gets the full voltage and can be switched on and off by itself, and one burned-out lamp does not darken the rest. But parallel currents add up, so he used high-resistance filaments to keep each lamp's current small and the copper mains affordable.
8. The galvanometer on the second coil jumped only when the battery on the first coil was connected or disconnected, not while the current was steady. It showed that a changing magnetic field induces a voltage.
9. Move the magnet faster, use a stronger magnet, or add turns. With 300 turns, about 60 mV.
10. They are the same kind of machine working in opposite directions: a motor turns electrical energy into motion; a generator turns motion into electrical energy. Spinning a motor's shaft makes it act as a generator.
11. The resistor has  $5 - 2 = 3 \text{ V}$  across it.  $R = 3 \div 0.020 = 150 \text{ } \Omega$  (use  $150 \text{ } \Omega$  or the next size up).
12. A tiny computer on one chip that runs one program to control a device.  
Examples: microwave oven, thermostat, washing machine, car, toy, traffic light.

## PORTFOLIO PIECE: A MEASURED AND PROGRAMMED SIGNAL LIGHT

Build a signal light that a microcontroller controls: two or more LEDs, each with a resistor you calculated, blinking in a pattern you program (a traffic light, a lighthouse code or a Morse message). Draw the circuit diagram, show your resistor calculations with Ohm's law, and measure the actual current through one LED with a multimeter. If you have no board, build the same circuit with batteries and a switch and work the program in the MakeCode simulator. Write a one-page report with your diagram, program, calculations, measurements and one improvement.

| LOOK FOR              | WHAT IT MEANS                                                                                     |
|-----------------------|---------------------------------------------------------------------------------------------------|
| <b>Circuit design</b> | A neat circuit diagram with standard symbols; every LED has a resistor.                           |
| <b>Calculations</b>   | Resistor values worked out correctly with Ohm's law and the units shown.                          |
| <b>Measurement</b>    | Current measured safely with the meter in line and compared with the calculation.                 |
| <b>Program</b>        | The program runs the planned pattern, uses a loop and delays, and is written out in the notebook. |
| <b>Improvement</b>    | One change is tested and explained, such as a button input or a new pattern.                      |

## UNIT 5

# PUBLIC UTILITIES

Turn on a tap, flip a switch or send a message, and you are using systems built by thousands of engineers and kept running every hour of every day by operators and line crews. In this unit you will see how water is made safe to drink, step by step, and test it yourself with a jar test. You will learn why water towers stand tall, and calculate the pressure that height gives.

Then you will follow Charles Parsons and his steam turbine into the power plant, and compare the ways we make electricity, by coal, gas, nuclear, falling water, wind and sunlight, the way an engineer compares them: by cost, reliability and what each one needs. Last, you will trace communication from the telegraph wire to a glass fiber thinner than a hair, starting with a glowing jet of water in Geneva in 1841. Serving a whole city well is one of the clearest ways engineers love their neighbors.

### PREREQUISITES

- Knows how a generator works (Lesson 4.3)
- Can calculate weight and pressure from height (Lessons 1.2 and 3.4)
- Can convert between units such as liters and cubic meters, and grams and kilograms

### MASTERY CHECKLIST

- ☐ I can name and explain the main steps of water treatment: coagulation, flocculation, settling, filtration and disinfection.
- ☐ I can calculate water pressure from the height of a tower and explain how pumps and towers work together.
- ☐ I can trace energy from fuel, falling water, wind or sunlight to the wires, and compare sources as engineering trade-offs.
- ☐ I can explain total internal reflection and calculate how long a signal takes to cross an ocean in a fiber.
- ☐ I can run a fair test with careful measurements and record it honestly.

## OPTIONAL KITS FOR THIS UNIT

- **Thames & Kosmos science kits:** Ages vary by kit. Several kits on renewable energy, water and power plants include small turbines, solar cells and generators that extend the turbine test in Lesson 5.3.
- **KiwiCo Eureka and Tinker crates:** Ages 9 and up (Tinker) and 14 and up (Eureka). Some crates build working pumps, water wheels and generators; check each crate's description for a fit with Lessons 5.2 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 Water Treatment: Coagulation, Filtration and Disinfection

2 sessions of 50 minutes

---

### 5.2 Pumps, Pressure and Water Towers: The Fairmount Water Works

2 sessions of 50 minutes

---

### 5.3 How Power Plants Make Electricity: Parsons's Turbine and the Trade-offs

2 sessions of 50 minutes

---

### 5.4 From Telegraph to Telephone to Fiber Optics: Colladon's Light Fountain

2 sessions of 50 minutes

---

## UNIT 5 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

List the main steps of water treatment in order and say what each does.

2. **10 pts**

Calculate: a plant treats 8 million liters of water a day with chlorine at 1.5 mg/L. How many kilograms of chlorine does it use each day?

3. (7 pts)

What did John Leal and George Fuller have to prove in court about chlorinating Jersey City's water, and how did they prove it?

4. (7 pts)

Why do operators run jar tests instead of always using the same amount of coagulant?

5. (10 pts)

Calculate: the water surface in a tower is 45 m above a house. What is the water pressure at the house when no water is flowing? Give the answer in kilopascals.

6. (8 pts)

Explain in two or three sentences how pumps and water towers work together.

7. (6 pts)

Why did Frederick Graff switch the Fairmount Water Works from steam engines to water wheels?

8. (8 pts)

What problem did Parsons find with Turbinia's first propellers, and how did he solve it?

9. (10 pts)

Calculate: water flows through a dam's turbine at  $4 \text{ m}^3$  per second and falls 25 m. Using  $\text{power} = 1,000 \times 9.8 \times \text{flow} \times \text{height}$ , find the power before losses, in megawatts.

10. (8 pts)

Give one strength and one weakness each for a wind farm and a natural gas plant.

11. (8 pts)

What is total internal reflection, and how does it let an optical fiber carry light around bends?

12. 10 pts

Calculate: light travels at about 200,000 km/s in glass. How long does a signal take to travel through a 6,000 km undersea fiber cable? Give the answer in milliseconds.

**ANSWER KEY**

1. Coagulation (a chemical lets tiny particles stick), flocculation (slow stirring forms floc), sedimentation (floc settles), filtration (sand catches what is left), disinfection (chlorine destroys germs).
2.  $8,000,000 \times 1.5 = 12,000,000 \text{ mg} = 12,000 \text{ g} = 12 \text{ kg}$ .
3. That the chlorinated water was much safer and the small dose did no harm. They measured bacteria in samples before and after treatment, day after day, and kept careful records.
4. Raw water changes with weather and season, and each water has a best dose; too little or too much leaves it cloudy. Testing finds the right dose for that day's water.
5.  $1,000 \times 9.8 \times 45 = 441,000 \text{ Pa} = 441 \text{ kPa}$  (about 64 psi).
6. Pumps lift water into the tower, often at night when demand is low. The height of the water gives pressure to the pipes all day by gravity, and the tower stores water for busy hours and fires.
7. The steam engines were costly to fuel, broke down often and one boiler exploded; water wheels driven by the river through a dam were far cheaper to run.
8. They spun so fast that the water formed vapor bubbles (cavitation), wasting power. He tested in a tank and redesigned the ship with three shafts and nine smaller propellers.
9.  $1,000 \times 9.8 \times 4 \times 25 = 980,000 \text{ W} \approx 0.98 \text{ MW}$ .
10. Wind: no fuel needed; but makes power only when the wind blows. Gas: can be turned up and down quickly and runs any time; but needs a steady fuel supply and fuel costs. (Other correct answers accepted.)
11. When light inside glass or water hits the surface at a shallow enough angle, it reflects back inside completely. In a fiber the light keeps reflecting off the boundary of the core, zigzagging along it even when the fiber bends.
12.  $6,000 \div 200,000 = 0.03 \text{ s} = 30 \text{ ms}$ .

## PORTFOLIO PIECE: A UTILITY ENGINEER'S REPORT

Choose one utility that serves your home (water, electricity or communication) and trace it from its source to your house, using a map, a visit to a public information center or website, and your own observations from safe public places. Then repeat one build from this unit with an improvement, such as a jar test with a narrower range of doses, a taller water tower model, or a turbine with redesigned blades. Write a two-page report with a labeled diagram of the system, at least two calculations from the unit using real or measured numbers, your test data, and a paragraph on the people who keep that utility running.

| LOOK FOR              | WHAT IT MEANS                                                                                                                                  |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>System diagram</b> | A clear, labeled diagram traces the utility from its source to the home.                                                                       |
| <b>Calculations</b>   | At least two correct calculations (dose, pressure, power or signal time) with units.                                                           |
| <b>Improved build</b> | The repeated build changes one variable, is tested fairly and has its data recorded.                                                           |
| <b>Explanation</b>    | The report explains the physics and engineering accurately in the student's own words.                                                         |
| <b>Service</b>        | A thoughtful paragraph on the operators, line workers or engineers who keep the utility running, and on staying safe around utility equipment. |

## 5.1 WATER TREATMENT: COAGULATION, FILTRATION AND DISINFECTION

### OBJECTIVES

- Name and explain the steps of a modern water treatment plant.
- Calculate a chemical dose from a concentration (milligrams per liter) and a flow.
- Run a jar test with alum to find the best coagulant dose for muddy water, and measure clarity fairly.

**Warm-up.** Stir a spoonful of garden soil into a clear jar of water and set it on the table. Look at it now, after five minutes and at the end of the lesson. Which particles settle quickly and which stay cloudy?

### WATCH

#### Water Treatment | Coagulation Flocculation Basics

American Water College · 3:51

[https://www.youtube.com/watch?v=qV\\_1jfmhpnA](https://www.youtube.com/watch?v=qV_1jfmhpnA)

### WHEN TO WATCH

After the physics paragraph, before the jar test.

### BACKUP VIDEO

#### WSO Water Treatment Grade 2: Jar Testing, Ch. 10

AmericanWaterWorks · 3:00

<https://www.youtube.com/watch?v=M-VHwq2flmk>

Before the build, to see how water operators run a real jar test.

### KEY TERMS

#### **coagulation**

Adding a chemical (a coagulant such as alum) that makes tiny particles stop pushing each other apart so they can stick together.

#### **flocculation**

Gentle, slow stirring that lets the sticky particles collect into larger clumps called floc.



**sedimentation**

Letting the heavy floc settle to the bottom of a quiet basin.

**filtration**

Passing water through beds of sand and other media to catch the particles that are left.

**disinfection**

Destroying or disabling germs, usually with chlorine, at a carefully measured dose.

**turbidity**

Cloudiness of water caused by tiny suspended particles.

**CORE IDEAS**

**The story.** In 1908 the people of Jersey City, New Jersey, drank water piped from the Boonton Reservoir. The water looked clean, but after heavy rains it sometimes carried the germs of typhoid fever, a disease that was still common in American cities. The city sued its water company to make it build sewers around the reservoir. The company's medical adviser, Dr. John L. Leal, proposed something faster and bolder: add a small, measured amount of chlorine to all the water, all the time. On September 26, 1908, working with the engineer George Warren Fuller, he began feeding chlorine into the Boonton supply. It was the first time an American city's drinking water was continuously disinfected.

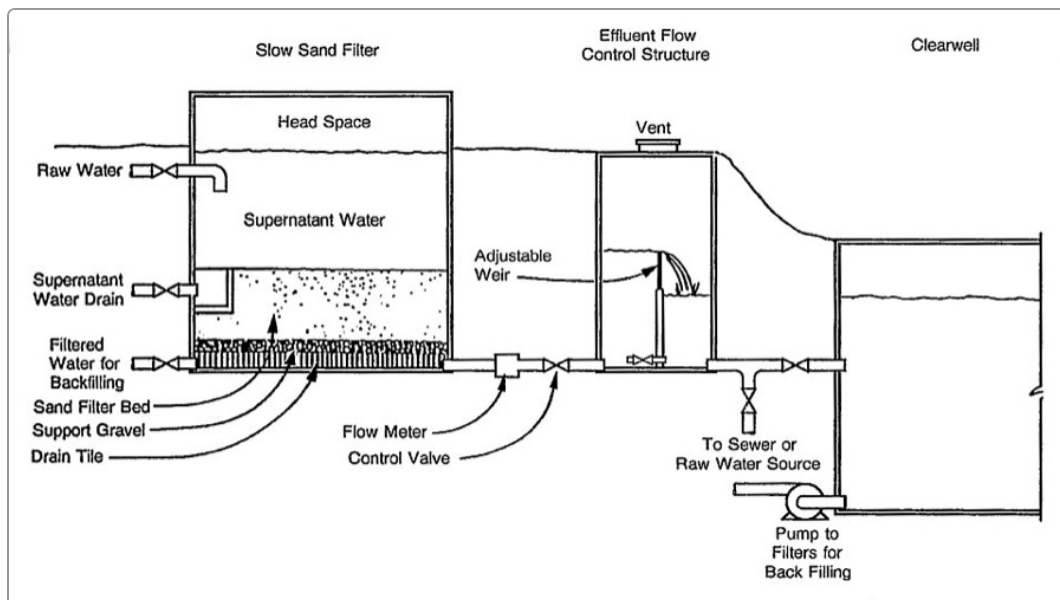
**How they figured it out.** Many people were afraid of "chemicals in the water," and the case went to court. Leal and Fuller had to prove two things with measurements: that the water was much safer, and that the tiny dose, a fraction of a milligram per liter, did no harm. They counted the bacteria in water samples before and after treatment, day after day, and kept careful records. The court accepted their evidence. Within a few years, cities all over the country added chlorine, and deaths from typhoid fell sharply. It is one of the greatest life-saving achievements of engineering.

**The physics.** The particles that make water cloudy are so small that they never settle on their own; each carries a tiny negative electric charge, so they repel each other. A **coagulant** such as alum (aluminum sulfate) cancels those charges, so the particles can stick. Slow stirring (**flocculation**) brings them together into floc big enough to sink (**sedimentation**). Sand **filters** catch most of what is left, and **disinfection** deals with germs. Doses are measured in milligrams per liter (mg/L). If a plant treats 20

million liters a day with chlorine at 1 mg/L, it needs  $20,000,000 \times 1 \text{ mg} = 20,000,000 \text{ mg} = 20 \text{ kilograms}$  of chlorine a day.

**The engineering.** Water engineers and licensed operators adjust the treatment every day, because a river after a storm is very different from the same river in a dry week. To choose the coagulant dose, operators run a **jar test**: six jars of raw water, each with a different dose, stirred and settled side by side. The dose that gives the clearest water wins, and they set the plant to match. They measure turbidity and chlorine continuously and test for germs every day. Clean water is not luck; it is careful measurement, done faithfully.

## PICTURE STUDY



*A Slow Sand Filter*, U.S. Environmental Protection Agency, 1990 · Diagram

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

This diagram from the U.S. Environmental Protection Agency shows a slow sand filter, the kind first built in London in 1829 and still used in many small towns. Follow the water from left to right.

### Look closely

- Find where the raw water comes in and where the clean water leaves.
- Find the sand filter bed, the support gravel and the drain tile. Why are they in that order?
- Find the flow meter and control valve. Why must an operator control how fast water flows through?
- Find the clearwell, where treated water is stored.

### Talk about it

1. Why does water pass through sand slowly in this kind of filter?
2. Where would you add chlorine, before or after the filter? Why?
3. How is this like the bottle filter you built, and how is it different?

**Safety first.** Never drink water from your jar test or filter, even if it looks clear. Alum is a food-grade pickling spice, but do not taste it, and wash your hands afterward. An adult should supervise.

## BUILD

### A Kitchen Jar Test

You will be the plant operator. You will make muddy “river water,” put it in four jars with different doses of alum, stir and settle them the way a treatment plant does, and measure which dose makes the clearest water. Then you will filter the best jar.

#### You will need

- Four identical clear jars or plastic cups (about 500 mL each) and a measuring cup
- Garden soil or clay, and water
- Alum (from the spice aisle) and measuring spoons ( $\frac{1}{8}$  and  $\frac{1}{4}$  teaspoon)
- A spoon for stirring, a stopwatch and masking tape for labels
- A ruler and a card with a bold black X drawn on it
- A plastic bottle filter: a cut bottle with a coffee filter, sand and gravel (from Grade 5) or a coffee filter alone

#### Steps

1. **Make the raw water.** Stir 2 tablespoons of soil into 2 liters of water. Let it stand 2 minutes so sand and gravel drop out, then pour the cloudy water off the top into a pitcher. This is your raw water.
2. Fill each jar with exactly 400 mL of raw water. Label them 0,  $\frac{1}{8}$ ,  $\frac{1}{4}$  and  $\frac{1}{2}$  (teaspoons of alum).
3. **Predict.** Which dose will give the clearest water? Is more always better?
4. **Coagulate.** Add the alum to each jar and stir each one fast for 1 minute.
5. **Flocculate and settle.** Stir each jar slowly and gently for 5 minutes (about one stir every 2 seconds). Then leave all four jars still for 20 minutes. Watch for floc forming.
6. **Measure clarity.** Hold the X card behind each jar. Then, using a clear tall glass, pour water from the top of each jar into the glass a little at a time until you can no longer see the X through the water from above. Measure the depth of water with the ruler. Deeper means clearer.

7. Make a table: dose, what the floc looked like, depth at which the X disappeared. Graph clarity against dose.
8. **Filter and improve.** Pour the clearest jar through your filter and measure its clarity again. Then try one more dose between your two best doses to find the best one more exactly.

#### **Tips**

- Keep everything the same except the dose: same jars, same water, same stirring, same time.
- Too much alum can make water cloudy again. That is why operators test instead of guessing.
- Look at the jars against a dark background to see the floc clearly.

#### **Check your work**

- ☐ I can name the steps of water treatment in order and explain each one.
- ☐ I can calculate a chemical dose from mg/L and a flow.
- ☐ I can explain why operators run jar tests.

#### **ENGINEER'S NOTEBOOK**

1. Draw the four jars after settling, labeled with their doses and clarity readings.
2. Draw a flow diagram of a treatment plant: intake, coagulation, flocculation, settling, filters, disinfection, storage, pipes to town.
3. Work it: a town uses 5 million liters of water a day and adds chlorine at 2 mg/L. How many kilograms of chlorine does it need each day? ( $5,000,000 \times 2 = 10,000,000$  mg = 10 kg.)

**From history.** Much earlier, in 1829, the engineer James Simpson built slow sand filters for the Chelsea Waterworks Company in London, and a few years after Jersey City, other cities began adding both filtration and chlorine. Today a treatment plant's operators must pass state exams and keep detailed records, just as Leal and Fuller did.

#### **COMMON MISTAKES**

- Thinking clear water is safe water. Germs are invisible; only disinfection and testing make water safe.
- Thinking more coagulant is always better. Each water has a best dose, found by testing.

- Stirring hard during flocculation, which breaks up the floc.

**Make it a game · Jar Test Dose.** Name the water treatment steps in order, as fast as you can: coagulation, flocculation, sedimentation, filtration and disinfection. Your parent times you. Then solve a dose puzzle: if the plant treats 100 liters per second at 2 milligrams per liter, how many milligrams per second are needed? Make three similar puzzles.

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

Clean, cold water is one of God’s simplest gifts. Engineers and operators who keep it safe serve every thirsty person in their town.

## 5.2 PUMPS, PRESSURE AND WATER TOWERS: THE FAIRMOUNT WATER WORKS

### OBJECTIVES

- Calculate water pressure from the height of water above a point.
- Explain how pumps, reservoirs and water towers work together in a water system.
- Build a model water tower and measure how its height changes the flow at a faucet.

**Warm-up.** Fill a drinking straw with water by dipping it, put your finger over the top and lift it out. Raise and lower the straw. Then let go of the top. What held the water in, and what pushed it out?

### WATCH

#### How Water Towers Work

Practical Engineering · 10:59

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

### WHEN TO WATCH

After the physics paragraph.

### BACKUP VIDEO

#### Do Pumps Create Pressure or Flow?

Practical Engineering · 10:38

[https://www.youtube.com/watch?v=m3i\\_5xP9PYU](https://www.youtube.com/watch?v=m3i_5xP9PYU)

After the build, for a deeper look at what pumps really do. Older students.

### KEY TERMS

#### **pump**

A machine that adds energy to water to lift it or push it through pipes.

#### **reservoir**

A large tank or basin that stores water.

#### **water tower**

A tank held high above the ground so gravity gives the water pressure in the pipes below.

#### **pressure head**

The height of water that would give a certain pressure; about 10 meters of head gives 98 kilopascals (about 14 psi).

**kilopascal (kPa)**

1,000 pascals; a unit of pressure. 1 psi  
is about 6.9 kPa.

**CORE IDEAS**

**The story.** In the early 1800s Philadelphia was a growing city that drank from wells, many of them dirty. In 1812 the city hired the engineer Frederick Graff to build a new waterworks on the Schuylkill River at a steep hill called Faire Mount. His plan was to pump river water up into reservoirs on top of the hill and let it flow down through pipes to the whole city by gravity. The Fairmount Water Works began pumping in 1815 with steam engines.

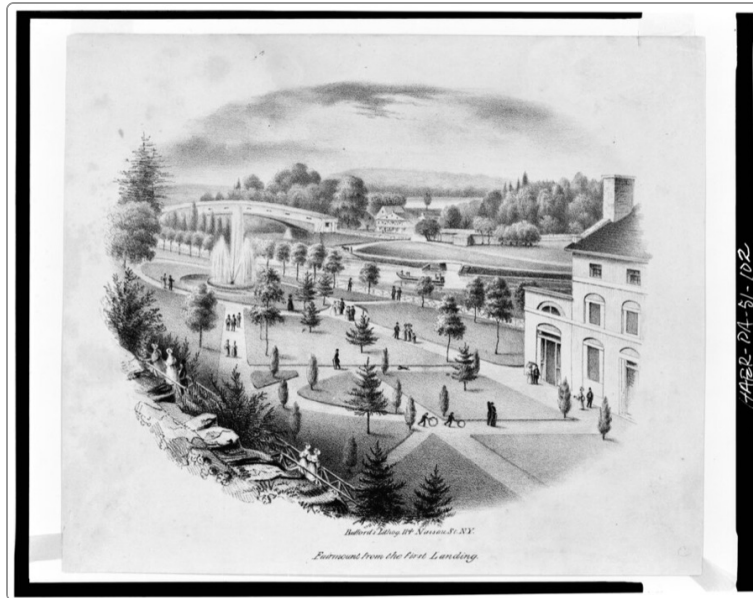
**How they figured it out.** The steam engines burned a great deal of expensive wood and coal, broke down often, and one boiler exploded. Graff measured the costs and changed course: in 1819–1822 he built a dam across the river and a mill house with great water wheels, so the falling river itself drove the pumps. It cost far less to run. Later, the wheels were replaced with more efficient water turbines. Graff also replaced the city's leaky wooden water mains with cast-iron pipes, among the first in America. The waterworks, with its classical buildings, became so admired that visitors came from Europe to see it.

**The physics.** Water pressure depends only on height:  $\text{pressure} = \text{density} \times g \times \text{height}$ . Every 10 meters of water gives  $1,000 \text{ kg/m}^3 \times 9.8 \text{ m/s}^2 \times 10 \text{ m} = 98,000 \text{ Pa}$ , or 98 kPa (about 14 psi). So a tank whose water surface stands 40 meters above a house gives about  $4 \times 98 = 392 \text{ kPa}$  (about 57 psi) at the house's tap when the water is still. When water flows, friction in the pipes uses up some of that pressure, so long, narrow or crowded pipes give less pressure at the tap. A **pump** gives water energy; a **water tower** stores that energy as height.

**The engineering.** Most towns pump water into towers or hilltop reservoirs, often at night when few people use water and electricity costs less, and let gravity supply pressure all day. The tower also stores water for the hour each morning when everyone showers at once, and for firefighters, who may need huge flows quickly. Engineers set the tower's height so that every home in its zone gets enough pressure (often 280–550 kPa, or 40–80 psi), and they divide hilly towns into pressure zones, each with its own tower or pump. A tall water tower is not decoration; its height is the pressure.



## PICTURE STUDY



*The Fairmount Water Works*, Unknown artist, About 1840 · Print · Free Library of Philadelphia

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

This print, about 1840, shows the Fairmount Water Works as visitors saw it: graceful buildings and gardens along the river. Hidden inside the buildings were water wheels driving pumps that lifted river water to reservoirs on the hill.

### Look closely

- Find the river and the long dam that raised its level to drive the water wheels.
- Find the buildings along the water. Which might hold the wheels and pumps?
- Find the fountain. What gives its water the pressure to rise?
- Look for the hill where the reservoirs sat.

### Talk about it

1. Why did Graff put the reservoirs on top of a hill?
2. Why would a city want its waterworks to be beautiful as well as useful?
3. How does the falling river supply the energy to pump water uphill?

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

## BUILD

### A Model Water Tower

You will build a water tower from a plastic bottle and a length of tubing, set it at different heights, and measure the flow at a “faucet” below. Then you will add a second faucet to see what happens when two houses use water at once.

#### You will need

- A 2-liter plastic bottle with its bottom cut off (the tank), turned upside down
- About 2 meters of clear aquarium tubing and a bottle cap with a hole that the tubing fits tightly (an adult makes the hole); modeling clay to seal
- A binder clip or clothespin to pinch the tubing shut (the faucet)
- A measuring cup, a stopwatch, a tape measure and books or a step stool to set the tank height
- A T-connector for aquarium tubing (optional, for the second faucet)

#### Steps

1. **Build.** Push the tubing through the cap and seal it with clay. Screw on the cap, hang or prop the bottle upside down, and run the tubing down to a measuring cup on the floor. Pinch the end shut with the clip.
2. **Calculate.** For tank heights of 50, 100 and 150 cm (measured from the faucet to the water surface), calculate the pressure at the faucet with  $\text{pressure} = 1,000 \times 9.8 \times \text{height in meters}$ .
3. **Predict.** If you double the height, will the flow double?
4. **Test.** Set the water surface 50 cm above the faucet. Fill the tank to a marked line, open the faucet and catch water for exactly 10 seconds. Measure the volume. Refill to the line between trials. Do three trials.
5. Repeat at 100 and 150 cm.
6. Make a table: height, pressure, average flow (mL per 10 s). Graph flow against height.
7. **Two houses.** Add a T-connector and a second length of tube so two faucets share one tank. Open both at once and measure each one's flow. How does it

compare with one faucet alone?

8. **Improve.** Design a way to keep the water level in the tank steady while it flows, like a pump refilling a tower, and test whether the flow stays steadier.

#### Tips

- Keep the water surface at the same mark at the start of every trial; the height is what you are testing.
- Squeeze bubbles out of the tubing before you begin; air pockets slow the flow.
- Flow does not grow as fast as pressure; it grows roughly with the square root of the height, because of how fast water speeds up. Look for that in your graph.

#### Check your work

- ☐ I can calculate pressure from water height.
- ☐ I can explain why towns pump water up into towers.
- ☐ I can explain what happened when two faucets shared one tank.

#### ENGINEER'S NOTEBOOK

1. Draw your model with the height, calculated pressure and measured flow written beside it for each test.
2. Draw a town water system: river or well, treatment plant, pump, tower, mains and houses on a hill and in a valley. Which houses get the most pressure?
3. Work it: a water tower's surface is 35 m above a fire hydrant. What is the pressure at the hydrant when no water is flowing? ( $1,000 \times 9.8 \times 35 = 343,000 \text{ Pa} = 343 \text{ kPa}$ , about 50 psi.)

**From history.** The Fairmount Water Works stopped pumping in 1909, after the city built newer plants with filtration. Its buildings still stand below the Philadelphia Museum of Art, which was built on the site of the old reservoirs on top of the hill, and they now house a center that teaches visitors about water.

#### COMMON MISTAKES

- Thinking a wider tower gives more pressure. Only the height of the water matters; a wider tank stores more water for longer.
- Thinking the pump makes the pressure in the pipes all day. Usually the tower does; the pump refills it.

- Measuring height from the bottom of the tank instead of from the water surface.

**Make it a game · Head and Pressure.** Your parent names a tower height such as 20 m. Calculate the pressure at the bottom using about 10 kPa per meter. Do five rounds, then reverse: given 150 kPa, find the height. Explain how pumps, reservoirs and the Fairmount Water Works work together. Perfect rounds earn a bonus.

## 5.3 HOW POWER PLANTS MAKE ELECTRICITY: PARSONS’S TURBINE AND THE TRADE-OFFS

### OBJECTIVES

- Trace the energy in a power plant from its source to the wires, and explain how a turbine drives a generator.
- Compare coal, natural gas, nuclear, hydro, wind and solar plants by cost, reliability and what each needs.
- Build a small wind turbine on a hobby motor and measure how blade design changes its electrical power.

**Warm-up.** Blow on a pinwheel gently and then hard. Now point a hair dryer (on the cool setting) at it. Which gives the most steady spin? What would happen to a city’s lights if the “wind” stopped?

### WATCH

#### The Steam Turbine: The Surprising Relationship of Engineering & Science

[engineerguy](#) · 11:24

<https://www.youtube.com/watch?v=-8lXXg8dWHk>

### WHEN TO WATCH

After the story and before the physics.

### BACKUP VIDEO

#### A Rare Look Inside a Power Plant’s Giant Steam Turbine

[Smithsonian Channel](#) · 2:24

<https://www.youtube.com/watch?v=RaRc0oHBk5M>

After the physics paragraph, for a look inside a real power-plant steam turbine.

### KEY TERMS

#### **turbine**

A wheel with many blades turned by moving steam, gas, water or wind.

#### **power plant**

A facility that turns another form of energy into electrical energy for the grid.

**efficiency**

Useful energy out  $\div$  energy in, often given as a percent.

**capacity factor**

How much electricity a plant actually makes in a year compared with what it would make running at full power all the time.

**dispatchable**

A power source that operators can turn up or down when needed.

**megawatt (MW)**

One million watts.

**CORE IDEAS**

**The story.** In 1884 Charles Parsons, the youngest son of an Irish earl, who had studied mathematics at Cambridge and then served an apprenticeship in an engineering works, built a new kind of steam engine. Instead of pushing a piston back and forth, steam rushed through many rows of small angled blades on a spinning shaft, like a series of tiny windmills. His first turbine drove a generator at 18,000 turns per minute. To show what it could do, he built a small ship, *Turbinia*, and in 1897, at a great naval review off Spithead for Queen Victoria's Diamond Jubilee, it raced past the lines of warships at over 34 knots, faster than any vessel afloat.

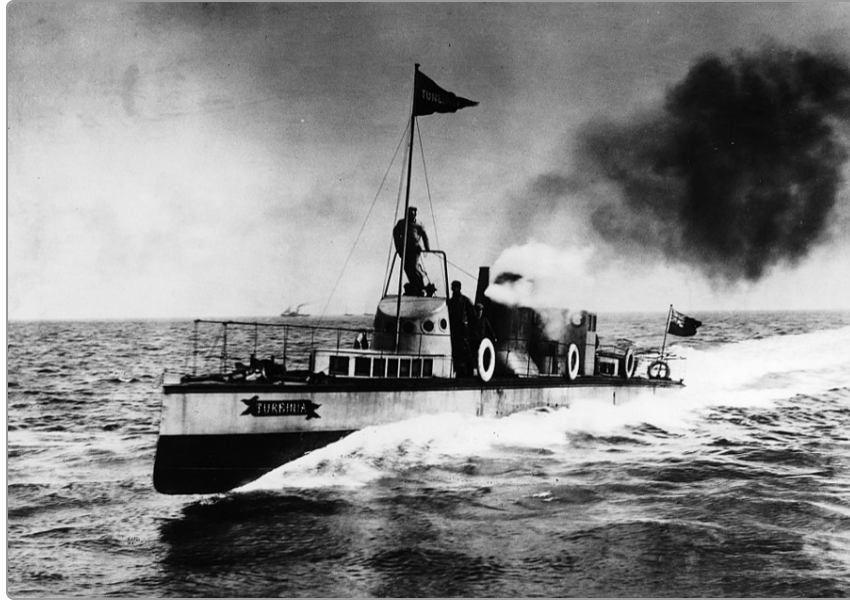
**How they figured it out.** *Turbinia* was slow at first. Parsons measured carefully and found the trouble was not the turbine but the propellers: they spun so fast that the water around them boiled into bubbles of vapor, a problem now called cavitation. He built a test tank, photographed the propellers in action, and redesigned the ship with three shafts and nine smaller propellers. Then she flew. Parsons's steam turbines soon drove ships and, even more, the generators of power stations. Today the steam turbine, descended from his, turns the generators in nearly every coal, gas and nuclear plant on Earth.

**The physics.** Every large power plant except solar panels uses Faraday's principle: something spins a generator. In **coal**, **gas** and **nuclear** plants, heat boils water into high-pressure steam that spins a turbine. In a **hydro** plant, falling water spins the turbine; its power is about  $\text{density} \times g \times \text{flow} \times \text{height}$ . For  $10 \text{ m}^3$  of water each second falling 50 m:  $1,000 \times 9.8 \times 10 \times 50 = 4,900,000 \text{ W}$ , or 4.9 MW, and with a 90% efficient turbine, about 4.4 MW. **Wind** spins the turbine directly. **Solar** cells turn sunlight straight into electric current with no moving parts. A typical coal or nuclear steam

plant turns about one third of its heat into electricity; a modern combined-cycle gas plant, which uses its hot exhaust to make more steam, reaches about 60%.

**The engineering.** Engineers compare sources honestly as trade-offs. Coal and nuclear plants run steadily day and night but cost a great deal to build. Gas plants are quicker to build and can be turned up and down quickly, but depend on a fuel supply. Nuclear plants need very little fuel and careful safety engineering. Hydro is cheap to run and can respond in minutes, but needs the right river and a dam. Wind and solar need no fuel, but make power only when the wind blows or the sun shines, so they have lower **capacity factors** and need other plants or storage to back them up. A reliable grid uses a mix, balanced minute by minute by operators who match supply to demand.

## PICTURE STUDY



*Turbinia at Speed*, Alfred John West (attributed), 1897 · Photograph

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

This photograph of *Turbinia* was taken in 1897, the year she stunned the naval review at Spithead. Her steam turbines spun her propellers far faster than any piston engine could.

### Look closely

- Look at the wave at the bow. What does it tell you about her speed?
- Find the funnel and the smoke. Where does the steam for the turbines come from?
- Look at the shape of the hull. Why is it so long and narrow?
- Find the people on deck. How large is the ship compared with them?

### Talk about it

1. Why did Parsons build a ship, instead of just showing his turbine in a factory?
2. What problem did he find with the propellers, and how did he fix it?
3. How is the turbine in this ship like the turbines in a power plant today?

**Safety first.** Keep fingers, hair and loose clothing away from the spinning turbine and the box fan. Use a fan with a grille, and stand to the side when it is on high. Wear safety glasses in case a blade flies off.



## BUILD

### Blade Test: A Wind Turbine Generator

You will build a small wind turbine on a hobby motor, which acts as a generator (Lesson 4.3), set it in front of a box fan, and measure its electrical power through a resistor. Then you will test how the number of blades changes the power.

#### You will need

- A small hobby motor (1.5–3 V) and a cork or bottle cap to fit on its shaft as a hub
- Card stock or a disposable plastic plate for blades, wooden skewers or craft sticks, and tape
- A box fan, a tape measure, and a stand (a stack of books) to hold the motor at the height of the fan's center
- A digital multimeter and a 100  $\Omega$  resistor as the “load”
- Safety glasses and the engineer's notebook

#### Steps

1. **Build the hub.** Press the cork onto the motor shaft. Make blades 8 cm long and 3 cm wide from card stock, each glued to a skewer stub, and push them into the cork at an equal angle (about 20° from flat).
2. Tape the motor to the stand 1 meter from the fan, facing it. Connect the 100  $\Omega$  resistor across the motor's terminals, and the meter (DC volts) across the resistor.
3. **Predict.** Will 2, 4 or 8 blades make the most power?
4. **Test.** Start with 2 blades. Turn the fan on medium, wait 10 seconds and record the steady voltage. Do three trials.
5. Repeat with 4 blades and 8 blades, keeping blade size, angle, distance and fan speed the same.
6. Calculate power for each:  $P = V^2 \div R$ . For example, 0.5 V across 100  $\Omega$  gives  $0.25 \div 100 = 0.0025$  W, or 2.5 milliwatts.
7. Make a table and a bar graph of power against number of blades.

8. **Improve.** Keep the best blade number and change one more thing (blade angle or blade length). Test it and record whether the power went up.

**Tips**

- A hobby motor needs a fairly fast spin to make a useful voltage; set the fan close enough to get a reading.
- Balance the blades so the turbine does not wobble; a wobble wastes energy and can throw a blade.
- Real wind turbines usually have three long, thin blades; see whether your results suggest why.

**Check your work**

- ☐ I can trace the energy path in a steam, hydro and wind plant.
- ☐ I can compare power sources as trade-offs without favoring one unfairly.
- ☐ I can calculate electrical power from voltage and resistance.

**ENGINEER'S NOTEBOOK**

1. Draw a steam power plant: fuel or reactor, boiler, turbine, generator, condenser and the wires to the grid. Label the energy at each step.
2. Make a trade-off table with a row for each source (coal, gas, nuclear, hydro, wind, solar) and columns for cost to build, fuel needed, runs at night, can be turned up quickly, and what land or water it needs.
3. Work it: a power plant burns fuel that gives 3,000 MW of heat and sends 1,050 MW of electricity to the grid. What is its efficiency? ( $1,050 \div 3,000 = 0.35$ , or 35%.)

**From history.** Parsons's company built turbines for power stations around the world, including some of the largest of their day. His *Turbinia* is preserved at the Discovery Museum in Newcastle upon Tyne in England, where visitors can still see her slender hull.

**COMMON MISTAKES**

- Thinking a power plant “makes” energy. It changes energy from one form to another, and some is always lost as heat.
- Thinking one source is best in every way. Each has strengths and weaknesses that engineers weigh for each place.
- Changing the fan speed between blade tests.

**Make it a game • Pick the Plant.** Your parent describes a town's needs: steady power at night, a windy coast, a river canyon. Choose coal, natural gas, nuclear, hydro, wind or solar, and defend the choice with cost, reliability and what each needs. Trace the energy from source to wires. Best argument wins a point each round.

## 5.4 FROM TELEGRAPH TO TELEPHONE TO FIBER OPTICS: COLLADON'S LIGHT FOUNTAIN

### OBJECTIVES

- Describe the path of communication technology from the telegraph to the telephone to optical fiber.
- Explain total internal reflection and how it keeps light inside a glass fiber.
- Build Colladon's light fountain, test what helps the light follow the stream, and calculate how long a signal takes to cross an ocean.

**Warm-up.** Fill a clear glass with water and look up through the side at the water's surface from below. What do you see on the underside of the surface? Write down what you think is happening to the light.

### WATCH

#### Fiber optic cables: How they work

[engineerguy](https://www.youtube.com/watch?v=0MwMkBET_5I) • 5:35

[https://www.youtube.com/watch?v=0MwMkBET\\_5I](https://www.youtube.com/watch?v=0MwMkBET_5I)

### WHEN TO WATCH

After the physics paragraph.

### BACKUP VIDEO

#### Total Internal Reflection in Water "Bucket of Light"

[Harvard Natural Sciences Lecture Demonstrations](https://www.youtube.com/watch?v=XrWB0KLXpn8) • 1:49

<https://www.youtube.com/watch?v=XrWB0KLXpn8>

Before the build, to see light trapped in a stream of water.

### KEY TERMS

#### **total internal reflection**

When light inside water or glass strikes the surface at a shallow enough angle, it reflects back inside completely instead of escaping.

#### **optical fiber**

A strand of very pure glass, thinner than a hair, that carries light signals by total internal reflection.

**submarine cable**

A communication cable laid on the ocean floor.

**signal**

A pattern of electric current, radio waves or light that carries information.

**bandwidth**

How much information a link can carry each second.

**CORE IDEAS**

**The story.** In 1841 Daniel Colladon, a professor in Geneva, was trying to show his students how water flows from a hole in a tank. The jet was hard to see in the lecture hall, so he lit it from behind through a window in the tank. To his surprise, the light did not shoot straight out. It followed the curving jet of water all the way down, and the stream glowed where it broke apart at the bottom. Colladon described his “light fountain” in 1842. It was a beautiful trick of physics, and more than a century later it became the idea behind the cables that carry the internet.

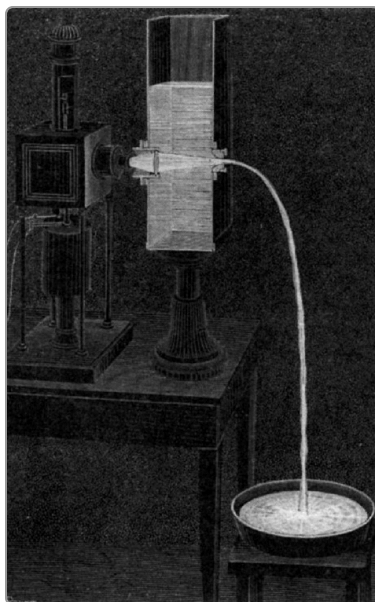
**How they figured it out.** The road from Colladon’s fountain to fiber optics ran through electric cables. Samuel Morse’s telegraph (1844) sent pulses of current along wires. The first cable across the Atlantic (1858) failed within weeks, but in 1866 the giant steamship *Great Eastern* laid a lasting one, with instruments designed by William Thomson, later Lord Kelvin, a devout Christian and one of the great physicists of his age, sensitive enough to detect the faint signals that reached the far side of the ocean. Alexander Graham Bell’s telephone (1876) carried voices over copper. But copper wires lose signal strength quickly and carry limited information. In 1966 Charles Kao and George Hockham calculated that glass could carry light signals for long distances if it were made pure enough. In 1970, after years of trial and error, three scientists at Corning Glass Works, Robert Maurer, Donald Keck and Peter Schultz, made glass fiber that did it.

**The physics.** Light bends when it passes from water or glass into air. If it hits the surface at a shallow enough angle, it cannot get out at all and reflects back inside: **total internal reflection**. In Colladon’s jet, the light kept bouncing off the inside of the water’s surface and was carried along the curve. An **optical fiber** has a core of very pure glass surrounded by a cladding of slightly different glass, so the light zigzags along the core for kilometers. Light in glass travels at about 200,000

kilometers per second. A fiber cable from New York to London, about 5,600 km, carries a signal across in  $5,600 \div 200,000 = 0.028$  seconds, or 28 milliseconds.

**The engineering.** One fiber can carry far more information than thousands of copper wires, because light can be switched on and off billions of times a second and many colors of light can share one fiber. The first transatlantic fiber-optic cable, TAT-8, went into service in 1988. Today more than 95% of the information crossing oceans travels through submarine fiber cables, laid by special ships much as the *Great Eastern* laid its copper cable. Engineers splice fibers with great precision, add amplifiers every 50 to 100 kilometers on long cables, and send crews to repair cables broken by anchors or earthquakes.

## PICTURE STUDY



*Colladon's Light Fountain*, Illustration in *La Nature*, 1884 · Engraving

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

This engraving from the French magazine *La Nature* (1884) shows Colladon's light fountain. A lamp shines into the tank, and the light follows the curving jet of water down into the basin.

### Look closely

- Find the lamp and the window it shines through.
- Follow the jet from the tank to the basin. Where is it brightest?
- Look at the basin. Why does the water glow where the jet breaks up?
- Find the tank. Why must the water level stay high?

### Talk about it

1. Why doesn't the light shoot straight out of the jet?
2. How is this jet of water like an optical fiber?
3. What would happen if the jet broke into drops near the top?

**Safety first.** Use a bright flashlight. If you use a laser pointer, it must be a low-power one (labeled Class 2 or under 1 milliwatt where possible), used only with an adult, and never pointed at anyone's eyes or reflected toward faces. Work over a sink or tub and keep electrical devices away from the water.

## BUILD

### Colladon's Light Fountain

You will rebuild Colladon's light fountain with a plastic bottle and a flashlight, and test what makes the light follow the stream farthest. Then you will send a short coded message by light to see how a signal can travel through a curved path.

#### You will need

- A clear 2-liter plastic bottle, a nail or pushpin (an adult makes the hole), and tape
- A small bright flashlight (or a low-power laser pointer with an adult)
- Aluminum foil and black paper to keep light from leaking out
- A sink or tub, a measuring cup and a ruler
- A dark room and the engineer's notebook

#### Steps

1. **Build.** Have an adult make a hole about 5 mm wide in the side of the bottle, 5 cm from the bottom. Cover the hole with tape and fill the bottle with water.
2. Wrap the bottle in foil except for a small window on the side opposite the hole. Shine the flashlight through the window straight at the hole.
3. **Predict.** When you remove the tape, where will the light go?
4. **Test.** In a dark room, over the sink, pull off the tape. Put your hand in the stream partway down. Is your hand lit where the water hits it? Measure how far along the stream the light stays visible.
5. **Fair test.** Try two hole sizes (3 mm and 6 mm) in two bottles, filled to the same level, with the same flashlight. Which stream carries the light farther? Do three trials each.
6. **Signal.** With a partner catching the light with a hand at the end of the stream, send a short Morse message by switching the flashlight on and off. Time how long the message takes.
7. Make a table: hole size, how far the light traveled, notes.



8. **Improve.** Change one thing to carry the light farther (a brighter light, a smoother hole, a thicker stream) and test it.

**Tips**

- A smooth, round hole makes a smooth stream, and a smooth stream carries light much better.
- The stream glows where it breaks into drops, because the light escapes there.
- Laser light shows the zigzag path best, but a good flashlight works and is safer.

**Check your work**

- ☐ I can explain total internal reflection.
- ☐ I can describe the path from the telegraph to fiber optics.
- ☐ I can calculate how long light takes to travel through a fiber.

**ENGINEER'S NOTEBOOK**

1. Draw the light fountain with arrows showing the light bouncing along inside the stream.
2. Draw a timeline: Colladon 1841, Morse 1844, Atlantic cable 1866, Bell 1876, Kao 1966, Corning fiber 1970, TAT-8 1988.
3. Work it: a fiber cable across the Pacific is 9,000 km long. How long does light take to cross it at 200,000 km/s? ( $9,000 \div 200,000 = 0.045 \text{ s} = 45 \text{ ms.}$ )

**From history.** Morse's first official message on his line from Washington to Baltimore in 1844 was "What hath God wrought," chosen from Numbers 23:23. The words still fit: every message sent through a glass fiber depends on laws of light that people did not make, only discovered and put to use.

**COMMON MISTAKES**

- Thinking light in a fiber goes perfectly straight. It zigzags, reflecting off the boundary again and again.
- Thinking most ocean-crossing internet traffic goes by satellite. Nearly all of it goes through undersea fiber cables.
- Changing the water level between trials, which changes the speed and shape of the stream.

**Make it a game • Light in a Stream.** Over a sink, shine a flashlight into a bottle with a stream pouring from a side hole, in a dim room, and watch the light follow the water. Explain total internal reflection to your parent. Then order telegraph, telephone and fiber optics, with one fact for each. Your parent quizzes on bandwidth.

**Scripture.** “Their line is gone out through all the earth, and their words to the end of the world.” (Psalm 19:4, KJV)

The psalm says the heavens speak of God’s glory to every land. Today cables and fibers also carry words to the ends of the world, built from the light He made.

## UNIT 5

# PUBLIC UTILITIES

Turn on a tap, flip a switch or send a message, and you are using systems built by thousands of engineers and kept running every hour of every day by operators and line crews. In this unit you will see how water is made safe to drink, step by step, and test it yourself with a jar test. You will learn why water towers stand tall, and calculate the pressure that height gives.

Then you will follow Charles Parsons and his steam turbine into the power plant, and compare the ways we make electricity, by coal, gas, nuclear, falling water, wind and sunlight, the way an engineer compares them: by cost, reliability and what each one needs. Last, you will trace communication from the telegraph wire to a glass fiber thinner than a hair, starting with a glowing jet of water in Geneva in 1841. Serving a whole city well is one of the clearest ways engineers love their neighbors.

### PREREQUISITES

- Knows how a generator works (Lesson 4.3)
- Can calculate weight and pressure from height (Lessons 1.2 and 3.4)
- Can convert between units such as liters and cubic meters, and grams and kilograms

### MASTERY CHECKLIST

- ☐ I can name and explain the main steps of water treatment: coagulation, flocculation, settling, filtration and disinfection.
- ☐ I can calculate water pressure from the height of a tower and explain how pumps and towers work together.
- ☐ I can trace energy from fuel, falling water, wind or sunlight to the wires, and compare sources as engineering trade-offs.
- ☐ I can explain total internal reflection and calculate how long a signal takes to cross an ocean in a fiber.
- ☐ I can run a fair test with careful measurements and record it honestly.

## OPTIONAL KITS FOR THIS UNIT

- **Thames & Kosmos science kits:** Ages vary by kit. Several kits on renewable energy, water and power plants include small turbines, solar cells and generators that extend the turbine test in Lesson 5.3.
- **KiwiCo Eureka and Tinker crates:** Ages 9 and up (Tinker) and 14 and up (Eureka). Some crates build working pumps, water wheels and generators; check each crate's description for a fit with Lessons 5.2 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 Water Treatment: Coagulation, Filtration and Disinfection

2 sessions of 50 minutes

---

### 5.2 Pumps, Pressure and Water Towers: The Fairmount Water Works

2 sessions of 50 minutes

---

### 5.3 How Power Plants Make Electricity: Parsons's Turbine and the Trade-offs

2 sessions of 50 minutes

---

### 5.4 From Telegraph to Telephone to Fiber Optics: Colladon's Light Fountain

2 sessions of 50 minutes

---

## UNIT 5 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

List the main steps of water treatment in order and say what each does.

2. **10 pts**

Calculate: a plant treats 8 million liters of water a day with chlorine at 1.5 mg/L. How many kilograms of chlorine does it use each day?

3. (7 pts)

What did John Leal and George Fuller have to prove in court about chlorinating Jersey City's water, and how did they prove it?

4. (7 pts)

Why do operators run jar tests instead of always using the same amount of coagulant?

5. (10 pts)

Calculate: the water surface in a tower is 45 m above a house. What is the water pressure at the house when no water is flowing? Give the answer in kilopascals.

6. (8 pts)

Explain in two or three sentences how pumps and water towers work together.

7. (6 pts)

Why did Frederick Graff switch the Fairmount Water Works from steam engines to water wheels?

8. (8 pts)

What problem did Parsons find with Turbinia's first propellers, and how did he solve it?

9. (10 pts)

Calculate: water flows through a dam's turbine at  $4 \text{ m}^3$  per second and falls 25 m. Using  $\text{power} = 1,000 \times 9.8 \times \text{flow} \times \text{height}$ , find the power before losses, in megawatts.

10. (8 pts)

Give one strength and one weakness each for a wind farm and a natural gas plant.

11. (8 pts)

What is total internal reflection, and how does it let an optical fiber carry light around bends?

12. 10 pts

Calculate: light travels at about 200,000 km/s in glass. How long does a signal take to travel through a 6,000 km undersea fiber cable? Give the answer in milliseconds.

**ANSWER KEY**

1. Coagulation (a chemical lets tiny particles stick), flocculation (slow stirring forms floc), sedimentation (floc settles), filtration (sand catches what is left), disinfection (chlorine destroys germs).
2.  $8,000,000 \times 1.5 = 12,000,000 \text{ mg} = 12,000 \text{ g} = 12 \text{ kg}$ .
3. That the chlorinated water was much safer and the small dose did no harm. They measured bacteria in samples before and after treatment, day after day, and kept careful records.
4. Raw water changes with weather and season, and each water has a best dose; too little or too much leaves it cloudy. Testing finds the right dose for that day's water.
5.  $1,000 \times 9.8 \times 45 = 441,000 \text{ Pa} = 441 \text{ kPa}$  (about 64 psi).
6. Pumps lift water into the tower, often at night when demand is low. The height of the water gives pressure to the pipes all day by gravity, and the tower stores water for busy hours and fires.
7. The steam engines were costly to fuel, broke down often and one boiler exploded; water wheels driven by the river through a dam were far cheaper to run.
8. They spun so fast that the water formed vapor bubbles (cavitation), wasting power. He tested in a tank and redesigned the ship with three shafts and nine smaller propellers.
9.  $1,000 \times 9.8 \times 4 \times 25 = 980,000 \text{ W} \approx 0.98 \text{ MW}$ .
10. Wind: no fuel needed; but makes power only when the wind blows. Gas: can be turned up and down quickly and runs any time; but needs a steady fuel supply and fuel costs. (Other correct answers accepted.)
11. When light inside glass or water hits the surface at a shallow enough angle, it reflects back inside completely. In a fiber the light keeps reflecting off the boundary of the core, zigzagging along it even when the fiber bends.
12.  $6,000 \div 200,000 = 0.03 \text{ s} = 30 \text{ ms}$ .

## PORTFOLIO PIECE: A UTILITY ENGINEER'S REPORT

Choose one utility that serves your home (water, electricity or communication) and trace it from its source to your house, using a map, a visit to a public information center or website, and your own observations from safe public places. Then repeat one build from this unit with an improvement, such as a jar test with a narrower range of doses, a taller water tower model, or a turbine with redesigned blades. Write a two-page report with a labeled diagram of the system, at least two calculations from the unit using real or measured numbers, your test data, and a paragraph on the people who keep that utility running.

| LOOK FOR              | WHAT IT MEANS                                                                                                                                  |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>System diagram</b> | A clear, labeled diagram traces the utility from its source to the home.                                                                       |
| <b>Calculations</b>   | At least two correct calculations (dose, pressure, power or signal time) with units.                                                           |
| <b>Improved build</b> | The repeated build changes one variable, is tested fairly and has its data recorded.                                                           |
| <b>Explanation</b>    | The report explains the physics and engineering accurately in the student's own words.                                                         |
| <b>Service</b>        | A thoughtful paragraph on the operators, line workers or engineers who keep the utility running, and on staying safe around utility equipment. |

## UNIT 6

# BOATS AND SHIPS

“They that go down to the sea in ships” have always trusted their lives to a few rules of physics. In this unit you will put numbers on those rules. You will calculate density, measure displacement, and predict how many pennies a boat can carry before you load it, then check your prediction in the tub. You will learn why a ship rides higher in salt water than in fresh, and how one determined man, Samuel Plimsoll, made it the law to paint a line on every ship’s side so that it could never again be loaded too deep.

Then you will compare the ways people have driven boats through the water, from oars and sails to paddle wheels, propellers and water jets, and stage your own version of the famous 1845 tug-of-war between a paddle steamer and a screw steamer. Last, you will follow the bathyscaphe *Trieste* to the deepest point in the ocean and build a Cartesian diver that sinks, rises and hovers at your command.



## PREREQUISITES

- Knows  $F = ma$  and  $\text{weight} = \text{mass} \times 9.8$  (Unit 1)
- Can calculate pressure from depth (Lessons 3.4 and 5.2)
- Can find volume of a box ( $\text{length} \times \text{width} \times \text{height}$ ) and convert between mL and  $\text{cm}^3$

## MASTERY CHECKLIST

- ☐ I can calculate density from mass and volume and use it to predict whether something floats.
- ☐ I can use Archimedes' principle to predict how much load a boat can carry, and test it.
- ☐ I can explain why ships float higher in salt water, what a load line is, and what makes a ship stable.
- ☐ I can explain how oars, sails, paddle wheels, propellers and jets push a boat, using Newton's third law and  $\text{thrust} = \text{mass of water per second} \times \text{change in speed}$ .
- ☐ I can explain how submarines and the *Triest* control their buoyancy, and make a Cartesian diver hover.

## OPTIONAL KITS FOR THIS UNIT

- **Thames & Kosmos boat and ship kits**: Ages vary by kit. Some kits build motorized and wind-powered boats that can extend the propulsion tests in Lesson 6.3.
- **LEGO Technic**: Ages 9 and up for most sets. Gears, axles and motors (in powered sets) can drive a paddle wheel or propeller boat with a sealed hull; fits Lesson 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 Displacement with Numbers: Why an Iron Ship Floats

2 sessions of 50 minutes

---

## 6.2 Stability and the Plimsoll Line

2 sessions of 50 minutes

---

## 6.3 Propulsion: Oar, Sail, Paddle, Screw and Jet

2 sessions of 50 minutes

---

## 6.4 Submarines and Ballast: The Trieste and a Cartesian Diver

2 sessions of 50 minutes

---

# UNIT 6 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **10 pts**

Calculate: a block has a mass of 360 g and a volume of  $450 \text{ cm}^3$ . What is its density? Will it float in water?

2. **8 pts**

State Archimedes' principle.

3. **8 pts**

Explain in two or three sentences how a ship made of steel, which is about 7.8 times as dense as water, can float.

4. **10 pts**

Calculate: a box-shaped barge is 12 m long and 5 m wide. How much deeper does it sink in fresh water when 18 tonnes of cargo is loaded?

5. **8 pts**

Why does a ship float higher in seawater than in fresh water?

6. **8 pts**

What was Samuel Plimsoll's cause, and what did the 1876 Merchant Shipping Act require?

7. (8 pts)

Predict: a cargo ship's crew stacks heavy steel beams high on its deck instead of low in the hold. What happens to its stability, and why?

8. (8 pts)

Why did the Navy tie HMS Rattler and HMS Alecto stern to stern in 1845, and what happened?

9. (10 pts)

Calculate: a propeller pushes 300 kg of water backward each second and increases its speed by 6 m/s. What is the thrust?

10. (8 pts)

How does a submarine dive and rise?

11. (6 pts)

Why did the Trieste use gasoline in its float instead of air?

12. (8 pts)

Explain what happens inside a Cartesian diver when you squeeze the bottle.

## ANSWER KEY

1. Density =  $360 \div 450 = 0.8 \text{ g/cm}^3$ . Less than water (1.0), so it floats.
2. The buoyant force on an object equals the weight of the fluid it displaces.
3. The steel is shaped into a hollow hull that encloses a large volume of air, so the ship's average density is less than water's. It sinks until it displaces water equal to its own weight, and then floats.
4. 18 tonnes of fresh water is  $18 \text{ m}^3$ . Waterline area =  $12 \times 5 = 60 \text{ m}^2$ . Extra depth =  $18 \div 60 = 0.3 \text{ m}$ .
5. Seawater is denser (about  $1.025 \text{ g/cm}^3$ ), so the ship needs to displace less volume of it to equal its weight.
6. He fought against overloaded, unsafe "coffin ships" that drowned sailors. The act required British ships to carry a load line showing the deepest they could be loaded.
7. It becomes less stable and may roll over, because the center of gravity rises, so the buoyancy has less ability to push it back upright when it tips.
8. To compare a screw propeller and paddle wheels fairly, with similar ships and engines. Rattler, with the propeller, towed Alecto backward at about 2.8 knots.
9. Thrust =  $300 \times 6 = 1,800 \text{ N}$ .
10. It floods ballast tanks with water to increase its average density and dive, and blows the water out with compressed air to decrease its density and rise.
11. Gasoline is lighter than water but hardly compresses, so it kept giving lift at great depth, where air would be crushed.
12. The squeeze raises the water pressure, which compresses the air bubble inside the diver; water enters, the diver's average density becomes greater than water's, and it sinks. Releasing lets the bubble expand and the diver rise.

## PORTFOLIO PIECE: A CARGO SHIP WITH A MEASURED CAPACITY

Design and build a model cargo ship from foil, card or a plastic container that will carry as much cargo as possible while staying stable. Before building, calculate its predicted capacity from the hull's dimensions. Mark a draft scale and a load line with at least 2 cm of freeboard. Test it in fresh and salt water, then load it until water comes over the side. Write a one-page report with your drawing, predicted and measured capacity, a draft-versus-load graph, a stability test with cargo high and low, and what you would change.

| LOOK FOR                        | WHAT IT MEANS                                                                                |
|---------------------------------|----------------------------------------------------------------------------------------------|
| <b>Design and prediction</b>    | A labeled drawing with dimensions and a correct capacity calculation done before testing.    |
| <b>Load line</b>                | A clear draft scale and load lines for fresh and salt water, with the freeboard rule stated. |
| <b>Testing and data</b>         | Draft measured at several loads in both waters and graphed; final capacity measured fairly.  |
| <b>Stability</b>                | A fair test of high versus low cargo, with results explained using center of gravity.        |
| <b>Analysis and improvement</b> | Prediction compared with the result, errors explained, and a specific improvement proposed.  |

## 6.1 DENSITY AND DISPLACEMENT WITH NUMBERS: WHY AN IRON SHIP FLOATS

### OBJECTIVES

- Calculate density from mass and volume, and compare it with the density of water.
- State Archimedes' principle and use it to calculate a boat's carrying capacity.
- Measure densities by displacement and predict, then test, how many pennies a clay boat can carry.

**Warm-up.** Drop a ball of modeling clay into a tub of water. It sinks. Now, without adding or removing any clay, can you make the same clay float? Try for three minutes and write down what worked.

### WATCH

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

Casual Navigation · 4:20

<https://www.youtube.com/watch?v=Z3vgsp4vKQs>

### WHEN TO WATCH

After the physics paragraph.

### BACKUP VIDEO

#### How Do Ships Float? | Things Explained: Buoyancy

GPB Education · 2:18

<https://www.youtube.com/watch?v=06TFRgPlmxU>

Before the build, for a short review of buoyancy.

### KEY TERMS

#### **density**

Mass divided by volume, often in grams per cubic centimeter ( $\text{g}/\text{cm}^3$ ).  
Water is about  $1.0 \text{ g}/\text{cm}^3$ .

#### **displacement**

The water pushed aside by a floating or sunken object; for a ship, the mass of water it pushes aside, which equals the ship's own mass.

**buoyant force**

The upward push of a fluid on an object in it.

**Archimedes' principle**

The buoyant force on an object equals the weight of the fluid it displaces.

**freeboard**

The height of a ship's side above the waterline.

**CORE IDEAS**

**The story.** The Roman writer Vitruvius (Lesson 3.2) tells a story set two hundred years before his own time. King Hiero of Syracuse gave a goldsmith a measured weight of gold to make a crown, then suspected that the smith had kept some gold and mixed in cheaper silver. He asked Archimedes to find out without harming the crown. Archimedes, Vitruvius says, noticed the water overflowing as he stepped into a bath and realized that a body pushes aside its own volume of water. He then compared how much water overflowed for the crown, for an equal weight of pure gold and for an equal weight of silver, and the crown spilled more than the gold. The smith was caught.

**How they figured it out.** Nearly two thousand years later, in 1586, a young Galileo pointed out that the overflow method would be hard to do accurately, because the difference in spilled water would be only a few spoonfuls. He suggested a better way that Archimedes could have used: hang the crown and an equal weight of gold on a balance, then lower both into water. The gold, being denser and smaller, is pushed up less, so the balance tips. This is Archimedes' own principle at work. Shipbuilders used the same principle to answer a question that once seemed impossible: how can a ship made of iron float? In 1787 the ironmaster John Wilkinson launched an iron barge on the River Severn, and it floated, to the surprise of many onlookers. Within a century iron and then steel ships ruled the seas.

**The physics.** **Density** = mass  $\div$  volume. Gold is 19.3 g/cm<sup>3</sup>, silver 10.5, steel about 7.8, oak about 0.75, water 1.0. A solid lump denser than water sinks. A 1,000-gram gold crown has a volume of  $1,000 \div 19.3 \approx 52$  cm<sup>3</sup>. If 300 g of it were silver, its volume would be  $700 \div 19.3 + 300 \div 10.5 \approx 36 + 29 = 65$  cm<sup>3</sup>: about 13 cm<sup>3</sup> more water spilled.

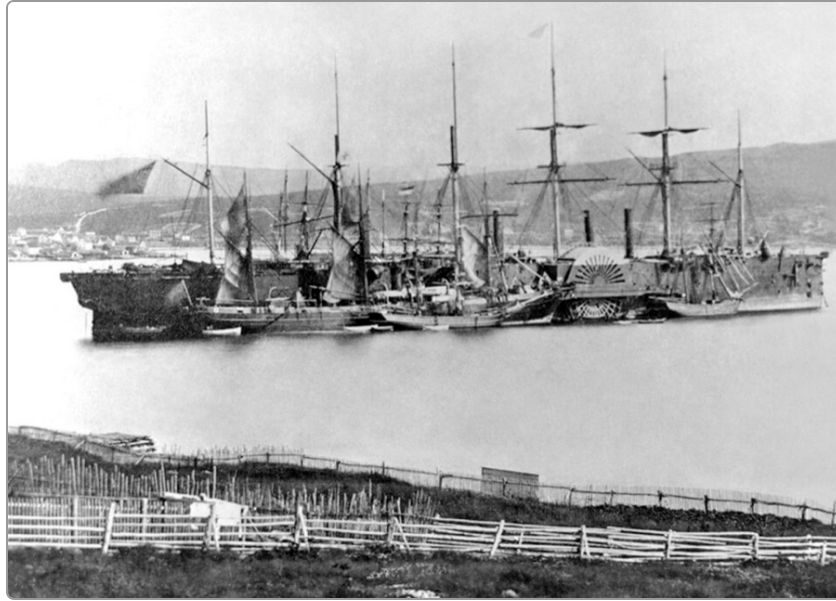
**Archimedes' principle** says the buoyant force equals the weight of the fluid displaced. A ship floats when it sinks just far enough to displace its own weight of

water. Shape a steel or clay hull so it encloses lots of air, and its **average** density, steel plus air, is less than water's.

**The engineering.** Naval architects begin every design with displacement: the total mass of hull, engines, fuel, cargo and crew must equal the mass of water the hull displaces at the planned waterline. A box-shaped barge 20 m long and 6 m wide that sinks 1.5 m into fresh water displaces  $20 \times 6 \times 1.5 = 180 \text{ m}^3$ , or 180 tonnes (each cubic meter of fresh water has a mass of 1,000 kg). Load another 12 tonnes and it sinks  $12 \div (20 \times 6) = 0.1 \text{ m}$  deeper. Engineers keep enough **freeboard** above the waterline so waves do not wash aboard, which is the subject of the next lesson.



## PICTURE STUDY



*The Great Eastern*, Unknown photographer, 1866 · Photograph

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

The *Great Eastern*, designed by Isambard Kingdom Brunel and launched in 1858, was by far the largest ship of her time. This photograph from 1866 shows her at Heart's Content, Newfoundland, after laying the Atlantic telegraph cable.

### Look closely

- Compare the *Great Eastern* with the smaller ships beside her. How many times longer is she?
- Find the paddle wheel on her side. She also had a screw propeller and sails.
- Look for her waterline. How much of her hull is below the water?
- Count the masts and funnels.

### Talk about it

1. The *Great Eastern* was made of iron. How could she float?
2. If she took on more cargo, what would happen to her waterline?
3. Why do you think one ship had paddle wheels, a propeller and sails all at once?

**Safety first.** An adult should be present whenever you work with a tub of water. Wipe up spills promptly.

## BUILD

### Predict the Load: A Clay Boat Challenge

You will measure the density of several objects by displacement, then shape a clay boat, measure its hull, and calculate how many pennies it should carry before it sinks. Then you will load it and see how close your prediction was.

#### You will need

- A measuring cup or graduated cylinder marked in mL (1 mL = 1 cm<sup>3</sup>)
- A kitchen scale that reads in grams
- Small objects to test: a ball of clay, a metal bolt, a wooden block, a rock
- 50 g of modeling clay for the boat, a ruler, and pennies (2.5 g each)
- A tub of water and the engineer's notebook

#### Steps

1. **Density by displacement.** Weigh each object. Put water in the measuring cup to a line you can read, drop the object in, and read the new level. The rise is the object's volume in cm<sup>3</sup>. Calculate density = mass ÷ volume. Which ones should float?
2. **Build.** Shape the 50 g of clay into an open, box-like boat with a flat bottom and straight sides. Measure the inside length, width and height of the hull in centimeters.
3. **Calculate.** The most water the hull can displace before water pours over the sides is about length × width × height (cm<sup>3</sup>), which is that many grams. Subtract the boat's mass (50 g). Divide by 2.5 g to get the predicted number of pennies. Write it down.
4. **Test.** Float the boat and add pennies one at a time, spread evenly, until it sinks. Record the number that it held (the last count before sinking).
5. Calculate your percent error: (actual – predicted) ÷ predicted × 100.
6. **Fair test.** Using the same 50 g of clay, make a second boat with a different shape (taller and narrower, or wider and shallower). Predict and test again.
7. Make a table: boat, length, width, height, hull volume, predicted pennies, actual pennies, percent error.

8. **Improve.** Design a third boat to carry as many pennies as possible. Use your numbers to decide its shape before you build it.

**Tips**

- Thin walls give more inside volume for the same clay, but walls that are too thin leak or collapse.
- Real boats usually sink early because they tip; spreading the pennies evenly keeps the boat level.
- Read the measuring cup at eye level, at the bottom of the curved water surface.

**Check your work**

- ☐ I can calculate density and use it to predict floating or sinking.
- ☐ I can state Archimedes' principle.
- ☐ I can predict a boat's capacity from its hull volume and explain my error.

**ENGINEER'S NOTEBOOK**

1. Make a density table for your test objects, with mass, volume and density, and mark which floated.
2. Draw your clay boats with their dimensions, predicted loads and actual loads.
3. Work it: a foil boat is 10 cm long, 8 cm wide and 3 cm deep and has a mass of 5 g. How many 2.5-gram pennies can it hold, at most? ( $10 \times 8 \times 3 = 240$  g of water;  $240 - 5 = 235$  g;  $235 \div 2.5 = 94$  pennies.)

**From history.** Ships are still measured by displacement. When people say a ship “displaces 100,000 tons,” they mean the ship and everything aboard have a mass of 100,000 tons, exactly equal to the water it pushes aside. Vitruvius's story is the earliest written account of Archimedes and the crown; Archimedes' own book *On Floating Bodies* states the principle itself.

**COMMON MISTAKES**

- Thinking heavy things sink and light things float. Density and shape decide, not weight alone.
- Forgetting to subtract the boat's own mass from the water it can displace.
- Reading the measuring cup from above, which gives the wrong volume.

**Make it a game • Clay Boat Bet.** Roll a ball of clay and shape another into a boat. Predict how many marbles each holds before sinking. Calculate density from mass and volume for a sample your parent chooses. Test the prediction and compare. Closest prediction wins. Explain displacement and the buoyant force in one sentence each.

## 6.2 STABILITY AND THE PLIMSOLL LINE

### OBJECTIVES

- Explain why a ship floats higher in salt water than in fresh water, and calculate the difference.
- Describe how Samuel Plimsoll's load line made ships safer, and read the marks on a ship's side.
- Measure draft against load in fresh and salt water, and test how the height of the load changes stability.

**Warm-up.** Float a fresh egg in a glass of tap water. It sinks. Stir in salt, a spoonful at a time, until it floats. Count the spoonfuls. What did the salt change?

### WATCH

#### THE PLIMSOLL LINE

Lloyd's Register Foundation Heritage Centre · 5:10

<https://www.youtube.com/watch?v=vuve8DU84Co>

### WHEN TO WATCH

After the story, before the physics.

### BACKUP VIDEO

#### Load Line on Ships- Plimsoll Line

marineinsight · 3:12

<https://www.youtube.com/watch?v=6E0bT6B5Zm4>

After the engineering paragraph, for a closer look at the marks painted on a ship's side.

### KEY TERMS

#### **draft**

How deep a ship sits in the water, measured from the waterline to the bottom of the keel.

#### **load line**

A mark on a ship's side showing the deepest it may legally be loaded; also called the Plimsoll line.

**center of gravity**

The point where all of a ship's weight seems to act.

**center of buoyancy**

The center of the underwater part of the hull, where the buoyant force seems to act.

**stability**

A ship's ability to come back upright after it is tipped by wind or waves.

**ballast**

Heavy material, often water or stone, placed low in a ship to make it stable.

**CORE IDEAS**

**The story.** In the 1860s and 1870s, hundreds of British sailors were lost every year on ships that were old, badly repaired or loaded so deep that waves swept straight over their decks. Some owners insured such “coffin ships” for more than they were worth. Samuel Plimsoll, a coal merchant who had become a member of Parliament, heard the sailors' stories and took up their cause. In 1873 he published a book, *Our Seamen*, describing what he had seen, and he pressed Parliament year after year. In 1876 the Merchant Shipping Act required British ships to carry a load line on their sides, and in 1890 the government took over the job of deciding where each ship's line must be painted.

**How they figured it out.** Plimsoll did not invent the idea of a limit; some shipowners and Lloyd's Register surveyors already used rules of thumb based on how much freeboard a ship needed. What Plimsoll fought for was a fair, measured line that every ship had to carry, enforced by inspectors, with no exceptions for powerful owners. Engineers then worked out the details: a ship needs more freeboard in winter storms and in the North Atlantic than in calm tropical seas, and it floats higher in dense salt water than in fresh river water. So the mark grew into a set of lines, one for each kind of water and season. An international agreement in 1930 spread load lines to ships of every nation.

**The physics.** Seawater, with its dissolved salt, has a density of about  $1.025 \text{ g/cm}^3$  ( $1,025 \text{ kg/m}^3$ ), so a ship displaces less volume of it to float. A ship with a mass of 10,000 tonnes (10,000,000 kg) displaces  $10,000,000 \div 1,025 \approx 9,756 \text{ m}^3$  of seawater, but  $10,000 \text{ m}^3$  of fresh water: about  $244 \text{ m}^3$  more. If its waterline area is  $2,000 \text{ m}^2$ , it sinks about  $244 \div 2,000 \approx 0.12 \text{ m}$  deeper when it sails from the sea into a river. **Stability** depends on two points. When a ship tips, the underwater part of the hull changes

shape and the **center of buoyancy** moves toward the low side, pushing it back up, as long as the **center of gravity** is low enough. Load heavy cargo high, and the ship can roll over.

**The engineering.** Every cargo ship now carries the Plimsoll mark: a circle with a line through it, and beside it a ladder of lines marked TF (tropical fresh), F (fresh), T (tropical), S (summer), W (winter) and WNA (winter North Atlantic). Before sailing, officers read the draft marks on the bow and stern to check that the ship is not too deep. Naval architects calculate stability for every way the ship might be loaded, and officers use loading computers to keep the center of gravity low, pumping ballast water into tanks low in the hull when the ship is light. An honest mark, honestly kept, saves lives.

## PICTURE STUDY



*Samuel Plimsoll with Sailors*, Unknown artist, About 1890

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

This photograph of a merchant ship's crew was published in a book about Samuel Plimsoll. These were the kind of men whose lives depended on whether their ship was loaded too deep.

### Look closely

- Look at the faces of the crew. How old are the youngest sailors?
- Find the ship's wheel. Who would steer, and what would the helmsman feel in a heavily loaded ship?
- Look at the deck. How close to the sea would it be if the ship were overloaded?
- Find the ship's dog.

### Talk about it

1. Why did Plimsoll care so much about men like these?
2. What would happen to an overloaded ship in a winter storm?
3. Why must a load line be painted where everyone, including the crew, can see it?

**Safety first.** Adult present near the tub. Salt water can sting cuts and eyes; rinse hands afterward.



## BUILD

### Draw Your Own Plimsoll Line

You will turn a plastic food container into a cargo ship, mark a draft scale on its side, and measure how deep it sits for each load in fresh water and in salt water. Then you will draw its load lines and test how high cargo makes it unstable.

#### You will need

- A rectangular plastic food container (about 15 × 10 cm) as the hull
- A strip of masking tape and a fine marker for a millimeter draft scale (or a paper ruler taped on)
- Pennies or washers (weighed) as cargo, and a kitchen scale
- Two tubs or a tub and a large bowl, water, and about 35 g of table salt per liter
- A small block or stack of washers taped on a craft stick to act as “high cargo”

#### Steps

1. Tape the scale vertically on the side of the hull, with 0 at the bottom. Weigh the empty hull.
2. **Fresh water.** Float the hull and read the draft. Add cargo 50 g at a time, spread evenly, up to 300 g, reading the draft each time.
3. **Predict.** Will the hull sit higher or lower in salt water? By about how much?
4. **Salt water.** Mix about 35 g of salt into each liter of water in the second tub (close to seawater) and repeat the measurements.
5. Make a table and graph draft against load for both waters on the same axes.
6. Choose a safe load line: the draft that leaves 2 cm of freeboard. Mark an F line and an S line on the hull where it sits at that limit in fresh and in salt water. Calculate how much more cargo the ship may carry in salt water.
7. **Stability test.** Load 150 g of cargo low and flat in the hull and push one edge down 1 cm; release and watch it right itself. Now move 100 g of it up onto the craft stick, 8 cm above the deck, and test again. Record what happens.

8. **Improve.** Add ballast (a few washers taped to the bottom) and repeat the high-cargo test. Does the ballast help?

**Tips**

- Read the draft at eye level, at the middle of the side, after the ripples settle.
- A long, steady hull gives more reliable readings than a small round one.
- Your draft graph should be close to a straight line for a box-shaped hull. Ask why.

**Check your work**

- ☐ I can explain why ships float higher in salt water.
- ☐ I can explain what the Plimsoll mark is and why it matters.
- ☐ I can explain how the center of gravity affects stability.

**ENGINEER'S NOTEBOOK**

1. Draw the Plimsoll mark with its circle and its TF, F, T, S, W and WNA lines, and explain each.
2. Graph your fresh- and salt-water drafts against load on one set of axes.
3. Work it: a barge's waterline area is  $150 \text{ m}^2$ . How much deeper does it sink if 30 tonnes of cargo is added in fresh water? ( $30 \text{ m}^3 \div 150 \text{ m}^2 = 0.2 \text{ m}$ .)

**From history.** After his death in 1898, Plimsoll was remembered by sailors around the world. A memorial to him stands on the Victoria Embankment in London. Lloyd's Register, founded in 1760, still inspects ships and checks their load lines today.

**COMMON MISTAKES**

- Thinking a ship floats lower in salt water. Denser water holds it higher.
- Thinking a bigger load line is safer. The line marks the deepest a ship may go; more freeboard is safer.
- Putting heavy cargo high "to keep it dry." High weight makes a ship less stable.

**Make it a game · Salt or Fresh?.** Float an egg or a toy in plain water and in salty water and note how high it floats. Predict, then check. Explain why a ship floats higher in salt water. Then draw a Plimsoll line from memory with its marks, and tell how Samuel Plimsoll's work made ships safer. Fewest labels missed wins.

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

An overloaded ship with a false certificate was a false balance that cost lives.  
Plimsoll’s honest line is an engineering form of a just weight.

## 6.3 PROPULSION: OAR, SAIL, PADDLE, SCREW AND JET

### OBJECTIVES

- Explain how oars, sails, paddle wheels, propellers and water jets push a boat forward, using Newton's third law.
- Calculate thrust from the mass of water pushed back each second and its change in speed.
- Build paddle-wheel and propeller boats with the same hull and power, and test them in speed trials and a tug-of-war.

**Warm-up.** Sit on a rolling desk chair on a smooth floor holding a heavy book. Throw the book forward (to someone ready to catch it, or onto a cushion). Which way do you roll? How is that like a boat's propeller?

### WATCH

#### How Ship Propellers Work: Thrust, Pitch & Movement Explained

[marineinsight](#) · 7:45

<https://www.youtube.com/watch?v=HoK4PWt0gt0>

### WHEN TO WATCH

After the physics paragraph.

### BACKUP VIDEO

#### Why Are 4 Blades Better Than 3?

[Casual Navigation](#) · 6:11

[https://www.youtube.com/watch?v=2cnKzCTJC\\_8](https://www.youtube.com/watch?v=2cnKzCTJC_8)

After the build, to see how engineers choose the number of propeller blades.

### KEY TERMS

#### **thrust**

The forward push that drives a boat or aircraft.

#### **propeller (screw)**

Twisted blades on a spinning shaft that push water backward, like a turning screw.

**paddle wheel**

A wheel with flat boards that dip into the water and push it backward as the wheel turns.

**water jet**

A pump that draws water in and blasts it out of a nozzle at the stern.

**drag**

The water's resistance to the hull moving through it.

**CORE IDEAS**

**The story.** For thousands of years, boats were driven by oars and sails. In the early 1800s, steam paddle wheels took over rivers and coasts. But paddle wheels were clumsy at sea: when a ship rolled, one wheel lifted out of the water while the other dug in. Inventors, including Francis Pettit Smith in England and John Ericsson, a Swede working in England and later America, patented screw propellers in 1836. The British Navy wanted proof. On April 3, 1845, in a flat calm in the North Sea, it tied two nearly identical steam sloops stern to stern: HMS *Rattler*, with a screw propeller, and HMS *Alecto*, with paddle wheels, each with engines of about the same power.

**How they figured it out.** Both ships went full speed ahead in opposite directions. *Rattler* towed *Alecto* backward at about 2.8 knots. It was not the first test, and *Rattler* had already won a series of races, but the tug-of-war made the result impossible to argue with, and the Navy soon ordered screw-driven ships. The tests were fair because the Navy made them fair: similar hulls and similar engines, so that only one thing, the propulsor, was different. Engineers kept testing for decades, trying two, three and four blades, different pitches and sizes, measuring speed and coal burned for each.

**The physics.** Every way of driving a boat obeys Newton's third law: push water (or air) backward, and it pushes you forward. An oar or paddle pushes water back directly. A propeller's twisted blades act like small rotating wings, flinging water backward. A water jet pumps water in and shoots it out the back. Thrust depends on how much water is pushed each second and how much its speed changes: **thrust = mass of water per second  $\times$  change in speed**, which is  $F = ma$  in another form. If a propeller pushes 500 kg of water backward every second and speeds it up by 4 m/s, the thrust is  $500 \times 4 = 2,000$  N. Moving lots of water a little gives more thrust for the

energy than moving a little water a lot. Sails work like wings, turning the wind and being pushed sideways and forward.

**The engineering.** Today almost all large ships use propellers, designed by computer and tested in model basins, often turning slowly with huge blades for efficiency. Fast ferries and rescue boats often use water jets, which work well in shallow water and have no exposed blades. Some ships use pods that swivel the whole propeller to steer. Engineers choose the propulsor to fit the job: speed, fuel use, shallow water, safety near swimmers, and cost. Paddle wheels survive mostly on river tour boats, where shallow water and charm still matter.

## PICTURE STUDY



*Rattler and Alecto Towing Stern to Stern*, Unknown artist, 1845 · Print · Royal Museums Greenwich

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

This print shows the famous test of April 3, 1845, in a perfect calm on the North Sea. *Rattler*, on the left, has a screw propeller hidden under her stern; *Alecto*, on the right, has paddle wheels. The caption below explains the trial.

### Look closely

- Find the tow line between the two ships.
- Find *Alecto*'s paddle wheel. Where is *Rattler*'s propeller?
- Look at the smoke from the funnels. Which way is each ship trying to go?
- Look at the sea. Why does a calm day make the test fairer?

### Talk about it

1. Which ship is winning, and how can you tell?
2. Why did the Navy choose two ships of nearly the same size and power?
3. What would happen to *Alecto*'s paddles if the ships were rolling in big waves?

**Safety first.** Wind rubber bands only as far as needed; an overwound band can snap. Wear safety glasses while winding. Adult present near the water.

## BUILD

### Paddle versus Screw: Speed Trials and a Tug-of-War

You will build two boats from identical hulls, one driven by a rubber-band paddle wheel and one by a rubber-band propeller, wind each the same number of turns, and test them for speed. Then you will tie them stern to stern, as the Navy did with *Rattler* and *Alecto*.

#### You will need

- Two identical hulls: half-gallon milk or juice cartons cut lengthwise, or two foam trays of the same size
- Rubber bands of the same size and craft sticks
- A small plastic propeller (from a craft store or a toy) and a paper clip for its shaft
- Card or plastic-lid pieces for paddle blades, and tape or waterproof glue
- A bathtub or long tub, a tape measure and a stopwatch; string for the tug-of-war
- Safety glasses

#### Steps

1. **Paddle boat.** Tape two craft sticks to extend past the stern of one hull. Stretch a rubber band between their ends and slip a paddle (two crossed card blades) into the band.
2. **Propeller boat.** On the second hull, hook a rubber band to a craft stick at the bow, run it along the hull, and connect it to the propeller on a paper-clip shaft mounted under the stern so the propeller is underwater.
3. Weigh both boats and add clay to the lighter one until their masses match.
4. **Predict.** Which boat will cross the tub faster? Which will win the tug-of-war?
5. **Speed trials.** Wind each band exactly 30 turns, release the boat at one end of the tub, and time it over 1 meter. Do three trials each and average.
6. **Tug-of-war.** Tie the boats stern to stern with 20 cm of string. Wind both 30 turns, set them in the middle of the tub, and let go together. Which way do they move, and how far? Do three rounds.



7. Record everything in a table, and calculate each boat's average speed in m/s.
8. **Improve.** Change one thing on the losing boat (paddle size, propeller pitch, number of blades) and test again.

#### Tips

- Count winding turns carefully; it is the “engine power” and must be the same for a fair test.
- A paddle wheel works best when only the lower blades dip into the water.
- If the propeller boat spins in circles, the propeller's twist is turning the hull; a small keel or rudder helps.

#### Check your work

- ☐ I can explain each kind of propulsion with Newton's third law.
- ☐ I can calculate thrust from water mass per second and change in speed.
- ☐ I can explain why the Navy tied Rattler and Alecto together, and what my own test showed.

#### ENGINEER'S NOTEBOOK

1. Draw both boats with arrows showing water pushed backward and thrust forward.
2. Make a table of speed trials and tug-of-war results.
3. Work it: a water jet takes in 80 kg of water each second and shoots it out 15 m/s faster than it came in. What is the thrust? ( $80 \times 15 = 1,200$  N.)

**From history.** John Ericsson went on to design the USS *Monitor*, an iron warship driven by a screw propeller, launched in 1862. Francis Pettit Smith's first propeller broke during a trial in 1837, leaving half a blade, and the little boat went faster; engineers learned from the accident that a shorter screw worked better.

#### COMMON MISTAKES

- Thinking a propeller pulls the boat by screwing into the water like a corkscrew into cork. It works by pushing water backward.
- Winding one boat more than the other and calling the test fair.
- Forgetting that the faster boat in open water is not always the stronger pusher; speed and pulling force are different tests.

**Make it a game • Thrust Tug-of-War.** Your parent states a puzzle: a boat pushes 2 kg of water back each second at 3 m/s. Calculate the thrust in newtons. Do three similar puzzles. Then compare oar, sail, paddle wheel, propeller and water jet in sixty seconds, naming Newton's third law each time. Highest score of the round wins.

## 6.4 SUBMARINES AND BALLAST: THE TRIESTE AND A CARTESIAN DIVER

### OBJECTIVES

- Explain how submarines and bathyscaphes dive, rise and hover by changing their average density.
- Calculate the water pressure at great depths.
- Build a Cartesian diver and a syringe-controlled submarine, and make each hover at mid-depth.

**Warm-up.** Hold an empty plastic bottle with the cap on and squeeze it. Then fill it with water and try to squeeze it. What is different? Which is easier to squash, air or water?

### WATCH

#### How Does a Submarine Sink and Rise? Soda Bottle Diver | Cartesian Diver Physics Experiment

NPS Physics · 7:20

<https://www.youtube.com/watch?v=tEglh7dt1C4>

### WHEN TO WATCH

Before the build. Pause before each squeeze and predict what the diver will do.

### KEY TERMS

#### **ballast tank**

A tank in a submarine that is filled with water to dive and blown full of air to rise.

#### **bathyscaphe**

A deep-diving craft with a crew sphere hung beneath a large float filled with gasoline, which is lighter than water.

#### **neutral buoyancy**

Having the same average density as the water, so an object neither sinks nor rises.

#### **Cartesian diver**

A small object with an air bubble inside a sealed bottle; squeezing the bottle squeezes the bubble and makes the diver sink.

## **compressible**

Able to be squeezed into a smaller volume. Air is very compressible; water hardly at all.

### **CORE IDEAS**

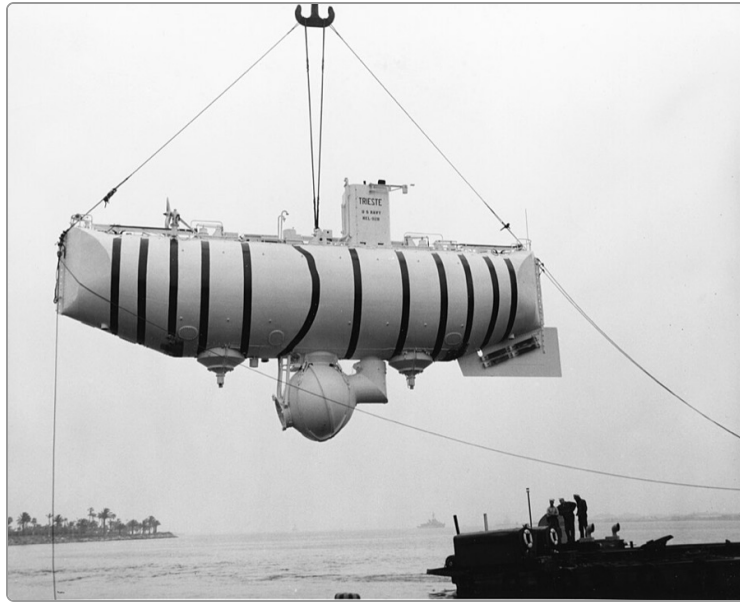
**The story.** On January 23, 1960, Jacques Piccard and U.S. Navy Lieutenant Don Walsh climbed into a steel sphere about 2 meters across, hung beneath the bathyscaphe *Trieste*, above the deepest place in the ocean, the Challenger Deep in the Pacific's Mariana Trench. They sank for nearly five hours, through total darkness, to a depth reported at the time as 35,800 feet, about 10,900 meters. Partway down, one of the outer window panes cracked with a loud bang, but they kept going. They spent about twenty minutes on the bottom, saw a flat creature they took to be a fish, and then rose for more than three hours to the surface. No one returned to that depth for 52 years.

**How they figured it out.** The *Trieste* was designed by Jacques's father, the Swiss scientist Auguste Piccard, who had already flown balloons into the stratosphere. A balloon and a bathyscaphe work the same way: a big bag of something lighter than the fluid around it lifts a small cabin. Piccard could not use an air-filled float, because the crushing pressure deep down would squash the air. So he filled the float with about 85,000 liters of gasoline, which is lighter than water but, like water, hardly compresses at all. To sink, *Trieste* carried about 9 tons of iron shot in hoppers held shut by electromagnets. To rise, the crew released shot, making the craft lighter. If the power failed, the magnets let go and the shot fell out on its own, so the craft would always float back up.

**The physics.** An object sinks if its average density is greater than the water's, rises if it is less, and hovers if they are equal (**neutral buoyancy**). A submarine changes its average density by filling **ballast tanks** with water to dive and blowing them out with compressed air to rise. Pressure grows with depth: at 10,900 m in seawater, pressure =  $1,025 \times 9.8 \times 10,900 \approx 109,000,000$  Pa, about 1,100 times the air pressure at the surface. Every square centimeter of *Trieste*'s sphere carried more than a tonne of force. In a **Cartesian diver**, squeezing the bottle raises the water pressure, which squeezes the air bubble in the diver; water enters, the diver's average density rises above the water's, and it sinks.

**The engineering.** Submarine engineers must balance a boat to within a few hundred kilograms, using small trim tanks to pump water fore and aft and in and out as the crew moves and supplies are used. Deep-diving craft use thick spheres, because a sphere spreads pressure evenly, and syntactic foam, a material made of tiny glass bubbles in resin, to give buoyancy without gasoline. Engineers also design every deep craft to come back up even if something fails, as Piccard did with his electromagnets. Planning for failure is a habit of good engineering.

## PICTURE STUDY



*The Bathyscaphe Trieste*, U.S. Navy photograph, About 1958–1959 · Photograph · Naval History and Heritage Command

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

This U.S. Navy photograph shows *Trieste* being lifted by a crane. The long striped body is the float, full of gasoline; the small ball underneath is the crew sphere where Piccard and Walsh rode to the bottom of the ocean.

### Look closely

- Find the crew sphere. How big is it compared with the float?
- Find the float. Why is it so much larger than the sphere?
- Look for the shot hoppers, the funnel-shaped tanks under the float that held the iron ballast.
- Find the name on the conning tower.

### Talk about it

1. Why was the crew sphere round?
2. Why did *Trieste* need so much gasoline?
3. What would happen if the electromagnets holding the iron shot lost power?

**Safety first.** Do not push the syringe so hard that the tubing pops off and sprays. Adult present near water.

## BUILD

### A Cartesian Diver and a Syringe Submarine

In part A you will build a Cartesian diver and tune it so that a gentle squeeze makes it sink and a careful squeeze makes it hover. In part B you will build a small submarine with a ballast tank controlled through a tube by a syringe, and measure how much water it must take in to dive.

#### You will need

- A 1- or 2-liter clear plastic bottle with cap, filled to the top with water
- A glass or plastic medicine dropper (or a bendy-straw piece folded and clipped, weighted with a paper clip or a little clay)
- A small plastic pill bottle or film canister with a lid, a few metal washers, clay and tape (the submarine)
- About 1 meter of aquarium tubing and a 20–60 mL plastic syringe
- A tub of water, a kitchen scale and the engineer's notebook

#### Steps

1. **Part A, tune the diver.** Test the dropper in a glass of water first. Draw in water until it barely floats, with just its top above the surface. Add a little clay if needed.
2. Put the diver into the full bottle and screw on the cap. Squeeze: it should sink. Release: it should rise. If it does not, adjust the water in the dropper and try again.
3. **Hover.** Practice squeezing just enough to make the diver hang still at mid-depth for 5 seconds. Watch the bubble inside the dropper: what happens to its size when you squeeze?
4. **Part B, build the sub.** Poke two small holes in the pill bottle: one in the bottom (water in) and one in the lid for the tubing. Push the tubing into the lid hole and seal it with clay. Tape washers to the bottom until the sub floats with only its top showing. Weigh it.
5. **Predict.** How many milliliters of water must the sub take in to sink? (Hint: once it floats just at the surface, only a little extra mass is needed.)

6. **Test.** Pull the syringe plunger to draw air out of the sub, so water flows in through the bottom hole. Read how many mL you pulled when the sub begins to sink. Push air back in to make it rise. Do three trials.
7. **Hover.** Try to make the sub hang still at mid-depth. Record how many mL of air were in the syringe when it hovered.
8. **Improve.** Change one thing (more washers, a bigger tank) and test again. Can you make the sub dive and rise more smoothly?

#### Tips

- A diver tuned to float very low needs only a gentle squeeze.
- Hovering is hard because a slight change makes the sub sink or rise; real submarine crews constantly trim.
- Write down the syringe reading at each moment the sub changes direction.

#### Check your work

- ☐ I can explain how ballast tanks make a submarine dive and rise.
- ☐ I can explain why the Trieste used gasoline and iron shot.
- ☐ I can calculate water pressure at great depth.

#### ENGINEER'S NOTEBOOK

1. Draw the Cartesian diver unsqueezed and squeezed, showing the size of the air bubble each time.
2. Draw the *Trieste*: the gasoline float, the crew sphere, the shot hoppers, and arrows for weight and buoyancy.
3. Work it: what is the water pressure 200 m down in seawater? ( $1,025 \times 9.8 \times 200 \approx 2,009,000$  Pa, about 2 million pascals, roughly 20 times surface air pressure.)

**From history.** In 2012 the filmmaker James Cameron dived alone to the Challenger Deep in *Deepsea Challenger*, the first person to return since 1960. Engineers had replaced Piccard's gasoline with syntactic foam, but the same buoyancy principle carried him down and back up.

#### COMMON MISTAKES

- Thinking a submarine dives by pointing down like a fish. It mainly changes its average density with ballast tanks.



- Filling the Cartesian diver's bottle only partway. The bottle must be full, or the squeeze compresses the air at the top instead of the bubble.
- Thinking deep water is denser enough to stop a sinking object. Water barely compresses, so it is nearly the same density at the bottom.

**Make it a game • Dive and Hover.** Predict whether a Cartesian diver will sink if you squeeze the bottle, and explain why in terms of density and compressible air. Then test. Your parent challenges you with ballast tank questions about the Trieste. Calculate the pressure at 100 m of depth. Three correct answers make you captain.

**Scripture.** “They that go down to the sea in ships, that do business in great waters; These see the works of the LORD, and his wonders in the deep.” (Psalm 107:23-24, KJV)  
Piccard and Walsh saw what no one had ever seen in the deepest sea. Engineering lets us see more of the wonders of God's creation.

## UNIT 6

# BOATS AND SHIPS

“They that go down to the sea in ships” have always trusted their lives to a few rules of physics. In this unit you will put numbers on those rules. You will calculate density, measure displacement, and predict how many pennies a boat can carry before you load it, then check your prediction in the tub. You will learn why a ship rides higher in salt water than in fresh, and how one determined man, Samuel Plimsoll, made it the law to paint a line on every ship’s side so that it could never again be loaded too deep.

Then you will compare the ways people have driven boats through the water, from oars and sails to paddle wheels, propellers and water jets, and stage your own version of the famous 1845 tug-of-war between a paddle steamer and a screw steamer. Last, you will follow the bathyscaphe *Trieste* to the deepest point in the ocean and build a Cartesian diver that sinks, rises and hovers at your command.

## PREREQUISITES

- Knows  $F = ma$  and  $\text{weight} = \text{mass} \times 9.8$  (Unit 1)
- Can calculate pressure from depth (Lessons 3.4 and 5.2)
- Can find volume of a box ( $\text{length} \times \text{width} \times \text{height}$ ) and convert between mL and  $\text{cm}^3$

## MASTERY CHECKLIST

- ☐ I can calculate density from mass and volume and use it to predict whether something floats.
- ☐ I can use Archimedes' principle to predict how much load a boat can carry, and test it.
- ☐ I can explain why ships float higher in salt water, what a load line is, and what makes a ship stable.
- ☐ I can explain how oars, sails, paddle wheels, propellers and jets push a boat, using Newton's third law and  $\text{thrust} = \text{mass of water per second} \times \text{change in speed}$ .
- ☐ I can explain how submarines and the *Trieste* control their buoyancy, and make a Cartesian diver hover.

## OPTIONAL KITS FOR THIS UNIT

- **Thames & Kosmos boat and ship kits**: Ages vary by kit. Some kits build motorized and wind-powered boats that can extend the propulsion tests in Lesson 6.3.
- **LEGO Technic**: Ages 9 and up for most sets. Gears, axles and motors (in powered sets) can drive a paddle wheel or propeller boat with a sealed hull; fits Lesson 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 Displacement with Numbers: Why an Iron Ship Floats

2 sessions of 50 minutes

---

## 6.2 Stability and the Plimsoll Line

2 sessions of 50 minutes

---

## 6.3 Propulsion: Oar, Sail, Paddle, Screw and Jet

2 sessions of 50 minutes

---

## 6.4 Submarines and Ballast: The Trieste and a Cartesian Diver

2 sessions of 50 minutes

---

# UNIT 6 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **10 pts**

Calculate: a block has a mass of 360 g and a volume of  $450 \text{ cm}^3$ . What is its density? Will it float in water?

2. **8 pts**

State Archimedes' principle.

3. **8 pts**

Explain in two or three sentences how a ship made of steel, which is about 7.8 times as dense as water, can float.

4. **10 pts**

Calculate: a box-shaped barge is 12 m long and 5 m wide. How much deeper does it sink in fresh water when 18 tonnes of cargo is loaded?

5. **8 pts**

Why does a ship float higher in seawater than in fresh water?

6. **8 pts**

What was Samuel Plimsoll's cause, and what did the 1876 Merchant Shipping Act require?

7. (8 pts)

Predict: a cargo ship's crew stacks heavy steel beams high on its deck instead of low in the hold. What happens to its stability, and why?

8. (8 pts)

Why did the Navy tie HMS Rattler and HMS Alecto stern to stern in 1845, and what happened?

9. (10 pts)

Calculate: a propeller pushes 300 kg of water backward each second and increases its speed by 6 m/s. What is the thrust?

10. (8 pts)

How does a submarine dive and rise?

11. (6 pts)

Why did the Trieste use gasoline in its float instead of air?

12. (8 pts)

Explain what happens inside a Cartesian diver when you squeeze the bottle.

#### ANSWER KEY

1. Density =  $360 \div 450 = 0.8 \text{ g/cm}^3$ . Less than water (1.0), so it floats.
2. The buoyant force on an object equals the weight of the fluid it displaces.
3. The steel is shaped into a hollow hull that encloses a large volume of air, so the ship's average density is less than water's. It sinks until it displaces water equal to its own weight, and then floats.
4. 18 tonnes of fresh water is  $18 \text{ m}^3$ . Waterline area =  $12 \times 5 = 60 \text{ m}^2$ . Extra depth =  $18 \div 60 = 0.3 \text{ m}$ .
5. Seawater is denser (about  $1.025 \text{ g/cm}^3$ ), so the ship needs to displace less volume of it to equal its weight.
6. He fought against overloaded, unsafe "coffin ships" that drowned sailors. The act required British ships to carry a load line showing the deepest they could be loaded.
7. It becomes less stable and may roll over, because the center of gravity rises, so the buoyancy has less ability to push it back upright when it tips.
8. To compare a screw propeller and paddle wheels fairly, with similar ships and engines. Rattler, with the propeller, towed Alecto backward at about 2.8 knots.
9. Thrust =  $300 \times 6 = 1,800 \text{ N}$ .
10. It floods ballast tanks with water to increase its average density and dive, and blows the water out with compressed air to decrease its density and rise.
11. Gasoline is lighter than water but hardly compresses, so it kept giving lift at great depth, where air would be crushed.
12. The squeeze raises the water pressure, which compresses the air bubble inside the diver; water enters, the diver's average density becomes greater than water's, and it sinks. Releasing lets the bubble expand and the diver rise.

## PORTFOLIO PIECE: A CARGO SHIP WITH A MEASURED CAPACITY

Design and build a model cargo ship from foil, card or a plastic container that will carry as much cargo as possible while staying stable. Before building, calculate its predicted capacity from the hull's dimensions. Mark a draft scale and a load line with at least 2 cm of freeboard. Test it in fresh and salt water, then load it until water comes over the side. Write a one-page report with your drawing, predicted and measured capacity, a draft-versus-load graph, a stability test with cargo high and low, and what you would change.

| LOOK FOR                        | WHAT IT MEANS                                                                                |
|---------------------------------|----------------------------------------------------------------------------------------------|
| <b>Design and prediction</b>    | A labeled drawing with dimensions and a correct capacity calculation done before testing.    |
| <b>Load line</b>                | A clear draft scale and load lines for fresh and salt water, with the freeboard rule stated. |
| <b>Testing and data</b>         | Draft measured at several loads in both waters and graphed; final capacity measured fairly.  |
| <b>Stability</b>                | A fair test of high versus low cargo, with results explained using center of gravity.        |
| <b>Analysis and improvement</b> | Prediction compared with the result, errors explained, and a specific improvement proposed.  |

## UNIT 7

# FLIGHT

In Grade 5 you followed the Wright brothers from kites to the first flight. This year you will measure lift yourself, on a kitchen scale in front of a box fan, and learn the formula that tells an aircraft designer how big a wing must be. You will see why the correct explanation of lift includes both lower pressure above the wing and air turned downward, and why the old “equal transit time” story is wrong.

Then you will learn how a pilot controls an airplane about three axes with ailerons, elevator and rudder; fly across the Atlantic with Charles Lindbergh, finding the way with only a compass, a clock and careful arithmetic; and stand in a snowy Massachusetts field with Robert Goddard as the first liquid-fueled rocket roars for two and a half seconds. Your own rocket, powered by water and air, will be launched outdoors with an adult.

### PREREQUISITES

- Knows the four forces of flight: lift, weight, thrust and drag (Grade 5)
- Knows Newton’s laws and  $F = ma$  (Unit 1)
- Can use a protractor to measure angles and a compass to find directions

### MASTERY CHECKLIST

- ☐ I can explain lift correctly, as pressure difference and air turned downward, and explain why the equal-transit-time story is wrong.
- ☐ I can use the lift equation to see how speed, wing area and angle of attack change lift.
- ☐ I can name the three axes of an airplane and the control surface for each, and explain how each one works.
- ☐ I can navigate by dead reckoning using heading, speed, time and wind.
- ☐ I can explain how a rocket works with Newton’s laws and calculate its acceleration and the height of a launch from its flight time.



## OPTIONAL KITS FOR THIS UNIT

- **Estes model rockets:** Ages 10 and up with an adult; motors must be handled and launched by an adult following the National Association of Rocketry safety code, outdoors in an open field. Beginner kits fit Lesson 7.4.
- **KiwiCo Tinker crates:** Ages 9 and up. Several crates build gliders, launchers and flying toys that extend Lessons 7.1–7.2; check each crate’s description.

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

|                                               |                          |
|-----------------------------------------------|--------------------------|
| <b>7.1 Lift: Pressure and Turning the Air</b> | 2 sessions of 50 minutes |
|-----------------------------------------------|--------------------------|

---

|                                                            |                          |
|------------------------------------------------------------|--------------------------|
| <b>7.2 Control Surfaces: Ailerons, Elevator and Rudder</b> | 2 sessions of 50 minutes |
|------------------------------------------------------------|--------------------------|

---

|                                                                         |
|-------------------------------------------------------------------------|
| <b>7.3 Lindbergh and Navigation: Dead Reckoning Across the Atlantic</b> |
|-------------------------------------------------------------------------|

2 sessions of 50 minutes

---

|                                                                |                          |
|----------------------------------------------------------------|--------------------------|
| <b>7.4 Goddard and Rockets: The First Liquid-Fueled Flight</b> | 2 sessions of 50 minutes |
|----------------------------------------------------------------|--------------------------|

---

## UNIT 7 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Explain in two or three sentences how a wing makes lift.

2. **6 pts**

What is wrong with the “equal transit time” explanation of lift?

3. **10 pts**

Calculate: using  $\text{lift} = \frac{1}{2} \times \text{density} \times \text{speed}^2 \times \text{area} \times \text{lift coefficient}$ , find the lift on a wing of  $10 \text{ m}^2$  flying at  $40 \text{ m/s}$  in air of density  $1.2 \text{ kg/m}^3$  with a lift coefficient of 0.6. What happens to the lift if the speed doubles?

4. (7 pts)

What is a stall?

5. (9 pts)

Name the three axes of an airplane and the control surface that controls each.

6. (8 pts)

Calculate: an elevator 6 m behind the center of gravity makes a force of 250 N. What torque does it produce?

7. (8 pts)

What problem did the Wrights find with wing warping in 1901, and how did they fix it?

8. (8 pts)

What is dead reckoning?

9. (10 pts)

Calculate: an airplane flies 3 hours heading due east at 110 miles per hour, with a 20-mile-per-hour wind blowing from the south. Where does it end up relative to its start?

10. (8 pts)

Why can a rocket work in space, where there is no air?

11. (10 pts)

Calculate: a rocket has a mass of 2 kg and its engine gives 60 N of thrust straight up. Find its weight, the net force and its acceleration. (Use  $9.8 \text{ m/s}^2$ .)

12. (8 pts)

Describe Goddard's flight of March 16, 1926, and why it mattered.

## ANSWER KEY

1. A wing at an angle of attack, often with camber, turns the passing air downward; by Newton's third law the air pushes the wing up. At the same time the air speeds up over the curved top and its pressure drops below the pressure underneath, and that pressure difference over the wing area is the lift.
2. It claims the air over the top must catch up with the air underneath at the back edge. Nothing makes that happen; tests show the air over the top arrives at the back sooner.
3.  $0.5 \times 1.2 \times 1,600 \times 10 \times 0.6 = 5,760$  N. Doubling the speed makes four times the lift (23,040 N).
4. A sudden loss of lift when the angle of attack is too large and the air stops flowing smoothly over the top of the wing.
5. Roll: ailerons. Pitch: elevator. Yaw: rudder.
6. Torque =  $250 \times 6 = 1,500$  N·m.
7. When they rolled into a turn, the raised wing's extra drag swung the nose the wrong way (adverse yaw), and the glider sometimes spun in. In 1902 they made the rudder movable and linked it to the wing warping.
8. Finding your position by starting from a known point and adding up the heading, speed and time traveled, with a correction for wind.
9. 330 miles east ( $110 \times 3$ ) and 60 miles north ( $20 \times 3$ ) of the start.
10. It pushes mass (its exhaust) backward, and by Newton's third law the exhaust pushes the rocket forward. It carries its own oxidizer, so it needs no air to burn or to push against.
11. Weight =  $2 \times 9.8 = 19.6$  N. Net force =  $60 - 19.6 = 40.4$  N. Acceleration =  $40.4 \div 2 = 20.2$  m/s<sup>2</sup>.
12. In Auburn, Massachusetts, his gasoline and liquid-oxygen rocket flew 2.5 seconds, rose 41 feet and landed 184 feet away. It was the first liquid-fueled rocket, the kind later used to reach space and the Moon.

## PORTFOLIO PIECE: A TESTED GLIDER WITH MEASURED CONTROLS

Design and build a glider from card, foam or balsa that flies at least 6 meters from a gentle hand launch. Use your wind-tunnel results from Lesson 7.1 to choose its wing angle and camber. Trim it to fly straight, then show that you can make it turn left, turn right, and fly a full circle using its control surfaces. Record at least three flights for each setting. Write a one-page report with a three-view drawing, your wind-tunnel graph, a table of flights, one torque or lift calculation, and what you would change.

| LOOK FOR                           | WHAT IT MEANS                                                                                 |
|------------------------------------|-----------------------------------------------------------------------------------------------|
| <b>Design</b>                      | A neat three-view drawing with wing area, center of gravity and control surfaces labeled.     |
| <b>Use of data</b>                 | Wing angle and shape chosen using wind-tunnel results, and the choice explained.              |
| <b>Fair testing</b>                | At least three flights per setting, with distance and direction recorded and averaged.        |
| <b>Control</b>                     | Showed straight flight, turns both ways and a circle, with the settings recorded.             |
| <b>Calculation and improvement</b> | One correct lift or torque calculation, and a specific improvement based on the test results. |

## 7.1 LIFT: PRESSURE AND TURNING THE AIR

### OBJECTIVES

- Explain lift correctly as both lower pressure above the wing and air turned downward, and explain why the equal-transit-time story is wrong.
- Use the lift equation to show how speed, wing area and angle of attack change lift.
- Measure lift on a kitchen-scale wind tunnel at different angles of attack, and compare a flat and a curved wing.

**Warm-up.** Hold a spoon loosely by its handle so the curved back hangs into a stream of water from a tap. Which way does the spoon move? Write down a guess about why, and keep it until the end of the lesson.

### WATCH

#### Understanding Aerodynamic Lift

The Efficient Engineer · 14:19

[https://www.youtube.com/watch?v=E3i\\_XHIVCeU](https://www.youtube.com/watch?v=E3i_XHIVCeU)

#### WHEN TO WATCH

After the physics paragraph. A thorough explanation for older students; pause often and retell each idea.

**Note:** The last minute is a sponsor message; you can stop when the teaching ends.

### BACKUP VIDEO

#### Lift: Bernoulli's Principle (How Things Fly Demonstration)

Smithsonian National Air and Space Museum · 2:12

[https://www.youtube.com/watch?v=3b9xCC\\_vaZQ](https://www.youtube.com/watch?v=3b9xCC_vaZQ)

Before the build, for a short museum demonstration of low pressure over a curved surface.

## KEY TERMS

### **lift**

The upward force on a wing, made as the wing turns the passing air downward and the pressure above the wing drops below the pressure underneath.

### **airfoil**

The cross-section shape of a wing, usually rounded at the front and thin at the back, often curved (cambered).

### **camber**

The curve of an airfoil from front to back.

### **angle of attack**

The angle between the wing and the oncoming air.

### **stall**

A sudden loss of lift when the angle of attack is too large and the air stops flowing smoothly over the top of the wing.

### **downwash**

Air turned downward behind a wing.

## CORE IDEAS

**The story.** In the 1880s an English engineer named Horatio Phillips built a wind tunnel, driving the air with a jet of steam, and tested wing shapes in it. He found that a curved, thick-fronted wing section made far more lift than a flat plate at the same speed, and that much of the lift came from the low pressure on its upper surface. He patented his curved “sustainers” in 1884, years before the Wright brothers began their work. In 1893 he tested a machine with fifty narrow wings stacked like a Venetian blind, tethered to a circular track, and it lifted off the ground.

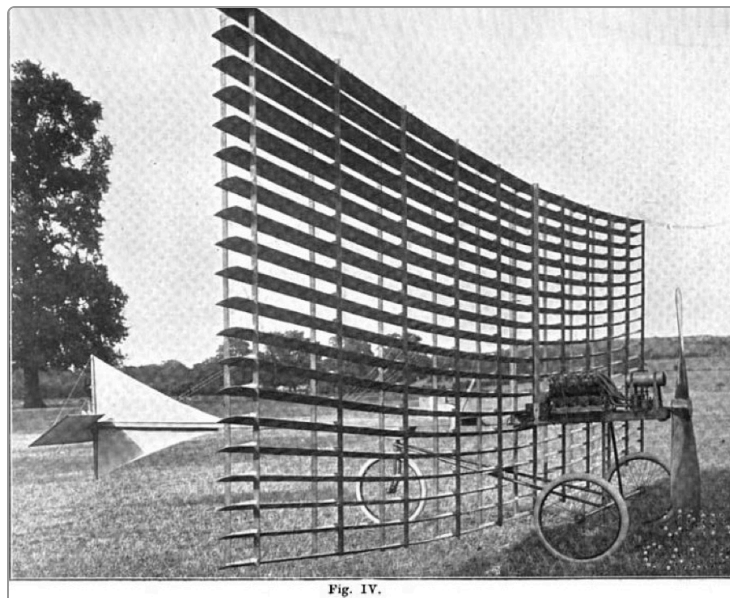
**How they figured it out.** Phillips measured, rather than guessed. He mounted each test wing on a balance in the air stream and read the lifting force directly, trying different curves and angles. Others, including Otto Lilienthal and later the Wrights, built on such measurements, and over the next decades scientists such as Ludwig Prandtl in Germany worked out the full theory. They confirmed two things that are both true at once: a wing lowers the pressure above it and raises it slightly below, and a wing turns a great mass of air downward behind it. These are two descriptions of the same event. A popular explanation says that air over the top must travel farther and so must go faster to “catch up” with the air underneath at the back edge.

That is false: wind-tunnel tests show the air over the top actually arrives at the back well before the air underneath, and nothing makes the two meet.

**The physics.** A wing set at an **angle of attack** and shaped with **camber** bends the airflow downward. By Newton's third law, if the wing pushes air down, the air pushes the wing up. Around the curved upper surface the air speeds up and its pressure drops, while the pressure underneath is a little higher; that pressure difference over the whole wing area is the lift. Engineers sum it up in the lift equation:  $\text{lift} = \frac{1}{2} \times \text{air density} \times \text{speed}^2 \times \text{wing area} \times \text{lift coefficient}$ . For a light airplane with 16 m<sup>2</sup> of wing at 50 m/s, with air density 1.2 kg/m<sup>3</sup> and a lift coefficient of 0.5:  $\text{lift} = 0.5 \times 1.2 \times 2,500 \times 16 \times 0.5 = 12,000 \text{ N}$ , enough to hold up about 1,200 kg. Because speed is squared, doubling the speed makes four times the lift. Increase the angle too far, though, and the flow tears away from the top of the wing: the wing **stalls**.

**The engineering.** Aircraft designers choose wing area, airfoil shape and speed together. A slow airplane needs a big wing; a fast jet can use a small one. For takeoff and landing, when speed is low, jets extend flaps and slats that increase camber and area. Pilots are trained to watch their airspeed and angle of attack closely, and airliners have warning systems that shake the control column before a stall. Every new wing is still tested in wind tunnels and in flight, measuring lift and drag just as Phillips did.

## PICTURE STUDY



*Horatio Phillips's 1904 Multiplane*, Unknown photographer, Published 1908 · Photograph

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

This photograph shows Horatio Phillips's 1904 multiplane, built on his discovery that curved, narrow wings make strong lift. In it he made short hops off the ground.

### Look closely

- Count the narrow wings stacked one above another.
- Look at a single wing. Is it flat or curved?
- Find the engine and propeller at the front.
- Find the small tail behind.

### Talk about it

1. Why might Phillips use many narrow wings instead of one wide one?
2. What problems would such a tall stack of wings have in a crosswind?
3. How did Phillips measure which wing shapes worked best?

**Safety first.** Use a box fan with its grille in place, and keep fingers away from the blades. Tape the wing stand down so it cannot blow into the fan.



## BUILD

### A Kitchen-Scale Wind Tunnel

You will mount a small wing on a stand that sits on a kitchen scale, blow air across it with a box fan, and read the lift as a drop in the scale reading. You will measure lift at several angles of attack, find the stall, and compare a flat wing with a cambered one.

#### You will need

- A box fan and a kitchen scale that reads in grams
- A stand: a lump of clay on a small plate with a pencil or skewer standing upright in it
- Card stock for wings, about 15 cm wide and 10 cm from front to back, and tape
- A protractor, a ruler, and books to raise the scale to the height of the fan's center
- Engineer's notebook

#### Steps

1. **Make two wings.** One flat. One cambered: fold the card over a pencil near the front edge and tape the back edges together so the top curves and the bottom is nearly flat.
2. Tape a wing to the top of the skewer at its middle, so you can twist the wing to set the angle of attack. Set the stand on the scale, 40 cm in front of the fan, with the wing at the height of the fan's center. Press the scale's tare button so it reads zero.
3. **Predict.** At which angle will the cambered wing make the most lift? When will it stall?
4. **Test.** Set the wing at  $0^\circ$ , turn the fan on high, wait 5 seconds, and read the scale. A negative reading (in grams) is lift. Record it. Turn the fan off and check that the scale returns to zero.
5. Repeat at  $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ ,  $20^\circ$  and  $25^\circ$ , three readings at each angle.
6. Repeat the whole set with the flat wing.

7. Make a table and graph lift (grams) against angle of attack for both wings on the same axes. Mark where each one stalls (where lift stops rising and falls).
8. **Improve and test speed.** At the best angle, move the stand to 80 cm from the fan (slower air) and measure again. Use the lift equation to explain the change. Then try one wing change of your own (longer span, more camber) and test it.

#### Tips

- Hold a thread taped to the wing's back edge in the airflow: it shows the downwash.
- Air from a box fan swirls. Cardboard drinking straws bundled in a box in front of the fan can straighten it.
- The scale may flicker; record the middle value over a few seconds.

#### Check your work

- ☐ I can explain lift correctly and say why the equal-transit-time story is wrong.
- ☐ I can use the lift equation to explain how speed and angle change lift.
- ☐ I can find a stall in my data and explain what happens to the airflow.

#### ENGINEER'S NOTEBOOK

1. Draw a cambered wing in the airflow with arrows for the flow, the downwash behind it, low pressure above and higher pressure below.
2. Graph lift against angle of attack for both wings and label the stall.
3. Work it: a glider has  $12 \text{ m}^2$  of wing and flies at  $25 \text{ m/s}$  with a lift coefficient of 1.0 in air of density  $1.2 \text{ kg/m}^3$ . What is its lift? ( $0.5 \times 1.2 \times 625 \times 12 \times 1.0 = 4,500 \text{ N}$ .)

**From history.** Phillips kept building multiplanes, and in 1907 one of his machines made a short powered hop of several hundred feet in England. His patents on cambered wing sections were among the first scientific contributions to the shape of the airplane wing, and every wing since has some camber or angle of attack to turn the air.

#### COMMON MISTAKES

- Saying the air over the top must catch up with the air underneath. It does not; it actually arrives at the back sooner.
- Thinking lift comes only from the bottom of the wing being pushed up. Most of the lift comes from low pressure on top.

- Thinking a steeper angle always gives more lift. Past the stall angle, lift falls suddenly.

**Make it a game • Myth Buster.** Play myth buster about lift. Your parent states the equal-transit-time story as a fact. You declare it wrong and give the correct explanation using lower pressure above the wing and air turned downward. Then say how speed, area and angle of attack change lift. Hold a card in a gentle breeze to demonstrate.

**Scripture.** “But they that wait upon the LORD shall renew their strength; they shall mount up with wings as eagles” (Isaiah 40:31, KJV)

Long before anyone understood lift, people longed to mount up with wings. God made the air so that, with patience and careful study, they could.

## 7.2 CONTROL SURFACES: AILERONS, ELEVATOR AND RUDDER

### OBJECTIVES

- Name the three axes of an aircraft (roll, pitch and yaw) and the control surface for each.
- Explain how a control surface creates a turning force (torque) and calculate a simple torque.
- Build a glider with movable control surfaces and test the effect of each one fairly.

**Warm-up.** Hold a paper airplane (or your hand, flat like a wing) in front of you. Tip it so one wing goes down (roll), so the nose goes up (pitch), and so the nose turns left (yaw). Which of these do you think a bird controls with its tail?

### WATCH

#### Aircraft Control Surfaces Explained | Ailerons, flaps, elevator, rudder and more

Joyplanes • 7:21

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

### WHEN TO WATCH

After the physics paragraph.

### BACKUP VIDEO

#### Aircraft Primary Flight Control Surfaces Explained | Ailerons, Elevators, and Rudders

Curious About Planes • 5:41

<https://www.youtube.com/watch?v=4xBXGKOp89g>

Before the build, to review roll, pitch and yaw.

### KEY TERMS

#### **roll**

Rotation about the line running from nose to tail; one wing goes up and the other down. Controlled by the ailerons.

#### **pitch**

Rotation that raises or lowers the nose. Controlled by the elevator.

**yaw**

Rotation that swings the nose left or right. Controlled by the rudder.

**aileron**

A hinged flap on the back edge of each wing; one goes up while the other goes down.

**torque**

A turning force:  $\text{force} \times \text{distance}$  from the turning point, measured in newton-meters (N·m).

**center of gravity**

The balance point of the aircraft, about which it turns.

**CORE IDEAS**

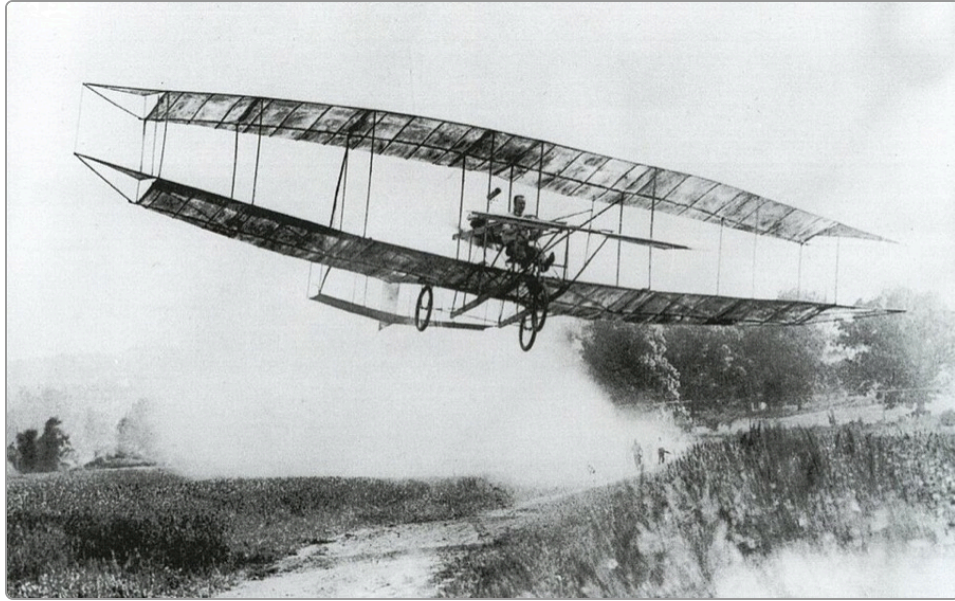
**The story.** The Wright brothers' great discovery was not the engine or even the wing, but **control**. In 1899 Wilbur, twisting a long, empty inner-tube box in his hands, saw how the two wings of a glider could be twisted in opposite directions to raise one and lower the other, as birds do with their wingtips. They called it wing warping and patented it in 1906. Meanwhile, in 1908, a group led by Alexander Graham Bell, including the motorcycle builder Glenn Curtiss, flew the *June Bug*, which used small separate flaps at its wingtips, which the French called *ailerons*, "little wings." On July 4, 1908, Curtiss flew it more than a kilometer to win a prize from *Scientific American*.

**How they figured it out.** The Wrights tested their controls on kites and gliders, crashing many times. In 1901 they found a frightening problem: when they warped the wings to roll into a turn, the glider sometimes swung its nose the wrong way and spun into the sand. The wing pulled up to raise it also had more drag, which yawed the nose toward it. In 1902 they solved it by making the tail rudder movable and linking it to the wing warping, so that roll and yaw were controlled together. Ailerons, being easier to build into stiff wings, later replaced wing warping on almost every airplane, though the Wrights argued for years in court that their patent covered them.

**The physics.** A control surface is a small wing. Deflect it, and it changes the lift on that part of the aircraft. Because it is far from the **center of gravity**, even a small force makes a large **torque**:  $\text{torque} = \text{force} \times \text{distance}$ . An elevator 5 m behind the center of gravity that makes 200 N of extra downward force produces  $200 \times 5 = 1,000$  N·m of torque, pitching the nose up. Ailerons work in pairs: the one that goes down adds lift to its wing, and the one that goes up reduces lift on the other wing, so the aircraft rolls. The rudder pushes the tail sideways to yaw the nose.

**The engineering.** To turn an airplane, a pilot rolls it with the ailerons so the lift tilts and pulls the airplane around the turn, uses a little rudder to keep the nose pointed along the turn, and adds a little elevator to keep from losing height. Designers size each surface and its distance from the center of gravity so that the airplane responds firmly but not too sharply, and they must locate the center of gravity carefully: too far back and the airplane becomes unstable. Large airliners now move their surfaces with hydraulic actuators commanded by computers, but the physics of each surface is exactly what the Wrights and Curtiss used.

## PICTURE STUDY



*The June Bug in Flight*, Unknown photographer, July 4, 1908 · Photograph

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

This photograph shows Glenn Curtiss flying the *June Bug* on July 4, 1908, when he won the *Scientific American* prize. Look closely at the ends of the wings.

### Look closely

- Find the ailerons at the wingtips. Which way would they move to roll left?
- Find the elevator at the front and the tail at the back.
- Find the pilot. Where does he sit?
- Look at the dust behind. What made it?

### Talk about it

1. Why are the ailerons at the wingtips rather than near the middle?
2. How did the Wrights control roll without ailerons?
3. What would happen if both ailerons moved the same way?

**Safety first.** Fly gliders where no one can be hit in the face, and never throw toward people or pets.

## BUILD

### A Glider with Working Controls

You will build a glider from a foam plate or card stock with cut flaps for ailerons, elevator and rudder, trim it to fly straight, and then test each control surface alone, changing only one at a time and recording what the glider does.

#### You will need

- Foam plates or stiff card stock, scissors and tape
- A paper clip or a little clay for nose weight
- A tape measure, masking tape for a launch line, and a protractor
- A long hallway, gym or calm outdoor space
- Engineer's notebook

#### Steps

1. **Build.** Cut a wing about 25 cm across and 6 cm deep, a body about 25 cm long, a horizontal tail and a vertical fin. Assemble them with tape or slots. Add nose weight until the glider balances about one third of the way back from the front of the wing.
2. Cut flaps 1.5 cm deep and 4 cm long into the back edge of each wingtip (ailerons), the horizontal tail (elevator) and the fin (rudder). Each should bend and hold its position.
3. **Trim.** With all flaps flat, throw gently from the launch line until the glider flies straight and level. Adjust nose weight if it dives or stalls.
4. **Predict.** For each control change below, write what you think the glider will do.
5. **Test pitch.** Bend the elevator up  $20^\circ$ . Throw three times and record distance and whether the nose rose, stalled or dove. Return it to flat.
6. **Test roll.** Bend the left aileron up  $20^\circ$  and the right aileron down  $20^\circ$ . Record which way the glider rolls and turns. Return them to flat.
7. **Test yaw.** Bend the rudder  $20^\circ$  to the left. Record the turn. Then combine left roll and left rudder for a coordinated turn and compare.



8. **Improve.** Set the controls to make the glider fly a gentle full circle and land near where it started. Record the settings that worked.

**Tips**

- Throw the same way each time: same height, same gentle push, wings level.
- Mark the landing point of each throw with a coin to measure distance and direction.
- Small bends make big changes; try  $10^\circ$  before  $20^\circ$ .

**Check your work**

- ☐ I can name the three axes and the control surface for each.
- ☐ I can calculate the torque from a control surface.
- ☐ I can explain why a turn uses ailerons and rudder together.

**ENGINEER'S NOTEBOOK**

1. Draw your glider from above and from the side, labeling ailerons, elevator, rudder and center of gravity.
2. Make a table: control setting, what the glider did, average distance.
3. Work it: a rudder 4 m behind the center of gravity makes a sideways force of 150 N. What torque does it make? ( $150 \times 4 = 600 \text{ N}\cdot\text{m}$ .)

**From history.** The long patent fight between the Wrights and Curtiss ended only when the United States entered the First World War in 1917 and the government arranged for aircraft makers to share patents. The *June Bug's* ailerons, simple hinged flaps, became the standard on nearly every airplane flying today.

**COMMON MISTAKES**

- Thinking the rudder alone turns an airplane. The airplane turns mainly by banking with the ailerons, so the tilted lift pulls it around.
- Bending both ailerons the same way. They must move in opposite directions to roll.
- Changing two controls between throws, so you cannot tell which change caused what.

**Make it a game • Three Axes Charades.** Stand with arms out as a glider. Roll, pitch or yaw on command from your parent, then name the control surface that causes it. Swap roles. Then calculate a simple torque: a 2 newton force acting 0.5 meters from the pivot. Fewest wrong answers over five rounds takes the point.

## 7.3 LINDBERGH AND NAVIGATION: DEAD RECKONING ACROSS THE ATLANTIC

### OBJECTIVES

- Explain dead reckoning: finding position from heading, speed, time and wind.
- Calculate distance from speed and time, and show how a crosswind pushes an aircraft off course.
- Plan and walk a dead-reckoning course with a compass and paces, and measure how far off you land.

**Warm-up.** Close your eyes and try to walk ten slow steps in a straight line across a room (with a partner watching to keep you safe). Open your eyes. How far off were you? What would help you stay on course?

### WATCH

#### History Brief: Charles Lindbergh and the Spirit of St. Louis

Reading Through History • 4:37

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

### WHEN TO WATCH

After the story.

### BACKUP VIDEO

#### Pilotage and Dead Reckoning

ERAU SpecialVFR • 8:52

<https://www.youtube.com/watch?v=u6AU5DfG8A0>

Before the build, to see how pilots navigate by dead reckoning and landmarks.

### KEY TERMS

#### **dead reckoning**

Finding your position by starting from a known point and adding up your heading, speed and time traveled.

#### **heading**

The compass direction the aircraft's nose is pointing.

**track**

The actual path over the ground, which a crosswind can push away from the heading.

**drift**

Sideways movement caused by wind.

**great circle**

The shortest route between two points on a globe.

**landfall**

The first sight of land after crossing the sea.

**CORE IDEAS**

**The story.** On the morning of May 20, 1927, Charles Lindbergh, a 25-year-old airmail pilot, took off alone from Roosevelt Field on Long Island in the *Spirit of St. Louis*, so heavy with fuel that it barely cleared the telephone wires at the end of the field. A prize of \$25,000 had been offered for the first nonstop flight between New York and Paris, and several famous crews had already crashed or disappeared trying. Thirty-three and a half hours later, after flying about 3,600 miles (5,800 km) through fog, sleet and darkness, fighting to stay awake, he landed at Le Bourget field near Paris before a crowd of 150,000 people.

**How they figured it out.** Lindbergh worked out his flight on paper before he left. With the Ryan Airlines engineers in San Diego, who built the airplane in about two months, he chose one engine for reliability, a single seat to save weight, and a huge fuel tank in front of the cockpit, so he had no forward window and looked ahead through a small periscope. He had no radio. He drew the great-circle route on his charts and divided it into segments about 100 miles long, each with its own compass heading, because the shortest path on a globe curves across a flat map. Over the ocean he flew by **dead reckoning**: hold the heading, watch the airspeed and the clock, estimate the wind from the waves, and keep track. When he reached the coast of Ireland at Dingle Bay, he was only a few miles off his planned track.

**The physics.** Dead reckoning is distance = speed  $\times$  time, with directions. Fly at 100 miles per hour for 2 hours on a heading of due east, and you go 200 miles east of your start through the air. But the air itself may be moving. If a 20-mile-per-hour wind blows from the north, it carries the airplane  $20 \times 2 = 40$  miles south in those two hours. Your **track** over the ground ends 200 miles east and 40 miles south of the start. To correct, a navigator turns the heading a little into the wind, so the drift

is cancelled. Lindbergh's average ground speed was about  $3,600 \div 33.5 \approx 107$  miles per hour.

**The engineering.** Navigators after Lindbergh added radio beacons, then radar, and now satellite positioning (GPS), which gives position within a few meters. But engineers build backups because any one system can fail: airliners carry inertial navigation, which is dead reckoning done by gyroscopes and accelerometers that measure every turn and change of speed. Pilots are still trained to navigate with a chart, a compass and a clock, and ships still keep a dead-reckoning plot. Careful arithmetic and honest record keeping found the way across the Atlantic, and they remain the backbone of navigation today.

## PICTURE STUDY



*Charles Lindbergh and the Spirit of St. Louis*, Unknown photographer, 1927 · Photograph · Library of Congress

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

This photograph was taken in 1927, soon after Lindbergh's flight. Behind him is the *Spirit of St. Louis*, built in about two months by Ryan Airlines in San Diego.

### Look closely

- Find the name on the nose. Where was the big fuel tank?
- Look for a forward window. How did Lindbergh see ahead?
- Find the single engine and propeller. Why did he want only one engine?
- Look at the long wing. Why would a heavily loaded airplane need a large wing?

### Talk about it

1. What instruments would Lindbergh need for dead reckoning?
2. Why did he have no radio and no second crew member?
3. How would a crosswind over the ocean change his track?

**Safety first.** Do the walking course in a yard, park or field with an adult, away from streets, water and parking lots. Walk, do not run, and keep your eyes up while you count paces.

## BUILD

### A Dead-Reckoning Course

You will measure your pace, plan a three-leg course with compass headings and distances, walk it using only a compass and a pace count, and measure how far from the target you finish. Then you will plot a Lindbergh-style flight with a crosswind on graph paper.

#### You will need

- A magnetic compass (or a compass app on a phone)
- A tape measure (at least 10 m) and a few markers (cones, flags or sticks)
- Graph paper, a ruler and a protractor
- An open yard, park or field and an adult helper
- Engineer's notebook

#### Steps

1. **Measure your pace.** Lay out 20 m with the tape. Walk it normally three times, counting steps. Calculate your average pace length in meters.
2. **Plan.** On graph paper, plan a triangle course with three legs, for example 30 m on a heading of  $0^\circ$  (north), 25 m on  $120^\circ$ , and back to the start. Convert each distance to paces.
3. **Predict.** How far from the starting marker do you think you will finish?
4. **Walk it.** From the starting marker, hold the compass flat, turn until the needle shows your first heading, pick a landmark straight ahead, and walk your paces toward it. Repeat for each leg. Mark where you finish.
5. Measure the distance and direction from your finish to the start (your error). Do the course three times and average the error.
6. **Plot a flight.** On graph paper, plot a 3-hour flight at 100 miles per hour heading due east with a 20-mile-per-hour wind from the north, one hour at a time (use 1 square = 10 miles). Where does the airplane end up?
7. Plan the correction: about what heading would keep the airplane on an eastward track? Test your idea on the graph paper.

8. **Improve.** Change one thing in your walking method (counting in groups of ten, picking a farther landmark, walking slower) and walk the course again. Did the error shrink?

#### Tips

- Keep the compass away from metal objects and phones, which can pull the needle.
- Errors add up over each leg; that is why Lindbergh checked landmarks whenever he could see one.
- Pace length changes uphill and downhill; real navigators correct for the same kind of thing with wind and fuel burn.

#### Check your work

- ☐ I can explain dead reckoning with  $\text{distance} = \text{speed} \times \text{time}$ .
- ☐ I can show how a crosswind changes an aircraft's track and how to correct for it.
- ☐ I can measure and reduce my own navigation error.

#### ENGINEER'S NOTEBOOK

1. Draw your planned triangle and your actual walked paths, with the error measured at the finish.
2. Draw Lindbergh's route from New York to Paris on a sketch map, with a few of the 100-mile segments and their headings.
3. Work it: an airplane flies 4 hours at 120 miles per hour heading north, with a 15-mile-per-hour wind from the west. Where does it end up? (480 miles north and 60 miles east of the start.)

**From history.** Lindbergh's *Spirit of St. Louis* now hangs in the Smithsonian National Air and Space Museum in Washington. Later in life he worked with Robert Goddard, the subject of the next lesson, and helped him find money to continue his rocket experiments.

#### COMMON MISTAKES

- Forgetting the wind. An airplane's heading and its track are not the same when wind blows across it.
- Mixing up "a wind from the north" (blowing toward the south) with "a wind toward the north."



- Measuring pace once instead of averaging several tries.

**Make it a game · Dead Reckoning Trip.** Plan a pretend flight. Pick a heading, a speed and a time, and compute the distance with a ruler and paper map. Your parent adds a crosswind, and you say how far you drift off course. Then guess your landfall. Retell Lindbergh's crossing in one minute, including the compass and great circle.

**Scripture.** “If I take the wings of the morning, and dwell in the uttermost parts of the sea; Even there shall thy hand lead me, and thy right hand shall hold me.” (Psalm 139:9-10, KJV)

Alone over the ocean, a navigator trusts his compass and his arithmetic. A Christian trusts that there is no place, even over the uttermost sea, beyond God's guiding hand.

## 7.4 GODDARD AND ROCKETS: THE FIRST LIQUID-FUELED FLIGHT

### OBJECTIVES

- Explain how a rocket works using Newton's second and third laws, and why it works in empty space.
- Calculate a rocket's net force and acceleration from its thrust and weight.
- Launch a water rocket with an adult, change one variable, and calculate its height from its flight time.

**Warm-up.** Blow up a balloon and let it go (in a room with nothing breakable). Watch its path. What is pushing it? Would it still fly if the room had no air in it at all? Write your answer before reading on.

### WATCH

#### The Story of Robert Goddard, Father of Modern Rocketry

NASA Goddard · 2:49

<https://www.youtube.com/watch?v=sGZZ2QHprHw>

### WHEN TO WATCH

After the story.

### BACKUP VIDEO

#### Great Minds: Robert Goddard, Original Rocket Scientist

SciShow Space · 4:20

<https://www.youtube.com/watch?v=jSlq1XsdUqA>

After the physics paragraph, for more on how Goddard's liquid-fueled rocket worked.

### KEY TERMS

#### **thrust**

The force that pushes a rocket forward as it throws mass (hot gas or water) backward.

#### **liquid-fueled rocket**

A rocket that pumps or pushes a liquid fuel and a liquid oxidizer (such as liquid oxygen) into a chamber where they burn.

**oxidizer**

The chemical a fuel needs in order to burn; a rocket carries its own, so it can work where there is no air.

**nozzle**

The shaped opening at the back of a rocket engine that speeds up the escaping gas.

**net force**

Thrust minus weight (and drag) for a rocket going straight up.

**CORE IDEAS**

**The story.** On October 19, 1899, a 17-year-old in Worcester, Massachusetts, named Robert Goddard climbed a cherry tree to trim its branches, looked up at the sky and imagined a machine that could rise to Mars. He spent the rest of his life working toward it. As a physics professor at Clark University, he published a paper in 1919, *A Method of Reaching Extreme Altitudes*, showing that rockets could reach very high altitudes and even the Moon. In January 1920 a famous newspaper mocked him in an editorial, claiming that a rocket could not work in empty space because it would have nothing to push against. Goddard did not argue. He went back to work.

**How they figured it out.** Powder rockets were weak and wasteful, so Goddard turned to liquids: gasoline for fuel and liquid oxygen as the **oxidizer**, pressurized and fed into a small combustion chamber. Many tests failed: chambers burned through, valves froze, engines would not light. On March 16, 1926, in a snow-covered field on his Aunt Effie's farm in Auburn, Massachusetts, his rocket finally rose. It flew for 2.5 seconds, climbed 41 feet and landed 184 feet away in a cabbage field. It was the first liquid-fueled rocket ever launched. Goddard went on to add gyroscope steering and better nozzles and received more than 200 patents. On July 17, 1969, as Apollo 11 flew to the Moon, the same newspaper printed a correction admitting that a rocket can indeed work in a vacuum.

**The physics.** A rocket works by Newton's third law: it throws mass backward at high speed, and the mass pushes the rocket forward. It does not need air to push against; in fact it works best in a vacuum, where there is no air to slow it. Going straight up, the **net force** is thrust minus weight, and Newton's second law gives the acceleration:  $a = (\text{thrust} - \text{weight}) \div \text{mass}$ . A water rocket with a mass of 0.5 kg weighs  $0.5 \times 9.8 = 4.9$  N. If its thrust is 30 N, the net force is  $30 - 4.9 = 25.1$  N, and  $a = 25.1 \div 0.5 \approx 50 \text{ m/s}^2$ ,

about five times gravity. You can estimate how high a rocket went from its total flight time: it spends about half the time going up, so height  $\approx 9.8 \times (\text{flight time})^2 \div 8$ . A flight of 4 seconds means about  $9.8 \times 16 \div 8 \approx 20$  m (this ignores air drag, so the real height is a little less).

**The engineering.** Rocket engineers fight weight at every turn, because every kilogram of structure is a kilogram less of fuel or payload. They shape the nozzle to speed the exhaust as much as possible, cool the engine walls with the fuel itself, steer by swiveling the engine, and stack rockets in stages so that empty tanks are dropped. And they test, again and again, on the ground before flight, as Goddard did. The Saturn V that carried Apollo 11 to the Moon burned liquid oxygen with a liquid fuel, the same basic arrangement Goddard first flew into a cabbage field.

## PICTURE STUDY



*Robert Goddard and His Rocket*, Esther C. Goddard (attributed), March 1926 · Photograph · NASA  
Image: [Wikimedia Commons](#), public domain

This photograph shows Goddard beside his first liquid-fueled rocket in its launch frame in March 1926. The rocket is the small part at the top; the long pipes below carried fuel and oxygen up to the motor.

### Look closely

- Find the rocket motor at the top of the frame. Unusually, the motor is at the front, pulling the tanks behind it.
- Find the tanks at the bottom.
- Find the pipes connecting the tanks to the motor.
- Look at the snow and the frame. Why launch in an empty field?

### Talk about it

1. Why did Goddard use liquid oxygen instead of air?
2. What forces act on this rocket at the moment it leaves the frame?
3. Why do you think later rockets put the motor at the bottom?

**Safety first.** Launch only outdoors in a large open field with an adult in charge, far from people, buildings, trees, roads and power lines. Everyone wears safety glasses and stands at least 10 meters back. Only the adult pumps and releases. Use only plastic soda bottles made for carbonated drinks, never glass, and never pump above 60 psi. Never stand over the rocket or aim it at anyone. If a launch fails, wait, release the pressure by pulling the stopper with a string from a distance, and then approach. Model rocket motors are only for adults following the National Association of Rocketry safety code.

## BUILD

### A Water Rocket Fair Test

You will build a rocket from a 2-liter soda bottle, launch it with water and air pressure from a bicycle pump, and run a fair test to find the amount of water that makes it fly highest. You will calculate each flight's height from its flight time.

#### You will need

- A 2-liter plastic soda bottle, card stock for fins and a nose cone, and duct tape
- A rubber stopper or cork that fits the bottle, with a needle inflation adapter pushed through it (an adult makes the hole)
- A bicycle pump with a pressure gauge
- A launch stand: a wire crate, a ring of bricks or a few stakes to hold the bottle upright, nose up
- A measuring cup, two stopwatches, safety glasses for everyone, and the engineer's notebook

#### Steps

1. **Build.** Tape three or four card fins evenly around the bottle near its mouth (which will point down), and a cone on the bottom of the bottle (which will point up). Check that the rocket stands straight on its fins.
2. **Predict.** Which will fly highest: 250 mL, 500 mL or 750 mL of water? Why might too much or too little be worse?
3. **Launch 1.** Pour in 500 mL of water. The adult inserts the stopper, sets the rocket on the stand, and everyone moves back at least 10 meters. The adult pumps to exactly 40 psi (read the gauge) and releases. Two timers time the flight from launch to landing.
4. Average the two times. Calculate height  $\approx 9.8 \times \text{time}^2 \div 8$ .
5. **Fair test.** Launch with 250 mL and 750 mL of water, at the same 40 psi, three launches for each amount.

6. Make a table: water volume, flight times, average time, calculated height. Graph height against water volume.
7. **Calculate.** Weigh your empty rocket. For your best launch, estimate the starting mass (rocket plus water: 1 mL of water = 1 g) and its weight in newtons.
8. **Improve.** Change one design detail (fin size, nose weight of a little clay, fin angle) and launch three more times with the best water amount. Did the height or the straightness of the flight improve?

#### Tips

- Some water must be in the bottle: it is the reaction mass the rocket throws backward. Air alone gives a short, weak flight.
- A little clay in the nose cone moves the center of gravity forward and makes the rocket fly straighter.
- Wind blows rockets off course; launch on a calm day, and launch straight up.

#### Check your work

- ☐ I can explain why a rocket works in empty space.
- ☐ I can calculate a rocket's net force and acceleration.
- ☐ I can calculate a launch height from flight time and explain my fair test.

#### ENGINEER'S NOTEBOOK

1. Draw Goddard's 1926 rocket with labels for the combustion chamber, nozzle, fuel and oxygen tanks, and the direction of thrust.
2. Graph height against water volume for your launches and circle the best amount.
3. Work it: a model rocket has a mass of 0.1 kg and its motor gives 6 N of thrust. What is its acceleration as it leaves the pad?  $((6 - 0.98) \div 0.1 \approx 50 \text{ m/s}^2)$

**From history.** Goddard died in 1945, twelve years before the first satellite reached orbit. NASA's Goddard Space Flight Center in Maryland, opened in 1959, is named for him, and the field in Auburn where his first liquid-fueled rocket flew is marked with a monument.

#### COMMON MISTAKES

- Thinking a rocket pushes against the air. It pushes against its own exhaust, and works even better in a vacuum.



- Forgetting to subtract the rocket's weight from the thrust before using  $F = ma$ .
- Changing the pressure and the water amount at the same time.

**Make it a game · Net Force Countdown.** Your parent calls out a rocket's weight and thrust, such as 10 newtons and 18 newtons. Calculate the net force and acceleration. Do five rounds. Then explain why a rocket works in empty space with Newton's second and third laws. Add one fact about Goddard's liquid-fueled flight. Beat your best total.

## UNIT 7

# FLIGHT

In Grade 5 you followed the Wright brothers from kites to the first flight. This year you will measure lift yourself, on a kitchen scale in front of a box fan, and learn the formula that tells an aircraft designer how big a wing must be. You will see why the correct explanation of lift includes both lower pressure above the wing and air turned downward, and why the old “equal transit time” story is wrong.

Then you will learn how a pilot controls an airplane about three axes with ailerons, elevator and rudder; fly across the Atlantic with Charles Lindbergh, finding the way with only a compass, a clock and careful arithmetic; and stand in a snowy Massachusetts field with Robert Goddard as the first liquid-fueled rocket roars for two and a half seconds. Your own rocket, powered by water and air, will be launched outdoors with an adult.

### PREREQUISITES

- Knows the four forces of flight: lift, weight, thrust and drag (Grade 5)
- Knows Newton’s laws and  $F = ma$  (Unit 1)
- Can use a protractor to measure angles and a compass to find directions

### MASTERY CHECKLIST

- ☐ I can explain lift correctly, as pressure difference and air turned downward, and explain why the equal-transit-time story is wrong.
- ☐ I can use the lift equation to see how speed, wing area and angle of attack change lift.
- ☐ I can name the three axes of an airplane and the control surface for each, and explain how each one works.
- ☐ I can navigate by dead reckoning using heading, speed, time and wind.
- ☐ I can explain how a rocket works with Newton’s laws and calculate its acceleration and the height of a launch from its flight time.

## OPTIONAL KITS FOR THIS UNIT

- **Estes model rockets:** Ages 10 and up with an adult; motors must be handled and launched by an adult following the National Association of Rocketry safety code, outdoors in an open field. Beginner kits fit Lesson 7.4.
- **KiwiCo Tinker crates:** Ages 9 and up. Several crates build gliders, launchers and flying toys that extend Lessons 7.1–7.2; check each crate’s description.

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

|                                               |                          |
|-----------------------------------------------|--------------------------|
| <b>7.1 Lift: Pressure and Turning the Air</b> | 2 sessions of 50 minutes |
|-----------------------------------------------|--------------------------|

---

|                                                            |                          |
|------------------------------------------------------------|--------------------------|
| <b>7.2 Control Surfaces: Ailerons, Elevator and Rudder</b> | 2 sessions of 50 minutes |
|------------------------------------------------------------|--------------------------|

---

|                                                                         |
|-------------------------------------------------------------------------|
| <b>7.3 Lindbergh and Navigation: Dead Reckoning Across the Atlantic</b> |
|-------------------------------------------------------------------------|

2 sessions of 50 minutes

---

|                                                                |                          |
|----------------------------------------------------------------|--------------------------|
| <b>7.4 Goddard and Rockets: The First Liquid-Fueled Flight</b> | 2 sessions of 50 minutes |
|----------------------------------------------------------------|--------------------------|

---

## UNIT 7 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Explain in two or three sentences how a wing makes lift.

2. **6 pts**

What is wrong with the “equal transit time” explanation of lift?

3. **10 pts**

Calculate: using  $\text{lift} = \frac{1}{2} \times \text{density} \times \text{speed}^2 \times \text{area} \times \text{lift coefficient}$ , find the lift on a wing of  $10 \text{ m}^2$  flying at  $40 \text{ m/s}$  in air of density  $1.2 \text{ kg/m}^3$  with a lift coefficient of 0.6. What happens to the lift if the speed doubles?

4. (7 pts)

What is a stall?

5. (9 pts)

Name the three axes of an airplane and the control surface that controls each.

6. (8 pts)

Calculate: an elevator 6 m behind the center of gravity makes a force of 250 N. What torque does it produce?

7. (8 pts)

What problem did the Wrights find with wing warping in 1901, and how did they fix it?

8. (8 pts)

What is dead reckoning?

9. (10 pts)

Calculate: an airplane flies 3 hours heading due east at 110 miles per hour, with a 20-mile-per-hour wind blowing from the south. Where does it end up relative to its start?

10. (8 pts)

Why can a rocket work in space, where there is no air?

11. (10 pts)

Calculate: a rocket has a mass of 2 kg and its engine gives 60 N of thrust straight up. Find its weight, the net force and its acceleration. (Use  $9.8 \text{ m/s}^2$ .)

12. (8 pts)

Describe Goddard's flight of March 16, 1926, and why it mattered.

## ANSWER KEY

1. A wing at an angle of attack, often with camber, turns the passing air downward; by Newton's third law the air pushes the wing up. At the same time the air speeds up over the curved top and its pressure drops below the pressure underneath, and that pressure difference over the wing area is the lift.
2. It claims the air over the top must catch up with the air underneath at the back edge. Nothing makes that happen; tests show the air over the top arrives at the back sooner.
3.  $0.5 \times 1.2 \times 1,600 \times 10 \times 0.6 = 5,760$  N. Doubling the speed makes four times the lift (23,040 N).
4. A sudden loss of lift when the angle of attack is too large and the air stops flowing smoothly over the top of the wing.
5. Roll: ailerons. Pitch: elevator. Yaw: rudder.
6. Torque =  $250 \times 6 = 1,500$  N·m.
7. When they rolled into a turn, the raised wing's extra drag swung the nose the wrong way (adverse yaw), and the glider sometimes spun in. In 1902 they made the rudder movable and linked it to the wing warping.
8. Finding your position by starting from a known point and adding up the heading, speed and time traveled, with a correction for wind.
9. 330 miles east ( $110 \times 3$ ) and 60 miles north ( $20 \times 3$ ) of the start.
10. It pushes mass (its exhaust) backward, and by Newton's third law the exhaust pushes the rocket forward. It carries its own oxidizer, so it needs no air to burn or to push against.
11. Weight =  $2 \times 9.8 = 19.6$  N. Net force =  $60 - 19.6 = 40.4$  N. Acceleration =  $40.4 \div 2 = 20.2$  m/s<sup>2</sup>.
12. In Auburn, Massachusetts, his gasoline and liquid-oxygen rocket flew 2.5 seconds, rose 41 feet and landed 184 feet away. It was the first liquid-fueled rocket, the kind later used to reach space and the Moon.

## PORTFOLIO PIECE: A TESTED GLIDER WITH MEASURED CONTROLS

Design and build a glider from card, foam or balsa that flies at least 6 meters from a gentle hand launch. Use your wind-tunnel results from Lesson 7.1 to choose its wing angle and camber. Trim it to fly straight, then show that you can make it turn left, turn right, and fly a full circle using its control surfaces. Record at least three flights for each setting. Write a one-page report with a three-view drawing, your wind-tunnel graph, a table of flights, one torque or lift calculation, and what you would change.

| LOOK FOR                           | WHAT IT MEANS                                                                                 |
|------------------------------------|-----------------------------------------------------------------------------------------------|
| <b>Design</b>                      | A neat three-view drawing with wing area, center of gravity and control surfaces labeled.     |
| <b>Use of data</b>                 | Wing angle and shape chosen using wind-tunnel results, and the choice explained.              |
| <b>Fair testing</b>                | At least three flights per setting, with distance and direction recorded and averaged.        |
| <b>Control</b>                     | Showed straight flight, turns both ways and a circle, with the settings recorded.             |
| <b>Calculation and improvement</b> | One correct lift or torque calculation, and a specific improvement based on the test results. |

## ROBOTS, CODING AND INVENTION

Every robot senses, thinks and acts. This unit looks closely at each part. You will learn how motors and gear trains give a robot the right mix of speed and strength, the way NASA engineers geared the wheels of the Lunar Roving Vehicle. You will write programs with loops and conditionals, the two ideas Ada Lovelace described for Charles Babbage's Analytical Engine in 1843, and use them to make a sensor-driven light.

Then you will measure the speed of sound with echoes, as Isaac Newton did in a college courtyard, and learn how a robot's ultrasonic sensor uses the same idea to measure distance. Last, you will study how a drone flies, from NASA's little *Ingenuity* helicopter on Mars to the quadcopters people fly at home, measure the thrust of a motor and propeller, and learn the FAA's rules for flying safely. The year ends with the family engineering fair.

### PREREQUISITES

- Knows Ohm's law and has programmed a blink (Unit 4)
- Knows  $F = ma$ , work and power (Unit 1)
- Can measure time with a stopwatch and calculate  $\text{speed} = \text{distance} \div \text{time}$

### MASTERY CHECKLIST

- ☐ I can calculate a gear ratio and explain how it trades speed for turning force (torque).
- ☐ I can write a program with a loop and a conditional (if-then-else) and test it with a sensor.
- ☐ I can measure the speed of sound and use  $\text{distance} = \text{speed} \times \text{time} \div 2$  for an echo sensor.
- ☐ I can explain how a quadcopter climbs, tilts and turns, and calculate thrust-to-weight.
- ☐ I can state the main FAA rules for recreational drone flyers and explain why each one keeps people safe.

## OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** Ages 8 and up. Its built-in light, temperature and motion sensors fit Lesson 8.2, and an add-on ultrasonic sensor fits Lesson 8.3. MakeCode is free.
- **Makeblock mBot:** Ages 8 and up. A small wheeled robot with geared motors, an ultrasonic distance sensor and a line-follower sensor, programmed with blocks. Fits Lessons 8.1–8.3.
- **Ryze Tello:** For older students with an adult; about 80 grams, under the FAA’s 250-gram registration weight, and programmable with Scratch-style blocks. Fits Lesson 8.4. Flyers must still take the free FAA TRUST test.
- **CrunchLabs Build Box:** Ages 8 and up. Monthly toys designed by Mark Rober that show gears, linkages and motors in action; good for the capstone and the family engineering fair.

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 Motors and Gears: The Lunar Roving Vehicle

2 sessions of 50 minutes

### 8.2 Loops and Conditionals: From Ada Lovelace to MakeCode

2 sessions of 50 minutes

### 8.3 Distance Sensors: Echoes and the Speed of Sound

2 sessions of 50 minutes

### 8.4 Drone Basics and the FAA’s Rules: Ingenuity on Mars

2 sessions of 50 minutes

## UNIT 8 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **10 pts**

Calculate: a 12-tooth gear drives a 48-tooth gear. What is the gear ratio? If the motor turns at 2,400 rpm, how fast does the output turn, and what happens to the torque?



2. (8 pts)

Why did each wheel of the Lunar Roving Vehicle have its own motor and an 80 : 1 gear reduction?

3. (8 pts)

What is a loop and what is a conditional? Give an example of each from a machine at home.

4. (7 pts)

What did Ada Lovelace write in Note G, and why is it important?

5. (8 pts)

Predict: a night-light program turns on the light when the light level is below 100. The room at dusk reads between 95 and 105. What will happen, and how can an engineer fix it?

6. (8 pts)

How did Newton measure the speed of sound at Trinity College?

7. (10 pts)

Calculate: an ultrasonic sensor hears an echo 4.0 ms after its ping. Using 343 m/s for the speed of sound, how far away is the object?

8. (7 pts)

Name two kinds of objects an ultrasonic sensor may fail to detect, and say why.

9. (8 pts)

Explain how a quadcopter moves forward and how it turns (yaws).

10. (10 pts)

Calculate: a drone has a mass of 0.4 kg and its rotors give a total thrust of 7.0 N. Find its weight, its thrust-to-weight ratio and its upward acceleration.

11. (8 pts)

List four FAA rules for recreational drone flyers.

12. **8 pts**

Why did Ingenuity have to fly autonomously, and what made flying on Mars hard?

## ANSWER KEY

1. Ratio =  $48 \div 12 = 4 : 1$ . Output =  $2,400 \div 4 = 600$  rpm. Torque is about 4 times greater (less a little lost to friction).
2. Separate motors gave backup if one failed. The reduction turned the fast, weak motor speed into slow, strong wheel torque for climbing over rocks and craters.
3. A loop repeats instructions (a thermostat checking the temperature again and again). A conditional checks something and decides what to do (if it is too cold, turn on the heat; else turn it off).
4. A step-by-step method for Babbage's Analytical Engine to calculate the Bernoulli numbers, using repeated cycles (loops). It is often called the first published computer program.
5. The light will flicker on and off as the reading wobbles around 100. Fix it with two thresholds (hysteresis), such as on below 90 and off above 120.
6. He stamped at one end of the cloister in Neville's Court and timed the echo with a pendulum, adjusting its length so its swings matched the stamp and echo, then used the cloister's length and the time.
7. Distance =  $343 \times 0.004 \div 2 \approx 0.69$  m (69 cm).
8. Soft objects (they absorb sound), slanted surfaces (they reflect the echo away), very small or very close objects. Any two with reasons.
9. To move forward it speeds up its rear rotors so it tilts forward and part of the thrust pushes it ahead. To turn, it speeds up the pair of rotors spinning one way and slows the pair spinning the other way, so their twisting no longer cancels.
10. Weight =  $0.4 \times 9.8 = 3.92$  N. Ratio =  $7.0 \div 3.92 \approx 1.8$ . Acceleration =  $(7.0 - 3.92) \div 0.4 = 7.7$  m/s<sup>2</sup>.
11. Any four: pass TRUST and carry proof; register drones of 250 g or more; fly at or below 400 feet in uncontrolled airspace; keep the drone in visual line of sight; get authorization in controlled airspace near airports; do not fly over people or moving vehicles; do not interfere with emergency response.
12. Radio signals take minutes to reach Mars, too slow for live control. The Martian air is only about 1% as dense as Earth's, so the rotors had to be large, light and spin very fast.

## PORTFOLIO PIECE: A SENSE-THINK-ACT MACHINE FOR THE FAMILY ENGINEERING FAIR

Design and build a small machine that senses, decides and acts: for example, a geared winch that lifts a flag when it gets dark, a cardboard robot vehicle that stops before it hits a wall, or a micro:bit alarm that sounds when a door opens. (If you have no microcontroller, use a switch as the sensor and a simple circuit as the decision.) Measure at least one thing about it, such as its gear ratio and lifting speed, its sensor threshold, or its stopping distance. Present it at the family engineering fair with your best build from each unit and their notebook pages, and explain one calculation to your guests.

| LOOK FOR                       | WHAT IT MEANS                                                                                                         |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| <b>Sense, think, act</b>       | The machine has a clear sensor (or switch), a decision (program or circuit) and an action, each labeled in a diagram. |
| <b>Measurement</b>             | At least one measured quantity recorded with units and used in a calculation.                                         |
| <b>Testing and improvement</b> | The machine was tested, a problem found, and one improvement made and retested.                                       |
| <b>Notebook</b>                | Dated pages with sketches, program or circuit diagram, data table and conclusions.                                    |
| <b>Presentation</b>            | At the fair, the student explains how the machine works and walks a guest through one calculation clearly.            |

## 8.1 MOTORS AND GEARS: THE LUNAR ROVING VEHICLE

### OBJECTIVES

- Calculate a gear ratio from tooth counts or pulley sizes.
- Explain how a gear reduction trades speed for torque, and calculate output speed.
- Build a motor-driven winch with and without a reduction belt, and measure the load it can lift and how fast.

**Warm-up.** Ride a bicycle with gears, or turn the pedals of an upside-down bicycle by hand. Try the lowest gear and then the highest. Which is easier to start? Which makes the wheel go farther per turn of the pedals?

### WATCH

#### How do Gear Ratios Work?

Concerning Reality • 4:15

<https://www.youtube.com/watch?v=mLu6rLz-MjQ>

### WHEN TO WATCH

After the physics paragraph. Pause at each ratio and work it out first.

### KEY TERMS

#### **gear ratio**

The number of teeth on the driven gear divided by the number on the driving gear (or the ratio of pulley sizes).

#### **gear reduction**

A gear train that makes the output turn slower but with more torque than the motor.

#### **actuator**

The part of a robot that makes it move, such as a motor.

#### **torque**

Turning force:  $\text{force} \times \text{distance from the axle}$ , in newton-meters.

#### **rpm**

Turns per minute: how many full turns a shaft makes in one minute.

#### **harmonic drive**

A compact gear system with a flexible toothed ring that gives a very large reduction in a small space.

## CORE IDEAS

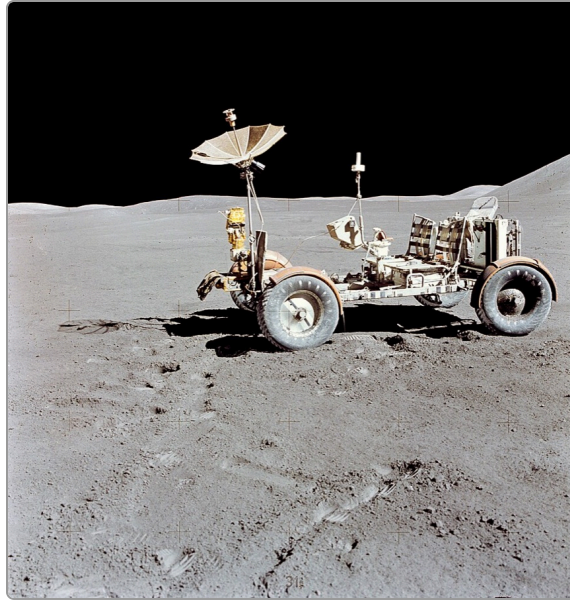
**The story.** On July 31, 1971, astronauts Dave Scott and Jim Irwin of Apollo 15 unfolded a strange car from the side of their lunar module and drove it across the Moon. The Lunar Roving Vehicle, built by Boeing with General Motors' Delco division, had to weigh only about 210 kilograms on Earth, fold up like a deck chair to fit into the lander, run on batteries, and carry two astronauts and their tools over dust, rocks and craters where no repair shop existed. Over three missions, rovers carried astronauts about 90 kilometers across the Moon.

**How they figured it out.** The engineers gave each of the four wheels its own small electric motor, so the rover could keep going even if one failed. But a small electric motor spins fast and has little torque, while a wheel climbing out of a crater needs to turn slowly with great force. Their answer was a **harmonic drive** inside each wheel, a compact gear system with a reduction of 80 to 1. They tested wheels of woven steel wire on simulated lunar soil, and built test rovers to drive on Earth. Everything was designed with backups: if a wheel's drive failed, it could be disconnected so the rover rolled on three.

**The physics.** A motor gives a certain power, and  $\text{power} = \text{torque} \times \text{turning speed}$ . A gear train cannot add power, but it can trade speed for torque. The **gear ratio** is the driven gear's teeth  $\div$  the driving gear's teeth. A 10-tooth gear driving a 40-tooth gear has a ratio of 4 : 1, so the output turns 4 times slower with about 4 times the torque (less a little lost to friction). The rover's motors turned thousands of times a minute. At 6,000 rpm, after the 80 : 1 reduction, a wheel turns  $6,000 \div 80 = 75$  rpm. A wheel about 0.8 m across goes about 2.5 m each turn ( $\pi \times \text{diameter}$ ), so  $75 \text{ rpm} \times 2.5 \text{ m} \approx 190$  m per minute, about 11 km/h, close to the rover's top speed.

**The engineering.** Robot designers choose the motor and gear ratio together. A robot arm that lifts heavy parts slowly needs a large reduction; a fast-spinning drone propeller needs none. Too little reduction and the motor stalls under load; too much and the robot crawls. Engineers also add encoders, sensors that count the motor's turns, so the robot knows how far it has moved, and they build in backups, as the rover's engineers did. The robot's brain decides what to do, but its gears decide what it can do.

## PICTURE STUDY



*The Lunar Roving Vehicle on the Moon, NASA (Apollo 15 crew), August 1971 · Photograph · NASA*

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

This photograph shows the Lunar Roving Vehicle on the Moon during Apollo 15 in 1971. Each of its four wheels has its own motor and gearbox hidden inside the hub.

### Look closely

- Find the wheels. They are woven steel wire, not rubber. Why?
- Find the hubs where the motors and harmonic drives are hidden.
- Find the dish antenna and camera. What were they for?
- Look at the tire tracks in the dust.

### Talk about it

1. Why give each wheel its own motor?
2. Why would the rover need a large gear reduction to climb out of a crater?
3. What would happen to an ordinary rubber tire on the Moon?

**Safety first.** Batteries only. Keep fingers and hair away from the spinning motor and belt, and do not let the motor run stalled for more than a few seconds; it gets hot.

## BUILD

### Geared Winch: Speed versus Strength

You will build a winch driven by a small hobby motor and test it two ways: with the string wound straight onto the motor shaft, and with a rubber-band belt from a small pulley to a big one. You will measure how much each can lift and how fast, and compare your results with the gear ratio.

#### You will need

- A small hobby motor (1.5–3 V), a 2 × AA battery holder and clip leads
- A small pulley for the motor shaft (a bead, a short piece of tubing or a thread spool) and a large pulley (a jar lid or a CD with a dowel axle)
- A rubber band for the belt, a dowel or pencil axle, tape, cardboard and a box to mount everything
- String, a paper cup and pennies (2.5 g each)
- A ruler, a stopwatch and the engineer's notebook

#### Steps

1. **Direct drive.** Tape the string to the motor shaft and the cup to the string. Mount the motor at the edge of a table. Add pennies until the motor can no longer lift the cup off the floor. Record the most it could lift, then time how long it takes to lift a 10-penny load 50 cm.
2. **Measure the ratio.** Measure the diameter of the small and large pulleys. The ratio is  $\text{large} \div \text{small}$  (for example,  $6 \text{ cm} \div 0.6 \text{ cm} = 10 : 1$ ).
3. **Predict.** With the belt reduction, how much more should it lift, and how much slower should it go?
4. **Geared drive.** Mount the large pulley on its axle, run the rubber-band belt from the motor pulley to the large pulley, and tape the string to the large pulley's axle. Repeat both tests: the most it can lift, and the time to lift 10 pennies 50 cm.
5. Make a table: setup, ratio, maximum load, time to lift 10 pennies, speed (cm/s).



6. Calculate the power used to lift the 10 pennies each way:  $(\text{mass in kg} \times 9.8 \times 0.5 \text{ m}) \div \text{time}$ . Were they about the same? Why might one be lower?
7. **Improve.** Change the ratio (a bigger or smaller big pulley) to lift a 60-penny load as quickly as possible. Test and explain your choice.

#### Tips

- The string should wind onto a thin axle; a thick drum acts like a bigger wheel and reduces the force.
- A slipping belt wastes the reduction. A slightly smaller rubber band, or a dab of rosin or glue on the pulley rims, helps.
- Lifting the same weight the same height is the same work; only the time (power) changes.

#### Check your work

- ☐ I can calculate a gear ratio.
- ☐ I can explain how a reduction trades speed for torque.
- ☐ I can use my data to choose a gear ratio for a job.

#### ENGINEER'S NOTEBOOK

1. Draw your winch in both setups, labeling the motor, pulleys, belt, axle and load, with the ratio written in.
2. Make the data table and a bar graph of maximum load for each setup.
3. Work it: a robot motor turns at 3,000 rpm and drives a wheel through a 50 : 1 gearbox. How fast does the wheel turn? (60 rpm.) If the wheel goes 0.3 m each turn, how far does the robot go in a minute? (18 m.)

**From history.** The three Apollo rovers are still parked on the Moon where the astronauts left them. On Earth, Mars rovers such as *Curiosity* and *Perseverance* use the same ideas: a separate motor and gearbox for each of six wheels, so the rover can keep driving if one fails.

#### COMMON MISTAKES

- Thinking gears create extra power. They trade speed for torque; friction always takes a little power away.
- Turning the ratio upside down. A small gear driving a big one slows the output and increases torque.

- Letting the motor run stalled, which wastes the battery and heats the motor.

**Make it a game · Gear Ratio Challenge.** Your parent draws two gears with 12 and 36 teeth. Calculate the gear ratio and the output speed for a 60 rpm input, and say what happens to torque. Race through five different pairs. Then explain why the Lunar Roving Vehicle needed gear reduction. Perfect rounds earn a bonus point.

## 8.2 LOOPS AND CONDITIONALS: FROM ADA LOVELACE TO MAKECODE

### OBJECTIVES

- Explain what a loop and a conditional (if-then-else) are, with examples from everyday machines.
- Describe Ada Lovelace's program for the Analytical Engine and why it matters.
- Write and test a sensor-controlled program with a loop and a conditional, and choose its threshold from measured data.

**Warm-up.** Write the instructions for brushing your teeth as if for a robot. Where do you repeat something (a loop)? Where do you check something and decide (an if)? Circle each one.

### WATCH

#### How to use micro:bit light sensor | Tutorial #6

Science Buddies • 5:44

[https://www.youtube.com/watch?v=tfk9F09I\\_5Y](https://www.youtube.com/watch?v=tfk9F09I_5Y)

### WHEN TO WATCH

Before the build. Follow along in MakeCode or the simulator.

### BACKUP VIDEO

#### The Story of Ada Lovelace: The World's First Computer Programmer

IET - Institution of Engineering and Technology • 2:45

<https://www.youtube.com/watch?v=J7ITqnEmf-g>

After the story, for more on Ada Lovelace and the Analytical Engine.

### KEY TERMS

#### **algorithm**

A step-by-step method for solving a problem.

#### **loop**

Instructions that repeat, either forever, a set number of times, or until something becomes true.

**conditional**

An instruction that checks whether something is true and does one thing if it is and another if it is not (if-then-else).

**variable**

A named place in a program that stores a number or word that can change.

**threshold**

The value at which a program switches from one action to another.

**bug**

A mistake in a program.

**CORE IDEAS**

**The story.** In the 1830s the English mathematician Charles Babbage designed the Analytical Engine, a steam-powered calculating machine that would read instructions from punched cards, as the Jacquard loom read weaving patterns. It was never finished, but in 1843 Ada Lovelace, a gifted young mathematician and Babbage's friend, translated an Italian engineer's article about it and added her own notes, three times longer than the article. In the last, Note G, she wrote out step by step how the Engine could calculate a series of numbers called the Bernoulli numbers. It is often called the first published computer program.

**How they figured it out.** Lovelace saw that the Engine did not need a new set of cards for every step. Some operations could be repeated in a **cycle**, which we now call a **loop**, and the Engine could test a result and take a different path depending on it, which we now call a **conditional**. She laid out her program as a table showing every operation and every variable at each step, and her notes even caught a mistake in Babbage's own figures: an early example of debugging. She also saw further than almost anyone of her time, writing that such a machine might one day work with music and other symbols, not only numbers.

**The physics.** A computer is an electrical machine that follows instructions very fast. A loop lets a few lines of code repeat millions of times. A conditional lets the machine respond to the world: **if** the sensor reading is below a threshold, **then** turn on the light, **else** turn it off. The micro:bit can measure light with its LED screen, giving a number from 0 (dark) to 255 (bright). Choosing the threshold is an engineering decision made from measurements: if a dim room reads 40 and a bright room reads 180, a threshold near the middle, about 110, separates them clearly. A

program that checks the sensor 10 times a second (a 100 ms pause in the loop) makes 36,000 checks an hour.

**The engineering.** Almost every machine with a computer in it is a loop with conditionals inside: a thermostat checks the temperature again and again and turns on the heat **if** it is too cold; a washing machine fills **until** the water reaches a level; a traffic light waits **until** a car is detected. Engineers test programs at the edges, the values right at the threshold, because that is where bugs hide. They add a small gap, called hysteresis, so that a light near the threshold does not flicker on and off.

## PICTURE STUDY

Diagram for the computation by the Engine of the Numbers of Bernoulli. See Note G. (page 722 of *esp.*)

| Number of Operations. | Variables used. | Variables receiving results. | Statement of Results.     | Data. |       |       |       |       |       |       |       |       |          | Working Variables. |       |       |       |       |       | Result Variables. |       |       |          |
|-----------------------|-----------------|------------------------------|---------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|--------------------|-------|-------|-------|-------|-------|-------------------|-------|-------|----------|
|                       |                 |                              |                           | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $y_1$              | $y_2$ | $y_3$ | $y_4$ | $y_5$ | $y_6$ | $y_7$             | $y_8$ | $y_9$ | $y_{10}$ |
| 1                     | $\times$        | $x_1 \times x_2$             | $x_3 = x_1 \times x_2$    | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 2                     | +               | $x_1 + x_2$                  | $x_4 = x_1 + x_2$         | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 3                     | +               | $x_1 + x_2$                  | $x_5 = x_1 + x_2$         | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 4                     | +               | $x_1 + x_2$                  | $x_6 = x_1 + x_2$         | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 5                     | +               | $x_1 + x_2$                  | $x_7 = x_1 + x_2$         | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 6                     | +               | $x_1 + x_2$                  | $x_8 = x_1 + x_2$         | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 7                     | +               | $x_1 + x_2$                  | $x_9 = x_1 + x_2$         | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 8                     | +               | $x_1 + x_2$                  | $x_{10} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 9                     | +               | $x_1 + x_2$                  | $x_{11} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 10                    | $\times$        | $x_1 \times x_2$             | $x_{12} = x_1 \times x_2$ | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 11                    | +               | $x_1 + x_2$                  | $x_{13} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 12                    | +               | $x_1 + x_2$                  | $x_{14} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 13                    | +               | $x_1 + x_2$                  | $x_{15} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 14                    | +               | $x_1 + x_2$                  | $x_{16} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 15                    | +               | $x_1 + x_2$                  | $x_{17} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 16                    | $\times$        | $x_1 \times x_2$             | $x_{18} = x_1 \times x_2$ | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 17                    | +               | $x_1 + x_2$                  | $x_{19} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 18                    | +               | $x_1 + x_2$                  | $x_{20} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 19                    | +               | $x_1 + x_2$                  | $x_{21} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 20                    | $\times$        | $x_1 \times x_2$             | $x_{22} = x_1 \times x_2$ | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 21                    | $\times$        | $x_1 \times x_2$             | $x_{23} = x_1 \times x_2$ | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 22                    | +               | $x_1 + x_2$                  | $x_{24} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 23                    | +               | $x_1 + x_2$                  | $x_{25} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 24                    | +               | $x_1 + x_2$                  | $x_{26} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |
| 25                    | +               | $x_1 + x_2$                  | $x_{27} = x_1 + x_2$      | 1     | 2     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0        | 0                  | 0     | 0     | 0     | 0     | 0     | 0                 | 0     | 0     | 0        |

Here follows a repetition of Operations thirteen to twenty-seven.

Ada Lovelace's Diagram for the Bernoulli Numbers, Ada Lovelace, 1843 · Printed table

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

This is the table from Note G of Ada Lovelace's 1843 notes. Each row is one step for the Analytical Engine. Near the bottom, a line explains that a group of operations is to be repeated: a loop.

### Look closely

- Find the first column. It numbers each operation, like line numbers in a program.
- Find the column of operations ( $\times$ ,  $-$ ,  $+$ ,  $\div$ ).
- Find the columns for variables, the Engine's stored numbers.
- Find the line near the bottom that says operations are repeated.

### Talk about it

1. Why is a loop so useful in this program?
2. Where in the table would the Engine need to make a decision?
3. How is this table like the flowchart of your night-light program?

## BUILD

### A Smart Night-Light

You will measure light levels in your home with a micro:bit (or the MakeCode simulator's light slider), choose a threshold from your data, and write a program with a loop and a conditional that turns on a light when it gets dark. Then you will improve it so it does not flicker at dusk.

#### You will need

- A BBC micro:bit and USB cable, or a computer with the free MakeCode simulator ([makecode.microbit.org](https://makecode.microbit.org))
- A battery pack for the micro:bit (optional, to carry it around)
- A flashlight and a box or cloth to make it dark
- Engineer's notebook

#### Steps

1. **Measure.** Write a short program: forever, show number (light level), pause 500 ms. Download it and record the light level in at least five places: a sunny window, a lit room, a dim hallway, under a cloth, and with a flashlight shining on it.
2. Make a table of places and readings. Choose a threshold between “dim” and “lit” and explain your choice.
3. **Predict.** What will happen if you choose a threshold right at the dim-hallway reading?
4. **Program.** Write: forever: if light level < threshold then show all LEDs (show icon of a filled square) else clear screen; pause 100 ms.
5. **Test.** Test it in each place from your table. Then test it slowly: cover the micro:bit gradually with your hand and watch the moment it switches. Does it flicker?
6. **Add a loop count.** Add a variable that counts how many times the light has turned on. Show it when button A is pressed.
7. **Improve.** Fix the flicker with two thresholds: turn on below one number (say 90) and off only above a higher one (say 130). Test again at dusk-level light

and record the difference.

### Tips

- In the simulator, drag the light-level slider on the micro:bit picture to test.
- Change one number at a time and test again. Save working versions.
- Read your program aloud as a sentence: “Forever, if it is dark, then light up, else turn off.”

### Check your work

- ☐ I can explain a loop and a conditional with examples.
- ☐ I can choose a threshold from measured data.
- ☐ I can describe Ada Lovelace’s program and why it matters.

## ENGINEER’S NOTEBOOK

1. Draw a flowchart of your night-light program, with a diamond for the if-then-else decision and an arrow back to the start for the loop.
2. Record your light-level table and mark your chosen threshold on a number line from 0 to 255.
3. Work it: a loop checks a sensor every 50 ms. How many checks does it make in one minute? ( $60,000 \text{ ms} \div 50 \text{ ms} = 1,200$ .)

**From history.** In 1980 the U.S. Department of Defense named a new programming language Ada in Lovelace’s honor. Babbage’s simpler Difference Engine No. 2 was finally built from his drawings by the Science Museum in London in 1991, and it worked, proving his designs were sound.

## COMMON MISTAKES

- Putting the decision outside the loop, so it is checked only once.
- Choosing a threshold without measuring, so the light comes on in the wrong conditions.
- Forgetting the pause in a loop, so the program checks thousands of times a second and is hard to watch or debug.

**Make it a game • If Then Else Game.** Act out a smart night-light. Your parent is the room, saying "dark" or "bright" at random. You respond according to a threshold, with a loop that keeps checking. Write the rule as if-then-else on paper. Then fix any bug your parent plants. Add one fact about Ada Lovelace's program.



## 8.3 DISTANCE SENSORS: ECHOES AND THE SPEED OF SOUND

### OBJECTIVES

- Describe how Isaac Newton measured the speed of sound with echoes.
- Use  $\text{distance} = \text{speed} \times \text{time} \div 2$  to explain how an ultrasonic distance sensor works.
- Measure the speed of sound outdoors by the echo-clap method, and test a distance sensor if one is available.

**Warm-up.** Stand in a hallway or stairwell and clap once. Do you hear an echo? Now stand in a room with soft furniture and clap. Write down why you think the echo is different.

### WATCH

#### Professor Val Gibson recreates Newton's famous speed of sound experiment in Neville's Court

Trinity College, Cambridge · 2:53

<https://www.youtube.com/watch?v=Gy7HqToiBvo>

### WHEN TO WATCH

After the story. Watch how the team times the echo in the same cloister Newton used.

### BACKUP VIDEO

#### Speed of sound activity - Measure the echo - Homemade Science with Bruce Yeany

Homemade Science with Bruce Yeany · 4:55

<https://www.youtube.com/watch?v=J97YSCnU4KM>

Before the build. This is exactly the clap-and-echo method you will use.

### KEY TERMS

#### **echo**

A sound reflected back from a surface.

#### **speed of sound**

How fast sound travels; in air at room temperature, about 343 meters per second.

**ultrasound**

Sound too high-pitched for people to hear, above about 20,000 vibrations per second.

**ultrasonic sensor**

A sensor that sends out a short ultrasonic ping and times the echo to find the distance to an object.

**sonar**

Using sound echoes underwater to find objects and measure depth.

**CORE IDEAS**

**The story.** In the 1680s Isaac Newton, working at Trinity College, Cambridge, wanted to test his calculation of how fast sound travels. Trinity's Nevile's Court has a long covered walk, a cloister, along one side. Newton stood at one end, stamped his foot and listened for the echo off the far end. He timed it with a pendulum, adjusting the pendulum's length until its swings matched the stamp and the returning echo, and from the length of the cloister and the time he worked out the speed. His measurement and his calculation did not quite agree, and Newton honestly wrestled with the difference; later scientists showed that his calculation had left out the warming of air as sound squeezes it.

**How they figured it out.** The key idea is that the echo travels to the wall and back, twice the distance. Newton could not time something so fast with a clock, so he used a repeating rhythm and made the rhythm match the echo, much as you will with claps. Later experimenters timed the flash of a distant cannon against its sound across many kilometers. By 1738 French scientists had measured the speed of sound in air quite accurately in this way. Today we know it is about 331 m/s at 0 °C and about 343 m/s at 20 °C: it is faster in warm air.

**The physics.** If sound travels to a wall and back in a time  $t$ , the distance to the wall is **distance = speed  $\times$  time  $\div$  2**. An **ultrasonic sensor** sends out a short ping of sound at about 40,000 vibrations per second, far too high for us to hear, and listens for the echo. If the echo returns after 5.8 milliseconds, the object is  $343 \times 0.0058 \div 2 \approx 0.99$  m away. Bats find insects in the dark in the same way. In 1794 the Italian priest and scientist Lazzaro Spallanzani showed that blinded bats could still fly through a room strung with wires, but bats with plugged ears could not, though no one then knew they were using sounds too high to hear.

**The engineering.** Ultrasonic sensors help robots avoid walls, help cars park, and measure the level of liquid in tanks. Ships use **sonar** (sound waves in water, which travel about 1,500 m/s) to measure depth. Engineers must allow for the sensor's limits: soft or slanted surfaces may not echo back, very close objects may be missed, and the speed of sound changes with temperature, so precise sensors measure the air temperature too. Many robots combine an ultrasonic sensor with other sensors, such as infrared or cameras, so that one sensor's blind spot is covered by another.

## PICTURE STUDY



*Nevile's Court, Trinity College, Cambridge, Unknown photographer, About 1870 · Photograph*

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

This photograph shows Nevile's Court at Trinity College, Cambridge, where Isaac Newton lived and worked. He timed echoes in a cloister of this court to measure the speed of sound.

### Look closely

- Find the covered walk, the cloister, along the ground floor.
- Imagine standing at one end and stamping. Where would the echo come from?
- Look at the hard stone surfaces. Why do they make strong echoes?
- Find the lawn. Would it echo as well?

### Talk about it

1. If the cloister were 70 m long, how long would the echo take to return? ( $2 \times 70 \div 343 \approx 0.41$  s.)
2. Why did Newton use a pendulum instead of a clock?
3. Why would soft surfaces make the experiment harder?

**Safety first.** Do the echo test in a schoolyard, park or empty lot with an adult, never near a street or parking area. Don't clap at people's ears. If you use an ultrasonic sensor, power it only from the micro:bit or Arduino over USB or its battery pack.

## BUILD

### Clap and Echo: Measuring the Speed of Sound

You will stand a measured distance from a large flat wall and clap in rhythm with the echo, as Newton matched his pendulum to his echo. From the distance and the time for twenty claps you will calculate the speed of sound. If you have a micro:bit or Arduino and an ultrasonic sensor, you will also test how accurately it measures distance.

#### You will need

- A large flat wall with open ground in front of it (the side of a school, church hall or gym), at least 50 meters away
- A long tape measure, or a trundle wheel, or a measured stride
- Two stopwatches and a helper
- A thermometer (or the day's temperature from a weather report)
- Optional: a micro:bit or Arduino with an HC-SR04 ultrasonic sensor, a ruler and a book to use as a target

#### Steps

1. **Measure.** Measure your distance from the wall carefully, at least 50 m (more is better). Record the temperature.
2. **Predict.** Using 343 m/s, how long should the echo take to return from your distance? (time =  $2 \times \text{distance} \div 343$ .)
3. **Find the rhythm.** Clap once and listen for the echo. Now clap again exactly when you hear each echo, so claps and echoes fall together in a steady rhythm.
4. **Time it.** When the rhythm is steady, your helper starts the stopwatch on one clap and stops it on the twenty-first, timing 20 intervals. Do five trials.
5. Calculate: each interval is one round trip, so speed =  $(2 \times \text{distance} \times 20) \div \text{time}$ . Average your five trials.
6. Compare your result with  $331 + 0.6 \times (\text{temperature in } ^\circ\text{C})$ , the expected speed for that day. Calculate your percent error.

7. **Optional sensor test.** Program the sensor to show distance in centimeters. Point it at a book at 10, 30, 60 and 100 cm, measured with a ruler. Record the sensor reading against the true distance. Then try a soft pillow and a book held at a slant.
8. **Improve.** Find your biggest source of error (reaction time, distance, rhythm) and change your method to reduce it. Test again.

#### Tips

- A wooden clapper (two boards slapped together) makes a sharper sound than hands.
- Timing 20 intervals instead of one spreads your reaction-time error over many echoes, just as Newton's pendulum did.
- Trees and other buildings make extra echoes; choose a spot where the wall is the only big surface in front of you.

#### Check your work

- ☐ I can explain how Newton used echoes to measure the speed of sound.
- ☐ I can calculate a distance from an echo time.
- ☐ I can explain the limits of an ultrasonic sensor.

#### ENGINEER'S NOTEBOOK

1. Draw your setup from above with the distance, the path of the sound to the wall and back, and your measured time.
2. Make a table of your five trials and the calculated speeds, with the average and percent error.
3. Work it: an ultrasonic sensor hears an echo after 2.0 ms. How far away is the object? ( $343 \times 0.002 \div 2 \approx 0.34$  m, or 34 cm.)

**From history.** After the *Titanic* sank in 1912, the Canadian inventor Reginald Fessenden built an underwater sound oscillator, and in 1914 he showed it could detect an iceberg by its echo about two miles away. His work led to sonar, which ships and submarines still use, and to the echo sounders that measure the depth of every harbor.

#### COMMON MISTAKES

- Forgetting to divide by 2. The echo time covers the trip there and back.
- Timing a single echo. Human reaction time is too slow; time many intervals.

- Expecting the sensor to see soft, slanted or tiny objects. They may not echo back toward the sensor.

**Make it a game • Echo Estimate.** Stand facing a far wall, clap, and have your parent time the echo with a stopwatch. Calculate the distance with speed times time divided by two, using about 343 meters per second. Predict first. Closest wins. Explain how an ultrasonic sensor works, and tell how Isaac Newton measured the speed of sound.

**Scripture.** “He that planted the ear, shall he not hear? he that formed the eye, shall he not see?” (Psalm 94:9, KJV)

Our sensors are copies of the senses God designed: ears that hear echoes, eyes that see light. The bat’s sonar was working long before ours.

## 8.4 DRONE BASICS AND THE FAA'S RULES: INGENUITY ON MARS

### OBJECTIVES

- Explain how a quadcopter climbs, hovers, tilts and turns by changing the speeds of its rotors.
- Calculate weight, thrust and thrust-to-weight ratio, and measure the thrust of a motor and propeller.
- State the FAA's main rules for recreational drone flyers and explain how each keeps people safe.

**Warm-up.** Hold a sheet of paper flat and drop it, then crumple it and drop it. Now imagine a helicopter in air one hundred times thinner than ours. What would its blades have to do to lift it? Write a guess.

### WATCH

#### HOW DO DRONES FLY?

The Travelling Scientist (Jesse Crowe) · 3:20

<https://www.youtube.com/watch?v=6Bc2nuOuRjM>

#### WHEN TO WATCH

After the physics paragraph. Pause at each rotor diagram and predict which way the drone will move.

**Note:** A small, independent science channel; chosen because it explains rotor speeds clearly with a real drone.

---

### BACKUP VIDEO

#### FAA TRUST Recreational Test: Everything you need to know

Pilot Institute Drones · 10:32

<https://www.youtube.com/watch?v=MFyfZ6d569s>

After the engineering paragraph, for a full explanation of the FAA's TRUST test. Parents may want to watch it too.



## KEY TERMS

### **quadcopter**

A drone with four rotors; two spin clockwise and two counterclockwise.

### **IMU**

Inertial measurement unit: a chip with gyroscopes and accelerometers that senses tilting and turning.

### **TRUST**

The FAA's free online Recreational UAS Safety Test, which recreational drone flyers in the United States must pass.

### **thrust-to-weight ratio**

The total thrust of the rotors divided by the drone's weight. It must be more than 1 to climb; about 2 gives good control.

### **visual line of sight**

Being able to see the drone with your own eyes the whole time it flies.

### **autonomous**

Able to carry out a task by itself, following its program and sensors.

## CORE IDEAS

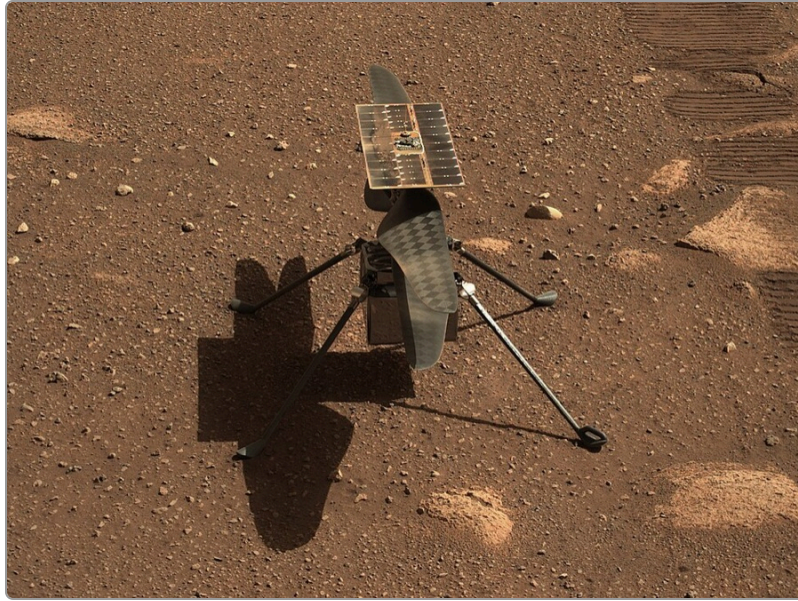
**The story.** On April 19, 2021, a small helicopter named *Ingenuity*, with a mass of only 1.8 kilograms, spun up its rotors on the floor of Jezero Crater on Mars, rose 3 meters, hovered for about 30 seconds, turned, and landed. It was the first powered, controlled flight of an aircraft on another planet. NASA engineers had hoped for five test flights; *Ingenuity* made 72 over nearly three years before a damaged rotor blade ended its flying in January 2024. A small piece of fabric from the Wright brothers' 1903 Flyer rode along under its solar panel.

**How they figured it out.** Mars's atmosphere is only about 1% as dense as Earth's, so a normal helicopter could not lift itself. Mars's gravity, about 38% of Earth's, helped, but the engineers at NASA's Jet Propulsion Laboratory still had to make *Ingenuity* extremely light and give it two stacked rotors, 1.2 meters across, spinning in opposite directions at about 2,400 rpm, many times faster than a helicopter on Earth. They tested it in a large vacuum chamber pumped down to Mars-like pressure, with a cable pulling upward to imitate Mars's weaker gravity. Because radio signals take minutes to reach Mars, no one could fly it with a joystick: *Ingenuity* flew **autonomously**, using its camera and its **IMU** to keep track of its tilt and position.

**The physics.** A drone hovers when its rotors' total thrust equals its weight. On Mars, *Ingenuity* weighed  $1.8 \text{ kg} \times 3.71 \text{ m/s}^2 \approx 6.7 \text{ N}$ ; on Earth it would weigh  $1.8 \times 9.8 \approx 17.6 \text{ N}$ . To climb, thrust must be greater than weight:  $a = (\text{thrust} - \text{weight}) \div \text{mass}$ . A **quadcopter** controls itself only by changing the speeds of its four rotors. Speed up all four, and it climbs. Speed up the two rear rotors, and it tilts forward and moves forward. Two rotors spin clockwise and two counterclockwise, so their twisting effects cancel; speed up one pair and slow the other, and the drone turns (yaws). A drone with a mass of 250 g weighs about 2.45 N, and designers like a **thrust-to-weight ratio** of about 2, so its four motors together should make about 4.9 N, about 1.2 N each.

**The engineering.** A drone adjusts its rotor speeds hundreds of times a second, using its IMU to stay level, a loop with conditionals like the ones you wrote in Lesson 8.2. Engineers balance battery size (more flight time) against weight (less climb), and add propeller guards, GPS and return-home features. The FAA sets rules to keep everyone safe in the air and on the ground. Recreational flyers must pass the free **TRUST** test and carry proof of it; register any drone that weighs 250 grams (0.55 lb) or more; fly at or below 400 feet in uncontrolled airspace; keep the drone within **visual line of sight**; get authorization before flying in controlled airspace near airports; and never fly over people or moving vehicles or interfere with emergency crews. Check the FAA's website for the current rules before any flight.

## PICTURE STUDY



*Ingenuity on Mars*, NASA/JPL-Caltech/ASU (Perseverance rover's Mastcam-Z camera), April 5, 2021 · Photograph · NASA

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

The Perseverance rover took this picture of *Ingenuity* on Mars on April 5, 2021, two weeks before its first flight. Notice how long the blades are for such a small aircraft.

### Look closely

- Find the two rotors, one above the other. Why do they spin in opposite directions?
- Find the solar panel on top. What does it charge?
- Find the four thin legs. Why so thin?
- Look at the ground. Where would be a good, flat spot to take off?

### Talk about it

1. Why did *Ingenuity* need such long blades spinning so fast?
2. How much did it weigh on Mars compared with on Earth?
3. Why couldn't engineers fly it with a joystick from Earth?

**Safety first.** Wear safety glasses for the thrust test, keep fingers and hair away from the propeller, and clamp or tape the motor firmly so it cannot jump. Batteries only. If you fly a real drone, an adult must supervise, the flyer must have passed TRUST, and you must follow the FAA's rules: never fly near people, roads, airports, power lines or emergency scenes.

## BUILD

### Thrust Test and a Drone Design

You will measure the thrust of a small motor and propeller on a kitchen scale at two battery voltages, then use your numbers to design a quadcopter on paper: how heavy it can be and still have a thrust-to-weight ratio of 2. You will finish by writing a safe-flight checklist based on the FAA's rules.

#### You will need

- A small hobby motor (1.5–3 V) with a propeller that fits it
- One and two AA batteries in holders, and clip leads
- A kitchen scale that reads in grams
- A cardboard tube or block, tape and clay to mount the motor so the propeller blows air upward
- Safety glasses and the engineer's notebook

#### Steps

1. **Mount.** Tape the motor to the top of the tube with the propeller on top, blowing air upward, so the thrust pushes the motor down onto the scale. (If your propeller blows the other way, reverse the battery leads.) Set the mount on the scale and press tare.
2. **Predict.** How many grams of thrust will one AA (1.5 V) make? Two AA (3 V)?
3. **Test.** Put on safety glasses. Connect one AA, wait for the reading to settle, and record the thrust in grams. Disconnect. Repeat three times, then three times with two AA cells.
4. Convert thrust to newtons:  $\text{grams} \div 1,000 \times 9.8$ .
5. **Design.** Suppose your drone uses four of these motors at 3 V. Calculate the total thrust. For a thrust-to-weight ratio of 2, what is the most the whole drone may weigh, in grams?
6. Make a weight budget table for your paper drone: four motors (weigh one), frame, battery, controller and wires. Does it fit under your limit? Is it under the FAA's 250-gram registration weight?

7. **Safety checklist.** Write a preflight checklist of at least eight items from the FAA rules and good practice (TRUST passed, weather, location away from airports and people, under 400 feet, line of sight, propellers checked, battery charged, adult present).
8. **Improve.** Change one thing in your test (a different propeller, or turning the propeller over) and measure the thrust again. How would the change affect your drone design?

#### Tips

- Hobby motors with toy propellers make only a few grams of thrust; real drone motors are much stronger and spin much faster.
- Run the motor only a few seconds at a time so the batteries do not drain between trials.
- Watch the scale for the middle of the flicker and record that.

#### Check your work

- ☐ I can explain how a quadcopter climbs, tilts and turns.
- ☐ I can calculate thrust-to-weight ratio from measurements.
- ☐ I can state the FAA's main rules for recreational flyers and why they matter.

#### ENGINEER'S NOTEBOOK

1. Draw a quadcopter from above with arrows showing each rotor's spin direction, and show which rotors speed up to move forward and to turn left.
2. Record your thrust data and your drone's weight budget table.
3. Work it: a 600-gram drone has four motors that each make 300 grams of thrust. What is its thrust-to-weight ratio? ( $1,200 \div 600 = 2$ .) Must it be registered with the FAA? (Yes; 600 g is more than 250 g.)

**From history.** The Wright brothers' first powered flight lasted 12 seconds; *Ingenuity's* first lasted about 39. Its flight zone on Mars was named Wright Brothers Field, and the patch of 1903 fabric it carried connects the first flight on Earth with the first on another world.

#### COMMON MISTAKES

- Thinking a quadcopter has movable flaps or a tail rotor. It controls itself only by changing the speeds of its four rotors.

- Thinking small drones need no rules. All recreational flyers must pass TRUST and follow the safety rules, whatever the drone's weight.
- Testing thrust with the propeller blowing down at the scale, which measures the airflow, not the thrust.

**Make it a game · Thrust to Weight.** Your parent names a drone's weight and each motor's thrust. Calculate the thrust-to-weight ratio and say whether it can climb or hover. Do five puzzles. Then explain how changing rotor speeds climbs, tilts and turns a quadcopter. State one FAA rule from the lesson, and one fact about Ingenuity on Mars.

## ROBOTS, CODING AND INVENTION

Every robot senses, thinks and acts. This unit looks closely at each part. You will learn how motors and gear trains give a robot the right mix of speed and strength, the way NASA engineers geared the wheels of the Lunar Roving Vehicle. You will write programs with loops and conditionals, the two ideas Ada Lovelace described for Charles Babbage's Analytical Engine in 1843, and use them to make a sensor-driven light.

Then you will measure the speed of sound with echoes, as Isaac Newton did in a college courtyard, and learn how a robot's ultrasonic sensor uses the same idea to measure distance. Last, you will study how a drone flies, from NASA's little *Ingenuity* helicopter on Mars to the quadcopters people fly at home, measure the thrust of a motor and propeller, and learn the FAA's rules for flying safely. The year ends with the family engineering fair.

### PREREQUISITES

- Knows Ohm's law and has programmed a blink (Unit 4)
- Knows  $F = ma$ , work and power (Unit 1)
- Can measure time with a stopwatch and calculate  $\text{speed} = \text{distance} \div \text{time}$

### MASTERY CHECKLIST

- ☐ I can calculate a gear ratio and explain how it trades speed for turning force (torque).
- ☐ I can write a program with a loop and a conditional (if-then-else) and test it with a sensor.
- ☐ I can measure the speed of sound and use  $\text{distance} = \text{speed} \times \text{time} \div 2$  for an echo sensor.
- ☐ I can explain how a quadcopter climbs, tilts and turns, and calculate thrust-to-weight.
- ☐ I can state the main FAA rules for recreational drone flyers and explain why each one keeps people safe.



## OPTIONAL KITS FOR THIS UNIT

- **BBC micro:bit:** Ages 8 and up. Its built-in light, temperature and motion sensors fit Lesson 8.2, and an add-on ultrasonic sensor fits Lesson 8.3. MakeCode is free.
- **Makeblock mBot:** Ages 8 and up. A small wheeled robot with geared motors, an ultrasonic distance sensor and a line-follower sensor, programmed with blocks. Fits Lessons 8.1–8.3.
- **Ryze Tello:** For older students with an adult; about 80 grams, under the FAA’s 250-gram registration weight, and programmable with Scratch-style blocks. Fits Lesson 8.4. Flyers must still take the free FAA TRUST test.
- **CrunchLabs Build Box:** Ages 8 and up. Monthly toys designed by Mark Rober that show gears, linkages and motors in action; good for the capstone and the family engineering fair.

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 Motors and Gears: The Lunar Roving Vehicle

2 sessions of 50 minutes

### 8.2 Loops and Conditionals: From Ada Lovelace to MakeCode

2 sessions of 50 minutes

### 8.3 Distance Sensors: Echoes and the Speed of Sound

2 sessions of 50 minutes

### 8.4 Drone Basics and the FAA’s Rules: Ingenuity on Mars

2 sessions of 50 minutes

## UNIT 8 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **10 pts**

Calculate: a 12-tooth gear drives a 48-tooth gear. What is the gear ratio? If the motor turns at 2,400 rpm, how fast does the output turn, and what happens to the torque?

2. (8 pts)

Why did each wheel of the Lunar Roving Vehicle have its own motor and an 80 : 1 gear reduction?

3. (8 pts)

What is a loop and what is a conditional? Give an example of each from a machine at home.

4. (7 pts)

What did Ada Lovelace write in Note G, and why is it important?

5. (8 pts)

Predict: a night-light program turns on the light when the light level is below 100. The room at dusk reads between 95 and 105. What will happen, and how can an engineer fix it?

6. (8 pts)

How did Newton measure the speed of sound at Trinity College?

7. (10 pts)

Calculate: an ultrasonic sensor hears an echo 4.0 ms after its ping. Using 343 m/s for the speed of sound, how far away is the object?

8. (7 pts)

Name two kinds of objects an ultrasonic sensor may fail to detect, and say why.

9. (8 pts)

Explain how a quadcopter moves forward and how it turns (yaws).

10. (10 pts)

Calculate: a drone has a mass of 0.4 kg and its rotors give a total thrust of 7.0 N. Find its weight, its thrust-to-weight ratio and its upward acceleration.

11. (8 pts)

List four FAA rules for recreational drone flyers.

12. **8 pts**

Why did Ingenuity have to fly autonomously, and what made flying on Mars hard?

## ANSWER KEY

1. Ratio =  $48 \div 12 = 4 : 1$ . Output =  $2,400 \div 4 = 600$  rpm. Torque is about 4 times greater (less a little lost to friction).
2. Separate motors gave backup if one failed. The reduction turned the fast, weak motor speed into slow, strong wheel torque for climbing over rocks and craters.
3. A loop repeats instructions (a thermostat checking the temperature again and again). A conditional checks something and decides what to do (if it is too cold, turn on the heat; else turn it off).
4. A step-by-step method for Babbage's Analytical Engine to calculate the Bernoulli numbers, using repeated cycles (loops). It is often called the first published computer program.
5. The light will flicker on and off as the reading wobbles around 100. Fix it with two thresholds (hysteresis), such as on below 90 and off above 120.
6. He stamped at one end of the cloister in Neville's Court and timed the echo with a pendulum, adjusting its length so its swings matched the stamp and echo, then used the cloister's length and the time.
7. Distance =  $343 \times 0.004 \div 2 \approx 0.69$  m (69 cm).
8. Soft objects (they absorb sound), slanted surfaces (they reflect the echo away), very small or very close objects. Any two with reasons.
9. To move forward it speeds up its rear rotors so it tilts forward and part of the thrust pushes it ahead. To turn, it speeds up the pair of rotors spinning one way and slows the pair spinning the other way, so their twisting no longer cancels.
10. Weight =  $0.4 \times 9.8 = 3.92$  N. Ratio =  $7.0 \div 3.92 \approx 1.8$ . Acceleration =  $(7.0 - 3.92) \div 0.4 = 7.7$  m/s<sup>2</sup>.
11. Any four: pass TRUST and carry proof; register drones of 250 g or more; fly at or below 400 feet in uncontrolled airspace; keep the drone in visual line of sight; get authorization in controlled airspace near airports; do not fly over people or moving vehicles; do not interfere with emergency response.
12. Radio signals take minutes to reach Mars, too slow for live control. The Martian air is only about 1% as dense as Earth's, so the rotors had to be large, light and spin very fast.

## PORTFOLIO PIECE: A SENSE-THINK-ACT MACHINE FOR THE FAMILY ENGINEERING FAIR

Design and build a small machine that senses, decides and acts: for example, a geared winch that lifts a flag when it gets dark, a cardboard robot vehicle that stops before it hits a wall, or a micro:bit alarm that sounds when a door opens. (If you have no microcontroller, use a switch as the sensor and a simple circuit as the decision.) Measure at least one thing about it, such as its gear ratio and lifting speed, its sensor threshold, or its stopping distance. Present it at the family engineering fair with your best build from each unit and their notebook pages, and explain one calculation to your guests.

| LOOK FOR                       | WHAT IT MEANS                                                                                                         |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| <b>Sense, think, act</b>       | The machine has a clear sensor (or switch), a decision (program or circuit) and an action, each labeled in a diagram. |
| <b>Measurement</b>             | At least one measured quantity recorded with units and used in a calculation.                                         |
| <b>Testing and improvement</b> | The machine was tested, a problem found, and one improvement made and retested.                                       |
| <b>Notebook</b>                | Dated pages with sketches, program or circuit diagram, data table and conclusions.                                    |
| <b>Presentation</b>            | At the fair, the student explains how the machine works and walks a guest through one calculation clearly.            |

## TOY LAB: THE PHYSICS OF PLAY

Toys are some of the most carefully engineered objects in your house. A toy must work the first time, every time, in the hands of someone who will drop it, twist it and leave it in the rain, and it must cost little and be safe for small children who put everything in their mouths. In this optional bonus unit you will take four toys apart, in your mind and sometimes on the workbench, and find the physics and the engineering inside.

You will measure the energy stored in a rubber band and a spring and trace it through a pull-back car's gear train, watch a drinking bird run as a tiny heat engine, follow radio control from Nikola Tesla's 1898 boat to the car on your floor, and finish as a toy safety engineer, building the small-parts test cylinder and running drop tests. Use this unit after the family engineering fair, over the summer, or in any week that needs something fun.

### PREREQUISITES

- Knows work, energy and power, and  $F = ma$  (Unit 1)
- Knows gear ratios and how motors work (Lessons 4.3 and 8.1)
- Can run a fair test and keep a data table

### MASTERY CHECKLIST

- ☐ I can trace how energy is stored and released in a rubber-band or pull-back car, and calculate a gear ratio.
- ☐ I can explain how a drinking bird works as a heat engine and what conditions make it run faster.
- ☐ I can explain how radio control works, from transmitter to motor and steering.
- ☐ I can explain the main toy safety tests and why they exist, and run a small-parts and drop test.
- ☐ I can take apart an old toy safely and explain how it was engineered.

## OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box:** Ages 8 and up. Monthly toys designed by Mark Rober, each built around a physics idea and explained in a video; a natural fit for this whole unit.
- **KiwiCo Tinker and Eureka crates:** Ages 9 and up (Tinker) and 14 and up (Eureka). Many crates build mechanical toys with springs, gears and motors; good companions to Lessons 9.1 and 9.3.
- **Snap Circuits:** Ages 8 and up. Snap-together circuits with motors, switches and (in some sets) a radio-controlled rover; useful for Lesson 9.3.

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

### 9.1 Rubber-Band and Pull-Back Cars: Stored Energy and Gear Trains

2 sessions of 50 minutes

---

### 9.2 The Drinking Bird: A Toy Heat Engine

2 sessions of 50 minutes

---

### 9.3 Radio-Controlled Cars: From Tesla's Boat to Your Floor

2 sessions of 50 minutes

---

### 9.4 Toy Safety Engineering: The Small-Parts Cylinder and the Drop Test

2 sessions of 50 minutes

---

## UNIT 9 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Trace the energy in a rubber-band car from your hand to the moving car, including where some energy is lost.

2. **10 pts**

Calculate: a band pulls with 8 N after stretching 0.25 m. About how much energy does it store? If a 0.2-kilogram car then moves at 2 m/s, what is its kinetic energy?

3. **8 pts**

Why does a pull-back car's gear train speed up the wheels, while the winch in Lesson 8.1 made its output slower?

4. **6 pts**

How did a toy help start the Wright brothers' interest in flight?

5. **10 pts**

Explain in two or three sentences how a drinking bird works.

6. **8 pts**

Predict: will a drinking bird dip faster on a dry, breezy day or a humid, still day? Why?

7. **6 pts**

Why must a drinking bird never be broken or heated?

8. **8 pts**

What did Tesla show at Madison Square Garden in 1898?

9. **10 pts**

Calculate: a toy drone's controller uses radio at 2.4 GHz. Using a speed of light of 300,000,000 m/s, what is the wavelength? What would a quarter-wave antenna's length be?

10. **8 pts**

What is the small-parts test cylinder, and what does it mean if an object fits inside it?

11. **10 pts**

Calculate: a 0.5-kilogram toy is dropped from 1.37 m. What energy does it have just before it hits the floor?



12. 8 pts

Name two dangers in toys besides small parts, and explain how engineers design against one of them.

**ANSWER KEY**

1. Your work stretches or twists the band (elastic potential energy); when released it turns the axle and wheels, giving the car kinetic energy; some energy is lost as heat in the band and bearings, sound, and friction with the floor.
2. Stored  $\approx \frac{1}{2} \times 8 \times 0.25 = 1$  J. Kinetic  $= \frac{1}{2} \times 0.2 \times 2^2 = 0.4$  J (so about 0.6 J was lost).
3. The pull-back spring turns slowly with strong force, so gears speed the wheels up for a fast car. The winch motor spins fast with little force, so gears slow it down to gain torque for lifting.
4. In 1878 their father brought home a rubber-band-powered toy helicopter based on Alphonse Pénaud's design; they played with it and built copies.
5. Water evaporating from the wet head cools it, lowering the vapor pressure inside the head. The higher pressure in the warm body pushes liquid up the neck, moving the center of gravity forward until the bird tips and drinks. Tipped, the pressures even out, the liquid drains back, and it swings upright to repeat.
6. On a dry, breezy day, because water evaporates faster from the head, cooling it more and making a bigger temperature difference.
7. The liquid inside is a harmful chemical, the glass can cut, and heating raises the pressure inside.
8. A boat in a pool controlled by radio, with no wires, obeying commands such as turning and flashing its lights.
9. Wavelength  $= 300,000,000 \div 2,400,000,000 = 0.125$  m (12.5 cm). Quarter wave  $\approx 3.1$  cm.
10. An official gauge about 3.17 cm (1¼ in) across, sized like a young child's throat. If an object fits completely inside in any position, it is a small part and is not allowed in toys for children under 3, because it is a choking hazard.
11. Energy  $= 0.5 \times 9.8 \times 1.37 \approx 6.7$  J.
12. Any two: sharp edges or points, small powerful magnets, button batteries, harmful paints, strings that could strangle. Example: button batteries are placed in compartments that need a screwdriver to open.

## PORTFOLIO PIECE: A SAFE, TESTED TOY

Design and build an original toy for a younger child that uses one physics idea from this unit or the year, such as stored elastic energy, a gear train, a pendulum or buoyancy. Before building, decide the age it is for and list the safety rules it must meet. Test it twice: once to measure how well it works (for example, distance, time or number of spins), and once with a small-parts check and drop test. Write a one-page design report with a labeled drawing, test data, one calculation, the safety tests and their results, and the improvements you made.

| LOOK FOR                              | WHAT IT MEANS                                                                           |
|---------------------------------------|-----------------------------------------------------------------------------------------|
| <b>Physics idea</b>                   | The toy clearly uses one physics idea, explained correctly in the report.               |
| <b>Performance test</b>               | A fair test of how well the toy works, with data recorded and at least one calculation. |
| <b>Safety testing</b>                 | Small-parts and drop tests done correctly for the chosen age, with results recorded.    |
| <b>Improvement</b>                    | At least one change made after testing, with before-and-after results.                  |
| <b>Craftsmanship and presentation</b> | Neat, durable toy and a clear report with a labeled drawing.                            |

## 9.1 RUBBER-BAND AND PULL-BACK CARS: STORED ENERGY AND GEAR TRAINS

### OBJECTIVES

- Explain how a stretched rubber band or wound spring stores energy and releases it as motion.
- Calculate the energy stored in a band from its pulling force and stretch, and a car's kinetic energy.
- Build a rubber-band car, test how winding changes distance, and examine the gear train of a pull-back car.

**Warm-up.** Stretch a rubber band a little, then a lot. Which takes more effort? Now hold it against your lip (gently) just after stretching it hard. What do you feel? Write a guess about where your effort went.

### WATCH

#### How does a Pull-Back Toy Car work?

Jared Owen • 5:02

[https://www.youtube.com/watch?v=QdvfiVebb\\_s](https://www.youtube.com/watch?v=QdvfiVebb_s)

### WHEN TO WATCH

After the physics paragraph, before the teardown.

### BACKUP VIDEO

#### How does a pull back car toy work?

Scitech's Toy Tear Down • 11:41

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

Before the optional teardown, to see a pull-back car taken apart carefully.

### KEY TERMS

#### **elastic potential energy**

Energy stored in a stretched, twisted or squeezed material that springs back.

#### **kinetic energy**

Energy of motion:  $\frac{1}{2} \times \text{mass} \times \text{speed}^2$ .

**spring motor**

A coiled steel spring that is wound up and releases its energy through gears.

**gear train**

A set of gears that passes motion from one shaft to another, changing speed and torque.

**energy loss**

Energy that ends up as heat and sound instead of useful motion.

**CORE IDEAS**

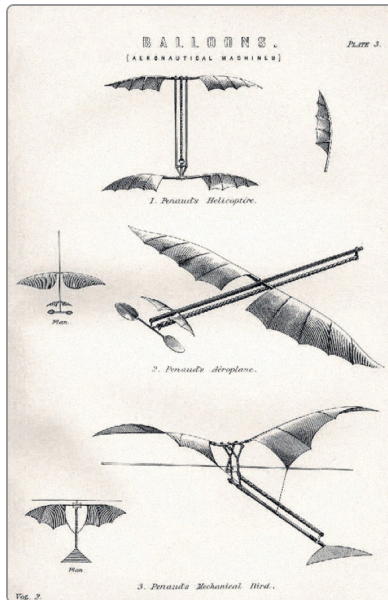
**The story.** In 1871 a young French inventor, Alphonse Pénau, flew a little model airplane he called the *Planophore* in the Tuileries Gardens in Paris. It was powered by a twisted rubber band turning a propeller, and it flew about 40 meters in 11 seconds, the first stable flight of a model airplane. He also made toy helicopters powered by rubber bands. In 1878 Bishop Milton Wright brought one home to his sons Wilbur and Orville. They played with it until it broke, then built their own copies. Years later the brothers said it was where their interest in flight began.

**How they figured it out.** Pénau had tried other power sources, but a rubber band stores a surprising amount of energy for its weight, and it can be twisted thousands of times and still spring back. Clockmakers had long used coiled steel springs to drive clocks, and toymakers soon used them too, in wind-up toys. The pull-back car, common in toy shops since the late 1900s, hides a small flat spring inside a plastic gearbox. Pulling the car backward winds the spring through the gears; letting go releases it. Toymakers tested many gear arrangements to find one that winds quickly, releases smoothly, and costs only a few cents to mold in plastic.

**The physics.** When you stretch a rubber band, the work you do is stored as **elastic potential energy**. For a band whose pull grows steadily as you stretch it, the stored energy is about  $\frac{1}{2} \times \text{final force} \times \text{stretch}$ . A band that pulls with 10 N after stretching 0.2 m stores about  $\frac{1}{2} \times 10 \times 0.2 = 1$  joule. When it lets go, that energy becomes **kinetic energy**,  $\frac{1}{2} \times \text{mass} \times \text{speed}^2$ , plus sound, heat and friction losses. A 0.1-kilogram car moving at 2 m/s has  $\frac{1}{2} \times 0.1 \times 2^2 = 0.2$  J of kinetic energy, so if the band stored 1 J, about four-fifths was lost along the way. A pull-back car's gear train works opposite to the winch in Lesson 8.1: the spring turns slowly with strong force, and the gears speed up the wheels.

**The engineering.** Toy engineers must balance stored energy, speed, cost and safety. More gear speed-up means faster wheels but less force, so the car stalls on carpet. A stronger spring goes farther but may be too stiff for a small child to wind. Gears are made of plastic by injection molding, and their teeth must be accurate to a fraction of a millimeter or they will skip. The spring must be enclosed so that, if it breaks, it cannot cut fingers, and every part must be too big to swallow. A good toy hides all of this inside a case that survives being dropped down the stairs.

## PICTURE STUDY



*Pénau's Flying Models*, Alphonse Pénau, 1875 · Engraving

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

This plate from an 1875 book shows three of Alphonse Pénau's rubber-powered flying models: a toy helicopter (like the one the Wright brothers played with), the *Planophore* airplane and a flapping bird.

### Look closely

- Find the helicopter at the top. Where is the rubber band, and how does it turn both propellers?
- Find the airplane in the middle. Where is the propeller?
- Find the long stick that holds the twisted rubber band in each model.
- Find the tail of the airplane. Why does it help the model fly steadily?

### Talk about it

1. Where is the energy stored in each model before it flies?
2. Why is rubber a good energy store for a flying toy?
3. Why did this toy helicopter interest two boys who later built the first airplane?

**Safety first.** Wear safety glasses when winding rubber bands; they can snap. Take apart only a cheap pull-back car with no batteries, with an adult, using a small screwdriver; if the spring is exposed, do not try to remove it, because a released spring can cut. Keep small gears and screws away from little children.

## BUILD

### Wind It and Measure It

You will build a rubber-band car, run a fair test of how the number of winds changes the distance it travels, and calculate its energy. Then, if you have an old pull-back car, you will open its case with an adult and count the teeth on its gears to find its gear ratio.

#### You will need

- A small cardboard or foam-board chassis about  $20 \times 8$  cm
- Two wooden skewers or dowels for axles, straws for bearings, and four wheels (bottle caps or old CDs)
- Rubber bands, a paper clip hook, tape and hot glue (adult)
- A tape measure, masking tape for a start line, and a kitchen scale
- Optional: an old pull-back car with no batteries and a small screwdriver
- Safety glasses and the engineer's notebook

#### Steps

1. **Build.** Tape straw bearings across the chassis, slide axles through them, and fix wheels on the axle ends. Hook one end of a rubber band to the front of the chassis and loop the other end around the rear axle.
2. Weigh the car. Wind the rear axle so the band winds around it, then set the car on the start line and let go.
3. **Predict.** If you double the number of winds, will the car go twice as far?
4. **Fair test.** Wind 5, 10, 15 and 20 turns. Release three times for each and measure the distance. Keep the surface and the band the same.
5. Make a table and a graph of distance against number of winds.
6. **Measure energy.** Hook the band to the kitchen scale (or hang the car from it by the band) and stretch it the same length it stretches in the car. Read the force in grams and change it to newtons ( $\div 1,000 \times 9.8$ ). Estimate the stored energy with  $\frac{1}{2} \times \text{force} \times \text{stretch}$ .
7. **Teardown (optional).** With an adult, remove the screws of the pull-back car and open the case. Sketch the gear train. Count the teeth on each gear and



calculate the overall ratio from the spring to the wheels.

8. **Improve.** Change one thing on your car (bigger rear wheels, a thinner band, less friction at the bearings) and test again. Did it go farther?

#### Tips

- Wheels that wobble waste energy; glue them straight on the axles.
- Too many winds can make the wheels spin and slip at the start. Notice whether that happens.
- For a gear pair, ratio = teeth on the driven gear  $\div$  teeth on the driving gear; multiply the ratios of each pair for the whole train.

#### Check your work

- ☐ I can explain how energy moves from a stretched band to a moving car.
- ☐ I can estimate stored energy and kinetic energy.
- ☐ I can explain what a pull-back car's gear train does.

#### ENGINEER'S NOTEBOOK

1. Draw your car from the side with arrows showing where energy is stored and where it is lost.
2. Graph distance against number of winds. Is it a straight line? Explain the shape.
3. Work it: a band pulls with 6 N after stretching 0.15 m. About how much energy does it store? ( $\frac{1}{2} \times 6 \times 0.15 = 0.45 \text{ J}$ )

**From history.** Pénaud also designed a full-sized airplane with a glass-domed cockpit and retractable landing gear, but he could not raise the money to build it. The rubber-band toy he invented outlived him and helped inspire the Wright brothers. Rubber-powered model airplanes are still flown in contests today.

#### COMMON MISTAKES

- Thinking energy is “used up.” It changes form; most of the lost energy becomes heat and sound.
- Changing the band or the floor partway through a fair test.
- Forcing a toy open. If screws are hidden or a spring is exposed, stop and ask an adult.

**Make it a game • Wind It, Measure It.** Wind a toy or a rubber-band car a set number of turns and predict how far it rolls. Measure the actual distance, then compare after adding more turns. Explain where the energy goes and name energy loss. Try to beat your longest roll by improving just one part.

## 9.2 THE DRINKING BIRD: A TOY HEAT ENGINE

### OBJECTIVES

- Explain how a drinking bird uses evaporation and a temperature difference to keep moving.
- Explain why it is a heat engine and why it runs faster in dry air.
- Run a fair test of how the air and water conditions change the bird's dipping rate.

**Warm-up.** Wet the back of one hand and leave the other dry. Blow gently on both. Which feels cooler? Write a guess about why, and keep it for the physics paragraph.

### WATCH

#### The Engineering of the Drinking Bird

[engineerguy](#) • 10:28

<https://www.youtube.com/watch?v=UCKC-QVcVn0>

### WHEN TO WATCH

After the physics paragraph. Pause when the bird tips and explain what has just happened inside it.

### KEY TERMS

#### **heat engine**

A machine that turns a flow of heat from a warmer place to a cooler place into motion.

#### **vapor pressure**

The pressure made by a liquid's vapor in a closed space; it rises as the temperature rises.

#### **humidity**

The amount of water vapor in the air. Wet things dry more slowly in humid air.

#### **evaporation**

Liquid turning into vapor at its surface, which carries heat away and cools what is left.

#### **center of gravity**

The balance point of an object; when it moves past the pivot, the object tips.

## CORE IDEAS

**The story.** The drinking bird, or “dippy bird,” is a glass toy shaped like a bird with a felt-covered head and a long neck, perched on a pivot beside a glass of water. It bobs forward, “drinks,” swings back up, and does it again, for hours, with no batteries and no winding. Toys like it were sold in China in the early 1900s, and in the 1940s American inventors patented their own versions, including a design patent granted to Robert T. Plate in 1947 for an “activated toy bird figure.” Millions have been sold since, and physics teachers have used it for decades to puzzle their students.

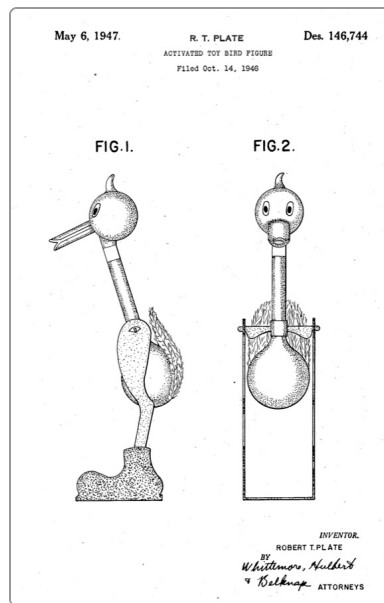
**How they figured it out.** The bird’s makers sealed a liquid that boils at a low temperature inside the glass, with most of the air pumped out, so the space above the liquid holds only its own vapor. They then had to get many details right: the exact amount of liquid, the position of the pivot, the length of the neck tube reaching down into the body, and the felt on the head that soaks up water. If the pivot is a millimeter too high or low, the bird never tips, or tips and stays down. Each bird is balanced before it leaves the factory.

**The physics.** Water evaporating from the wet felt cools the head, just as a wet hand feels cool in a breeze. The cooler head has a lower **vapor pressure** inside than the warmer body, so the higher pressure in the body pushes liquid up the neck tube into the head. As the liquid rises, the bird’s **center of gravity** moves forward past the pivot, and the bird tips down to “drink.” When it tips, the bottom of the neck tube comes out of the liquid in the body, vapor bubbles up, the pressures even out, the liquid drains back, and the bird swings upright with its felt freshly wetted. The bird is a real **heat engine**: it runs on heat flowing from the warm room into the cooler head, and it stops if the head and body are the same temperature. Because evaporation is slow in humid air, it dips slowly on a muggy day and quickly in dry air or a breeze.

**The engineering.** A drinking bird turns only a tiny fraction of the heat flowing through it into motion, far less than 1%, but engineers use the same physics on a grand scale. Cooling towers at power plants cool water by evaporation, and evaporative coolers cool homes in dry climates. The toy also shows why toy makers must think about safety: the liquid inside is a chemical that is harmful to breathe or swallow, so the glass must be strong, the bird must be labeled for older children, and

the instructions warn never to break it or place it in sunshine or near heat, where the pressure inside could rise.

#### PICTURE STUDY



*The 1947 Drinking Bird Design Patent, Robert T. Plate (inventor), U.S. design patent 146,744, May 6, 1947*  
· Patent drawing

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

This drawing comes from a 1947 United States design patent for an “activated toy bird figure,” one version of the drinking bird. A design patent protects the look of a product.

#### Look closely

- Find the head, the long neck tube and the round body.
- Find the pivot where the bird balances.
- Look at Fig. 2. How does the neck tube reach down into the body?
- Find the patent number and date at the top.

#### Talk about it

1. Where in the bird does the liquid move when the head is cooled?
2. Why must the pivot be in exactly the right place?
3. Why would an inventor want to patent the look of a toy?

**Safety first.** Never break, open, heat or shake a drinking bird hard: the liquid inside is harmful, and broken glass cuts. Keep it out of direct sunlight and away from heaters and small children. If one breaks, leave the room, open a window, and let an adult clean it up with gloves.

## BUILD

### How Fast Does the Bird Drink?

You will set up a drinking bird and count how many times it dips per minute in different conditions, changing one thing at a time, to find out what makes this heat engine run faster or slower.

#### You will need

- A drinking bird (sold inexpensively as a science toy)
- A glass of room-temperature water, a glass of cold water, and a glass of warm (not hot) water
- A small fan, a large clear plastic bag or box (to make a humid space), and a stopwatch
- A thermometer (optional) and the engineer's notebook

#### Steps

1. **Set up.** Place the bird on a steady table out of the sun, with its beak just able to dip into a full glass of room-temperature water. Wet its head and give it a gentle tap to start. Wait 10 minutes for it to settle into a rhythm.
2. **Measure.** Count the dips in 5 minutes and divide by 5 for dips per minute. Do this three times.
3. **Predict.** Will a breeze, cold water, warm water or humid air make it dip faster or slower?
4. **Test breeze.** Set a small fan on low 1 meter away, blowing across the head. Wait 5 minutes, then count for 5 minutes.
5. **Test humid air.** Turn off the fan and set a clear box or bag loosely over the bird and the glass for 15 minutes. Count again.
6. **Test water temperature.** Remove the cover and change to cold water, then to warm water, waiting 10 minutes after each change before counting.
7. Make a table and bar graph of dips per minute for each condition.
8. **Improve.** Using what you learned, set up the conditions to make the bird dip as fast as possible safely (no heat lamps or sunlight). Record your best rate and explain why it worked.

### Tips

- Always wait for the bird to settle after a change; it needs time to reach a new temperature.
- If it stops, check that the beak still reaches the water and that the felt is wet.
- Write down the room temperature and weather each time; humidity changes from day to day.

### Check your work

- ☐ I can explain each step of the drinking bird's cycle.
- ☐ I can explain why it is a heat engine and why it slows in humid air.
- ☐ I can explain my fair-test results and why safety rules for this toy matter.

### ENGINEER'S NOTEBOOK

1. Draw the bird in two positions, upright and dipping, with arrows showing liquid moving and labels for warm body, cool head, vapor and pivot.
2. Make the bar graph of dips per minute for each condition.
3. Work it: a bird dips 6 times a minute. How many times does it dip in 8 hours? ( $6 \times 60 \times 8 = 2,880$ .)

**From history.** Engineers have built larger drinking-bird-style engines as experiments, and some have suggested using the same principle to pump water using the evaporation of a damp surface. The toy remains popular because it makes invisible physics, heat flow and evaporation, easy to watch.

### COMMON MISTAKES

- Thinking the bird is a perpetual-motion machine. It runs on heat from the room and stops when the water is gone or the air is too humid.
- Thinking the bird drinks water into its body. The water only wets the felt on the outside.
- Changing two conditions at once, such as adding the fan and the cold water together.

**Make it a game • Thirsty Bird Riddle.** Your parent gives riddles about the drinking bird: "I need a wet head and dry air" or "I am a heat engine in a toy." Answer with evaporation, vapor pressure, center of gravity or humidity. Then draw its parts and explain why it drinks faster in dry air. Score a point per correct riddle.



## 9.3 RADIO-CONTROLLED CARS: FROM TESLA'S BOAT TO YOUR FLOOR

### OBJECTIVES

- Describe Nikola Tesla's 1898 radio-controlled boat and how radio control works.
- Calculate the wavelength of a radio signal from its frequency, and explain how a motor's speed and the steering are controlled.
- Take apart a broken RC car safely and identify its parts, or test a working one fairly for speed and range.

**Warm-up.** Point a TV remote at a mirror and press a button while someone watches the TV. Does it still work? Now think about a toy car that works from the next room. How is its signal different?

### WATCH

#### Nikola Tesla's Radio Controlled Boat | Brilliancy at its peak

Sabin Civil Engineering · 7:55

<https://www.youtube.com/watch?v=oQyal7Bt1lg>

### WHEN TO WATCH

After the story.

### BACKUP VIDEO

#### How does an RC car work? Hobby Electronics Explained for Beginners!

Hobbies Direct · 7:23

[https://www.youtube.com/watch?v=TZ\\_l9gQHgv4](https://www.youtube.com/watch?v=TZ_l9gQHgv4)

Before the build, to see the parts inside a hobby RC car.

### KEY TERMS

#### **radio wave**

An invisible wave of electricity and magnetism that travels at the speed of light and can pass through walls.

#### **frequency**

How many waves pass each second, measured in hertz (Hz); 1 gigahertz (GHz) is a billion hertz.

**wavelength**

The length of one wave: speed of light  $\div$  frequency.

**transmitter and receiver**

The transmitter in the controller sends coded radio signals; the receiver in the car picks them up and decodes them.

**servo**

A small motor with a sensor and feedback that turns to a commanded position, often used for steering.

**pulse-width modulation (PWM)**

Switching a motor on and off very fast; the longer the on-time, the faster the motor runs.

**CORE IDEAS**

**The story.** In September 1898, at the Electrical Exhibition in New York’s Madison Square Garden, the inventor Nikola Tesla set a small boat in an indoor pool and invited visitors to call out commands: turn left, stop, flash the lights. Standing across the hall with a control box, and with no wires to the boat, Tesla made it obey. Some onlookers thought there must be a trained monkey hidden inside. Tesla had patented the idea that year as a method of controlling “vessels or vehicles” by radio, and he called it a “teleautomaton.”

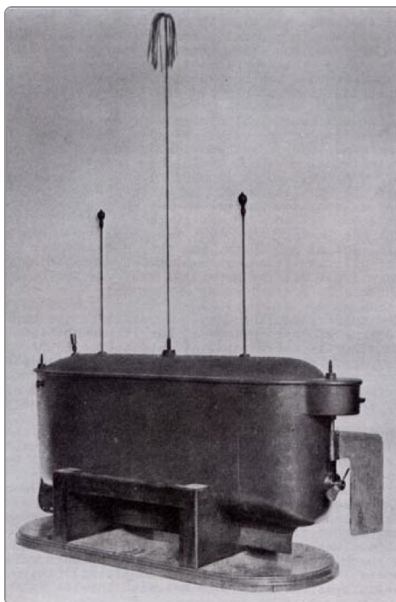
**How they figured it out.** Radio waves had been produced and detected by Heinrich Hertz only about ten years earlier, and wireless telegraphy was brand new. Tesla’s challenge was not just to send a signal, but to make the boat tell one command from another. His receiver used a sensitive detector that closed a circuit each time a radio pulse arrived, and a clever stepping switch that moved to the next position with each pulse, so different numbers of pulses meant different actions. Today’s RC cars do the same job with a digital code: every fraction of a second, the controller sends a packet of numbers giving the throttle and steering settings, and the car’s receiver chip decodes it.

**The physics.** Radio waves travel at the speed of light, about 300,000,000 m/s. Most RC toys today use 2.4 GHz (2,400,000,000 waves per second), so the wavelength is  $300,000,000 \div 2,400,000,000 = 0.125$  m, 12.5 cm. That is why the antenna wires inside are often a few centimeters long; good antennas are often about a quarter of the wavelength, about 3 cm here. Inside the car, the drive motor’s speed is set by **pulse-width modulation**: the electronics switch the motor on and off thousands of times a second; on half the time gives roughly half power. A gear train reduces the motor’s

speed and increases its torque at the wheels, and the steering uses a small **servo** or a simple motor and spring to turn the front wheels.

**The engineering.** An RC car is a robot with a human brain: the person senses and thinks, and the car acts. Engineers design the radio so that many cars can run at once without interfering, by giving each controller a code and pairing it with its own car. They protect the electronics from bumps and dust, choose gear ratios for speed or climbing, and design the battery compartment so that small children cannot open it, because swallowed button batteries can cause serious injury. Tesla's idea now guides drones, planetary rovers, and the robotic arms surgeons operate from a few feet away.

## PICTURE STUDY



*Tesla's Radio-Controlled Boat, Nikola Tesla, 1898 · Photograph*

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

This photograph shows the boat Tesla built for his radio-control exhibition in 1898. The rods on top are antennas and signal lights; inside were his receiver, batteries and motors.

### Look closely

- Find the antenna rods. Which one do you think received the radio signal?
- Find the rudder at the stern. How would a motor turn it?
- Look for a propeller. Where would it be?
- Look at the size of the hull. Where would the batteries fit?

### Talk about it

1. How did Tesla make the boat tell one command from another?
2. Why did some visitors think a monkey was hidden inside?
3. How is this boat like a modern RC car or drone?

**Safety first.** Take apart only a broken RC car that uses ordinary AA or AAA batteries, and remove the batteries first. Never open a car or controller with a built-in rechargeable (lithium) battery pack, a button or coin cell, or a wall charger plug; set those aside for an adult to recycle. Use a screwdriver with an adult, and keep small screws and parts away from little children.

## BUILD

### RC Car: Teardown or Test Drive

Choose one or both. In the teardown, you will open a broken RC car (AA or AAA batteries only) and find and sketch its antenna, receiver board, drive motor, gear train and steering. In the test drive, you will measure a working RC car's speed on two surfaces and its range, as a fair test.

#### You will need

- A broken toy RC car that uses AA or AAA batteries (for the teardown), or a working one (for the test drive)
- Small screwdrivers, a muffin tin or egg carton for screws, and a magnifying glass
- A tape measure, masking tape and a stopwatch
- The engineer's notebook

#### Steps

1. **Teardown, prepare.** Remove all batteries. Photograph the car from every side. With an adult, remove the screws one at a time and put each in a labeled cup.
2. **Identify.** Find the antenna wire, the receiver circuit board, the drive motor, the gear train to the rear wheels, and the steering parts at the front. Sketch each and label it.
3. **Count.** Count the teeth on each gear from the motor to the wheels and calculate the overall gear ratio. Measure the antenna wire's length and compare it with a quarter of 12.5 cm.
4. **Test drive, predict.** Will the car be faster on a smooth floor or on carpet? How far away can you drive it before it stops responding?
5. **Speed test.** Mark a 3-meter course. Get the car moving at full speed before the start line and time it across. Three runs on smooth floor and three on carpet. Calculate speed in m/s.
6. **Range test.** Outdoors in a safe, open, car-free place, drive the car away from you in steps of 5 meters, checking that it still responds. Record the distance

where control fails. Repeat with a wall or tree between you and the car.

7. Record your results in tables.

8. **Improve.** For the teardown, write two ideas the engineers used to save cost and one to make the toy safer. For the test drive, change one thing (fresh batteries, a different surface) and test again.

#### Tips

- Take a photo at each stage of the teardown so you can see how parts fit together.
- Many toy cars steer with a small motor and a spring that recenters the wheels instead of a true servo; look for which one yours uses.
- Weak batteries reduce both speed and range; use the same batteries for a fair comparison.

#### Check your work

- ☐ I can explain how Tesla's boat and a modern RC car are controlled by radio.
- ☐ I can calculate a radio wavelength from its frequency.
- ☐ I can name the main parts inside an RC car and what each does.

#### ENGINEER'S NOTEBOOK

1. Draw a block diagram: controller (buttons → transmitter) → radio waves → receiver → motor driver → motor → gears → wheels, and the steering branch.
2. Record your gear-tooth counts and ratio, or your speed and range tables.
3. Work it: an old RC toy used 27 MHz (27,000,000 Hz). What was its wavelength? ( $300,000,000 \div 27,000,000 \approx 11$  m.) Why do you think its antenna was a long telescoping rod?

**From history.** Tesla's 1898 patent for radio control was decades ahead of its time; few people saw a practical use for it. Today radio-controlled toys are one of the most common ways young people first meet motors, gears, batteries and radio, and many engineers say their careers started with one.

#### COMMON MISTAKES

- Thinking radio needs a straight line of sight like a TV remote's infrared light. Radio passes through walls, though it gets weaker.

- Opening a toy with a rechargeable lithium battery pack. Never do it; damaged lithium cells can catch fire.
- Thinking a faster motor always makes a better car. Gear ratio decides whether the car is fast or strong.

**Make it a game · Wavelength Wager.** Your parent calls a frequency in megahertz. Use wavelength equals 300 divided by frequency in meters to calculate the wavelength. Five rounds against the clock. Then explain how Tesla's 1898 boat was steered by radio, and how PWM and a servo control a toy car's speed and steering.

## 9.4 TOY SAFETY ENGINEERING: THE SMALL-PARTS CYLINDER AND THE DROP TEST

### OBJECTIVES

- Explain why toy safety standards exist and what the main tests check for.
- Build a small-parts test cylinder to the official dimensions and use it to test objects.
- Run a drop test on a homemade toy, calculate the energy of the drop, and improve the design.

**Warm-up.** Look at the warning labels on three toy packages or game boxes in your house. Copy the warnings and the ages they give. Why do you think a toy for a 7-year-old might be dangerous for a 2-year-old?

### WATCH

#### Toy safety testing

[commercecommission](https://www.youtube.com/watch?v=IA3-krJP-7A) • 2:38

<https://www.youtube.com/watch?v=IA3-krJP-7A>

#### WHEN TO WATCH

After the how-they-figured-it-out paragraph. Watch the drop, tension and torque tests, then plan your own drop test.

### BACKUP VIDEO

#### Toy Testing | I Didn't Know That

[National Geographic](https://www.youtube.com/watch?v=Beqcsr1gEHQ) • 2:29

<https://www.youtube.com/watch?v=Beqcsr1gEHQ>

After the engineering paragraph, to see more toy tests in a laboratory, including pull, bite and fire tests.

### KEY TERMS

#### **choking hazard**

A small object that can block a young child's airway if swallowed or inhaled.

#### **small-parts test cylinder**

An official gauge, shaped like a slanted tube 3.17 cm (1¼ in) across, the size of a young child's throat; anything that fits inside is a small part.



**standard**

An agreed set of rules and tests that a product must pass.

**drop test**

Dropping a toy from a set height onto a hard surface to see whether it breaks into dangerous pieces.

**sharp edge test**

A test for edges and points that could cut or pierce skin.

**design margin**

Designing something to be stronger or safer than the minimum needed.

**CORE IDEAS**

**The story.** Before the 1970s, there were few rules for toys in America, and many children were hurt by toys that broke into small pieces, had sharp edges, or used dangerous paints. In 1972 Congress created the U.S. Consumer Product Safety Commission, and in 1979 it issued a rule for toys meant for children under 3: no part, whole or broken off in use, may fit into a special test cylinder sized like a small child's throat. Since then, toy makers, testing laboratories and engineers have built a whole system of tests, collected in a standard called ASTM F963, which most toys sold in the United States must meet.

**How they figured it out.** The cylinder's size came from measuring the throats and mouths of young children, and from studying real accidents: which objects children choked on, and what size they were. Engineers then asked how toys actually break. Children drop them, bite them, pull on them and twist them, so the standard imitates those abuses. A toy for a child under 18 months is dropped several times from 4.5 feet (about 1.37 m) onto a hard floor; after each drop, inspectors check whether any small part has come loose. Other tests pull on eyes and buttons, twist off wheels, and check edges with a special tape that shows whether they would cut. As new dangers appeared, such as small, powerful magnets and button batteries, the rules were updated.

**The physics.** A drop test gives the toy a measured amount of energy. Energy of the fall = mass  $\times$  9.8  $\times$  height. A 200-gram toy dropped from 1.37 m hits the floor with  $0.2 \times 9.8 \times 1.37 \approx 2.7$  joules, all delivered in a few thousandths of a second. Hard, brittle plastic cracks under that sudden force; softer plastic flexes and survives. Engineers soften the impact by rounding corners, using tougher plastics, adding ribs inside the case, and making sure that if anything does break, the pieces are too big to swallow.

Magnets are dangerous for a different reason: if a child swallows two strong magnets, they can pull toward each other through the walls of the intestines.

**The engineering.** Toy safety engineers design with the test in mind from the first sketch: big parts for little children, screws that need a tool to reach the battery compartment, no sharp points, and paints tested for lead and other harmful metals. Then they test samples to failure, often with a **design margin**, so that the toy passes even if one batch of plastic is a little weaker. Safety rules can seem like a nuisance, but each one was written because a child was hurt. Following them faithfully is one way engineers love their smallest neighbors.

## PICTURE STUDY



*A Clockwork Tin Fire Engine*, Unknown toymaker (photograph: Speelgoedmuseum Deventer), Early 20th century; photographed 2015 · Photograph · Speelgoedmuseum (Toy Museum), Deventer, Netherlands

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

This clockwork fire engine, from the early 1900s, is now in a toy museum in the Netherlands. It was made of thin printed tin and run by a wound-up spring, as many toys were before plastic.

### Look closely

- Find the edges of the tin body and ladder. Would they be smooth or sharp if bent?
- Find the small parts, such as the ladder and wheels. Could any of them come off?
- Look for where the winding key would go.
- Look at the paint. Toy paints of that time sometimes contained lead.

### Talk about it

1. Which modern safety test might this toy fail, and why?
2. How would you redesign it to be safe for a three-year-old?
3. Why do you think toymakers moved from tin to plastic?

**Safety first.** Keep every small object you test, and the cylinder itself, away from babies and toddlers; put them in a closed box when you are done. Never test with button batteries or magnets: simply set them aside as items that are always dangerous for little children. Wear safety glasses during drop tests.

## BUILD

### Be a Toy Safety Lab

You will build a small-parts test cylinder from card stock to the official dimensions, test a collection of household objects with it, then design a simple toy for a toddler, drop-test it, and improve it until it passes.

#### You will need

- Card stock, tape, a ruler, a pencil and scissors
- A collection of safe objects to test: a coin, a bead, a bottle cap, a crayon, a large button, a toy block, a marble, a grape-sized ball of clay
- Materials for a toy: cardboard, a small plastic bottle, tape, clay, string
- A tape measure, a kitchen scale and a hard floor (tile or wood)
- Safety glasses and the engineer's notebook

#### Steps

1. **Build the cylinder.** Roll card stock into a tube with an inside diameter of 3.17 cm (1¼ inches) and tape it. Close the bottom with a slanted floor so the tube is 2.54 cm (1 inch) deep on the short side and 5.7 cm (2¼ inches) deep on the long side. Check the measurements carefully; they matter.
2. **Predict.** List your test objects and predict which will fit entirely inside the cylinder (a small part) and which will not.
3. **Test.** Place each object into the cylinder without pressing. If it fits completely below the rim in any position, it is a small part and unsafe for children under 3. Record the results.
4. **Design a toddler toy.** Design a simple shaker, stacking toy or pull toy for a child under 3. Draw it and list every part. Make sure no part could fit in the cylinder, even if it came loose.
5. **Build it and weigh it.** Calculate the energy of a drop from 1.37 m:  $\text{mass (kg)} \times 9.8 \times 1.37$ .
6. **Drop test.** Wearing safety glasses, drop the toy 5 times from 1.37 m (4.5 ft) onto the hard floor, landing it on different sides. After each drop, inspect it and test any loose piece in the cylinder.

7. Record the results in a table: drop number, how it landed, damage, any small parts.
8. **Improve.** Redesign the weakest point (stronger joints, rounded corners, no loose caps) and repeat the drop test until the toy passes all five drops.

#### Tips

- Turn each object in different directions when testing; the rule says “in any orientation.”
- Shakers filled with beans or beads must be sealed so firmly that a drop and a pull cannot open them.
- Real labs also do a pull test: you can hang a 1-kilogram bag from any part a child could grab and see if it comes off.

#### Check your work

- ☐ I can explain why the small-parts rule and drop tests exist.
- ☐ I can build and use a small-parts test cylinder correctly.
- ☐ I can calculate the energy of a drop and improve a design to survive it.

#### ENGINEER'S NOTEBOOK

1. Draw the small-parts cylinder with its dimensions, and list which objects passed and failed.
2. Draw your toddler toy before and after improvement, labeling what you changed and why.
3. Work it: a 0.35-kilogram toy is dropped from 0.91 m (3 ft). What energy does it have when it hits the floor? ( $0.35 \times 9.8 \times 0.91 \approx 3.1$  J.)

**From history.** Toy testing laboratories today run hundreds of tests, from flammability of costumes to the loudness of toy sounds. Some test engineers spend their careers trying to break toys in every way a child might, so that real children will not be hurt.

#### COMMON MISTAKES

- Testing only whether a toy is small, not whether a piece could break off. The test applies to parts after abuse too.
- Building the cylinder by eye. A few millimeters change which objects pass.
- Thinking safety rules are only for babies' toys. Older children's toys also have rules for sharp edges, magnets, batteries and paints.

**Make it a game • Safety Lab Inspection.** Be the safety lab. Your parent collects ten small household objects. Predict which fit inside a paper-tube small-parts cylinder, then test them. Explain what each test checks: choking, sharp edges and drops. Tell why a design margin matters. Closest predictions win, and every failed toy gets a one-sentence fix.

**Scripture.** “Take heed that ye despise not one of these little ones” (Matthew 18:10, KJV)

Jesus told His disciples to take special care of children. Engineers who design safe toys are taking heed for the little ones.

## TOY LAB: THE PHYSICS OF PLAY

Toys are some of the most carefully engineered objects in your house. A toy must work the first time, every time, in the hands of someone who will drop it, twist it and leave it in the rain, and it must cost little and be safe for small children who put everything in their mouths. In this optional bonus unit you will take four toys apart, in your mind and sometimes on the workbench, and find the physics and the engineering inside.

You will measure the energy stored in a rubber band and a spring and trace it through a pull-back car's gear train, watch a drinking bird run as a tiny heat engine, follow radio control from Nikola Tesla's 1898 boat to the car on your floor, and finish as a toy safety engineer, building the small-parts test cylinder and running drop tests. Use this unit after the family engineering fair, over the summer, or in any week that needs something fun.

### PREREQUISITES

- Knows work, energy and power, and  $F = ma$  (Unit 1)
- Knows gear ratios and how motors work (Lessons 4.3 and 8.1)
- Can run a fair test and keep a data table

### MASTERY CHECKLIST

- ☐ I can trace how energy is stored and released in a rubber-band or pull-back car, and calculate a gear ratio.
- ☐ I can explain how a drinking bird works as a heat engine and what conditions make it run faster.
- ☐ I can explain how radio control works, from transmitter to motor and steering.
- ☐ I can explain the main toy safety tests and why they exist, and run a small-parts and drop test.
- ☐ I can take apart an old toy safely and explain how it was engineered.



## OPTIONAL KITS FOR THIS UNIT

- **CrunchLabs Build Box:** Ages 8 and up. Monthly toys designed by Mark Rober, each built around a physics idea and explained in a video; a natural fit for this whole unit.
- **KiwiCo Tinker and Eureka crates:** Ages 9 and up (Tinker) and 14 and up (Eureka). Many crates build mechanical toys with springs, gears and motors; good companions to Lessons 9.1 and 9.3.
- **Snap Circuits:** Ages 8 and up. Snap-together circuits with motors, switches and (in some sets) a radio-controlled rover; useful for Lesson 9.3.

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

### 9.1 Rubber-Band and Pull-Back Cars: Stored Energy and Gear Trains

2 sessions of 50 minutes

---

### 9.2 The Drinking Bird: A Toy Heat Engine

2 sessions of 50 minutes

---

### 9.3 Radio-Controlled Cars: From Tesla's Boat to Your Floor

2 sessions of 50 minutes

---

### 9.4 Toy Safety Engineering: The Small-Parts Cylinder and the Drop Test

2 sessions of 50 minutes

---

## UNIT 9 REVIEW

Answer each question. Show your work for every calculation, with units, and use complete sentences for explanations. The review is worth 100 points.

1. **8 pts**

Trace the energy in a rubber-band car from your hand to the moving car, including where some energy is lost.

2. **10 pts**

Calculate: a band pulls with 8 N after stretching 0.25 m. About how much energy does it store? If a 0.2-kilogram car then moves at 2 m/s, what is its kinetic energy?

3. **8 pts**

Why does a pull-back car's gear train speed up the wheels, while the winch in Lesson 8.1 made its output slower?

4. **6 pts**

How did a toy help start the Wright brothers' interest in flight?

5. **10 pts**

Explain in two or three sentences how a drinking bird works.

6. **8 pts**

Predict: will a drinking bird dip faster on a dry, breezy day or a humid, still day? Why?

7. **6 pts**

Why must a drinking bird never be broken or heated?

8. **8 pts**

What did Tesla show at Madison Square Garden in 1898?

9. **10 pts**

Calculate: a toy drone's controller uses radio at 2.4 GHz. Using a speed of light of 300,000,000 m/s, what is the wavelength? What would a quarter-wave antenna's length be?

10. **8 pts**

What is the small-parts test cylinder, and what does it mean if an object fits inside it?

11. **10 pts**

Calculate: a 0.5-kilogram toy is dropped from 1.37 m. What energy does it have just before it hits the floor?

12. 8 pts

Name two dangers in toys besides small parts, and explain how engineers design against one of them.

**ANSWER KEY**

1. Your work stretches or twists the band (elastic potential energy); when released it turns the axle and wheels, giving the car kinetic energy; some energy is lost as heat in the band and bearings, sound, and friction with the floor.
2. Stored  $\approx \frac{1}{2} \times 8 \times 0.25 = 1$  J. Kinetic  $= \frac{1}{2} \times 0.2 \times 2^2 = 0.4$  J (so about 0.6 J was lost).
3. The pull-back spring turns slowly with strong force, so gears speed the wheels up for a fast car. The winch motor spins fast with little force, so gears slow it down to gain torque for lifting.
4. In 1878 their father brought home a rubber-band-powered toy helicopter based on Alphonse Pénaud's design; they played with it and built copies.
5. Water evaporating from the wet head cools it, lowering the vapor pressure inside the head. The higher pressure in the warm body pushes liquid up the neck, moving the center of gravity forward until the bird tips and drinks. Tipped, the pressures even out, the liquid drains back, and it swings upright to repeat.
6. On a dry, breezy day, because water evaporates faster from the head, cooling it more and making a bigger temperature difference.
7. The liquid inside is a harmful chemical, the glass can cut, and heating raises the pressure inside.
8. A boat in a pool controlled by radio, with no wires, obeying commands such as turning and flashing its lights.
9. Wavelength  $= 300,000,000 \div 2,400,000,000 = 0.125$  m (12.5 cm). Quarter wave  $\approx 3.1$  cm.
10. An official gauge about 3.17 cm ( $1\frac{1}{4}$  in) across, sized like a young child's throat. If an object fits completely inside in any position, it is a small part and is not allowed in toys for children under 3, because it is a choking hazard.
11. Energy  $= 0.5 \times 9.8 \times 1.37 \approx 6.7$  J.
12. Any two: sharp edges or points, small powerful magnets, button batteries, harmful paints, strings that could strangle. Example: button batteries are placed in compartments that need a screwdriver to open.

## PORTFOLIO PIECE: A SAFE, TESTED TOY

Design and build an original toy for a younger child that uses one physics idea from this unit or the year, such as stored elastic energy, a gear train, a pendulum or buoyancy. Before building, decide the age it is for and list the safety rules it must meet. Test it twice: once to measure how well it works (for example, distance, time or number of spins), and once with a small-parts check and drop test. Write a one-page design report with a labeled drawing, test data, one calculation, the safety tests and their results, and the improvements you made.

| LOOK FOR                              | WHAT IT MEANS                                                                           |
|---------------------------------------|-----------------------------------------------------------------------------------------|
| <b>Physics idea</b>                   | The toy clearly uses one physics idea, explained correctly in the report.               |
| <b>Performance test</b>               | A fair test of how well the toy works, with data recorded and at least one calculation. |
| <b>Safety testing</b>                 | Small-parts and drop tests done correctly for the chosen age, with results recorded.    |
| <b>Improvement</b>                    | At least one change made after testing, with before-and-after results.                  |
| <b>Craftsmanship and presentation</b> | Neat, durable toy and a clear report with a labeled drawing.                            |