

SCHOOL LAUNCH • GEOGRAPHY K-12

# GRADE 6 GEOGRAPHY: PHYSICAL GEOGRAPHY: THE EARTH'S SYSTEMS

*A year of true stories about the working earth, from Pliny the Younger watching Vesuvius bury Pompeii and Marie Tharp mapping the hidden ridge beneath the Atlantic to Benjamin Franklin charting the Gulf Stream for the mail ships, the great Mississippi flood of 1927 and the Dutch dikes and Delta Works that hold back the North Sea, each one taken apart to see how the land, the air and the water move and then tried in miniature with clay, a paint-tray stream, a sponge mountain and a pan of colored water at the kitchen table.*

First edition

*"And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;" (Acts 17:26, KJV)*

## COURSE GUIDE

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This course studies the physical earth as one working whole through a school year in eight units: maps of the land's shape, the moving earth, volcanoes and earthquakes, weathering, erosion and rivers, climate as physical geography, the great biomes, oceans and currents, and living with natural hazards. Each unit is built around real places and moments: a USGS map of Mount St. Helens before and after 1980, Alfred Wegener's puzzle of the continents in 1912, Marie Tharp and Bruce Heezen's map of the ocean floor, Pliny the Younger's letters about Vesuvius in AD 79, the San Francisco earthquake of 1906, the glaciers that carved Yosemite, the rain shadow of the Cascades, Wladimir Köppen's climate zones, the layers of the Amazon, Franklin's chart of the Gulf Stream, the tides of the Bay of Fundy and the Galveston hurricane of 1900. The lessons describe the processes we can observe and measure, and take no position on the age of the earth.

Every lesson follows the same path. First comes **the story**: a real person, place and date. Then **how they figured it out**: what people saw, what they measured, what puzzled them and how the explanation came together. Then **the big idea** underneath, explained for a sixth grader: contour lines, plate boundaries, seismic waves, meanders and deltas, the sun's angle, rain shadows, gyres, tides and convection. Last, the student does it with his or her own hands: slicing a clay mountain into contours, shaking block towers on a homemade shake table, running water down a stream table and building a dike and polder in a pan, then drawing it all in a map notebook.

A thread runs through every grade of the School Launch Geography series: **technology overcoming geography**. In this grade it is the story of people learning to live safely where nature is dangerous. Lessons marked ✨ follow the engineers who build buildings that ride out earthquakes, the Dutch who drained lakes and held back the sea with dikes, windmills and the Delta Works, the levees of the Mississippi, the Galveston seawall raised after the storm of 1900, Franklin's chart that sped the mail ships across the Atlantic, and the radar and forecasts that now give warning before a tornado.

The course is written for Christian families and teaches the earth as the work of a faithful Creator, who "laid the foundations of the earth, that it should not be removed for ever" (Psalm 104:5). In Job 38 God Himself leads a tour of physical geography, from the foundations of the earth to the springs of the sea, the treasures of the snow and the way of the lightning, and the student reads it alongside the science. The series verse reminds us that the lands we study were made for people to live in: "And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;" (Acts 17:26).

### WHO IT IS FOR

Written for students in grade 6 (about ages 11-12) who read on their own, can measure with a ruler in centimeters and inches, read a simple bar or line graph, and work with decimals and simple ratios. A parent or teacher reads along when it helps, joins in the projects and

supervises anything involving a knife, an oven or hot water. Measurements are given in both metric and U.S. units (kilometers and miles, meters and feet). Nothing needs to be bought beyond ordinary household items: modeling clay or potatoes, dental floss, a paint tray, sand, a sponge, a spray bottle, food coloring, building blocks and a graph-paper notebook.

## HOW TO USE THIS COURSE

**The weekly rhythm.** The year has 32 lessons in eight units, one lesson a week, with an optional ninth unit, the Map Lab. Session 1 (about 45 minutes) is the warm-up, the video, the teaching and the picture study. Session 2 (about 45 minutes) is the project, the worked examples, the practice and the map notebook. In the last week of each unit, add a third session for the unit review and the unit project. Units 5 and 7 pair naturally, since ocean currents carry much of the heat that shapes climate; you may teach them back to back if you like.

**The ★ and ⚙ marks.** Ten lessons are marked ★. Together they make the *quarter path*, a one-quarter version of the course for families who want a shorter study: contour lines and the potato mountain, the inside of the earth, Vesuvius, weathering, weather and climate, Köppen's zones, the rain forest, the Gulf Stream and the Netherlands. Lessons marked ⚙ carry the technology thread, the engineering that lets people live safely beside volcanoes, rivers, coasts and storms. All of Unit 8 carries it.

**The map notebook.** Use one graph-paper composition book for the whole year. Every unit adds a map the student draws or reads: a topographic map of a local hill, the world's plates with volcanoes and earthquakes plotted, the Ring of Fire, the Mississippi delta through time, a Köppen climate map, the world's biomes, the major ocean currents and a hazard map of the United States. Date every page, give it a title, a key, a north arrow and a scale, and write one sentence about what the map shows.

**Worked examples and practice.** Each lesson has three worked examples that show the thinking step by step, such as finding the height of a point between two contour lines, telling which way a river flows from the bends of its contours, or reading a climate chart. Then come ten practice questions, with answers given for the parent. Have the student try every question first, then check together and talk through any mistakes; the *common mistakes* list in each lesson shows where students usually go wrong.

**Unit review and unit project.** Each unit ends with a short review (60 points, 8–12 items) and a unit project that pulls the unit together, such as a clay contour model, a plate-boundary map, a shake-table report, a stream-table map, a rain-shadow model, a biome field guide, a currents map or a model dike and polder. Keep the unit projects in one folder for the year. The optional Map Lab adds four lessons of puzzles and games: a contour map puzzle, plate boundary detective, climate mystery cities and a stream-table map.

**Where this course fits.** Grade 6 is the physical-geography year of the School Launch K–12 Geography series. It builds on the explorers and map projections of Grade 5 and prepares the student for the regions of the world in Grade 7 and the rivers, ports and straits of Grade 8. It pairs well with the School Launch Engineering & Physics courses, which build the

bridges, towers and machines this course sees standing against wind and water, and with the Business & Finance courses, which follow the trade that rivers, harbors and ocean currents carry.

## **SCOPE AND SEQUENCE**

### **Unit 1: Maps of the Land's Shape (1-4)**

Contour lines that join points of equal height; reading USGS topographic quadrangles; slicing a clay or potato mountain into its contour map; and drawing the side view of a hike as a profile.

### **Unit 2: The Moving Earth (5-8)**

Crust, mantle and core, learned from earthquake waves; spreading, colliding and sliding plate boundaries and Wegener's puzzle of 1912; the Himalaya and the Alps; and the Mid-Atlantic Ridge rising above the sea in Iceland.

### **Unit 3: Volcanoes and Earthquakes (9-12)**

Vesuvius and Pompeii in AD 79 through the letters of Pliny the Younger; shield, cinder-cone and composite volcanoes; the San Francisco earthquake and fire of 1906; and buildings designed to ride out the shaking.

### **Unit 4: Weathering, Erosion and Rivers (13-16)**

How ice, roots and rain break rock; rivers that cut valleys, wind into meanders and leave oxbow lakes; the Nile and the Mississippi building deltas and floodplains; and the glaciers that carved Yosemite and the Great Lakes.

### **Unit 5: Climate as Physical Geography (17-20)**

The difference between the day's weather and the long pattern of a place; latitude and the sun's angle; altitude, prevailing winds and the rain shadow of the Cascades; and Wladimir Köppen's system of climate types.

### **Unit 6: Biomes (21-24)**

The layers of life in the Amazon rain forest; the Sahara, the steppe and the prairie; the oak and maple forests of the temperate lands and the spruce and fir of the taiga; and the permafrost and short summer of the tundra.

### **Unit 7: Oceans and Currents (25-28)**

Benjamin Franklin's chart of the Gulf Stream for faster mail ships; how wind and the earth's spin turn the great gyres; the moon's pull, the Bay of Fundy and harbor planning; and why London is mild and Labrador cold at the same latitude.

### **Unit 8: Living with Natural Hazards (29-32)**



The Dutch dikes, windmills and Delta Works; the Mississippi flood of 1927 and the levees of the Corps of Engineers; the Galveston hurricane of 1900 and the seawall that followed; and the radar and forecasts that give warning in Tornado Alley.

### **Unit 9: Bonus: Map Lab (Optional)**

Four lessons of map games and puzzles: matching contour maps to landforms, matching earthquakes to plate edges, guessing cities from their climate charts and mapping a homemade stream table.

### **MATERIALS**

- **Map notebook (a graph-paper composition book):** One for the whole year: contour maps, profiles, plate maps, climate charts, current maps and the hazard map.
- **A world atlas or wall map, and a globe if you have one:** Used in every unit for finding places, plates, climates, biomes and currents. A free printable outline map works too.
- **A ruler marked in centimeters and inches, colored pencils and a fine black pen:** For contour lines, profiles, keys and scale bars.
- **Modeling clay or a few large potatoes, dental floss and a butter knife:** For the contour models in Unit 1. A parent helps with any cutting.
- **A paint tray or baking pan, sand or soil, and a cup or watering can:** For the stream table in Unit 4, the dike and polder in Unit 8 and the Map Lab.
- **Graham crackers, frosting and a paper plate:** For the plate model in Unit 2.
- **Building blocks, drinking straws, tape, a sturdy box lid or tray and rubber balls or marbles:** For the shake-table test in Unit 3.
- **A kitchen sponge, a spray bottle, a clear glass pan, food coloring, ice cubes and warm water:** For the rain-shadow model in Unit 5 and the convection current in Unit 7.
- **A shoebox and craft supplies:** For the biome boxes in Unit 6, or plain paper for a biome field guide instead.
- **Optional: one of the books or resources listed in a unit:** Never required. See the list in each unit.

### **GRADING**

Grades come mostly from the projects, the map notebook and the practice, because physical geography is learned by seeing, measuring and drawing. A project that did not work as expected but is honestly recorded and explained earns full credit.

- Projects (careful work, honest observations and the explain-it step): 30%
- Map notebook (dated maps with title, key, north arrow and scale): 20%
- Practice questions: 10%
- Unit reviews: 20%
- Unit projects: 20%

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

- Grade the process, not just the result. Did the student predict, observe carefully, measure, record honestly and explain what happened and why?
- A map earns full marks when it has a date, a title, a key, a north arrow, a scale in kilometers and miles, and one sentence about what it shows.
- Each unit review is worth 60 points. It may be done orally for a student who writes slowly; the parent writes down the answers.
- Practice is graded for effort and corrections: a question missed, then corrected and explained, counts as done.
- Keep each unit project in one folder. Together they make a fine record of the year.

## **A NOTE TO PARENTS**

You do not need to be a geologist or a meteorologist to teach this course. Read the story aloud together, watch the video, and then work beside the student in the project. Ask “What do you see?”, “What do you think will happen?” and “Why did it happen that way?” Those three questions are most of what a good science teacher does. The answers to every practice question are given for you.

The course teaches physical geography as processes we can observe and measure: rivers cutting and building, volcanoes erupting, plates moving, winds and currents carrying heat and rain. It takes no position on the age of the earth, and it treats climate as physical geography, explained by latitude, altitude, winds, currents and mountains, without asking you or your child to take a side in present-day public debates. Natural hazards are taught with an eye to preparation: the dikes, levees, seawalls, building codes and warning systems that keep people safe.

Some projects use water, sand, a knife or warm water from the tap, so stay nearby and expect a little mess. Above all, the course hopes to raise a young person who looks at a hillside, a river or a storm cloud with understanding and wonder, and who hears in the shape of the land the question God asked Job: “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding” (Job 38:4).

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## **Unit 9: Bonus: Map Lab** (optional)

9.1 Contour Map Puzzle

9.2 Plate Boundary Detective

9.3 Climate Mystery Cities

9.4 Make a Stream-Table Map

★ quarter path · ⚙ technology overcoming geography

## MAPS OF THE LAND'S SHAPE

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When God asked Job, “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding” (Job 38:4), He began a tour of the whole physical world: the sea, the snow, the mountains and the deep. This year you will take that tour as a geographer. You will start where every physical geographer starts: with a map that shows the **shape of the land**, its hills and valleys, cliffs and streams, drawn on a flat sheet of paper with nothing but lines.

You will climb Schiehallion in Scotland with the men who tried to weigh the earth in 1774 and watch Charles Hutton invent lines of equal height to understand it. You will follow the topographers of the U.S. Geological Survey with their plane tables, learn to read the famous 7.5-minute quadrangles, and watch Lake Mead draw contour lines on the canyon walls as it filled behind Hoover Dam. You will slice a clay mountain with dental floss to make your own contour map, and you will see how scientists used profiles to measure what Mount St. Helens lost on May 18, 1980.

By the end of the unit you will be able to look at a page of brown lines and see the land rise and fall, measure real distances and slopes, and draw the side view of any hike. These skills come back in every unit this year, from volcanoes and rivers to rain shadows and floodplains.

### BEFORE YOU BEGIN

- Can multiply and divide whole numbers and decimals, and find a fraction of a number
- Can use a ruler in inches and centimeters
- Knows the cardinal directions and can read a map scale bar
- Knows what latitude and longitude are (from earlier grades)

### MASTERY CHECKLIST

- I can explain what a contour line is and state the rules contour lines follow.
- I can find the contour interval of a map and read the elevation of a point, and I can tell steep ground from gentle ground by the spacing of the lines.
- I can read a USGS 7.5-minute quadrangle: its scale, colors and symbols, and its hills, ridges, valleys, saddles, cliffs, depressions and stream directions.
- I can measure distances on a 1:24,000 map in feet, miles, meters and kilometers.
- I can make a contour map by slicing a model mountain, and explain why a shoreline is a contour line.
- I can draw a profile from a contour map and calculate elevation gain, grade and vertical exaggeration.

## OPTIONAL BOOKS AND RESOURCES

- **USGS topoView** (<https://ngmdb.usgs.gov/topoview/>): Free. Find and download any USGS topographic map, including old and new 7.5-minute quadrangles of your own area and of Mount St. Helens. A parent may help with downloading and printing a section of the map.
- **USGS Mount St. Helens page (Cascades Volcano Observatory)** (<https://www.usgs.gov/volcanoes/mount-st.-helens>): Free. Photographs, maps and plain explanations of the 1980 eruption and of how scientists still watch the volcano today (Lessons 1.2 and 1.4).

## 1.1 CONTOUR LINES ★

### OBJECTIVES

- Explain what a contour line is and state the rules that every contour line follows.
- Find the contour interval of a map, read the elevation of a point, and tell steep ground from gentle ground by the spacing of the lines.
- Tell how Charles Hutton used lines of equal height to understand the mountain Schiehallion in the 1770s, and stake out a real contour line with a homemade A-frame level.

**Warm-up.** Make a fist and rest it on the table, knuckles up. Stack coins or thin books to make a little platform about 1 cm high, rest a washable marker on it, and have a helper slide the marker all the way around your fist so it draws a line at exactly that height. Add more coins and draw a second line about 1 cm higher, then a third. Keep your fist still and look straight down at it. Where are the lines close together? Where are they far apart? Which parts of your fist are steep?

**Watch.** *Contour Lines* (Bozeman Science, 5:50). <https://www.youtube.com/watch?v=9kNkpQTwPc0>

With the big idea: watch the first part, where Paul Andersen shows how each contour line joins points of equal height and how lines that sit close together mean a steep slope.

**Note:** Captions were not available to check; preview it first. The second half moves on to electric fields (equipotential lines), a physics topic beyond this lesson, so you can stop once the topographic map part ends. Uses contour lines as an analogy for electric-field equipotential lines, which the lesson does not cover.

**Backup video.** *Understanding contour lines with Steve Backshall and Ordnance Survey* (Ordnance Survey, 1:15). [https://www.youtube.com/watch?v=4i\\_6eToM3X8](https://www.youtube.com/watch?v=4i_6eToM3X8)

With On the map: watch Steve Backshall show how the thin lines on a map mark height and how their spacing tells you whether a hill is gentle or steep. Note: Captions were not available to check; preview it first. This is from Britain's national mapping agency, so expect British terms and heights in metres. Uses Ordnance Survey (British) maps and metric heights, not USGS maps in feet.

### KEY TERMS

#### elevation

The height of a place above mean sea level, the zero line from which mapmakers measure.

#### contour line

A line on a map that joins points of equal elevation. Walking along one on the ground, you would go neither up nor down.

#### contour interval



The difference in elevation between one contour line and the next, such as 10 feet or 20 meters. It is printed in the map's margin.

**index contour**

A darker, labeled contour line, usually every fifth line, that makes counting easier.

**relief**

The difference between the highest and lowest points in an area; how hilly or flat the land is.

**depression contour**

A closed contour line with short ticks (hachures) pointing inward, marking a hollow that is lower than the land around it.

**CORE IDEAS**

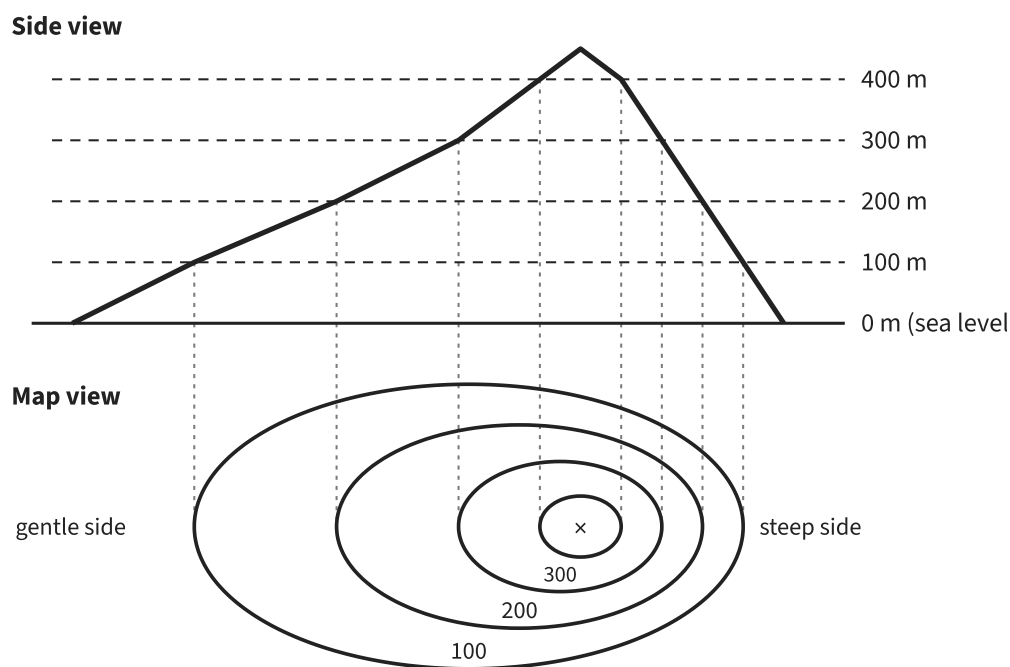
**The story.** In the summer of 1774 a little camp stood on the slopes of Schiehallion, a lonely mountain in the Highlands of Scotland. Nevil Maskelyne, the Astronomer Royal of Great Britain, had come to try something that sounds impossible: to weigh the whole earth. Isaac Newton had taught that every mass pulls on every other mass, so a great mountain ought to pull a hanging plumb line a tiny bit toward itself. If Maskelyne could measure that tiny tug, and if someone could work out how big the mountain was, the mountain's pull could be compared with the pull of the whole earth. Schiehallion was picked because it stands nearly alone and has a long, even ridge, a shape that is easier to measure. For months, through wind and rain, Maskelyne watched the stars from small observatories on the north and south sides of the mountain while surveyors climbed all over it measuring heights.

**How they figured it out.** Measuring the tug was only half the work. The other half fell to Charles Hutton, a mathematician who was handed the surveyors' pages of numbers: the height of point after point on the mountain. A list of numbers does not look like a mountain. So Hutton drew lines on his plan of Schiehallion joining all the points that stood at the same height. Suddenly the mountain's shape appeared on flat paper. Where the lines crowded together the slope was steep; where they spread apart the ground was gentle; and the long ridge showed up as stretched rings, one inside another. With the shape in hand Hutton could work out the mountain's volume piece by piece. In 1778 he reported that the earth as a whole is about four and a half times as heavy as the same amount of water. Careful modern measurements give about five and a half, so his answer was in the right neighborhood. But his lines of equal height turned out to be a gift to every mapmaker after him.

**The big idea.** A **contour line** is a line on a map that joins points of equal **elevation**, or height above sea level. If you could walk along a contour line on the real ground, you would never go uphill or downhill. Contour lines obey a few rules. Every point on one line has the same elevation. A contour line never splits and never crosses another line, because one spot cannot have two heights. (The rare exception is an overhanging cliff, where one line passes under another.) Every contour line closes on itself in a loop, though the loop may run off the edge of the map. A set of closed loops one inside another marks a hilltop, with the highest point inside the smallest loop.

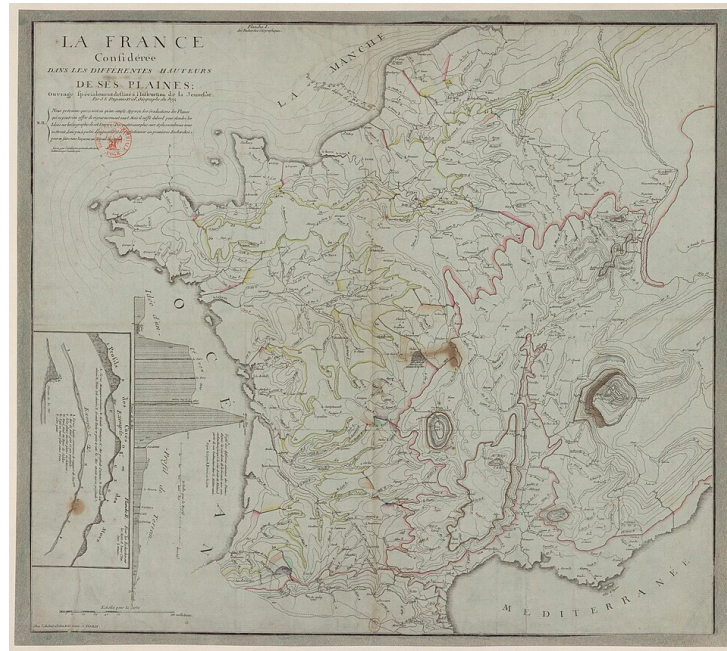
**How to read the lines.** The difference in height between one line and the next is the **contour interval**. On a map of flat farmland it might be 5 or 10 feet; in steep mountains it might be 40 feet or more; on metric maps it is often 10 or 20 meters. To make counting easy, every fifth line is drawn darker and labeled with its elevation. These are **index contours**. Spacing tells steepness: lines packed close together mean steep ground, lines far apart mean a gentle slope, and a wide space with no lines at all means nearly flat land. A loop marked with short ticks pointing inward shows a **depression**, a hollow lower than the land around it. Look at the figure: the same hill is drawn from the side and from above. Each level slice through the hill becomes one ring on the map, and the steep side gets the crowded rings.

**On the map.** You have seen contour lines in nature without knowing it. The edge of a calm lake is a perfect contour line, because still water lies level: every point of the shoreline is at the same height. A bathtub ring is a contour line around the tub. Farmers use the idea too. On hilly fields they plow and plant along the contours, so that each furrow catches rainwater instead of letting it rush downhill and carry the soil away. On a modern map of Schiehallion, the summit stands at 1,083 meters (3,553 feet), and its contour lines still make the long, stretched loops that Hutton drew, tight on the steep slopes and loose along the gentle ridge. When you read them, you are reading the handiwork of the Creator who, as Isaiah says, “weighed the mountains in scales, and the hills in a balance.”



*Each level slice through the hill (top) becomes one contour ring on the map (bottom). The steep side has crowded lines; the gentle side has lines far apart.*

## PICTURE STUDY



*La France considérée dans les différentes hauteurs de ses plaines (France Seen in the Different Heights of Its Plains)*, Jean-Louis Dupain-Triel, 1791 · Engraved map · Bibliothèque nationale de France, Paris (Département Cartes et plans); other copies survive in national map libraries

Jean-Louis Dupain-Triel was a French engineer and mapmaker. In 1791, while the French Revolution was remaking his country, he published this map of all of France with lines that join places of equal height. It is one of the earliest maps to use contour lines for an entire country, only a few years after Hutton drew his lines around one Scottish mountain.

Dupain-Triel did not have airplanes, satellites or even a full survey of heights. He had to build his lines from the measurements that existed in his day. Look at his map as a first try at a great idea: showing the height of a whole nation on a flat sheet of paper.

### Look closely

- Find the sea along the coasts of France. What height do the lines start from?
- Trace one line with your finger as far as you can. Does it ever cross another line?
- Find a place where the lines crowd together and a place where they spread far apart. Which is steeper ground?
- Look in the margins for a title, a scale, or any drawing of the land seen from the side.

### Talk about it

1. Why would a map of heights be useful to a government planning roads and canals in 1791?
2. What would make Dupain-Triel's lines less exact than the lines on a modern map?
3. How is his map like Hutton's plan of Schiehallion, and how is it different?

**Safety first.** An adult should help with any sawing or drilling when building the A-frame. Work on a gentle slope in your own yard or a park where you have permission, and pull up all stakes when you finish.

## **PROJECT: STAKE OUT A REAL CONTOUR LINE WITH AN A-FRAME LEVEL**

Farmers around the world have used a simple wooden A-frame and a hanging weight to find level lines across a hillside, so they can plow, plant or build terraces along the contour. You will build one and use it to mark a real contour line on a slope. When you finish, you will be able to walk along your line of stakes and stay at exactly the same height the whole way.

### **You will need**

- Two straight sticks or boards about 4 feet (1.2 m) long, for the legs
- One straight stick or board about 3 feet (0.9 m) long, for the crossbar
- Screws and a screwdriver, or strong cord for lashing
- String about 4 feet (1.2 m) long and a weight (a large washer, nut or small rock tied in a cloth)
- A marker or pencil
- 10 to 15 stakes: garden stakes, chopsticks, or clothespins on sticks; a few bright ribbons
- A tape measure and a gently sloping lawn or field

### **Steps**

1. Join the two long sticks at the top in an upside-down V, with the feet about 4 feet (1.2 m) apart. Fasten the crossbar across the middle of both legs to make a capital letter A.
2. Tie the string to the top of the A and hang the weight so it swings just below the crossbar. This is a plumb line; it always hangs straight down.
3. Find the level mark. Stand the A on the flattest ground you can find and mark where the string crosses the crossbar. Now turn the A around so the legs swap places, set the feet in the same two spots, and mark again. The true level mark is exactly halfway between your two marks. Make it dark.
4. On your slope, push in a first stake. Set one foot of the A right beside it.
5. Swing the other foot up or down the hill, keeping it on the ground, until the string hangs exactly over the level mark. Both feet are now at the same height. Push in a stake at the second foot.
6. Move the A forward: put the first foot at the new stake and swing the second foot again until the string hangs on the mark. Stake it. Keep going across the slope until you have 8 to 12 stakes.
7. Stand back and look at your line of stakes. It is a real contour line. Does it curve? Where does it bend uphill, and where does it bend downhill?
8. Optional second line: from your first stake, find a point about 30 cm (1 foot) higher up the slope by holding a straight board level from the uphill ground out over the stake

and measuring the gap. Run a second contour line from there. Measure how far apart your two lines are at several places. Where they are closest, the slope is steepest.

9. Draw a map of your slope in your notebook from above, with the stakes as dots and the contour lines joining them.

### Tips

- Check the level mark more than once. If your mark is a little off, every step adds the error and your line drifts uphill or downhill.
- A line that bends uphill usually crosses a small hollow or gully; a line that bends downhill usually crosses a little ridge or bump.
- On a windy day, let the weight settle before you read the string, or hang it inside a jar to keep it still.

### Check your work

- I can explain why the plumb line shows when both feet of the A are level.
- I staked a line of equal height and drew it as a contour line on my map.
- I can tell from two contour lines where my slope is steeper.

### MAP NOTEBOOK

1. Draw the side view of a hill with one steep side and one gentle side. Cut it with four level dashed lines, then draw the map view underneath with four rings, like the lesson figure.
2. Write the rules of contour lines in your own words in a box titled “Contour Rules,” with a tiny drawing beside each rule.
3. Draw a lake with a rocky island in it and two contour lines around the island. Label the shoreline as a contour line and give it an elevation.

**From history.** Hutton was not the first to draw lines of equal value. In 1701 the astronomer Edmond Halley published a chart of the Atlantic Ocean with curved lines joining places where a compass needle pointed the same amount away from true north, to help sailors find their way. Dutch surveyors had already drawn lines of equal depth in rivers and harbors as early as 1584, and mapmakers later used the same trick of joining equal values for heights on land, and today weather maps use it for lines of equal air pressure and temperature.

## WORKED EXAMPLES

**Example 1.** On a map, two index contours are labeled 500 m and 600 m. Between them are four thinner lines. What is the contour interval, and what are the elevations of the four thin lines?

1. Four thin lines between two index lines divide the space into 5 equal steps (count the gaps, not the lines).
2. The difference in height is  $600\text{ m} - 500\text{ m} = 100\text{ m}$ .
3. Each step is  $100\text{ m} \div 5 = 20\text{ m}$ .
4. Counting up from 500 m: 520 m, 540 m, 560 m and 580 m.

**Answer:** The contour interval is 20 m (about 66 feet). The thin lines are 520, 540, 560 and 580 m.

**Example 2.** A surveyor measured two spot heights 3 cm apart on a map: 120 m and 180 m. The ground rises evenly between them. Where does the 150 m contour line cross the line between the two points? Where does the 140 m line cross?

1. The total rise is  $180\text{ m} - 120\text{ m} = 60\text{ m}$  over 3 cm of map.
2. 150 m is 30 m above 120 m, which is  $30 \div 60 = 1/2$  of the way. Half of 3 cm is 1.5 cm.
3. 140 m is 20 m above 120 m, which is  $20 \div 60 = 1/3$  of the way. One third of 3 cm is 1 cm.
4. This is exactly how Hutton turned scattered heights into lines: he placed each line in its fair share of the space between measured points.

**Answer:** The 150 m line crosses 1.5 cm from the 120 m point (halfway). The 140 m line crosses 1 cm from the 120 m point.

**Example 3.** On a map with a scale of 1:25,000 and a contour interval of 20 m, two neighboring contour lines are 5 mm apart. How far apart are they on the ground, and how steep is the slope (rise divided by run, as a percent)?

1. At 1:25,000, 1 mm on the map is 25,000 mm on the ground.  $5\text{ mm} \times 25,000 = 125,000\text{ mm}$ .
2.  $125,000\text{ mm} = 125\text{ m}$  (about 410 feet).
3. The ground rises 20 m (one contour interval) in 125 m across.
4.  $\text{Slope} = 20 \div 125 = 0.16$ , which is 16 percent.

**Answer:** The lines are 125 m (about 410 feet) apart on the ground, and the slope is 16 percent, a steep hill to walk up.



## PRACTICE

1. **EASY** What is a contour line? Use the word elevation in your answer.
2. **EASY** Look at the figure. Which side of the hill is steeper, the left or the right? How can you tell from the map view alone?  
*(Use the map or drawing “Use the map view to decide which side is steeper.” shown earlier in this lesson.)*
3. **EASY** Index contours on a map are labeled 1,000 feet and 1,100 feet, with four thin lines between them. What is the contour interval?
4. **MEDIUM** The contour interval is 10 m. You start on the 250 m contour and walk straight uphill, crossing 7 more contour lines. What is your elevation now?
5. **MEDIUM** Two spot heights are 6 cm apart on a map: 410 m and 470 m. The ground rises evenly. How far from the 410 m point does the 450 m contour cross?
6. **MEDIUM** A mountain lake has its surface at 312 m above sea level. Explain why its shoreline is a contour line.
7. **MEDIUM** Many U.S. maps use a 40-foot contour interval. How many meters is that? Many European maps use a 20 m interval. How many feet is that? (1 foot = 0.3048 m)
8. **HARD** Why can two contour lines never cross on a normal map? What is the one rare exception?
9. **HARD** On a 1:50,000 map with a 20 m contour interval, two contour lines are only 2 mm apart. How far apart are they on the ground, and what is the slope as a percent?
10. **CHALLENGE** Schiehallion’s summit is 1,083 m above sea level. On a map with a 50 m contour interval (lines at 50, 100, 150 m and so on), how many contour lines would you cross climbing from sea level to the summit? What is the summit’s height in feet?

## COMMON MISTAKES

- Counting the lines instead of the gaps when finding the contour interval. Four thin lines between two index lines make five steps, not four.
- Thinking closely spaced lines mean a high place. Close lines mean a steep place; a high plateau can have no lines at all on top.
- Forgetting that elevation is measured from sea level, not from the bottom of the hill or the ground where you stand.

**Make it a game • Contour Climb.** A parent draws a hill on a whiteboard or paper with contour lines and labels only the index line and the interval. The parent points to a spot; you have ten seconds to say its elevation, or the range it lies between (for example, “between 340 and 360 meters”). Score one point for a correct answer and a bonus point if you can also say whether the ground there is steep or gentle. Switch roles after ten turns.

**Scripture.** “Who hath measured the waters in the hollow of his hand, and meted out heaven with the span, and comprehended the dust of the earth in a measure, and weighed the mountains in scales, and the hills in a balance?” (Isaiah 40:12, KJV)

Maskelyne and Hutton worked for months to weigh one Scottish mountain, and they came out about one-fifth off. God measured and weighed every mountain at creation. Careful measuring is a way of thinking God's thoughts after Him, and it teaches us humility about how great His work is.

#### Practice answers

1. A contour line is a line on a map that joins points of equal elevation (height above sea level).
2. The right side. On the map view the rings are crowded close together on the right and spread far apart on the left.
3.  $100 \text{ ft} \div 5 \text{ steps} = 20 \text{ feet}$ .
4.  $250 \text{ m} + 7 \times 10 \text{ m} = 320 \text{ m}$  (about 1,050 feet).
5.  $450 - 410 = 40 \text{ m}$  out of a 60 m rise, which is  $\frac{2}{3}$  of the way.  $\frac{2}{3} \times 6 \text{ cm} = 4 \text{ cm}$  from the 410 m point.
6. Still water lies level, so every point where the water meets the land is at the same height, 312 m. A line joining points of equal elevation is a contour line.
7.  $40 \times 0.3048 = 12.2 \text{ m}$ .  $20 \div 0.3048 = 65.6 \text{ feet}$  (about 66 feet).
8. Where two lines crossed, one spot would have two different elevations, which is impossible. The exception is an overhanging cliff, where the ground at one height juts out over lower ground, so one line passes under another.
9.  $2 \text{ mm} \times 50,000 = 100,000 \text{ mm} = 100 \text{ m}$  (about 330 feet).  $\text{Slope} = 20 \div 100 = 0.20 = 20 \text{ percent}$ .
10. Lines at 50, 100, ... , 1,050 m:  $1,050 \div 50 = 21 \text{ lines}$ . The summit (1,083 m) is inside the 1,050 m loop.  $1,083 \text{ m} \div 0.3048 \approx 3,553 \text{ feet}$ .



## 1.2 READING A TOPOGRAPHIC MAP

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### OBJECTIVES

- Read the margin of a USGS 7.5-minute quadrangle: its scale, contour interval, colors and symbols.
- Recognize hilltops, ridges, valleys, saddles, cliffs, depressions and the direction a stream flows from the pattern of contour lines.
- Measure real distances on a 1:24,000 map in feet, miles, meters and kilometers.

**Warm-up.** Without looking at anything, draw a quick map of your street or yard and show which way is uphill and which is downhill. How did you show it: arrows, shading, words? Compare with a family member's map. Today you will learn the way the mapmakers of the United States Geological Survey show up and down on every sheet they print.

**Watch.** *Lesson 8 - U.S. Geological Survey Topographic Maps* (USGS Trainings, 10:57). [https://www.youtube.com/watch?v=TC7JpjL\\_Fok](https://www.youtube.com/watch?v=TC7JpjL_Fok)

After the story: watch the short history of USGS topographic maps to see how the survey that began in 1879 led to today's US Topo maps, and notice what each map shows.

**Note:** Captions were not available to check; preview it first. This is an adult training video, so the parts on how maps are made and downloaded may be dry for students; the history section at the start fits the lesson best.

### KEY TERMS

#### **topographic map**

A map that shows the shape and elevation of the land with contour lines, along with water, roads, buildings and names.

#### **quadrangle**

A USGS map sheet bounded by lines of latitude and longitude. A 7.5-minute quadrangle covers 7.5 minutes of latitude by 7.5 minutes of longitude.

#### **scale 1:24,000**

One unit on the map stands for 24,000 of the same units on the ground: 1 inch = 2,000 feet, and 1 cm = 240 m.

#### **saddle**

A low dip on a ridge between two higher points, shown by contour lines shaped like an hourglass.

#### **rule of V's**

Where contour lines cross a stream they bend into V's that point upstream, the opposite way from the water's flow.

#### **benchmark**

A brass or bronze disk set in rock or concrete by surveyors, marked “BM” on the map with its exact elevation.

## CORE IDEAS

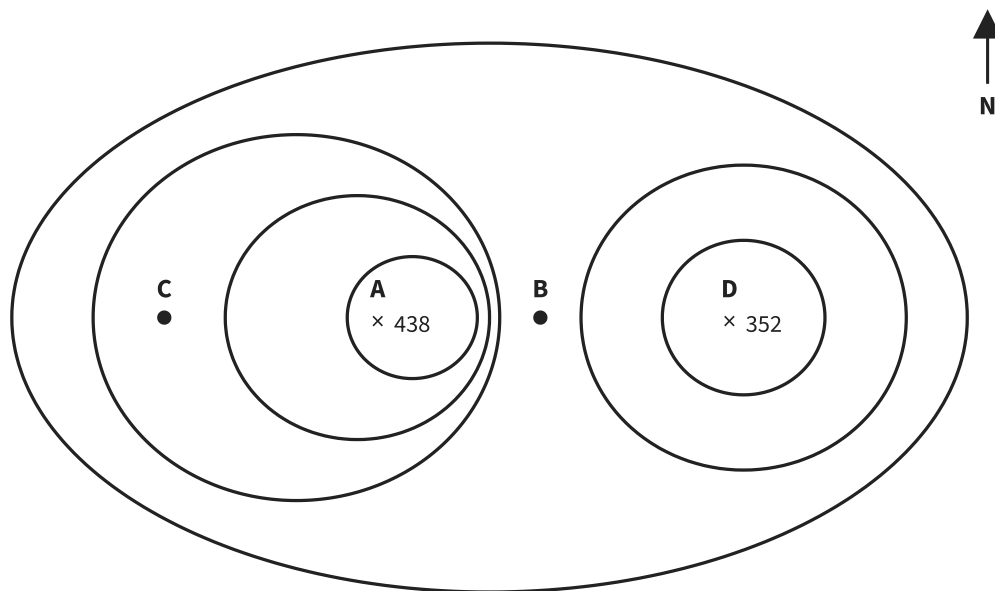
**The story.** On March 3, 1879, Congress created the United States Geological Survey, the USGS, to study the lands and rocks of a growing nation. Much of the West had never been mapped with care. In 1881 John Wesley Powell, the one-armed Civil War veteran who had led a boat party through the Grand Canyon in 1869, became the Survey’s director, and he pushed for something bold: a topographic map of the whole United States. Field parties under Henry Gannett, the Survey’s chief geographer, packed mules and headed into the mountains. A topographer set up a plane table, a flat drawing board on a tripod, and sighted through an alidade, a ruler with a small telescope on it, at a helper holding a tall marked rod far away. From each sighting he worked out how far away the rod stood and how much higher or lower, and he sketched the contour lines on his sheet while looking at the real hills in front of him.

**How it worked.** Drawing the whole country by plane table would have taken a very long time, so the work sped up with new tools. From the 1930s, and especially after World War II, mapmakers used pairs of overlapping photographs taken from airplanes. Seen through a special viewer, the two photos merge into one picture in which the hills seem to stand up in three dimensions, and an operator could trace a contour line by keeping a tiny floating dot right on the ground of the picture. The best-known result is the **7.5-minute quadrangle**. Each sheet covers a block of land 7.5 minutes of latitude tall and 7.5 minutes of longitude wide, about 8.6 miles (13.9 km) from north to south, at a scale of 1:24,000. The USGS made about 55,000 of these sheets to cover the 48 states joined together, finishing in 1992. Today every one can be downloaded free.

**The big idea.** A **topographic map** shows the shape of the land with contour lines, and much more. USGS maps use the same colors on every sheet: brown for contour lines, blue for water (streams, lakes and marshes), green for woods, black for things people built and for names, and red for main roads and land-survey lines. The margin gives the map’s name, its scale, the contour interval, the date, and a small diagram showing true north and magnetic north. A scale of 1:24,000 means 1 inch on the map stands for 24,000 inches, or 2,000 feet, on the ground; 1 centimeter stands for 240 meters. A small × with a number is a spot elevation, and “BM” marks a **benchmark**, a brass disk set by surveyors whose exact height is printed beside it.

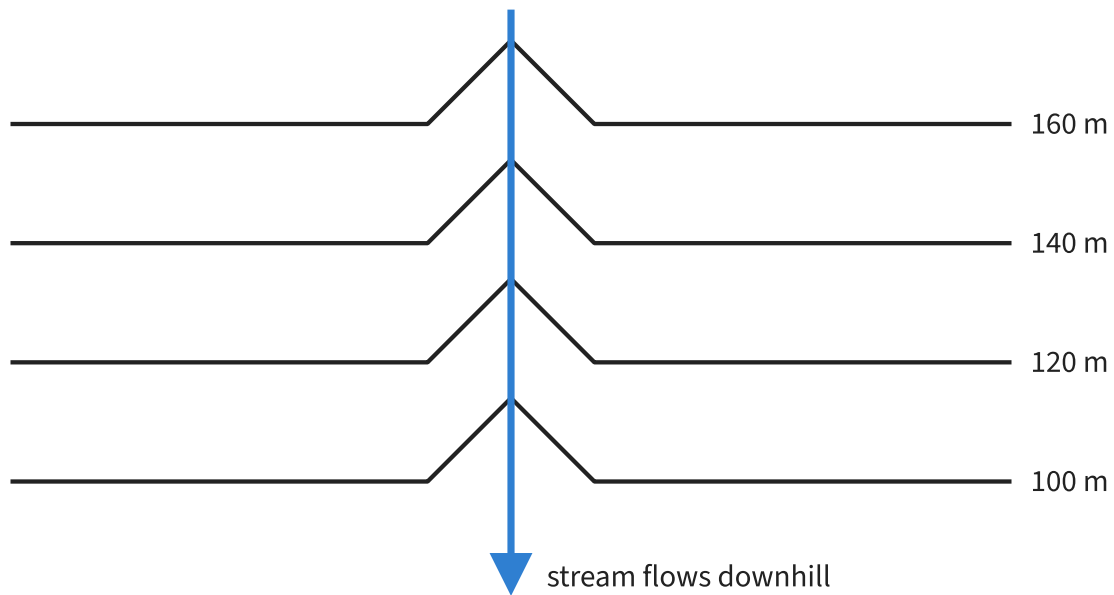
**Reading the landforms.** Once you know the patterns, a quadrangle turns into a picture. A **hilltop** is a set of closed loops. A **ridge** shows as contours bent into long U’s or V’s that point downhill, away from the high ground. A **valley** shows as contours bent into V’s that point uphill. Where a stream runs down a valley, the V’s point upstream, the opposite way from the flowing water; this is the **rule of V’s**. A **saddle** is the low dip on a ridge between two summits, with contour lines shaped like an hourglass; trails and roads often cross a range at a saddle. A **cliff** shows as lines so close that they nearly touch or merge. A **depression** is a loop with short ticks, called hachures, pointing inward and downward.

**On the map.** The practice map in this lesson has two hills joined by a saddle. Before you look at the letters, find both summits, find the saddle, and decide which side of the western hill is steep. Then get a real quadrangle of your own area from the USGS and try the same things there. Find the stream nearest your home and look for the V's in its valley. Find the highest and lowest points on the sheet. A person who reads a topographic map well can picture the ground before ever walking it. Hikers use these maps to plan routes, engineers use them to lay out roads and pipelines, farmers use them to plan ponds and terraces, and rescue teams use them to search the mountains.



Contour interval 100 m. The outermost line is 100 m.

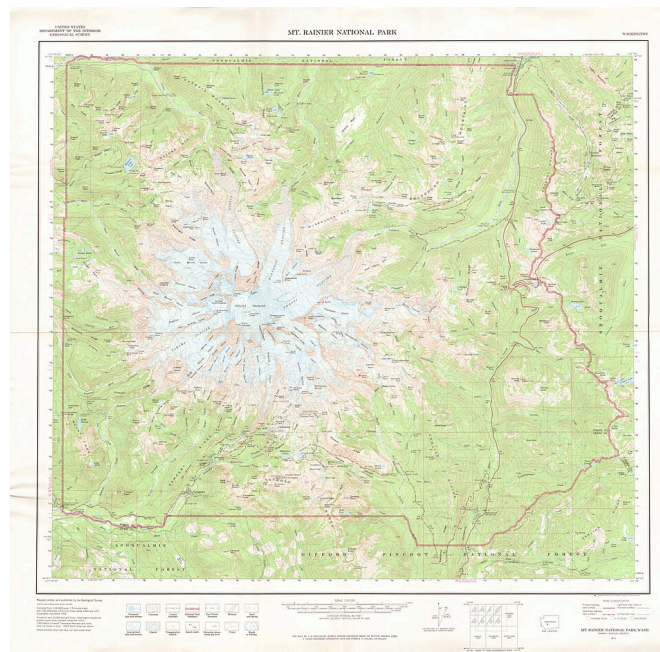
*A practice topographic map. Contour interval 100 m; the outermost line is 100 m.*



Each V points upstream, toward higher ground.

*The rule of V's: contour lines point upstream where they cross a stream. The water flows the opposite way, downhill.*

## PICTURE STUDY



*Mount Rainier National Park, Washington: USGS topographic map, U.S. Geological Survey, 1971 · Printed topographic map · U.S. Geological Survey (public domain); copies in map libraries and free scans online*

Mount Rainier is the tallest mountain in Washington, a volcano that rises to 14,410 feet (4,392 m), far above the hills around it. It is covered with more glacier ice than any other peak in the lower forty-eight states. Mapmakers of the U.S. Geological Survey measured it carefully and printed this map of the whole national park around it.

A topographic map like this one turns a mountain into lines. Brown lines show the shape of the land, blue lines show the shape of the ice and the water, and the spacing of the lines tells you where the ground is steep or gentle. Once you learn to read them, you can picture the mountain without ever seeing a photograph.

### **Look closely**

- Find the summit. How can you tell it is the highest place on the map?
- Look at the rings of contour lines around the top. Are they nearly round or stretched out? Where do they crowd together?
- Find the glaciers, drawn with blue contour lines. Which way do they flow away from the summit?
- Find the contour interval and the scale in the margin of the map. How many feet of height does each line stand for?

### **Talk about it**

1. Where would a trail up the mountain be easiest to climb? How can you tell from the lines?
2. Why do the rivers on this map all seem to start near the mountain and flow outward?
3. Mount Rainier and Mount St. Helens are both volcanoes. If one of them changed shape in an eruption, how would its topographic map have to change?

## **PROJECT: MY OWN QUADRANGLE: A FEATURE HUNT**

Every place in the 48 states lies on a USGS 7.5-minute quadrangle. You will find the one that covers your home, print part of it, color it by height, and hunt for every landform you learned in this lesson.

### **You will need**

- A printout of your local USGS quadrangle (download it free from USGS topoView; a parent can help) or a paper map from a library or outdoor store
- Colored pencils in five or six colors
- A piece of string about 30 cm (12 inches) long and a ruler
- A highlighter and a pencil

### **Steps**

1. Find your home or church on the map. Mark it with a small star.
2. Read the margin. Write down the quadrangle name, the date, the scale and the contour interval.
3. Find two index contours near your home and trace them with the highlighter. Read their elevations.
4. Color the land between contours in bands, like a layer cake: one color for the lowest band, the next color for the next, and so on up to the hilltops. This is called layer tinting.

5. Hunt for features and label each one on the map: a hilltop, a ridge, a valley, a saddle, a steep slope or cliff, a stream (draw an arrow showing which way it flows by the rule of V's), and a benchmark or spot elevation.
6. Choose a route from your home to a park or hill. Lay the string along it, then straighten the string on the ruler. Use the scale to find the distance in feet, miles and kilometers.
7. Write three sentences describing the land along your route as if you were giving directions to a hiker.

### Tips

- If your area is very flat, look for the nearest river valley or ridge on the sheet. Even small rises show up.
- Older quadrangles may show newer buildings and roads in purple; these were added from aerial photos without a new field survey.
- Keep this map. You will use it again for the unit portfolio.

### Check your work

- I can read the scale, contour interval and date in the margin of a quadrangle.
- I found and labeled at least six landforms, including a stream with its flow direction.
- I measured a real route and gave its length in miles and kilometers.

### MAP NOTEBOOK

1. Draw the contour patterns for six landforms in a chart: hilltop, ridge, valley with stream, saddle, cliff and depression. Label each.
2. Copy the USGS color key (brown, blue, green, black, red) and draw one small symbol for each color.
3. Draw a 2-inch scale bar for a 1:24,000 map and mark it in feet (0, 2,000, 4,000 feet).

**From history.** Henry Gannett, who led much of the Survey's early mapping, also helped found the National Geographic Society in 1888 and later served as its president. He loved exact names and numbers and worked to give American places clear, official names. The highest mountain in Wyoming, Gannett Peak, about 13,800 feet (4,200 m) high in the Wind River Range, is named for him.

## WORKED EXAMPLES

**Example 1.** On a 1:24,000 quadrangle, a trail from a parking lot to a lookout measures 5.5 inches. How long is the trail in feet, miles and kilometers?

1. At 1:24,000, 1 inch on the map = 24,000 inches on the ground =  $24,000 \div 12 = 2,000$  feet.
2.  $5.5 \text{ inches} \times 2,000 \text{ feet} = 11,000 \text{ feet}$ .
3.  $11,000 \div 5,280 \text{ feet per mile} = 2.08 \text{ miles}$ .
4.  $11,000 \text{ feet} \times 0.3048 = 3,353 \text{ m}$ , about 3.35 km.

**Answer:** 11,000 feet, about 2.1 miles or 3.35 km. (The real walk is a little longer, because the map measures flat distance, not the extra length of climbing up and down.)

**Example 2.** A 7.5-minute quadrangle is 7.5 minutes of latitude tall. One degree of latitude is about 69 miles (111 km). How tall is the area the map covers? How tall is the printed map at 1:24,000?

1.  $7.5 \text{ minutes} = 7.5 \div 60 = 0.125 \text{ degree}$ .
2.  $0.125 \times 69 \text{ miles} = 8.6 \text{ miles}$ ;  $0.125 \times 111 \text{ km} = 13.9 \text{ km}$ .
3.  $8.6 \text{ miles} \times 5,280 = \text{about } 45,500 \text{ feet on the ground}$ .
4. At 1 inch = 2,000 feet:  $45,500 \div 2,000 = \text{about } 22.8 \text{ inches}$ .

**Answer:** About 8.6 miles (13.9 km) of ground from north to south, printed about  $22\frac{3}{4}$  inches tall. That is why a quadrangle is a big sheet you fold up for the trail.

**Example 3.** Look at the stream figure. The contour lines are labeled 100, 120, 140 and 160 m. Which way does the stream flow, and which way do the V's point?

*(Use the map or drawing "Use the labels to find which way is downhill." shown earlier in this lesson.)*

1. Find the elevations: 160 m is at the top of the figure and 100 m at the bottom, so the land slopes down toward the bottom.
2. Water always flows downhill, so the stream flows from the 160 m line toward the 100 m line, toward the bottom.
3. The V's point toward the top, the high ground. That is upstream, as the rule of V's says.

**Answer:** The stream flows toward the bottom of the figure (downhill, from 160 m to 100 m). The V's point the opposite way, upstream.



## PRACTICE

1. **EASY** On a USGS topographic map, what do these colors show: brown, blue, green, black?
2. **EASY** What does the scale 1:24,000 mean? How many feet on the ground does 1 inch on the map stand for?
3. **MEDIUM** In the practice map, point B lies between the two hills. Between which two elevations is B? What is this landform called?  
*(Use the map or drawing "Contour interval 100 m; the outermost line is 100 m." shown earlier in this lesson.)*
4. **MEDIUM** In the practice map, which side of the western hill (summit A) is steeper, the east side or the west side? Explain.  
*(Use the map or drawing "Look at the spacing of the lines on each side of summit A." shown earlier in this lesson.)*
5. **MEDIUM** In the practice map, between which two elevations does point C lie?  
*(Use the map or drawing "Count the lines from the outside in." shown earlier in this lesson.)*
6. **MEDIUM** On a 1:24,000 map, a stretch of river measures 3.25 inches. How long is it in feet, miles and kilometers?
7. **MEDIUM** On a 1:24,000 map, two benchmarks are 8 cm apart. How far apart are they on the ground in kilometers and miles?
8. **HARD** On a quadrangle you find a closed brown loop with short ticks pointing inward. What does it show? Name one kind of real place it might be.
9. **HARD** In the practice map, summit A is 438 m and summit D is 352 m. How much higher is A than D, in meters and in feet?  
*(Use the map or drawing "The spot elevations are printed beside the x marks." shown earlier in this lesson.)*
10. **CHALLENGE** In two or three sentences, explain why contour lines bend into a V that points upstream where they cross a stream.

## COMMON MISTAKES

- Thinking the V's of a stream point the way the water flows. They point upstream; water flows the other way, downhill.
- Mixing up a ridge and a valley. Both bend contours into U's or V's; check the labels. If the point of the bend aims toward lower numbers, it is a ridge; toward higher numbers, a valley.
- Using the map scale in the wrong units: at 1:24,000, 1 inch is 2,000 feet, not 24,000 feet.

**Make it a game • Landform Bingo.** Each player makes a 3-by-3 bingo card with nine landforms or symbols: hilltop, ridge, valley, saddle, cliff, depression, stream, benchmark, index contour. Spread out a real quadrangle. Take turns: find one of your landforms on the map, point to it, and explain how you know (for example, "V's pointing uphill with a blue line"). If the other players agree, mark the square. Three in a row wins.



**Scripture.** “In his hand are the deep places of the earth: the strength of the hills is his also.” (Psalm 95:4, KJV)

A topographic map shows both the deep places and the hills: valleys, depressions, ridges and summits. Every one of them, from the deepest canyon to the highest peak, belongs to the Lord who made it.

#### Practice answers

1. Brown: contour lines. Blue: water. Green: woods. Black: things people built (roads, buildings, railroads) and names.
2. One unit on the map stands for 24,000 of the same units on the ground. 1 inch stands for 24,000 inches, which is 2,000 feet.
3. B is inside the 100 m line but outside both 200 m lines, so it lies between 100 m and 200 m. It is a saddle.
4. The east side. The 200, 300 and 400 m lines are crowded close together on the east and spread far apart on the west.
5. C is inside the 200 m line and outside the 300 m line of the western hill, so it lies between 200 m and 300 m.
6.  $3.25 \times 2,000 = 6,500$  feet.  $6,500 \div 5,280 = 1.23$  miles.  $6,500 \times 0.3048 = 1,981$  m, about 1.98 km.
7. 1 cm = 240 m, so 8 cm = 1,920 m = 1.92 km.  $1.92 \div 1.609 =$  about 1.19 miles.
8. A depression: the ground inside the loop is lower than the ground around it. It could be a sinkhole, a volcanic crater, a quarry pit or a pond basin.
9.  $438 - 352 = 86$  m.  $86 \div 0.3048 =$  about 282 feet.
10. A stream cuts a valley, so the ground along the stream is lower than the ground on either side. To stay at the same height, a contour line has to travel up the valley until it reaches the stream at that elevation, then come back out the other side. That makes a V whose point is upstream, toward the higher ground the water comes from.

## 1.3 A POTATO MOUNTAIN ★

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### OBJECTIVES

- Build a model mountain from clay or a potato and slice it at equal heights to draw its contour map.
- Explain why every contour line is like a shoreline at one water level.
- Use a vertical scale to give each slice a real elevation, and find a model's contour interval and vertical exaggeration.

**Warm-up.** Fill a clear glass or jar halfway with water and stand a pinecone, a rough rock or a small toy in it. Look from the side: where the water touches the object, the waterline is perfectly level. Mark it with a washable marker or a strip of tape. Add a little more water and mark the new line. Every waterline you mark is a contour line drawn by the water itself.

**Watch.** *How to Draw Contour Lines on a Map* (Scott Brande, 4:00).

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

Before the project: watch how plotted elevation points are joined with smooth, labeled lines, then use the same steps when you trace the contour lines of your potato mountain.

**Note:** Captions were not available to check; preview it first. Draws contour lines from plotted elevation points instead of slicing a model at water levels as the project does; the idea of lines of equal height is the same.

### KEY TERMS

#### **model**

A small copy of something real that keeps its shape and proportions.

#### **vertical scale**

How much real height each unit of the model's height stands for, such as 1 cm = 250 m.

#### **horizontal scale**

How much real distance across the ground each unit of the model or map stands for.

#### **registration marks**

Holes or marks that line up from layer to layer, so each slice is traced in exactly the right place.

#### **vertical exaggeration**

How many times taller a model or drawing is made than its true shape, found by dividing the horizontal scale by the vertical scale.

### CORE IDEAS

**The story.** In the early 1930s thousands of workers labored in Black Canyon on the Colorado River, on the border between Nevada and Arizona, to build Hoover Dam. The dam rose as a

curved wall of concrete about 726 feet (221 m) high, and President Franklin Roosevelt dedicated it on September 30, 1935. Behind it the river had already begun to back up, and a new lake, Lake Mead, slowly filled the desert canyons. As the water rose, it crept up every canyon wall and pushed into every side gully. Islands appeared where ridges had been, and old hilltops slowly went under. When full, the lake reached more than 100 miles (160 km) up the canyons. Today, where the water has stood for a long time, a pale band of minerals left by the water marks the canyon walls. Follow that band with your eye and you will notice something wonderful: it is perfectly level all the way around every bend.

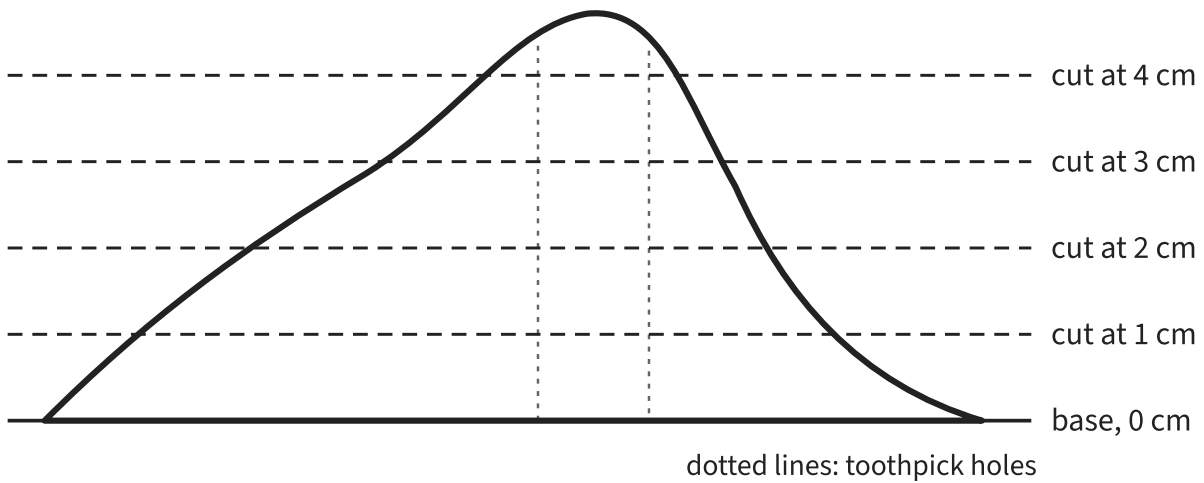
**How it worked.** Why is the band level? Because still water always lies flat. At any moment, every point along the edge of the lake was at exactly the same height. That means the shoreline of Lake Mead was a contour line, drawn on the land by the water itself. As the lake rose ten feet, then ten feet more, it drew a new contour line at each level. Mapmakers have long explained contour lines this way: imagine the sea rising around a mountain, 100 meters at a time, and mark the shoreline at each step. Looking down from above, you would see the shorelines as rings, one inside another, exactly like the rings of a contour map. If you could flood a mountain in your kitchen, you could make its map.

**The big idea.** You can do almost the same thing with a model and a knife or a string. A level cut through a model mountain shows exactly where a shoreline would be if water rose to that height. So if you slice a clay or potato mountain into layers of equal thickness, every cut face is the shape of one contour line. Stack the slices back up in order, trace around each one from the bottom up on the same sheet of paper, and you have a contour map of your mountain. Two things must be true. Each cut must be **level**, because a tilted cut is like a tilted lake, which cannot happen. And the slices must be **equal in thickness**, because a contour map uses one contour interval. To keep the traced outlines lined up, push two toothpicks or skewers straight down through the model before you cut. The holes become **registration marks**: line up the holes in each slice with the dots on your paper.

**Scales and exaggeration.** A model is useful only when we know what it stands for. If your clay mountain is 8 cm tall and it stands for a real mountain 2,000 m tall, the **vertical scale** is  $1\text{ cm} = 250\text{ m}$ . A slice every 1 cm then gives a contour interval of 250 m. Modelers often make mountains taller than their true shape so the hills are easy to see. If 1 cm across the model stands for 500 m but 1 cm up stands for 250 m, the model is twice as tall as it should be: it has a **vertical exaggeration** of 2. Raised-relief maps of whole states are usually exaggerated this way; without it, even the Rockies would look almost flat on a map you could hang on a wall.

**On the map.** When you trace your slices, you will see the shapes of real landforms. A cone-shaped peak gives nearly round rings. A long ridge gives stretched ovals. A flat-topped mesa gives a crowd of lines at its steep rim and an empty space on top. The side where you pinched the clay steep will have lines close together, and the gentle side will have lines far apart, just like the hill in Lesson 1.1. People have used this same truth about level water for centuries. Rice farmers in the hills of Asia build terraces that follow the contours, so that each small field holds a flat sheet of water. The psalmist saw water's obedience too: the

waters “go up by the mountains; they go down by the valleys unto the place which thou hast founded for them.”



*Slice the model at equal heights. The toothpick holes (dotted) pass through every slice and line up the tracings.*

## PICTURE STUDY



*Shinano Province: The Moon Reflected in the Paddy Fields at Sarashina, Mount Kyōdai (Mount Obasute), No. 25 from the series Famous Views of the Sixty-odd Provinces, Utagawa Hiroshige, 1853 · Color woodblock print · Many impressions survive in museum collections around the world*

Utagawa Hiroshige was one of the great Japanese printmakers of the 1800s. In the 1850s he made a series of prints showing a famous view from each province of Japan. For Shinano, a mountain province, he chose the hillside near Mount Obasute, which was famous for the

“moon in every field”: on autumn nights, travelers climbed up to see the full moon reflected in each of the many small, flooded rice terraces.

Every terrace is a little level shelf cut into the slope and filled with water. Its edge follows a contour line, because water must lie flat. A hillside of terraces is a contour map you can walk on.

### Look closely

- Find the small fields on the hillside. How are their shapes different from square fields on flat land?
- Look at the edges of the fields. Do they run straight up the hill or across it?
- Find the moon in the sky. Can you find any of its reflections in the water?
- Find the people or houses, if any. How big are they compared to the hillside?

### Talk about it

1. Why must every rice terrace be level?
2. Where would the terraces be narrow, on a steep slope or a gentle one? Why?
3. How is a hillside of terraces like the stack of slices from your potato mountain?

**Safety first.** An adult should do all cutting of a raw potato with a knife. Dental floss can cut fingers if you pull it hard; wrap each end around a pencil and pull on the pencils. Do not eat modeling clay.

## PROJECT: A CONTOUR MODEL FROM CLAY AND DENTAL FLOSS

You will sculpt a mountain, slice it into equal layers with dental floss, and trace the layers to make a contour map. This is the unit’s main hands-on project. Keep your model and your map: you will use both again in Lesson 1.4 to draw a profile, and in your unit portfolio.

### You will need

- About 1 pound (450 g) of non-hardening modeling clay or play dough, or one large baking potato (cut by an adult)
- Unflavored dental floss and two pencils
- A ruler marked in centimeters
- Two wooden skewers or long toothpicks
- A cutting board or tray
- Paper, a sharp pencil and a fine marker
- A clear plastic box or jar and a cup of water (for the optional water method)

### Steps

1. Sculpt a mountain on the board about 5 to 6 cm tall and 12 to 15 cm across. Give it character: make one side steep and one side gentle, add a ridge running off one side and a valley pressed in with your thumb. Make the bottom flat.

2. Push the two skewers straight down through the mountain all the way to the board, one near each side of the summit. Pull them out carefully. These holes are your registration marks.
3. Stand the ruler beside the mountain and press tiny dots into the clay at 1, 2, 3 and 4 cm (and 5 cm if it is tall enough) above the board, all the way around. Make the dots at the same height on every side.
4. Wrap the ends of the floss around two pencils. Starting at the top cut, hold the floss level and pull it straight through the clay along the dots. Lift off the top piece and set it aside in order. Cut the next layer down in the same way, and keep going until you reach the bottom layer.
5. Set the bottom layer on your paper. Trace around it and mark the two skewer holes as dots.
6. Place the next layer on the paper on its own, with its skewer holes exactly over the dots. Trace around it. Repeat for every layer, ending with the top piece. Your nested outlines are a contour map.
7. Choose a vertical scale (for example, 1 cm = 200 m) and label each line with its elevation. The bottom outline is 0 m, the first cut is 200 m, and so on. Write the contour interval in a corner and add a north arrow.
8. Mark the highest point with a small × and write its elevation.
9. Optional water method: rebuild the mountain, stand it in a clear box, and pour in water 1 cm deep at a time. After each pour, look straight down through the lid (or from above) and trace the shoreline onto a sheet of clear plastic laid on top. Compare this map with your sliced map.

### **Tips**

- Chill the clay or potato for a few minutes before cutting; cold clay cuts more cleanly.
- Keep the floss tight and level, and pull it toward you slowly. A wobbly cut makes a wobbly contour line.
- If your slices squash out of shape, gently press them back with your fingers before tracing.
- Leave the slices stacked on the skewers between sessions so you can use them again in Lesson 1.4.

### **Check your work**

- My contour lines are nested, never cross, and are labeled with elevations.
- My map shows close lines on my mountain's steep side and wide lines on its gentle side.
- I can tell my model's vertical scale and contour interval.

### **MAP NOTEBOOK**

1. Draw your mountain from the side before you cut it, with dashed lines at each cut height. Label each line with its height in centimeters and its elevation in meters.

2. Draw a lake rising around an island in three stages. Show the island getting smaller, and label each shoreline as a contour line.
3. Sketch the contour patterns of three model shapes: a cone, a long ridge and a flat-topped mesa.

**From history.** Thomas Jefferson's son-in-law, Thomas Mann Randolph, plowed the hillsides at Monticello in Virginia along level lines instead of straight up and down the slopes. Each furrow then held the rain instead of turning into a little gully. In letters written around 1813, Jefferson praised this horizontal plowing for saving the soil of his hilly farm. In the 1930s the U.S. Soil Conservation Service taught contour plowing to farmers across the country for the same reason.

## WORKED EXAMPLES

**Example 1.** Your clay model is 8 cm tall and stands for a mountain 2,000 m tall. You slice it every 1 cm. What is the vertical scale? What is the contour interval? What elevations do the cuts stand for?

*(Use the map or drawing "Each level cut becomes one contour line." shown earlier in this lesson.)*

1. Vertical scale:  $2,000 \text{ m} \div 8 \text{ cm} = 250 \text{ m per cm}$ , so  $1 \text{ cm} = 250 \text{ m}$ .
2. A slice every 1 cm gives a contour interval of 250 m (about 820 feet).
3. The cuts are at 1, 2, 3, 4, 5, 6 and 7 cm. Multiply each by 250 m: 250, 500, 750, 1,000, 1,250, 1,500 and 1,750 m.
4. The bottom outline is 0 m, and the summit (8 cm) is 2,000 m, inside the 1,750 m loop.

**Answer:** Vertical scale  $1 \text{ cm} = 250 \text{ m}$ ; contour interval 250 m (about 820 ft); seven cut lines at 250, 500, 750, 1,000, 1,250, 1,500 and 1,750 m.

**Example 2.** The same model is 12 cm wide and stands for a mountain 6 km (3.7 miles) wide. The vertical scale is  $1 \text{ cm} = 250 \text{ m}$ . What is the horizontal scale, and what is the vertical exaggeration?

1. Horizontal scale:  $6 \text{ km} \div 12 \text{ cm} = 0.5 \text{ km per cm}$ , so  $1 \text{ cm} = 500 \text{ m}$ .
2. Vertical exaggeration = horizontal scale  $\div$  vertical scale =  $500 \text{ m} \div 250 \text{ m} = 2$ .
3. So the model is twice as tall, for its width, as the real mountain.

**Answer:** Horizontal scale  $1 \text{ cm} = 500 \text{ m}$ ; vertical exaggeration 2 (the model is twice as steep-looking as the real mountain).



**Example 3.** A reservoir behind a dam rises from 1,050 feet to 1,200 feet above sea level. The map of the canyon has contour lines every 25 feet. How many new contour lines does the shoreline reach as the water rises? How much did the water rise in meters?

1. The contour lines above 1,050 feet are at 1,075, 1,100, 1,125, 1,150, 1,175 and 1,200 feet.
2. Count them: 6 lines. Another way:  $(1,200 - 1,050) \div 25 = 150 \div 25 = 6$ .
3.  $150 \text{ feet} \times 0.3048 = 45.7 \text{ m}$ .

**Answer:** The shoreline reaches 6 new contour lines. The water rose 150 feet, about 45.7 m.

## PRACTICE

1. **EASY** Why must every cut through your model mountain be level?
2. **EASY** Why do we push skewers through the model before slicing it?
3. **MEDIUM** A model is 6 cm tall. You slice it every 1.5 cm. How many cuts do you make, and how many outlines will your map have (counting the base)?
4. **MEDIUM** The vertical scale of a model is 1 cm = 200 m. What elevation does a cut 3 cm above the base stand for, in meters and feet?
5. **MEDIUM** A real mountain is 1,800 m tall. You build a model 9 cm tall and slice it every 1 cm. What is the contour interval in meters and feet?
6. **MEDIUM** Look at the figure. On which side of the model will the traced contour lines be closest together? Why?  
*(Use the map or drawing "Compare the left and right slopes." shown earlier in this lesson.)*
7. **HARD** A lake rises from 210 m to 290 m around a hill. The map has contour lines every 20 m (at 200, 220, 240 m and so on). How many contour lines does the shoreline pass as the water rises?
8. **HARD** A raised-relief model has a horizontal scale of 1 cm = 500 m and a vertical scale of 1 cm = 100 m. What is its vertical exaggeration? Will the mountains look steeper or gentler than they really are?
9. **HARD** A model mountain has a flat top. What will the contour map of that top look like?
10. **CHALLENGE** In a few sentences, explain how the filling of Lake Mead behind Hoover Dam "drew" contour lines on the canyon walls, and why the pale band on the walls is level all the way around.

## COMMON MISTAKES

- Cutting slices of different thicknesses. A contour map needs one contour interval, so every slice must be the same thickness.
- Tracing each slice on a new sheet of paper. All the outlines go on one sheet, lined up by the registration marks, to make one map.



- Forgetting to give the map a vertical scale. Without it, the lines show the shape but not the real elevations.

**Make it a game · Rising Sea, Count the Islands.** Use the contour map you made of your mountain (or one a parent draws with two or three hills). A parent calls out a sea level, such as “300 meters!” Each player quickly counts how many islands would stick out of the water at that level and which hilltops they are. One point for the right count. Then the sea rises 100 meters and you play again until everything is under water.

**Scripture.** “They go up by the mountains; they go down by the valleys unto the place which thou hast founded for them.” (Psalm 104:8, KJV)

Psalm 104 praises God for setting the waters in their places. Water always settles level and runs to the lowest place, which is why a lake’s shore traces a perfect contour line. The order we can measure in the world is the order the Creator built into it.

#### Practice answers

1. Each cut stands for a contour line, which joins points of equal height. A level cut is like a shoreline of still water; a tilted cut would join points of different heights.
2. The holes are registration marks. Lining up the holes in each slice with the dots on the paper keeps every traced outline in the right place.
3. Cuts at 1.5, 3 and 4.5 cm: 3 cuts (the 6 cm mark is the summit). The map has 4 outlines: the base plus three cut faces.
4.  $3 \times 200 \text{ m} = 600 \text{ m}$ .  $600 \div 0.3048 = \text{about } 1,969 \text{ feet}$ .
5.  $1,800 \text{ m} \div 9 \text{ cm} = 200 \text{ m per cm}$ , so the interval is 200 m, about 656 feet.
6. On the right side. The model is steeper there, so each slice is only a little smaller than the one below it on that side, and the outlines crowd together.
7. The lines between 210 and 290 m are 220, 240, 260 and 280 m: 4 lines. The water stops at 290 m, between the 280 and 300 m lines.
8.  $500 \div 100 = 5$ . The mountains look 5 times steeper (taller for their width) than they really are.
9. The top will be one large closed loop with no lines inside it (or only a spot elevation), because no level cut passes through the flat top. If the sides are steep, the lines below the rim will be crowded together.
10. Still water lies flat, so at every moment the lake’s edge touched the canyon walls at exactly the same elevation. That shoreline was a contour line. As the lake rose, it drew a new contour line at each height. Where the water stood for a long time, it left minerals on the rock, and because the water surface was level, the band it left is level too, following one elevation around every bend and side canyon.

## 1.4 PROFILES AND CROSS-SECTIONS

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### OBJECTIVES

- Draw a topographic profile along a line on a contour map.
- Calculate elevation gain, average slope (grade) and vertical exaggeration from a map and a profile.
- Describe how the eruption of May 18, 1980, changed the profile of Mount St. Helens, and tell a profile from a geologic cross-section.

**Warm-up.** Lay a towel over a few books and a bowl on the table so it makes hills and a valley. Crouch down so your eyes are level with the tabletop and look at it from the side. Trace the top edge in the air with your finger, then sketch that up-and-down line on paper. You have just drawn a profile: the shape of the land seen from the side.

**Watch.** *Mount St. Helens: May 18, 1980* (USGS, 7:30). <https://www.youtube.com/watch?v=Ec30uU0G56U>

After the story: listen to the USGS scientists explain how they measured the growing bulge and how the mountain's shape changed when the north side collapsed.

**Note:** Captions were not available to check; preview it first. The scientists talk about losing their colleague David Johnston and 56 others who died in the eruption. The video does not show how to draw a topographic profile; use the lesson for that.

**Backup video.** *Mount St. Helens May 18, 1980 Eruption Story* (Mount St. Helens Institute, 7:24). <https://www.youtube.com/watch?v=XmkMv2RwN9o>

After the story: watch for the 8:32 a.m. earthquake, the landslide of the north face and the new crater it left behind. Note: Captions were not available to check; preview it first. The eruption story includes the people who died. The video does not show how to draw a topographic profile; use the lesson for that.

### KEY TERMS

#### profile

A side view of the surface of the land along a line, showing how it rises and falls.

#### cross-section

A side view of a slice through the earth that shows what lies below the surface (rock layers, faults, a volcano's insides) as well as the surface itself.

#### elevation gain

The total amount of climbing on a route, adding up every uphill part.

#### grade

The steepness of a slope: rise divided by run, often written as a percent. A road that rises 6 m in 100 m has a 6 percent grade.

#### vertical exaggeration

How many times the vertical scale of a profile is stretched compared with its horizontal scale.

## CORE IDEAS

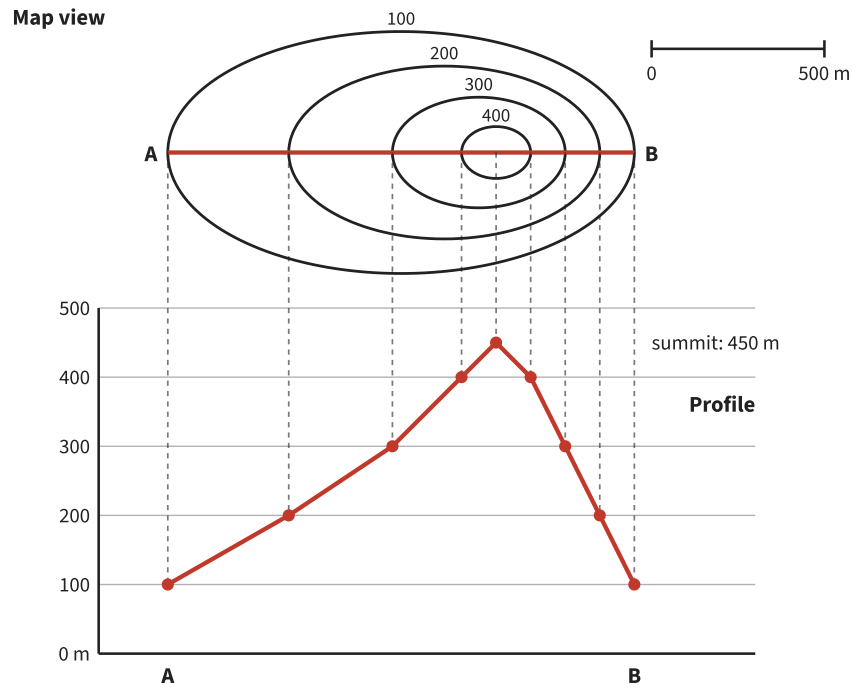
**The story.** In the spring of 1980, Mount St. Helens in southern Washington was waking up. Small earthquakes shook it, steam blasted from its summit, and its north side swelled outward in a great bulge, growing by as much as 5 feet (1.5 m) a day. Scientists of the U.S. Geological Survey measured the bulge again and again. At 8:32 on the morning of May 18, 1980, an earthquake shook loose the whole bulging north side. It slid away in the largest landslide ever recorded, and the pressure inside the volcano burst out sideways in a blast that flattened forests for miles. David Johnston, a young USGS volcanologist watching from a ridge about 6 miles (10 km) north, radioed, “Vancouver! Vancouver! This is it!” He was among the 57 people who died that day.

**How they figured it out.** When the ash cleared, the mountain had a new shape. Its summit had dropped from 9,677 feet (2,950 m) to 8,363 feet (2,549 m), and in place of the snowy cone was a horseshoe-shaped crater more than a mile (about 2 km) across, open to the north. Mapmakers flew over the mountain, photographed it, and drew new contour lines. Then scientists could do something simple and powerful: draw a **profile** of the mountain along the same line on the old map and on the new map, and lay one over the other. The space between the two lines showed exactly where the rock had gone, and from many such profiles they worked out that about 2.5 cubic kilometers (0.6 cubic mile) of mountain had slid away. Profiles drawn in later years showed a new dome of lava slowly growing inside the crater, a change you can measure from map to map.

**The big idea.** A contour map shows the land from above; a profile shows it from the side. To draw one, choose a line on the map, such as a hiking trail from point A to point B. Lay the straight edge of a strip of paper along the line. Make a tick on the strip everywhere a contour line crosses it, and write that contour’s elevation beside the tick. Mark the ends A and B, too. Next, draw a graph: a horizontal line as long as A to B, and a vertical scale of elevations on the left. Lay the strip along the bottom of the graph and, above each tick, put a dot at the right elevation. Connect the dots with a smooth line, rounding off the tops of hills and the bottoms of valleys, since a summit is a little higher than the last contour around it. The figure shows a profile drawn this way across the hill from Lesson 1.1.

**Reading a profile.** A profile makes steepness easy to see and easy to measure. The **grade** of a slope is the rise divided by the run: if a trail climbs 350 m in 950 m across, its grade is about 37 percent. The **elevation gain** of a hike adds up every uphill stretch, which is why a trail that goes up and down many times can tire you more than its highest point suggests. Most profiles are drawn with **vertical exaggeration**, stretching the heights so that gentle hills show up. A **cross-section** goes one step further: it shows not only the surface but what lies under it, such as layers of rock, a fault, or the pipe of magma inside a volcano. Geologists draw cross-sections from profiles, adding what they learn from rocks, wells and earthquake waves.

**On the trail.** Hikers' guidebooks print profiles so walkers know where the hard climbs are. Road and railroad engineers have always drawn profiles before they build, because a heavy train or truck can climb only a gentle grade. Pipeline and canal builders use them too. When you draw the profile of your own clay mountain and then cut the model along the same line, you can check your drawing against the real shape. Every profile is a reminder that the land is not flat paper. It rises and falls as God made it, and as Isaiah wrote of the day the Lord comes, "Every valley shall be exalted, and every mountain and hill shall be made low."



*Drawing a profile from A to B. Each place the line crosses a contour becomes a dot at that elevation.  
Horizontal scale: the bar is 500 m. Vertical exaggeration: 2.*

## PICTURE STUDY



*Mount St. Helens, the Day Before the Eruption*, Harry Glicken, U.S. Geological Survey, May 17, 1980 · Color photograph · U.S. Geological Survey (public domain)

Harry Glicken was a young volcanologist working with the USGS team that watched Mount St. Helens in the spring of 1980. He had been keeping watch from an observation post on a ridge north of the volcano, and on May 17 his colleague David Johnston took his place there. That day Glicken took this photograph of the north side of the mountain. The next morning the north side was gone.

Look at the picture as a scientist would. It is the last view of the mountain's old profile. Photographs taken from the same area after the eruption, such as those by USGS photographer Lyn Topinka in 1982, show the new profile: a broken, flat-topped mountain with a deep crater facing the camera.

### Look closely

- Trace the outline of the mountain against the sky with your finger. That outline is a profile. Is it smooth or rough?
- Find the bulge on the north side. Where does the smooth cone shape change?
- Look at the snow and the forest. What can you tell about how high the mountain was compared with the land around it?
- If you can, find an after photo taken from the north and compare the two outlines.

### Talk about it

1. Why did the USGS scientists measure the bulge again and again in the weeks before May 18?
2. Which part of the old profile disappeared in the eruption?

3. How do careful measurements and warnings help protect people who live near volcanoes?

## **PROJECT: PROFILE OF A HIKE ACROSS MY MOUNTAIN**

You will use the contour map of your clay mountain from Lesson 1.3 to plan a hike straight across it, draw the hike's profile, and then check your profile by cutting the model itself along the same line. Then you will draw a profile for a real trail on your local quadrangle.

### **You will need**

- Your clay mountain (slices stacked on skewers) and its contour map from Lesson 1.3
- Graph paper, a ruler, a pencil and a colored pencil
- A strip of plain paper about 3 cm (1 inch) wide
- Dental floss and two pencils
- Your local quadrangle from Lesson 1.2

### **Steps**

1. On your contour map, draw a straight line across the mountain through or near the summit. Label the ends A and B. This is your hike.
2. Lay the paper strip along the line. Make a tick everywhere the line crosses a contour line, and write the elevation beside each tick. Mark A and B.
3. On graph paper, draw a horizontal line the same length as A to B. Draw a vertical scale on the left with your contour elevations evenly spaced (for example, 1 cm of graph for each contour interval).
4. Lay the strip along the horizontal line. Above each tick, put a dot at the correct elevation. Connect the dots with a smooth curve, rounding the summit.
5. Now restack your clay slices on the skewers and press them gently together. Lay the contour map beside the model to find line A-B, and mark A and B on the model with toothpicks.
6. Hold the floss straight up and down and pull it through the model along line A-B. Pull the two halves apart and look at the cut face. That edge is the true profile.
7. Hold your drawn profile next to the cut face. Write two sentences on how well they match and why they might differ.
8. On your local quadrangle, choose a real trail, road or path that climbs a hill. Draw its profile the same way and find its elevation gain and its steepest part.

### **Tips**

- Your drawn profile will match the model best if your vertical scale on paper is the same as the slice thickness (for example, 1 cm of graph per 1 cm slice).
- Remember to round the summit. The top of a hill is higher than the last contour line, but lower than the next one would be.
- Write the vertical exaggeration on every profile you draw so a reader knows how stretched it is.



### Check your work

- My profile has a labeled horizontal scale and vertical scale.
- My dots are at the right elevations above each contour crossing, joined by a smooth line.
- I compared my drawn profile with the cut model and explained the differences.

### MAP NOTEBOOK

1. Draw two profiles of Mount St. Helens one above the other on the same scale: before 1980 with a summit of 9,677 feet, and after with a summit of 8,363 feet and a crater on the north side. Shade the part that slid away.
2. Draw a simple cross-section of a hill that shows three rock layers underneath its surface, and label the surface line as the profile.
3. Draw the profile of the walk from your front door to the nearest high point you know, from memory. Later, check it on your quadrangle.

**From history.** Railroad builders lived by their profiles. In 1854 the Pennsylvania Railroad opened its famous Horseshoe Curve near Altoona, Pennsylvania. Instead of running straight at the steep Allegheny Front, the track swings around the head of a valley in a great curve, adding distance so that trains can climb at a grade of less than 2 percent. Engineers chose the route by drawing profile after profile until they found one gentle enough for steam locomotives to pull long trains to the top, and trains still use the curve today.

### WORKED EXAMPLES

**Example 1.** Use the figure. Hike line A–B starts on the 100 m contour (A), crosses the 200, 300 and 400 m contours, passes over the 450 m summit, and comes back down to the 100 m contour (B). What is the elevation gain from A to the summit, in meters and feet? How long is the hike across the map?

*(Use the map or drawing “Read the crossings and the scale bar.” shown earlier in this lesson.)*

1. Elevation gain to the summit:  $450\text{ m} - 100\text{ m} = 350\text{ m}$ .
2.  $350\text{ m} \div 0.3048 = \text{about } 1,148\text{ feet}$ .
3. On the figure, the scale bar is 100 units long for 500 m, so 1 unit = 5 m. A is at 100 and B is at 370 across:  $270\text{ units} \times 5\text{ m} = 1,350\text{ m}$ .
4.  $1,350\text{ m} = 1.35\text{ km} = \text{about } 0.84\text{ mile}$ .

**Answer:** The hike climbs 350 m (about 1,150 feet) to the summit and covers about 1.35 km (0.84 mile) across the map from A to B.

**Example 2.** Use the figure again. The summit is 190 units east of A and 80 units west of B (1 unit = 5 m). Find the average grade of the west side (A to summit) and the east side (summit to B). Which way would you rather climb?

1. West side run:  $190 \times 5 \text{ m} = 950 \text{ m}$ . Rise: 350 m. Grade =  $350 \div 950 = 0.37$ , about 37 percent.
2. East side run:  $80 \times 5 \text{ m} = 400 \text{ m}$ . Rise: 350 m. Grade =  $350 \div 400 = 0.875$ , about 88 percent.
3. The east side is more than twice as steep, a scramble rather than a walk. The profile shows this at a glance: the line drops sharply toward B.

**Answer:** West side about 37 percent; east side about 88 percent. Climb up the gentler west side from A.

**Example 3.** Before May 18, 1980, the summit of Mount St. Helens was 9,677 feet (2,950 m). Afterward the highest point was 8,363 feet (2,549 m). How much height did the mountain lose? On a profile with a vertical scale of 1 cm = 100 m, how far apart would the two summits be?

1. In feet:  $9,677 - 8,363 = 1,314$  feet.
2. In meters:  $2,950 - 2,549 = 401 \text{ m}$ . (Check:  $1,314 \times 0.3048 = 400.5 \text{ m}$ .)
3. On the profile:  $401 \text{ m} \div 100 \text{ m per cm} = \text{about } 4.0 \text{ cm}$ .

**Answer:** The mountain lost 1,314 feet (about 401 m) of height. On the profile, the old summit would be about 4 cm above the new high point.

## PRACTICE

1. **EASY** What is a topographic profile?
2. **EASY** How is a geologic cross-section different from a profile?
3. **MEDIUM** In the figure, line A-B first crosses the 300 m contour at 230 units across. A is at 100 units. How far is that crossing from A on the ground (1 unit = 5 m)? Give meters and miles.  
*(Use the map or drawing "Use the scale bar: 100 units = 500 m." shown earlier in this lesson.)*
4. **MEDIUM** A trail starts at 1,250 m and ends at a summit of 1,830 m, climbing all the way. What is the elevation gain in meters and feet?
5. **MEDIUM** A trail goes from 600 m up to 900 m, down to 750 m, then up to 1,100 m. What is the total elevation gain? The total descent? The net change from start to finish?
6. **MEDIUM** A profile has a horizontal scale of 1 cm = 1 km and a vertical scale of 1 cm = 200 m. What is the vertical exaggeration?
7. **HARD** A mountain road climbs 120 m over 2 km of horizontal distance. What is its average grade? Give the climb and distance in feet and miles too.



8. **HARD** In the figure, the profile is drawn with a vertical exaggeration of 2. If you redrew it with no exaggeration, how would it look, and why do mapmakers usually exaggerate? (Use the map or drawing “Horizontal: 1 unit = 5 m. Vertical: 1 unit = 2.5 m.” shown earlier in this lesson.)
9. **HARD** When you draw a profile, why should you round off the top of a hill instead of making a sharp point at the highest contour?
10. **CHALLENGE** Along a straight line, a map gives these elevations: 0 km, 300 m; 0.5 km, 400 m; 1.0 km, 500 m; 1.5 km, 400 m; 2.0 km, 300 m; 2.5 km, 400 m. Sketch the profile. Where is the ridge top and where is the valley? What is the average grade from 0 to 1.0 km?

## COMMON MISTAKES

- Spacing the dots evenly along the bottom instead of at the true places where the contours cross the line. The horizontal distances come from the map.
- Forgetting to label the scales and the vertical exaggeration, so a reader thinks a gentle hill is a cliff.
- Counting only the highest point when finding elevation gain. Every uphill stretch adds to the climb, even after a downhill.

**Make it a game • Blind Profile.** One player secretly draws a profile with three or four ups and downs on graph paper. Without showing it, the player calls out the elevations at each tick: “Zero kilometers, 200 meters; half a kilometer, 350 meters...” The other player draws the profile from the spoken numbers. Compare the drawings, then switch. Score a point if your partner’s drawing has the same number of hills and valleys as yours, and a bonus point if they correctly name the steepest stretch.

**Scripture.** “Every valley shall be exalted, and every mountain and hill shall be made low: and the crooked shall be made straight, and the rough places plain:” (Isaiah 40:4, KJV)

Isaiah describes the way being prepared for the Lord as if a road builder flattened the profile of the land. A profile shows every valley and every hill on a journey. God promises that nothing in the way can stop His coming.

### Practice answers

1. A side view of the land’s surface along a line, showing how it rises and falls.
2. A profile shows only the surface line. A cross-section also shows what lies beneath the surface, such as rock layers, faults or magma.
3.  $230 - 100 = 130$  units.  $130 \times 5 \text{ m} = 650 \text{ m}$ .  $650 \div 1,609 = \text{about } 0.40 \text{ mile}$ .
4.  $1,830 - 1,250 = 580 \text{ m}$ .  $580 \div 0.3048 = \text{about } 1,903 \text{ feet}$ .
5. Gain:  $(900 - 600) + (1,100 - 750) = 300 + 350 = 650 \text{ m}$  (about 2,133 feet). Descent: 150 m. Net change:  $1,100 - 600 = 500 \text{ m up}$ .
6.  $1 \text{ km} = 1,000 \text{ m}$ .  $1,000 \div 200 = 5$ . The profile is stretched 5 times taller than the true shape.
7.  $120 \div 2,000 = 0.06 = 6 \text{ percent}$ . 120 m is about 394 feet; 2 km is about 1.24 miles.

8. It would be half as tall, so the hill would look lower and gentler (its true shape). Mapmakers exaggerate so that small rises and gentle slopes are easy to see on the page.
9. The summit is higher than the last contour line it lies inside (but lower than the next contour would be), and real hilltops are usually rounded. A sharp point at the last contour would make the hill too low and the wrong shape.
10. The profile rises to a ridge top of 500 m at 1.0 km, falls to a valley bottom of 300 m at 2.0 km, and rises again to 400 m at 2.5 km. Average grade from 0 to 1.0 km:  $200 \text{ m} \div 1,000 \text{ m} = 0.20 = 20 \text{ percent}$ .

## UNIT 1 REVIEW

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Answer each question. Show your work for calculations, give units, and use complete sentences for explanations. Each question is worth 6 points. The review is worth 60 points.

1. (6 pts) What is a contour line? State two rules that every contour line follows.
2. (6 pts) Two index contours are labeled 700 feet and 800 feet, with four thin lines between them. What is the contour interval? Give the elevations of the four thin lines.
3. (6 pts) Two spot heights are 4 cm apart on a map: 260 m and 340 m. The ground rises evenly between them. How far from the 260 m point does the 300 m contour cross? How far does the 280 m contour cross?
4. (6 pts) Who drew lines of equal height around the Scottish mountain Schiehallion, and why did he need to know the mountain's shape?
5. (6 pts) On a 1:24,000 quadrangle, a trail measures 4.5 inches. How long is it in feet, miles and kilometers?
6. (6 pts) Where contour lines cross a creek, they bend into V's that point northeast. Which way does the creek flow? Explain using the rule of V's.
7. (6 pts) Name the landform shown by each pattern: (a) closed loops one inside another; (b) an hourglass shape of contours between two summits; (c) lines so close they nearly merge; (d) a closed loop with short ticks pointing inward.
8. (6 pts) A clay model 10 cm tall stands for a mountain 2,500 m tall. You slice it every 2 cm. What is the vertical scale? What is the contour interval? What elevations do the cuts stand for?
9. (6 pts) Explain why the shoreline of a calm lake is a contour line, and how this idea helps us make a contour map of a model mountain.
10. (6 pts) A hike goes from 1,200 m up to 1,650 m, down to 1,500 m, then up to a summit of 1,900 m. What is the total elevation gain in meters and feet? What is the net change from start to summit? Before 1980, Mount St. Helens was 9,677 feet tall; afterward its highest point was 8,363 feet. How much height did it lose?

### UNIT PROJECT: A TOPOGRAPHIC MAP OF A LOCAL HILL

Choose a hill near your home that you can visit. Find it on your USGS quadrangle and draw your own large, neat contour map of it: copy its contour lines, label the index contours, the contour interval, the summit elevation, a scale bar in miles and kilometers, and a north arrow, and mark any streams with arrows showing which way they flow. Then draw a line across the hill along a real path or trail, draw its profile with labeled scales and vertical exaggeration, and give the elevation gain and the steepest grade.

Walk the hill with a parent if you can, and add a short field note on how the real slopes compared with your map. Display your map beside the clay-and-floss contour model and the traced contour map you made in Lesson 1.3.

- **Accuracy:** Contour lines, elevations, interval, stream directions and scale are copied and labeled correctly.

- **Profile and calculations:** The profile is drawn from true contour crossings with labeled scales; elevation gain, grade and vertical exaggeration are calculated correctly with units.
- **Model and field work:** The clay model and its traced map are complete and match; the field note compares the map with the real hill.
- **Care:** The map and profile are neat, clearly lettered, colored with a sensible key, and easy to read.

#### Answer key

1. A contour line joins points of equal elevation on a map. Rules (any two): every point on one line has the same elevation; contour lines never cross or split (except at an overhanging cliff); every line closes on itself, though it may run off the map; close lines mean steep ground and wide lines mean gentle ground.
2.  $100 \div 5 = 20$  feet. The thin lines are 720, 740, 760 and 780 feet.
3. 300 m is 40 of the 80 m rise, halfway: 2 cm from the 260 m point. 280 m is 20 of 80, one quarter: 1 cm from the 260 m point.
4. Charles Hutton. Nevil Maskelyne measured how much the mountain pulled a plumb line in 1774, and Hutton needed the mountain's size and shape (its volume) to compare its pull with the whole earth's pull and work out how heavy the earth is.
5.  $4.5 \times 2,000 = 9,000$  feet.  $9,000 \div 5,280 = 1.70$  miles.  $9,000 \times 0.3048 = 2,743$  m, about 2.74 km.
6. Southwest. The V's point upstream, toward higher ground, so the water flows the opposite way, downhill toward the southwest.
7. (a) a hilltop or summit; (b) a saddle; (c) a cliff or very steep slope; (d) a depression.
8.  $2,500 \text{ m} \div 10 \text{ cm} = 250 \text{ m}$ . Slices every 2 cm give a contour interval of 500 m (about 1,640 feet). Cuts at 2, 4, 6 and 8 cm stand for 500, 1,000, 1,500 and 2,000 m.
9. Still water lies level, so every point on the shoreline is at the same elevation. If water rose around a mountain step by step, each shoreline would be a contour line. Slicing a model at equal, level heights does the same thing: each cut face has the shape of a shoreline at that height, so tracing the slices gives a contour map.
10. Gain:  $450 + 400 = 850$  m, about 2,789 feet. Net change:  $1,900 - 1,200 = 700$  m. Mount St. Helens lost  $9,677 - 8,363 = 1,314$  feet (about 401 m).

## THE MOVING EARTH

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The ground under our feet feels like the most solid thing in the world, and in a good sense it is: “Who laid the foundations of the earth, that it should not be removed for ever” (Psalm 104:5). Yet careful measurement shows that the earth is not still. Beneath a thin rocky crust lie a deep mantle of hot rock that flows very slowly and a core of iron, part liquid and part solid. The surface is broken into great plates that move a few centimeters a year, pulling apart, pushing together and grinding past one another. In this unit you will learn what lies inside the earth, how its plates meet, how colliding plates raise the highest mountains on earth, and how a spreading ridge has built a whole island in the North Atlantic.

You will meet the people who figured it out: Andrija Mohorovičić reading earthquake records in Zagreb in 1909, Inge Lehmann finding the inner core in 1936, Alfred Wegener fitting the continents together in 1912, Horace-Bénédict de Saussure studying folded rocks on Mont Blanc, the surveyors who measured Mount Everest, and Marie Tharp drawing the hidden mountains of the ocean floor. You will build plates from graham crackers and frosting, squeeze clay into mountains, sound a hidden sea floor, and finish with a map of the world’s plates with its volcanoes and earthquakes plotted along their edges.

### BEFORE YOU BEGIN

- Can read a world map and find the continents and oceans
- Can multiply and divide whole numbers and decimals and find a percent
- Can convert between kilometers and miles and between meters and feet with a given factor
- Has read a contour map or drawn a profile (Unit 1)

### MASTERY CHECKLIST

- I can name the earth’s layers and give their depths, and explain how earthquake waves revealed them.
- I can tell Wegener’s story and the evidence for moving continents: coastlines, fossils and rock belts.
- I can describe spreading, colliding and sliding plate boundaries and name a real place for each.
- I can explain how colliding continents fold and stack the crust into mountains like the Himalaya and the Alps.
- I can calculate ocean depth from an echo-sounding time and plate movement from a yearly rate.
- I can explain why Iceland stands on the Mid-Atlantic Ridge and how its people live with and use the moving ground.

## OPTIONAL BOOKS AND RESOURCES

- **USGS Latest Earthquakes map** (<https://earthquake.usgs.gov/earthquakes/map/>): Free. A live world map of recent earthquakes from the U.S. Geological Survey. Watch for a week and see how the dots line up along plate edges; use it for the unit map and the portfolio.
- **Smithsonian Global Volcanism Program** (<https://volcano.si.edu/>): Free. The Smithsonian's catalog of the world's volcanoes with locations and eruption reports. Use it to find volcanoes to plot on your plate map.

## 2.1 INSIDE THE EARTH ★

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### OBJECTIVES

- Name and describe the earth's layers (crust, mantle, outer core and inner core) with their depths in kilometers and miles.
- Explain how scientists learned about the inside of the earth from earthquake waves, using the work of Andrija Mohorovičić, Beno Gutenberg and Inge Lehmann.
- Use the gap between P waves and S waves to estimate how far away an earthquake was, and draw the earth's layers to scale.

**Warm-up.** Take three closed containers from the kitchen that look alike, such as a full jar of honey, a jar of rice and an empty jar (wrap them in towels so you cannot see inside). Tap each one gently with a spoon, roll it across the table, and give it a little shake. Without opening them, guess what is inside each one and say what clue told you. Scientists study the inside of the earth the same way: they cannot open it, so they listen to how it rings and shakes.

**Watch.** *Reading Earthquakes: Visualizing Earth's Interior* / California Academy of Sciences (California Academy of Sciences, 1:20). <https://www.youtube.com/watch?v=UoW6wamumOU>

With the big idea: watch how earthquake waves bend and slow down as they pass through the crust, mantle and core, just as Mohorovičić used seismograph records to find the base of the crust.

**Note:** Captions were not available to check; preview it first. It is a short museum animation of just over a minute.

### KEY TERMS

#### **crust**

The thin, rocky outer layer of the earth: about 5 to 10 km (3 to 6 mi) thick under the oceans and about 35 km (22 mi) thick under most of the continents.

#### **mantle**

The thick layer of hot, solid rock under the crust, reaching down about 2,900 km (1,800 mi). Its rock can flow very slowly, like stiff putty.

#### **core**

The earth's center, made mostly of iron and nickel: a liquid outer core and a solid inner core.

#### **seismic wave**

A wave of energy that travels through the earth from an earthquake. A seismograph records it.

#### **P wave and S wave**



P (primary) waves push and pull the rock, travel fastest and pass through solids and liquids. S (secondary) waves shake the rock side to side, travel slower and cannot pass through liquids.

### **Moho**

The boundary between the crust and the mantle, named for Andrija Mohorovičić, who found it in 1909.

## **CORE IDEAS**

**The story.** On the morning of October 8, 1909, an earthquake shook the Kupa River valley about 40 km (25 mi) southeast of Zagreb, in what is now Croatia. In Zagreb, Andrija Mohorovičić, the director of the city's weather observatory, had recently set up new seismographs, machines that draw a wavy line on paper when the ground shakes. He gathered the records from his own station and from stations across Europe and laid them side by side. Something puzzled him. Stations close to the earthquake recorded one set of waves, but stations more than about 200 km (125 mi) away recorded *two* sets, and one set had arrived sooner than it should have.

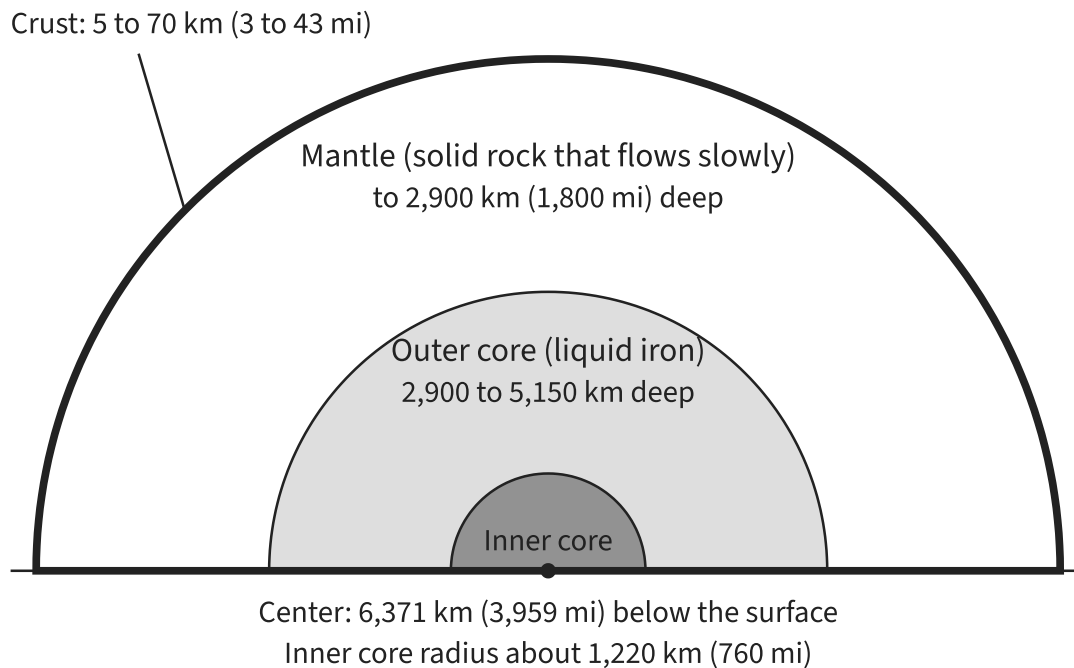
**How they figured it out.** Mohorovičić reasoned that some of the waves had dived down into deeper, harder rock where waves travel faster, raced along it and then come back up, like a driver who takes a longer road because it is a highway. He worked out that this faster rock begins about 54 km (34 mi) down. He had found the bottom of the crust. That boundary is still called the **Moho** in his honor. Other scientists used the same method. In 1914 Beno Gutenberg calculated that a great change lies about 2,900 km (1,800 mi) down, where the mantle meets the core. Earthquake waves of one kind, the **S waves**, never come out on the far side of the earth from an earthquake. Because S waves cannot travel through liquid, the outer core must be liquid. Then in 1936 a Danish scientist named Inge Lehmann studied faint waves from earthquakes in the Pacific that should not have reached her stations at all. She showed they had bounced off something hard deep inside the liquid core: a solid **inner core**.

**The big idea.** The earth is built in layers, like a peach with a thin skin, thick flesh and a hard pit. The **crust** is the skin: about 5 to 10 km (3 to 6 mi) thick under the oceans and about 35 km (22 mi) thick under most continents, thicker still under high mountains. Below it lies the **mantle**, about 2,900 km (1,800 mi) of hot, solid rock. The mantle is solid enough to carry earthquake waves, yet over long periods it flows very slowly, like a stick of warm modeling clay. Below that is the **outer core**, liquid iron and nickel, from about 2,900 to 5,150 km (1,800 to 3,200 mi) down. At the very center is the solid **inner core**, a ball of iron and nickel about 1,220 km (760 mi) in radius, thought to be about as hot as the surface of the sun yet squeezed solid by the weight above it. The center lies 6,371 km (3,959 mi) beneath your feet.

**Another clue.** In 1798 the English scientist Henry Cavendish measured the pull of gravity between heavy lead balls in a shed at his home and worked out that the whole earth is about 5.5 times as heavy as the same amount of water. But ordinary surface rock is only about 2.7 times as heavy as water. So the inside of the earth must be made of something much heavier than the rocks we stand on. Iron fits the clue, and the earthquake waves agree. Two very

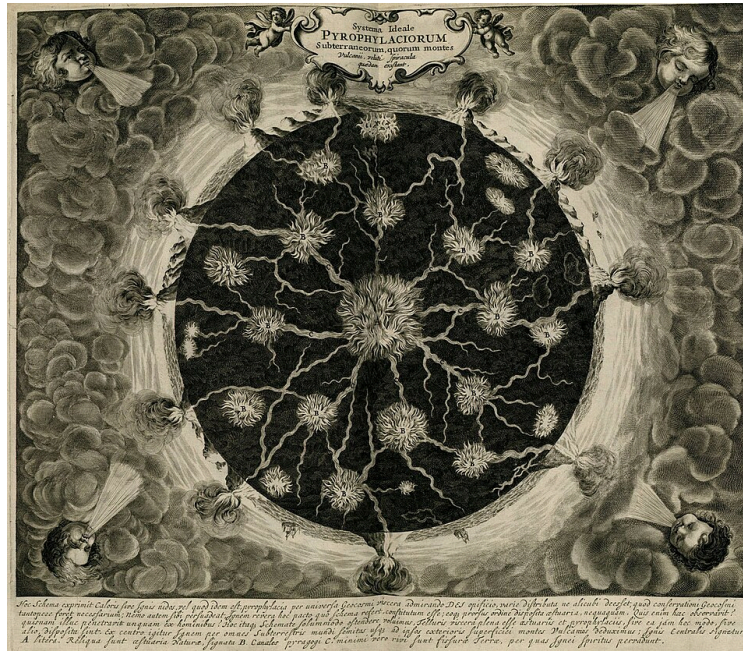
different kinds of evidence, a balance in a shed and a seismograph in Zagreb, point to the same answer.

**On the map.** No one has ever drilled through the crust. The deepest hole ever made, the Kola Superdeep Borehole in the far north of Russia, reached 12,262 m (about 7.6 mi) in 1989 and stopped, because the rock was too hot for the drill. That is only about a third of the way through the continental crust there, and a tiny scratch compared with the 6,371 km to the center. Everything we know about the deep earth comes from careful measurement and reasoning: seismograph stations around the world, the weight of the earth, and the way the planet behaves as a magnet because of its moving liquid core. When an earthquake strikes today, hundreds of stations record it within minutes, and each one adds a line to our picture of the inside of the world God made.



*The earth's layers, drawn to scale except for the crust, which would be thinner than the line.*

## PICTURE STUDY



*Systema Ideale Pyrophylaciorum Subterraneorum (the ideal system of underground fires), from Mundus Subterraneus, Athanasius Kircher, 1665 · Engraving in a printed book · Printed in Amsterdam; copies are held in many rare-book libraries*

Athanasius Kircher was a German Jesuit priest and scholar who taught in Rome and wrote about almost everything: languages, music, magnets, China and the earth. In 1638 he traveled through southern Italy, saw Mount Etna and Stromboli smoking, and had himself lowered into the crater of Vesuvius to look. In his great book *Mundus Subterraneus* (The Underground World), printed in 1665, he drew the inside of the earth as he imagined it: a central fire feeding volcanoes through a web of channels.

Kircher had no seismographs, so his picture was a careful guess built from what he could see on the surface. Comparing his engraving with a modern diagram shows how much has been learned by measuring, and also how much curiosity and wonder the early scholars brought to the question.

### Look closely

- Find the great fire at the center. What layer of the modern earth is in that place?
- Follow the channels of fire outward. Where do they come out on the surface?
- Find any places where Kircher drew water or air inside the earth.
- Compare the thickness of the outer shell in Kircher's picture with the crust in the diagram in this lesson.

### Talk about it

1. What did Kircher get partly right about the inside of the earth? What did he get wrong?

2. Why could later scientists draw a better picture than Kircher without ever going deeper than he did?
3. What does this picture teach about the difference between a guess and a measurement?

## **PROJECT: A JOURNEY TO THE CENTER ON A PAPER STRIP**

You will make a scale drawing of the earth from the surface to the center on one long strip of paper, where 1 centimeter stands for 100 km. When you are done, you will see with your own eyes how thin the crust is and how deep the core lies.

### **You will need**

- A strip of paper at least 70 cm long (adding-machine tape, or sheets of printer paper taped end to end)
- Meter stick or yardstick with centimeters
- Colored pencils or markers in four colors
- Pencil and a calculator

### **Steps**

1. Draw a line across one end of the strip and label it "Surface (0 km)."
2. Use the scale 1 cm = 100 km. Work out each distance: the Moho under a continent (35 km = 0.35 cm), the bottom of the mantle (2,900 km = 29 cm), the bottom of the outer core (5,150 km = 51.5 cm) and the center (6,371 km = about 63.7 cm).
3. Measure from the surface line and mark each boundary. Label each one in both km and miles.
4. Color the crust (a very thin band, about 3.5 mm), the mantle, the outer core and the inner core, each a different color.
5. Add a tiny tick for the Kola Superdeep Borehole at 12.3 km. How many millimeters from the surface is it?
6. Write the names Mohorovičić (1909), Gutenberg (1914) and Lehmann (1936) beside the boundary each one discovered.
7. Roll out your strip and walk a family member from the surface to the center, telling what each layer is made of and how we know.

### **Tips**

- The crust band is so thin that you may need a sharp pencil. That is the lesson: we live on a very thin skin.
- If your paper is short, use the scale 1 cm = 200 km and divide each length by two.

### **Check your work**

- I marked all four layers at the right distances on my scale strip.
- I can explain which layer is liquid and how S waves showed it.

- I can tell how deep the deepest hole goes compared with the whole trip to the center.

## MAP NOTEBOOK

1. Draw the half-circle diagram of the earth's layers and label each layer with its depth in km and miles.
2. Draw two seismograph lines: one from a station that received both P and S waves, and one from a station on the far side of the earth that received only P waves. Label the gap.
3. Make a small chart with three columns, Scientist, Year, What they found, for Mohorovičić, Gutenberg, Lehmann and Cavendish.

**From history.** Inge Lehmann worked for years as the chief seismologist at the Royal Danish Geodetic Institute in Copenhagen, reading seismograph records by hand and keeping her notes on cards in oatmeal boxes. Her 1936 paper had one of the shortest titles in the history of science: “P’,” the symbol for a wave that passes through the core. She lived to the age of 104 and kept studying the earth all her life.

## WORKED EXAMPLES

**Example 1.** A seismograph station records the first P wave from an earthquake, and 25 seconds later the first S wave arrives. Seismologists use a handy rule for nearby earthquakes: the earthquake is about 8 km away for every second between the P wave and the S wave. About how far away was the earthquake, in kilometers and miles?

1. P waves travel faster than S waves, so the farther the earthquake, the bigger the gap between them.
2. Multiply the gap by 8 km per second:  $25 \times 8 = 200$  km.
3. Convert to miles (1 km is about 0.62 mi):  $200 \times 0.62 = 124$  mi.

**Answer:** About 200 km (about 124 mi) away.

**Example 2.** On a scale drawing, the earth's radius of 6,371 km is drawn as 10 cm. How far from the center should you draw the edge of the outer core (which lies 2,900 km below the surface) and the edge of the inner core (5,150 km below the surface)? How thick would a 35 km crust be on the drawing?

*(Use the map or drawing "Measure this diagram: the outer core's radius is a little more than half the ear" shown earlier in this lesson.)*

1. Find each radius measured from the center. Outer core:  $6,371 - 2,900 = 3,471$  km. Inner core:  $6,371 - 5,150 = 1,221$  km.
2. The scale is 10 cm for 6,371 km, so each centimeter stands for about 637 km.
3. Outer core:  $3,471 \div 637 \approx 5.4$  cm. Inner core:  $1,221 \div 637 \approx 1.9$  cm.
4. Crust:  $35 \div 637 \approx 0.055$  cm, which is about half a millimeter.

**Answer:** Outer core edge about 5.4 cm from the center, inner core edge about 1.9 cm, and the crust only about 0.5 mm thick, thinner than a pencil line.

**Example 3.** S waves are never recorded at stations more than about  $103^\circ$  of arc around the earth from an earthquake. One degree of arc along the earth's surface is about 111 km (69 mi). How far along the surface does this S-wave "shadow" begin, and what does the shadow tell us?

1. Multiply degrees by kilometers per degree:  $103 \times 111 = 11,433$  km, about 11,400 km.
2. In miles:  $103 \times 69 = 7,107$  mi, about 7,100 mi.
3. S waves cannot pass through liquid. Waves headed to the far side of the earth would have to go through the core, and they never arrive, so the outer core must be liquid.

**Answer:** The S-wave shadow begins about 11,400 km (7,100 mi) from the earthquake. It shows that the outer core is liquid.

## PRACTICE

1. **EASY** Name the four layers of the earth from the outside in.
2. **EASY** Which layer is liquid? What two metals make up most of the core?
3. **EASY** Who found the boundary between the crust and the mantle, in what year, and what is the boundary called?
4. **MEDIUM** A station records an S wave 40 seconds after the P wave. Using the rule of 8 km per second of gap, how far away was the earthquake in km and miles?
5. **MEDIUM** An earthquake is 480 km away. About how many seconds after the P wave should the S wave arrive?
6. **MEDIUM** Ocean crust is about 7 km thick and continental crust about 35 km thick. How many times thicker is the continental crust? Give both thicknesses in miles too.



7. **MEDIUM** The Kola Superdeep Borehole reached 12,262 m. Convert this to kilometers and miles, and find what fraction of a 35 km continental crust it went through.
8. **HARD** How thick is the outer core in kilometers and miles? (It runs from 2,900 km to 5,150 km below the surface.)
9. **HARD** Henry Cavendish found that the earth as a whole is about 5.5 times as heavy as water, but surface rock is about 2.7 times as heavy as water. What does this tell us about the inside of the earth, and which later evidence agreed?
10. **CHALLENGE** In a short paragraph, explain how Inge Lehmann discovered the inner core in 1936, and why the inner core is solid even though it is hotter than the liquid outer core.

## COMMON MISTAKES

- Thinking the mantle is a sea of melted lava. The mantle is solid rock that carries S waves; it only flows very slowly, like stiff putty. Melted rock forms only in small pockets.
- Mixing up P and S waves. P waves arrive first and go through liquids; S waves arrive second and stop at liquids.
- Drawing the crust far too thick. On a drawing of the whole earth, the crust is thinner than a pencil line.

**Make it a game • P Wave, S Wave.** Players line up as “layers” across the room: some are Solid (standing) and one or two are Liquid (sitting). A messenger sends two signals from one end: a P wave (a gentle push on the shoulder passed from player to player) and an S wave (a side-to-side wiggle passed by holding hands). Solid players pass both. Liquid players can pass only the P push. Whoever is at the far end must say which waves arrived and guess where the liquid layer is. Swap places and play again.

**Scripture.** “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding.” (Job 38:4, KJV)

God asked Job about the foundations of the earth, and no man had seen them. We still cannot see them, but by patient measuring we have learned a little of how deep and wonderfully layered they are. Humble questions lead to real knowledge.

### Practice answers

1. Crust, mantle, outer core, inner core.
2. The outer core is liquid. The core is made mostly of iron and nickel.
3. Andrija Mohorovičić, in 1909 (from the October 8, 1909 earthquake near Zagreb). It is called the Moho.
4.  $40 \times 8 = 320$  km, about 199 mi (about 200 mi).
5.  $480 \div 8 = 60$  seconds, one minute.
6.  $35 \div 7 = 5$  times thicker. 7 km is about 4.3 mi; 35 km is about 22 mi.
7.  $12,262 \text{ m} = 12.3 \text{ km}$ , about 7.6 mi.  $12.3 \div 35 \approx 0.35$ , so about one third of the crust.
8.  $5,150 - 2,900 = 2,250$  km, about 1,400 mi.
9. The inside must be made of much heavier material than surface rock, such as iron. The earthquake waves studied by Gutenberg and Lehmann agreed: they showed a large dense

core with a liquid outer part and a solid inner part.

10. Lehmann studied faint P waves from Pacific earthquakes that arrived at stations where they should not have reached if the core were all liquid. She showed they had bounced off a boundary deep inside the core, so there must be a separate inner core. The inner core is solid because the enormous weight of all the layers above squeezes it so hard that the iron cannot melt, even though it is very hot.



## 2.2 PLATES AND THEIR EDGES

### OBJECTIVES

- Tell the story of Alfred Wegener's 1912 idea of drifting continents and the evidence he used: matching coastlines, fossils and rock belts.
- Describe the three kinds of plate boundaries (spreading, colliding and sliding) and name a real example of each.
- Use measured plate speeds in centimeters and inches per year to calculate how far plates move over a lifetime.

**Warm-up.** Tear an old magazine page into five or six irregular pieces. Mix them up and hand them to someone else. How fast can they fit the page back together? Ask them what clues they used: the shapes of the edges, the lines of print running across the tears, or the pictures that continue from piece to piece. Keep those three kinds of clues in mind; Alfred Wegener used the same ones on a map of the world.

**Watch.** 5. *Transform Plate Boundaries* / *Vivid Earth Science* (UTD GEOSCIENCE STUDIO, 6:45). <https://www.youtube.com/watch?v=I7DoEkK6RDo>

As review: after you learn the three kinds of plate edges, watch this to see how plates slide past each other at a transform boundary such as the San Andreas Fault.

**Note:** Captions were not available to check; preview it first. University plate-tectonics videos often give ages in millions of years; the lesson describes plate movement without giving those ages. Covers only transform boundaries, not all three boundary types or Wegener's story.

### KEY TERMS

#### plate

A huge, rigid slab of the earth's crust and the top of the mantle that moves slowly as one piece. The earth's surface is broken into about a dozen large plates and several smaller ones.

#### continental drift

Alfred Wegener's idea (1912) that the continents were once joined and have moved apart across the earth's surface.

#### spreading (divergent) boundary

A plate edge where two plates move apart and melted rock rises to make new crust, as at the Mid-Atlantic Ridge.

#### colliding (convergent) boundary

A plate edge where two plates push together. One plate may slide down under the other, or the crust may crumple into mountains.

#### sliding (transform) boundary

A plate edge where two plates grind sideways past each other, as along the San Andreas Fault in California.

### **fault**

A crack in the earth's crust along which the rocks on either side have moved.

## **CORE IDEAS**

**The story.** On January 6, 1912, a young German scientist named Alfred Wegener stood before a meeting of geologists in Frankfurt and told them something startling: the continents move. Wegener was a weather scientist who had explored Greenland, not a rock expert, and he had been studying a world map. He noticed what many schoolchildren notice: the bulge of South America fits into the curve of Africa like two pieces of a jigsaw puzzle. He proposed that all the continents had once been joined in one great landmass and had since drifted apart. In 1915 he set out his evidence in a book, *The Origin of Continents and Oceans*.

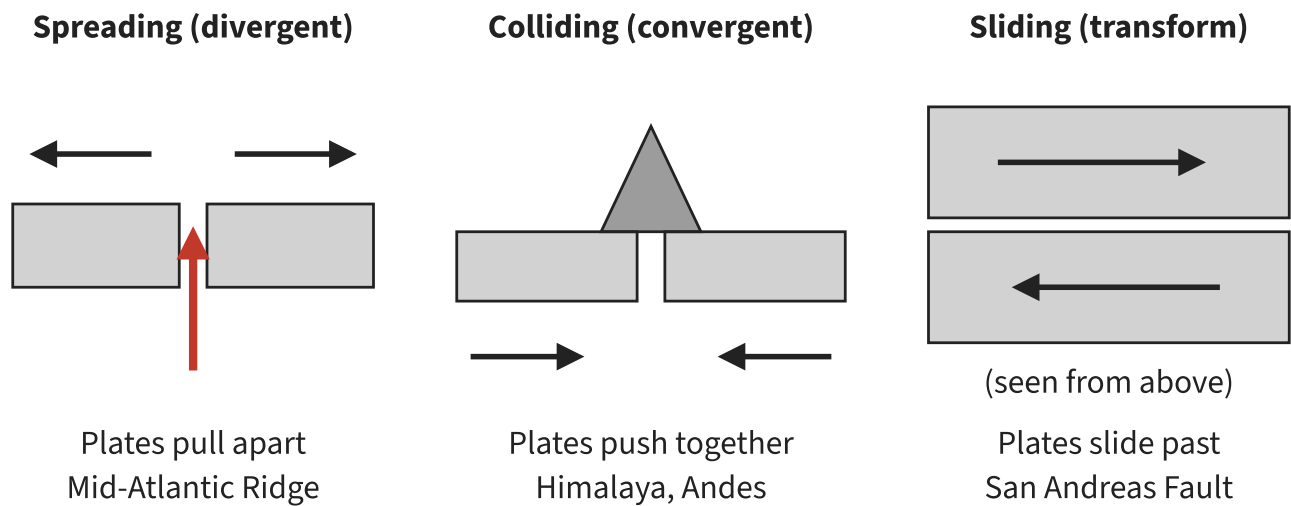
**How they figured it out.** Wegener gathered three kinds of clues, the same ones you used to rebuild the torn page. First, the **shapes**: the edges of the continents, especially the edges of their underwater shelves, fit together. Second, the **pictures that continue across the tear**: fossils of the same small freshwater reptile, *Mesosaurus*, are found in South America (Brazil and Uruguay) and in southern Africa (South Africa and Namibia), and nowhere else. It could never have swum the salty Atlantic. Fossils of the same seed fern, *Glossopteris*, are found in South America, Africa, India, Australia and Antarctica. Third, the **lines of print**: rock belts and old mountain chains line up across the ocean. The Appalachian Mountains of North America match ranges in Scotland and Norway. Many geologists rejected Wegener's idea, because he could not explain what force could push whole continents. Wegener died on the Greenland ice cap in 1930, still gathering evidence.

**The answer from the sea floor.** The missing piece came from the ocean. In the 1950s and 1960s, ships mapped the sea floor with echo sounders and towed magnetometers behind them. They found a mountain range running down the middle of the Atlantic with a valley along its crest, and stripes of rock on either side that matched like a mirror. In 1962 Harry Hess, a geologist at Princeton who had commanded a Navy transport ship and run its echo sounder during World War II, explained it: new crust forms at the ridges and spreads away on both sides. The continents do not plow through the ocean floor like ships. They ride along on **plates** of crust and upper mantle, moved by the slow flow of the hot mantle beneath.

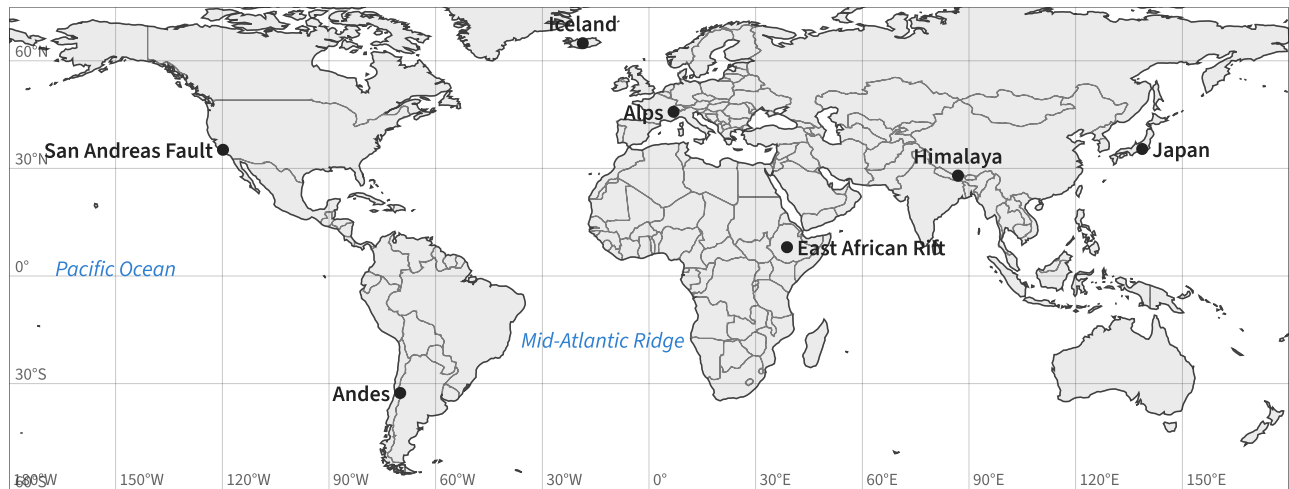
**The big idea.** The earth's surface is a shell broken into about a dozen large plates (among them the Pacific, North American, South American, Eurasian, African, Antarctic and Indo-Australian plates) and several smaller ones, such as the Nazca and Philippine plates. Plates meet in three ways. At a **spreading boundary** they pull apart and melted rock rises to fill the gap, as along the Mid-Atlantic Ridge and the rift valleys of East Africa. At a **colliding boundary** they push together. Where ocean crust meets a continent, the heavier ocean plate slides down under the other into the mantle, and a line of volcanoes rises, as in the Andes. Where two continents meet, neither sinks, and the crust crumples into great mountains like the Himalaya. At a **sliding boundary** the plates grind past each other sideways, as along

California's San Andreas Fault, where the Pacific Plate moves northwest past the North American Plate.

**On the map.** Today we do not have to guess how fast plates move. GPS stations bolted to solid rock measure their motion to the millimeter. The North Atlantic widens about 2.5 cm (1 inch) a year, about as fast as your fingernails grow. The Pacific Plate near Hawaii moves northwest about 7 cm (almost 3 inches) a year. Plot the world's earthquakes and volcanoes on a map, and you will find that most of them fall along narrow lines. Those lines are the edges of the plates, where the earth's great pieces push, pull and grind. Knowing where those edges lie tells engineers and families where to build strongly and where to prepare.

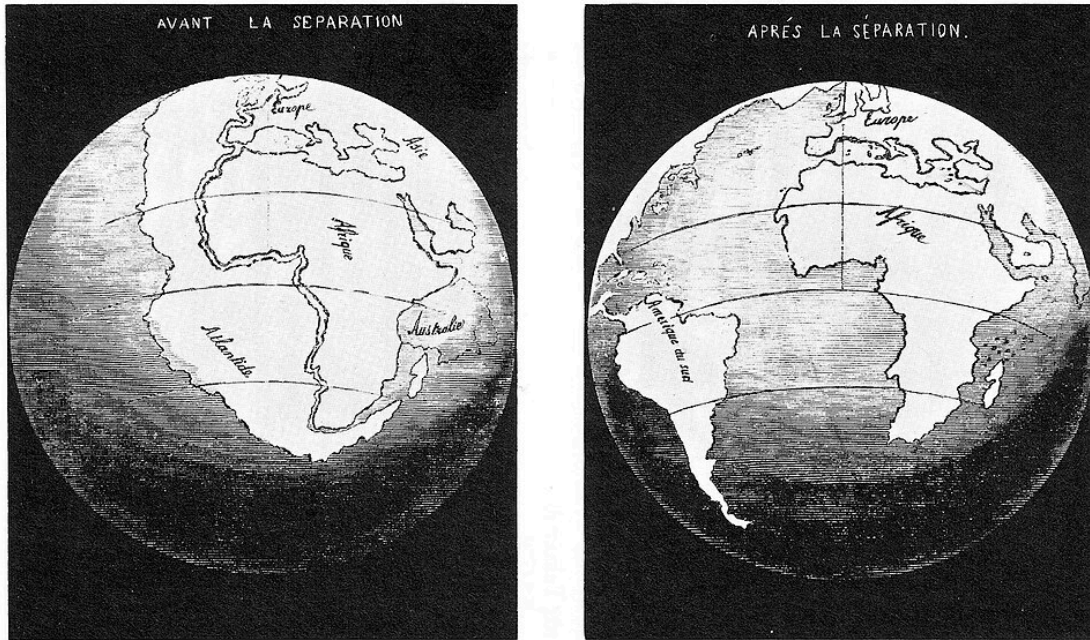


*The three kinds of plate boundaries.*



*Some places where plates meet. Each one is a spreading, colliding or sliding boundary.*

## PICTURE STUDY



*The continents before and after their separation, from *La Création et ses mystères dévoilés*, Antonio Snider-Pellegrini, 1858 · Printed map illustrations in a book · Published in Paris; copies are held in rare-book libraries*

More than fifty years before Wegener, a French-American writer named Antonio Snider-Pellegrini noticed the same puzzle fit. In his 1858 book *La Création et ses mystères dévoilés* (Creation and Its Mysteries Revealed), printed in Paris, he drew two maps: one with the Americas pushed against Europe and Africa, and one with the Atlantic open between them. He also pointed out that the same kinds of fossil plants are found in the coal beds of Europe and North America.

His explanation for how the continents moved was not the one scientists accept today, and few people took his maps seriously. But his drawings are among the first to show the idea that would later change geography, and they show how a careful look at a map can raise a question that takes generations to answer.

### Look closely

- On the left-hand map, find where Brazil touches Africa. Does it match the fit you see on a globe?
- Find North America. What does it touch on the left-hand map?
- Compare the two maps. What has opened up between them?
- Look for any places where the fit is not perfect. Why might mapmakers in 1858 have drawn some coasts differently?

### Talk about it

1. Snider-Pellegrini and Wegener both started with the shapes of coastlines. What extra evidence did Wegener add?
2. Why do you think so many scientists did not accept the idea at first?
3. What did the mapping of the sea floor finally add to the puzzle?

## PROJECT: GRAHAM-CRACKER-AND-FROSTING PLATE MODEL

Graham crackers make good plates: stiff and brittle like crust. A layer of frosting makes a good mantle: soft enough that the crackers can slide and sink, but thick enough to hold them up. With a few crackers you can act out all three kinds of plate boundaries and see what happens at each one.

### You will need

- 4 to 6 whole graham crackers (break each one into two squares)
- A tub of white frosting (or thick peanut butter)
- A paper plate and a butter knife
- A small cup of water and a paper towel
- Ledger notebook and pencil for sketches

### Steps

1. Spread a layer of frosting about 1 cm (half an inch) thick on the paper plate. This is the mantle.
2. **Sliding boundary.** Lay two cracker squares side by side on the frosting with their edges touching. Press down gently and slide one away from you and the other toward you. Listen and watch: the edges catch, crumble and jerk. Sketch what you see and label it San Andreas Fault.
3. **Spreading boundary.** Lay two fresh squares edge to edge. Press down and slowly pull them apart. Watch the frosting rise into the gap. Sketch it and label it Mid-Atlantic Ridge.
4. **Colliding boundary, ocean meets continent.** Lay one dry square (continent) beside one square whose edge you have dipped quickly in water (ocean plate). Push them together so the soft, wet edge slides under the dry one. Sketch it and label it Andes.
5. **Colliding boundary, continent meets continent.** Dip the edges of two squares in water for a second, lay them on the frosting and push them slowly together. The soft edges crumple and rise instead of sinking. Sketch it and label it Himalaya.
6. Under each sketch, write one sentence telling which way the plates moved and what formed.
7. Clean up, and share the leftover crackers with whoever helped.

### Tips

- Dip the cracker edges for only a second or two; too long and they fall apart.
- Move slowly. Real plates move only a few centimeters a year, far slower than your hands, and moving slowly shows the shapes best.

### Check your work

- I modeled all three kinds of plate boundaries.
- I can name a real place for each kind.
- I can explain why an ocean plate sinks but two continents crumple into mountains.

### MAP NOTEBOOK

1. Trace or sketch a world map and draw arrows showing how South America and Africa fit together. Mark where Mesosaurus fossils are found on both.
2. Draw the three boundary diagrams from this lesson and write a real place under each one.
3. Start your unit map: on an outline world map, lightly draw the edges of the seven largest plates and label each plate.

**From history.** Alfred Wegener died in November 1930 on the Greenland ice cap. He had led a sledge journey to resupply a weather station in the middle of the ice, and he and his Greenlandic companion Rasmus Villumsen set out back toward the coast in bitter cold. Neither reached it. Wegener's body was found the next spring, carefully buried in the snow by Villumsen, who was never found. Thirty years later the sea-floor maps proved that Wegener had seen something true.

### WORKED EXAMPLES

**Example 1.** GPS stations show that the North Atlantic Ocean widens about 2.5 cm (about 1 inch) a year. How much wider does it become in 80 years, about one long human life? Give the answer in meters and feet.

1. Multiply the yearly rate by the number of years:  $2.5 \text{ cm} \times 80 = 200 \text{ cm}$ .
2. Change centimeters to meters:  $200 \text{ cm} = 2 \text{ m}$ .
3. In inches:  $1 \text{ inch} \times 80 = 80 \text{ inches}$ . Divide by 12:  $80 \div 12 \approx 6.7 \text{ ft}$ .

**Answer:** About 2 m (about 6.7 ft, a little taller than a tall man).



**Example 2.** Use the boundary map. For each place, decide which kind of boundary it lies on: (a) the San Andreas Fault, (b) Iceland, (c) the Himalaya.

*(Use the map or drawing “Use the map to locate each place.” shown earlier in this lesson.)*

1. (a) Along the San Andreas Fault the Pacific Plate moves northwest past the North American Plate, side by side. That is a sliding (transform) boundary.
2. (b) Iceland sits on the Mid-Atlantic Ridge, where the North American and Eurasian plates pull apart. That is a spreading (divergent) boundary.
3. (c) In the Himalaya, India pushes north into Asia, continent against continent. That is a colliding (convergent) boundary.

**Answer:** (a) sliding, (b) spreading, (c) colliding.

**Example 3.** The Pacific Plate near Hawaii moves about 7 cm (about 2.75 inches) a year toward the northwest. A GPS station was set up on the Big Island in the year 2000. About how far had it moved by 2025, in centimeters, meters and feet?

1. Find the number of years:  $2025 - 2000 = 25$  years.
2. Multiply by the rate:  $7 \text{ cm} \times 25 = 175 \text{ cm} = 1.75 \text{ m}$ .
3. In inches:  $2.75 \times 25 \approx 69$  inches.  $69 \div 12 \approx 5.7$  ft.

**Answer:** About 175 cm, or 1.75 m (about 5.7 ft), toward the northwest.

## PRACTICE

1. **EASY** In what year and city did Alfred Wegener first present his idea of drifting continents?
2. **EASY** Name the three kinds of plate boundaries and say how the plates move at each.
3. **EASY** Why is the Mesosaurus fossil good evidence that South America and Africa were once joined?
4. **MEDIUM** Look at the boundary map. Which boundary type is found at the Andes, and what happens to the ocean plate there?  
*(Use the map or drawing “Find the Andes on the map.” shown earlier in this lesson.)*
5. **MEDIUM** The North Atlantic widens about 2.5 cm a year. How much wider was it in 2012 than when Wegener spoke in 1912? Give the answer in meters and feet.
6. **MEDIUM** Which mountain chain in North America matches old mountain ranges in Scotland and Norway?
7. **MEDIUM** If a fence is built straight across a sliding boundary where the plates move 3.5 cm a year past each other, and the fault creeps steadily, how far apart will the two halves of the fence be after 40 years, in cm and inches?
8. **HARD** Why did many geologists reject Wegener’s idea in his lifetime, and what discovery in the 1950s and 1960s changed their minds?

9. **HARD** When ocean crust collides with a continent, the ocean plate sinks. When two continents collide, neither sinks. Explain why, using your graham-cracker model.
10. **CHALLENGE** A student says, “If the plates move only about 2.5 cm a year, plate movement can’t matter to people.” Write two or three sentences answering this.

## COMMON MISTAKES

- Thinking the continents float on a sea of liquid rock. The plates rest on the solid mantle, which flows only very slowly.
- Thinking only the continents move. Whole plates move, and most plates carry both ocean floor and land.
- Mixing up the boundary names: spreading = apart, colliding = together, sliding = side by side.

**Make it a game • Boundary Charades.** Write the names San Andreas Fault, Mid-Atlantic Ridge, Andes, Himalaya, East African Rift, Iceland and Japan on slips of paper. Two players act out the boundary with their hands as plates (pushing together, pulling apart or sliding past) while the others guess first the kind of boundary and then the place. One point for the boundary type, one for the place, and a bonus point for finding it on a globe.

**Scripture.** “Who laid the foundations of the earth, that it should not be removed for ever.” (Psalm 104:5, KJV)

The plates move a few centimeters a year, and yet the earth as a whole stays steady and dependable. Seasons come, rivers run, and fields can be planted generation after generation. Even the earth’s motions follow the orderly ways God built into His creation, which is why they can be measured and understood.

## Practice answers

1. 1912, in Frankfurt, Germany (January 6, 1912).
2. Spreading (divergent): plates move apart. Colliding (convergent): plates push together. Sliding (transform): plates slide sideways past each other.
3. Mesosaurus was a small freshwater reptile that could not have crossed the salty Atlantic, yet its fossils are found only in southern South America (such as Brazil) and southern Africa (such as South Africa). The simplest explanation is that the two lands were once joined.
4. A colliding (convergent) boundary. The heavier ocean plate (the Nazca Plate) slides down under South America into the mantle, and volcanoes rise above it.
5.  $100 \text{ years} \times 2.5 \text{ cm} = 250 \text{ cm} = 2.5 \text{ m}$ , about 8.2 ft (100 inches).
6. The Appalachian Mountains.
7.  $3.5 \times 40 = 140 \text{ cm}$  (1.4 m), about 55 inches (about 4.6 ft).
8. Wegener could not explain what force could move whole continents. Mapping of the sea floor showed a mid-ocean ridge with matching stripes of rock on both sides, and Harry Hess (1962) explained that new crust forms at the ridges and spreads apart, carrying the continents on plates.



9. Ocean crust is thinner and heavier (denser), so it slides under the lighter continent into the mantle, like the soft wet cracker sliding under the dry one. Continental crust is thick and light, so both pieces float high; instead of sinking they crumple, fold and pile up into mountains, like the two wet cracker edges rising.
10. Plates move slowly and steadily, but along their edges the rocks often stick and then slip suddenly. Several meters of built-up movement can be released in seconds as an earthquake, and colliding plates feed volcanoes. That is why most earthquakes and volcanoes lie along plate edges, and why people there need strong building codes and warning systems.

## 2.3 MOUNTAINS BUILT BY COLLISION

### OBJECTIVES

- Explain how the collision of two plates folds, stacks and thickens the crust into great mountain ranges such as the Himalaya and the Alps.
- Describe the evidence on the mountains themselves: folded rock layers seen by Horace-Bénédict de Saussure and sea fossils near the summit of Mount Everest.
- Compare mountain heights in meters and feet and calculate how much a layer of rock is shortened when it is folded.

**Warm-up.** Lay a bath towel flat on a smooth table. Put one hand on each end and slowly push the ends toward each other. Watch what the towel does in the middle. Now stack three different colored hand towels or napkins and push again. Where do the highest folds form, and what happens to the length of the towel from end to end?

**Watch.** *Why Europe is Building a 57KM Tunnel Through a Mountain?* (Railways Explained, 23:25). <https://www.youtube.com/watch?v=9jz-RfCEdx4>

After the story: watch how engineers dug a railway tunnel deep under the Alps, and notice the hard rock and great mountain weight the builders had to deal with.

**Note:** Captions were not available to check; preview it first. It runs about 23 minutes and is about the tunnel rather than how the Alps formed, and it may include a short Patreon or merchandise plug; skip that part. The lesson suggests the Gotthard Base Tunnel; make sure the video is about that tunnel (57 km) and not the Brenner Base Tunnel.

### KEY TERMS

#### fold

A bend in layers of rock caused by squeezing, like a wrinkle in a rug pushed against a wall.

#### fold mountains

Mountains made when colliding plates squeeze, fold and stack layers of rock, as in the Himalaya and the Alps.

#### mountain root

The thick part of the crust that reaches deep into the mantle beneath a high mountain range, like the hidden part of an iceberg.

#### limestone

A rock made mostly from the shells and skeletons of sea creatures, usually formed on the floor of a shallow sea.

#### triangulation

Measuring distances and heights by measuring angles from the two ends of a known base line, the method used to measure Mount Everest in the 1800s.

## CORE IDEAS

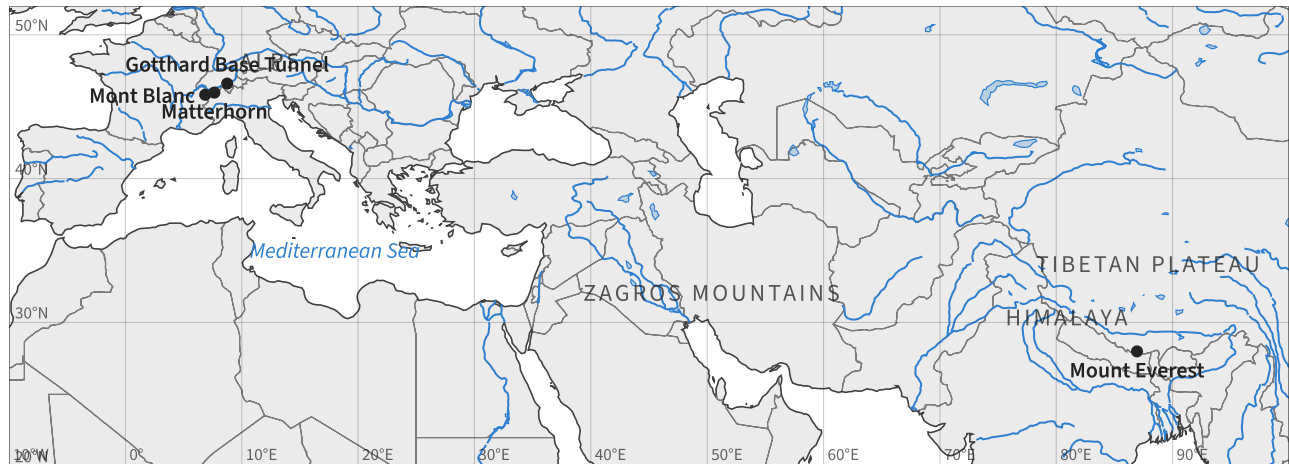
**The story.** On August 3, 1787, a Swiss scientist named Horace-Bénédict de Saussure reached the top of Mont Blanc, the highest mountain in the Alps, with his servant and a team of guides from the village of Chamonix. He had offered a reward years earlier to the first person to find a way up, and Jacques Balmat and Michel-Gabriel Paccard had claimed it the summer before. Saussure did not climb for glory. He carried a barometer to measure the height, a thermometer and notebooks, and he spent hours at the top making measurements. On his many journeys through the Alps he studied something that puzzled him: rock layers that should lie flat like the pages of a book were bent into arches, waves and even S-shapes on the mountain walls.

**How they figured it out.** Rock layers usually form flat, one on top of another, from mud, sand and shells settling in water. So a fold means that something squeezed the layers sideways after they formed, the way your hands squeezed the towel. Far to the east, the same clue appears on the highest mountain in the world. In 1852 Radhanath Sikdar, a mathematician working for the Great Trigonometrical Survey of India, calculated from careful triangulation that a peak the surveyors called Peak XV was the highest on earth. In 1856 the Survey announced its height as 29,002 feet, and it was later named Mount Everest after the Survey's former head, Sir George Everest. When climbers finally reached the top, they found that the rock near the summit is limestone holding the broken remains of sea creatures, such as the stems of sea lilies. The top of the world was once the floor of a sea.

**The big idea.** Great mountain ranges like the Himalaya and the Alps rise where two plates carrying continents collide. Continental crust is thick and light, so neither plate sinks far into the mantle. Instead the crust crumples. Layers of rock fold, crack and slide over one another in great sheets, stacking up like a pile of rugs shoved against a wall. The crust there becomes about twice its normal thickness, as much as 70 km (43 mi) under Tibet, and it pushes down into the mantle as a deep **root** while it rises into high peaks. In the Himalaya, the plate carrying India is pushing north into Asia. GPS stations show that India still moves north about 4 to 5 cm (about 2 inches) a year, and part of that squeeze is taken up in the Himalaya. In the Alps, the African Plate and a small plate that carries Italy push north against Europe. The top of the famous Matterhorn is made of rock that came from that southern plate.

**On the map.** The Himalaya curve for about 2,400 km (1,500 mi) along the northern edge of India, with ten peaks over 8,000 m (26,000 ft). Behind them lies the Tibetan Plateau, a vast high land averaging about 4,500 m (14,800 ft). Mount Everest stands 8,849 m (29,032 ft) by the joint Chinese and Nepali survey announced in 2020. The Alps curve for about 1,200 km (750 mi) from France through Switzerland, Italy and Austria; Mont Blanc stands about 4,806 m (15,770 ft), changing a little from year to year with the thickness of the ice on its top. Follow the line of collision mountains on a map, from the Atlas of Morocco and the Alps through the Zagros of Iran to the Himalaya, and you are tracing one long seam where Africa, Arabia and India press against Eurasia.

**Technology overcoming geography.** For most of history the Alps were a wall between northern Europe and Italy, crossed only by steep passes closed by snow much of the year. Engineers have pierced that wall again and again. The Gotthard Base Tunnel in Switzerland, opened in 2016, runs about 57 km (35 mi) straight through the roots of the mountains, the longest railway tunnel in the world, with up to 2,300 m (7,500 ft) of rock overhead. Trains now cross under the Alps on a nearly flat track, carrying freight and passengers where mule trains once struggled over the pass.



*The great collision belt: the Alps and the Himalaya lie on the same long seam between Eurasia and the plates to the south.*

## PICTURE STUDY



*The Schmadribach Falls, Joseph Anton Koch, 1821–1822 · Oil on canvas · Neue Pinakothek, Munich*

Joseph Anton Koch was an Austrian painter who walked through the Swiss Alps as a young man and spent most of his life painting landscapes in Rome. He painted the Schmadribach Falls, high in the Lauterbrunnen valley of the Bernese Oberland, more than once. In this

version he stacks the whole mountain world in one tall picture: snowfields and a glacier at the top, then cliffs, forests and the falling stream, and at the bottom a quiet valley with shepherds and their flocks.

Koch painted the mountains with great care for their real shapes. Look at the cliffs and ledges and you can see the tilted, layered rock that Saussure studied and that the collision of plates pushed up and folded.

### **Look closely**

- Start at the top of the painting and move down. List the levels you see, from snow to valley floor.
- Find the cliff faces. Can you see lines or ledges that might be layers of rock?
- Find the people and animals. How does their size help you feel the height of the mountains?
- Follow the water from the glacier to the bottom. Where is it coming from?

### **Talk about it**

1. How is this painting like a cross-section of a mountain from top to bottom?
2. What does the painting suggest about how hard it was to cross the Alps before tunnels and railways?
3. Why might a painter and a scientist both climb a mountain? What would each be looking for?

## **PROJECT: SQUEEZE A MOUNTAIN RANGE**

You will build flat layers of “rock” from colored play dough or modeling clay and squeeze them from the sides, just as colliding plates squeeze the crust. Then you will measure how much shorter and taller your range became and slice it open to see the folds inside.

### **You will need**

- Play dough or modeling clay in 3 or 4 colors
- A rolling pin and a ruler with centimeters
- Two small wooden blocks or thick books to push with
- Waxed paper and a piece of dental floss or a plastic knife
- Ledger notebook and pencil

### **Steps**

1. Roll each color into a flat sheet about 5 mm (a quarter inch) thick, 20 cm (8 in) long and 5 cm (2 in) wide.
2. Stack the sheets on waxed paper, one on top of another. These are flat layers of rock formed on a sea floor. Measure and record the length and the height of the stack.
3. Place a block at each end. Push the blocks slowly toward each other, a little at a time, keeping the stack from popping up off the table at the ends.

4. Stop when the stack is about 12 cm long. Measure the new length and the highest point.
5. Find the percent of shortening:  $(\text{old length} - \text{new length}) \div \text{old length} \times 100$ .
6. Cut the model in half the long way with dental floss. Draw the folds you see inside, color them, and label any place where one layer slid over another.
7. Under your drawing, write which real mountain range your model is most like and why.

### Tips

- Slightly chilled clay folds better; warm clay just squishes.
- Push the two blocks evenly, as if India and Asia were both moving, and keep a flat hand on top of the ends.

### Check your work

- I measured my model before and after squeezing and found the percent of shortening.
- I drew the folds inside my model.
- I can explain why squeezing makes mountains grow taller and their crust thicker.

### MAP NOTEBOOK

1. Draw a cross-section of the Himalaya: India on the left, Tibet on the right, the folded crust in the middle with a deep root below.
2. On your unit map, trace the collision belt from the Atlas Mountains through the Alps and the Zagros to the Himalaya. Mark Mont Blanc, the Matterhorn and Mount Everest.
3. Make a bar graph comparing the heights of Mount Everest, Mont Blanc, the Matterhorn and the highest point in your state, in both meters and feet.

**From history.** Radhanath Sikdar was a gifted Bengali mathematician who joined the Great Trigonometrical Survey of India in 1831 as a young man. The survey measured angles to Peak XV from six stations on the plains of northern India, more than 100 km (60 mi) away, and Sikdar's job was to turn those angles into a height, correcting for the curve of the earth and the bending of light through the air. The Survey's chief, Andrew Waugh, proposed naming the peak after his predecessor George Everest, who had in fact never seen it. Tibetans already called the mountain Chomolungma, and Nepalis call it Sagarmatha.

## WORKED EXAMPLES

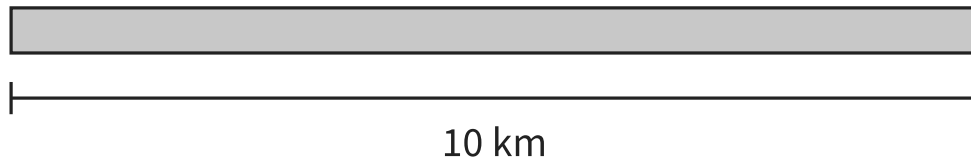
**Example 1.** Mount Everest is 8,849 m tall and Mont Blanc is about 4,806 m. How much taller is Everest in meters? Convert the difference to feet (1 m is about 3.28 ft). About how many Mont Blancs tall is Everest?

1. Subtract:  $8,849 - 4,806 = 4,043$  m.
2. Convert:  $4,043 \times 3.28 \approx 13,260$  ft.
3. Divide:  $8,849 \div 4,806 \approx 1.84$ .

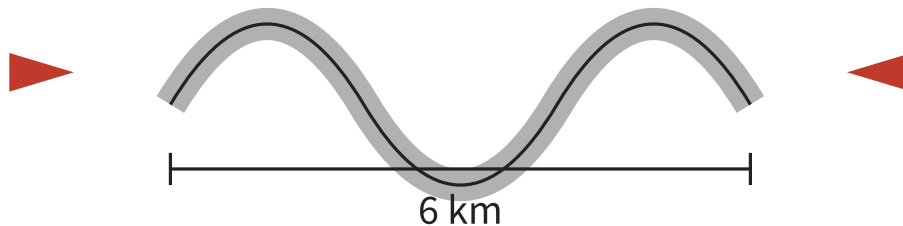
**Answer:** Everest is about 4,043 m (about 13,260 ft) taller, almost twice as tall as Mont Blanc (about 1.8 times).

**Example 2.** A layer of rock 10 km long is squeezed by colliding plates into folds that now stretch only 6 km from end to end. By what percent was it shortened? If the rock layer is a strip of paper 10 cm long, how long would the folded strip be?

Before: a flat layer



After squeezing: folds



*Folding makes a layer reach a shorter distance while piling it higher.*

1. Find how much shorter:  $10 - 6 = 4$  km.
2. Divide by the original length:  $4 \div 10 = 0.40$ , which is 40%.
3. Folding does not change the true length of the layer, only how far it reaches. A 10 cm strip shortened by 40% reaches  $10 \times 0.60 = 6$  cm.

**Answer:** Shortened by 40%; the paper model would reach 6 cm (about 2.4 in).



**Example 3.** In 1856 the Great Trigonometrical Survey announced the height of Peak XV (Mount Everest) as 29,002 ft. The survey announced in 2020 gives 8,849 m. Convert the 2020 figure to feet ( $1 \text{ m} \approx 3.281 \text{ ft}$ ; the official figure, from 8,848.86 m, is 29,032 ft) and find the difference between the two measurements.

1. Convert:  $8,849 \times 3.281 \approx 29,034$ , and the official figure is 29,032 ft (the survey gave 8,848.86 m).
2. Subtract:  $29,032 - 29,002 = 30 \text{ ft}$ .
3. In meters:  $30 \div 3.28 \approx 9 \text{ m}$ .

**Answer:** The 2020 height is about 29,032 ft, only about 30 ft (9 m) more than the 1856 figure: a difference of about one part in a thousand. The surveyors of the 1800s, working with telescopes and angles from more than 100 km (60 mi) away, were remarkably accurate.

## PRACTICE

1. **EASY** Which two great landmasses are colliding to raise the Himalaya?
2. **EASY** What did Horace-Bénédict de Saussure notice about rock layers in the Alps, and what did it mean?
3. **EASY** What kind of rock is found near the top of Mount Everest, and what does it contain?
4. **MEDIUM** Convert the height of the Matterhorn, 4,478 m, to feet.
5. **MEDIUM** India moves north about 4 cm a year. How far does it move in 50 years? Give the answer in meters and feet.
6. **MEDIUM** Normal continental crust is about 35 km thick. Under Tibet it is about 70 km thick. How many times thicker is it, and why?
7. **MEDIUM** Look at the collision belt map. Name, from west to east, three mountain ranges that lie along the seam where southern plates press against Eurasia.  
(Use the map or drawing “Use the map to find the ranges from west to east.” shown earlier in this lesson.)
8. **HARD** The Gotthard Base Tunnel is 57 km long. A train goes through it at an average of 200 km/h. How many minutes does the trip through the tunnel take? How long is the tunnel in miles?
9. **HARD** Why do colliding continents build mountains instead of one plate sliding down into the mantle, as an ocean plate does?
10. **CHALLENGE** In a short paragraph, explain how a geologist standing on a cliff in the Alps could find evidence that the mountain was squeezed by colliding plates. Name at least two clues.

## COMMON MISTAKES

- Thinking collision mountains are volcanoes. The Himalaya and the Alps are made of folded and stacked rock, not piles of lava.
- Forgetting the root. A high mountain range has thick crust reaching down into the mantle, not just a tall top.
- Mixing up meters and feet when comparing heights. Always check the unit: 8,849 m is 29,032 ft.

**Make it a game · Peak to Peak.** Write the names and heights of ten real mountains on cards in both meters and feet (for example Everest 8,849 m, K2 8,611 m, Mont Blanc about 4,806 m, the Matterhorn 4,478 m, Kilimanjaro 5,895 m, Denali 6,190 m, Mount Whitney 4,421 m, Mount Fuji 3,776 m, Mount Elbrus 5,642 m, Aconcagua 6,961 m). Deal out the cards face down. Each player turns one over; the taller mountain wins both cards, but the winner must say which continent it is on and whether it is a volcano or a mountain of folded and raised rock (or ask a parent to check). Play until one player holds all the cards.

**Scripture.** “Who hath measured the waters in the hollow of his hand, and meted out heaven with the span, and comprehended the dust of the earth in a measure, and weighed the mountains in scales, and the hills in a balance?” (Isaiah 40:12, KJV)

It took the surveyors of India years of work with telescopes and pages of arithmetic to measure one mountain. The prophet reminds us that God weighs all the mountains as easily as a merchant weighs grain. Our careful measuring is a small way of thinking His thoughts after Him.

### Practice answers

1. The plate carrying India and the Eurasian Plate (Asia).
2. Layers that should be flat were bent into folds and arches. It meant the rock had been squeezed from the sides after it formed.
3. Limestone holding the remains of sea creatures, such as pieces of sea lilies. It shows the rock formed on a sea floor and was pushed up.
4.  $4,478 \times 3.28 \approx 14,690$  ft (the usual figure is 14,692 ft).
5.  $4 \times 50 = 200$  cm = 2 m, about 6.6 ft.
6.  $70 \div 35 = 2$ , twice as thick. The collision squeezed and stacked the crust, piling it up into high land above and a deep root below.
7. The Alps, the Zagros Mountains and the Himalaya (the Atlas Mountains of Morocco also lie farther west).
8.  $57 \div 200 = 0.285$  hours  $\times 60 \approx 17$  minutes.  $57 \times 0.62 \approx 35$  mi.
9. Continental crust is thick and light, so it is too buoyant to sink far into the heavier mantle. Instead the crust crumples, folds and stacks up, growing taller above and thicker below.
10. The geologist would look for rock layers that are folded into arches and waves instead of lying flat, showing sideways squeezing. The geologist might find sheets of rock that have slid over other layers. Sea fossils in limestone high on the mountain show the rock formed under the

sea and was raised. And rocks like those at the top of the Matterhorn, which match the plate to the south, show that two plates have been pushed together.

## 2.4 THE MID-ATLANTIC RIDGE AND ICELAND

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### OBJECTIVES

- Tell how Marie Tharp and Bruce Heezen mapped the hidden mountains of the ocean floor and found the rift valley along the Mid-Atlantic Ridge.
- Describe Iceland as a place where a spreading ridge rises above the sea, using Þingvellir, Surtsey (1963) and Heimaey (1973) as examples.
- Calculate ocean depths from echo-sounding times and draw a profile of the sea floor.

**Warm-up.** Stand facing a large wall about 20 big steps away, outdoors if you can, and clap your hands sharply once. Can you hear the echo come back? Now walk closer and clap again. Does the echo come back sooner or later? Ships measured the depth of the ocean the same way: they sent a sound down and timed how long it took to bounce back from the bottom.

**Video.** Coming soon. Marie Tharp's ocean-floor map, the Mid-Atlantic Ridge and Iceland's rift valley at Þingvellir: search NASA Earth Observatory, Library of Congress (Marie Tharp maps), Smithsonian; candidates needing vetting: NOAA Ocean Exploration, USGS; Homeschool Pop (Alternate) for a short review of sea-floor spreading.

### KEY TERMS

#### **mid-ocean ridge**

A long underwater mountain range where two plates spread apart and new ocean crust forms. The Mid-Atlantic Ridge runs about 16,000 km (10,000 mi) down the Atlantic.

#### **rift valley**

A long valley that forms where the crust is pulled apart, as along the crest of the Mid-Atlantic Ridge and at Þingvellir in Iceland.

#### **echo sounding**

Measuring the depth of water by sending a sound pulse down and timing how long it takes to bounce back from the bottom.

#### **sea-floor spreading**

The process by which melted rock rises at a mid-ocean ridge, cools into new crust and moves away on both sides.

#### **profile**

A side view of the shape of the land or sea floor along a line, drawn from a series of measured heights or depths.

### CORE IDEAS

**The story.** In 1952, in an office at Columbia University's Lamont Geological Observatory in New York, a young woman named Marie Tharp was drawing the bottom of the Atlantic

Ocean. Women were not allowed on the research ships in those days, so she worked from the records the ships brought back: long paper rolls of echo soundings. Her partner, the geologist Bruce Heezen, gathered the data at sea; Tharp turned thousands of numbers into pictures. As she plotted six long profiles across the North Atlantic, she saw the same shape in every one: a great mountain range in the middle of the ocean with a deep V-shaped notch along its crest. She decided it was a rift valley, a place where the earth was being pulled apart.

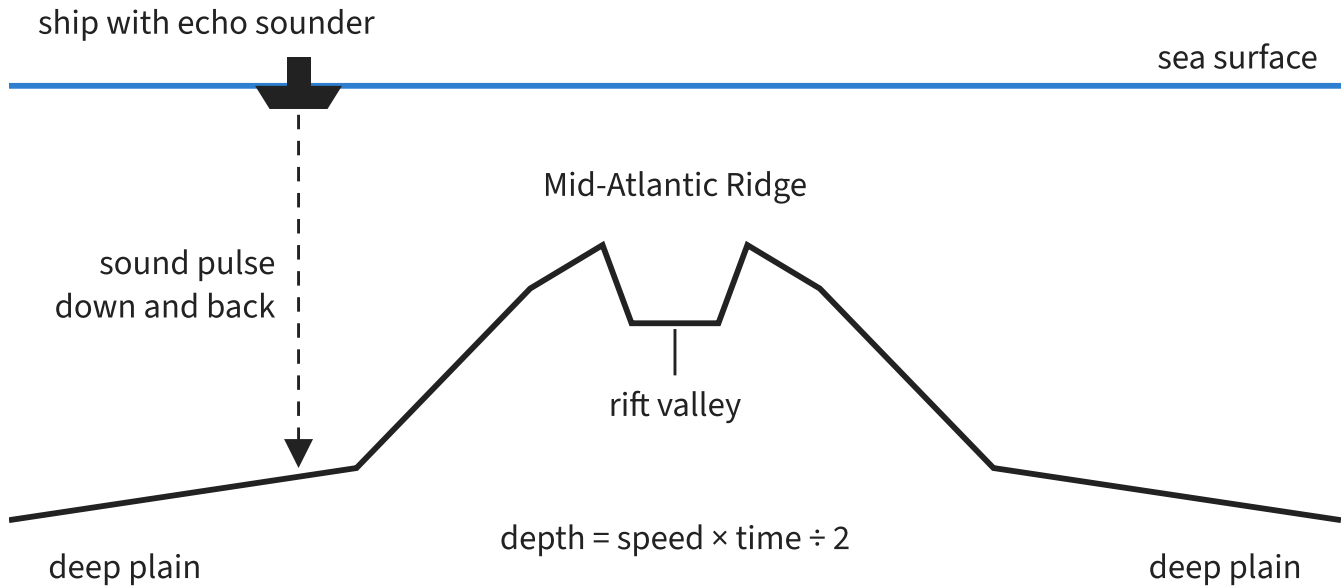
**How they figured it out.** Heezen did not believe her at first. A rift valley meant the sea floor was spreading, and that sounded too much like Wegener's drifting continents, an idea most American geologists still rejected. Then another worker in the lab plotted the locations of earthquakes under the Atlantic, and the earthquakes fell in a narrow line exactly along Tharp's rift valley. Two sets of evidence, the shape of the bottom and the shaking of the earth, matched. Tharp and Heezen went on to map the floor of every ocean. In 1977 the Austrian painter Heinrich Berann turned their work into a great painted map of the whole world's ocean floor, showing a ridge that winds around the globe like the seam on a baseball, about 65,000 km (40,000 mi) long.

**The big idea.** A mid-ocean ridge is a spreading boundary. Along its crest, two plates pull apart, hot rock from the mantle rises, partly melts and fills the crack, then cools into new ocean crust. The new crust is warm and stands high, which is why the ridge rises about 2,500 m (8,200 ft) above the deep ocean plains on either side. As it moves away from the crest it cools and sinks lower. Along the Mid-Atlantic Ridge the North American and South American plates move west and the Eurasian and African plates move east. The ocean widens about 2.5 cm (1 inch) a year, slowly and steadily, with small earthquakes and eruptions along the crest.

**On the map.** Almost all of the Mid-Atlantic Ridge lies under 2 to 3 km (1 to 2 mi) of water. In one place it rises above the sea: Iceland. There a large supply of hot rock from the mantle has built the ridge up into an island about 103,000 square km (40,000 square mi). At Þingvellir, about 40 km (25 mi) east of Reykjavík, you can walk down a rift valley between cliffs that mark the edges of the two plates. Iceland's people held their national assembly, the Althing, there from the year 930. Across Iceland the plates move apart about 2 cm (0.8 inch) a year. People have watched new land being made. On November 14, 1963, fishermen off the south coast saw dark smoke rising from the sea; within days a new island, Surtsey, had appeared, and it grew for three and a half years to about 2.7 square km (1 square mi) and 174 m (571 ft) high. Since then waves have worn it down to about half that area, an observed rate of erosion that scientists still measure.

**Living on a spreading ridge.** In January 1973 a fissure split open on the island of Heimaey, right beside its town. The fishing fleet, kept in harbor that night by a storm, carried almost all of the island's 5,300 people to the mainland within hours. As the lava crept toward the harbor, the town's lifeline, workers ran pipes from pumping ships and sprayed millions of tons of cold seawater onto the front of the flow for months. The lava cooled, thickened and stopped, and the harbor was saved; it is even better sheltered today. Icelanders also put the ridge to work. Hot water from deep wells heats about nine of every ten homes in the country,

and steam turns turbines in geothermal power plants. The same restless ground that brings danger also brings warmth to a land near the Arctic Circle.

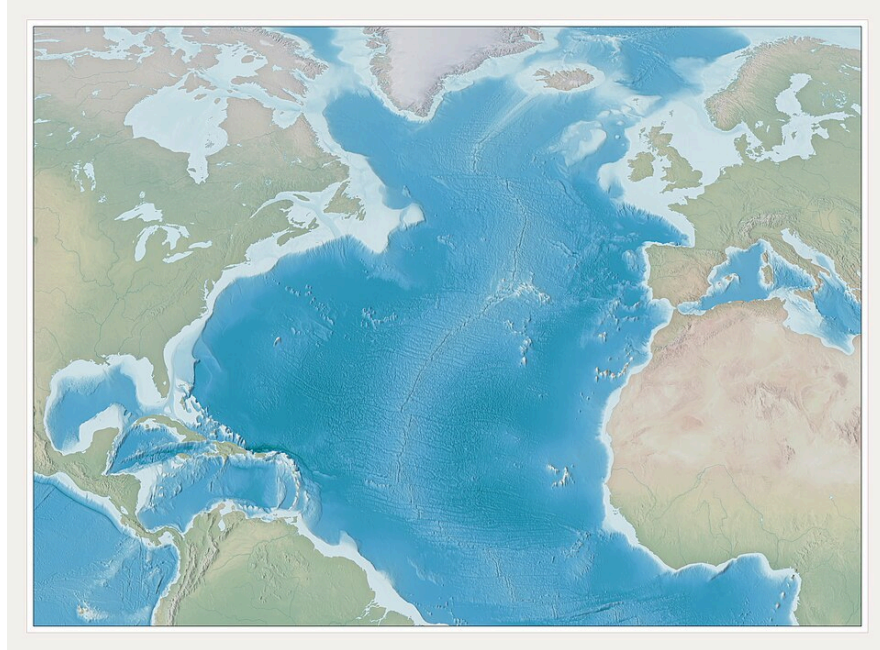


*Echo sounding across a mid-ocean ridge. Notice the rift valley along the crest that Marie Tharp found in 1952.*



*Iceland, where the Mid-Atlantic Ridge rises above the sea. The rift zones are drawn approximately.*

## PICTURE STUDY



*North Atlantic Seafloor*, Tom Patterson, 2020 · Digital shaded-relief map made from ocean depth measurements · Published free for anyone to use at [shadedrelief.com](http://shadedrelief.com) (public domain)

Tom Patterson is an American mapmaker who spent his career drawing maps for the U.S. National Park Service. Like the painter Heinrich Berann, who painted the famous ocean-floor map of Bruce Heezen and Marie Tharp in 1977, Patterson wanted to show what the bottom of the sea would look like if all the water were drained away. In 2020 he made this map of the North Atlantic from thousands of depth measurements gathered by ships, and gave it away free for anyone to use.

Patterson tipped the land so you seem to be looking at it from an airplane, and he made the heights more than ten times taller than they really are so that you can see them clearly. The sea floor that Heezen and Tharp first pieced together from soundings now lies plainly in front of you, with the Mid-Atlantic Ridge running right down the middle.

### Look closely

- Find the Mid-Atlantic Ridge. Trace it with your finger from north to south. What shape does it follow?
- Look closely along the crest of the ridge. Can you see a valley running down its center?
- Find the many short breaks that cut across the ridge. Which way do they run compared with the ridge?
- Find Iceland. What happens to the ridge where it reaches the island?

### Talk about it

1. Why does the Mid-Atlantic Ridge run almost exactly halfway between the Americas and Europe and Africa?



2. How does this map support Wegener's puzzle from Lesson 2.2?
3. Marie Tharp first drew this ridge at a desk from long lists of depth numbers. What does her work show about the value of careful, patient work?

## **PROJECT: SOUND THE SEA FLOOR LIKE MARIE THARP**

Marie Tharp drew the ocean floor without ever seeing it, from lines of depth measurements. You will do the same. A partner builds a hidden "sea floor" inside a covered box, and you measure its depth through holes in the lid, then plot a profile and guess what lies beneath before you open it.

### **You will need**

- A shoebox with a lid
- Modeling clay or play dough (and crumpled paper to save clay)
- A wooden skewer or thin dowel, marked every centimeter with a pen
- A ruler, pencil, and graph paper
- A sharp pencil to poke holes (a parent can help)

### **Steps**

1. Your partner builds a sea floor in the box without letting you see: flat deep plains near both ends and a ridge in the middle with a narrow valley along its top. They put the lid on.
2. Draw a straight line down the middle of the lid the long way. Mark a point every 2 cm along the line, number the points, and poke a small hole at each mark.
3. At each hole, lower the skewer straight down until it touches the bottom. Read the depth in centimeters at the top of the lid and record it in a table: Hole number, Depth.
4. On graph paper, plot each hole number along the bottom and the depth going downward from the top line. Connect the points to draw a profile of your hidden sea floor.
5. Mark the ridge, the plains and any valley on your profile. Compare it with the echo-sounding diagram in this lesson.
6. Open the box and compare your profile with the real shape. Where were you right? Where would more holes have helped?
7. Trade places and build a sea floor for your partner to sound.

### **Tips**

- Keep the skewer straight up and down, just as an echo sounder sends its pulse straight down.
- Holes closer together make a more accurate map. Tharp's best maps came from places where the ships had crossed many times.

### **Check your work**

- I measured and recorded the depth at every hole.

- I plotted a profile and labeled the ridge, valley and plains.
- I can explain how Marie Tharp found the rift valley from echo soundings.

## MAP NOTEBOOK

1. Draw a profile across the Atlantic from North America to Africa: continental shelf, deep plain, the Mid-Atlantic Ridge with its rift valley, another deep plain, and the shelf of Africa.
2. Draw a map of Iceland and mark the rift zones, Reykjavík, Þingvellir, Surtsey and Heimaey. Color the North American Plate side and the Eurasian Plate side differently.
3. Finish your unit map: add the Mid-Atlantic Ridge and mark at least ten volcanoes and ten earthquake places along plate edges.

**From history.** Surtsey was protected from the moment it appeared. Iceland allowed only a few scientists to land on it, so that they could watch how life arrives on bare new land. Within a couple of years the first flowering plant, sea rocket, had sprouted from seeds washed ashore; birds soon nested and brought more seeds; insects arrived on the wind. Scientists still visit each summer to count what has come, and the island was named a UNESCO World Heritage Site in 2008.

## WORKED EXAMPLES

**Example 1.** Sound travels through seawater at about 1,500 m (about 4,900 ft) per second. A ship's echo sounder sends a ping straight down and hears the echo 4 seconds later. How deep is the water, in meters and feet?

*(Use the map or drawing "Depth = speed of sound  $\times$  time  $\div$  2." shown earlier in this lesson.)*

1. In 4 seconds the sound travels  $1,500 \times 4 = 6,000$  m.
2. That distance is down *and* back up, so divide by 2:  $6,000 \div 2 = 3,000$  m.
3. Convert to feet:  $3,000 \times 3.28 \approx 9,840$  ft.

**Answer:** The water is about 3,000 m (about 9,840 ft, almost 2 mi) deep.

**Example 2.** A ship crossing the Atlantic records an echo time of 6.6 seconds over the deep plain and 3.4 seconds over the crest of the Mid-Atlantic Ridge. Using 1,500 m per second, find both depths and how high the ridge rises above the plain.

1. Plain:  $1,500 \times 6.6 \div 2 = 4,950$  m.
2. Ridge crest:  $1,500 \times 3.4 \div 2 = 2,550$  m.
3. Height of ridge above plain:  $4,950 - 2,550 = 2,400$  m. In feet:  $2,400 \times 3.28 \approx 7,870$  ft.

**Answer:** The plain is about 4,950 m deep and the crest about 2,550 m deep, so the ridge rises about 2,400 m (about 7,870 ft) above the plain, higher than many mountains on land.

**Example 3.** Across Iceland the two plates move apart about 2 cm (0.8 inch) a year. The Althing first met at Þingvellir in the year 930. If the rate has stayed about the same, how much wider has Iceland grown between 930 and 2025? Give the answer in meters and feet.

*(Use the map or drawing “Þingvellir lies in the western rift zone.” shown earlier in this lesson.)*

1. Find the number of years:  $2025 - 930 = 1,095$  years.
2. Multiply by the rate:  $2 \text{ cm} \times 1,095 = 2,190$  cm.
3. Convert:  $2,190 \text{ cm} = 21.9 \text{ m}$ , about 22 m. In feet:  $21.9 \times 3.28 \approx 72$  ft.

**Answer:** About 22 m (about 72 ft), roughly the length of two school buses, since the first Althing.

## PRACTICE

1. **EASY** What did Marie Tharp discover along the crest of the Mid-Atlantic Ridge in 1952, and what did it mean?
2. **EASY** Which two plates meet in Iceland, and what kind of boundary is it?
3. **EASY** What new island appeared off Iceland’s south coast in November 1963?
4. **MEDIUM** An echo returns 5 seconds after the ping. Using 1,500 m per second, how deep is the water in meters and feet?
5. **MEDIUM** The ocean floor is 6,000 m deep. How many seconds will an echo take to return?
6. **MEDIUM** Surtsey reached about 2.7 square km in area. Waves have since worn it down to about 1.3 square km. About what percent of its area has been lost?
7. **MEDIUM** The Mid-Atlantic Ridge is about 16,000 km long and the whole world’s mid-ocean ridge system about 65,000 km. Convert both to miles, and find what fraction of the world system the Mid-Atlantic Ridge makes up.
8. **HARD** Look at the map of Iceland. Is Reykjavík on the North American Plate or the Eurasian Plate? What about the east coast of Iceland? Explain how you can tell, and say

why Heimaey had an eruption in 1973.

*(Use the map or drawing “Compare each place with the rift zones.” shown earlier in this lesson.)*

9. **HARD** How did the people of Heimaey save their harbor from the lava in 1973, and why did it work?
10. **CHALLENGE** Write a short paragraph explaining why the ridge stands high in the middle of the ocean and the sea floor gets deeper as you move away from it toward the continents.

## COMMON MISTAKES

- Forgetting to divide by 2 in echo sounding. The time measured is for the sound going down and coming back.
- Thinking the Mid-Atlantic Ridge is a single straight line. It is broken into many short pieces offset by sliding faults that cross it.
- Thinking Iceland is splitting in half in one great crack. The spreading is spread across rift zones tens of kilometers wide, with many cracks and small eruptions.

**Make it a game · Spreading Ridge Stripes.** Cut a slot in the middle of a shoebox lid. Fold a long strip of paper in half and push the fold up through the slot so that one half goes left and one half goes right. One player is the ridge: each time the caller says “Erupt!”, the ridge pulls out 3 cm of paper on each side and colors the new strip at the slot in a color the caller names. After eight eruptions, open the strips. Players earn a point for each pair of stripes that match on both sides of the ridge and must explain why the pattern is a mirror image.

**Scripture.** “Hast thou entered into the springs of the sea? or hast thou walked in the search of the depth?” (Job 38:16, KJV)

When God spoke to Job, no person had ever seen the floor of the deep sea. Marie Tharp never walked there either, yet by patient measuring she drew a picture of the great ridge that circles the earth. The depths that were hidden from Job are part of the world God made and knows completely.

## Practice answers

1. A rift valley, a V-shaped valley along the top of the ridge. It meant the sea floor was being pulled apart there, a spreading boundary.
2. The North American Plate and the Eurasian Plate. It is a spreading (divergent) boundary.
3. Surtsey.
4.  $1,500 \times 5 \div 2 = 3,750$  m, about 12,300 ft.
5. The sound travels 12,000 m down and back.  $12,000 \div 1,500 = 8$  seconds.
6.  $2.7 - 1.3 = 1.4$  square km lost.  $1.4 \div 2.7 \approx 0.52$ , about 52%, roughly half.
7.  $16,000 \text{ km} \approx 10,000 \text{ mi}$ ;  $65,000 \text{ km} \approx 40,000 \text{ mi}$ .  $16,000 \div 65,000 \approx 0.25$ , about one quarter.
8. Reykjavík lies west of the western rift zone, so it is on the North American Plate. The east coast lies east of all the rift zones, so it is on the Eurasian Plate. Heimaey sits at the southern

end of the eastern rift zone, right in the active spreading area, which is why the ground split open and erupted there.

9. They pumped seawater from ships and pipes onto the front of the lava flow for months. The cold water cooled the lava so it hardened and thickened into a wall, slowing and finally stopping the flow before it closed the harbor.
10. At the ridge, hot rock rises from the mantle and forms new crust that is still warm. Warm rock takes up more room and is lighter, so it stands high. As the new crust spreads away from the ridge on both sides it cools, shrinks a little and becomes heavier, so it sinks lower. That is why the sea floor slopes down from the ridge crest to the deep plains on each side.

## UNIT 2 REVIEW

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Answer each question. Show your work for calculations, give measurements in both metric and U.S. units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (6 pts) Name the four layers of the earth in order from the surface to the center, and tell which one is liquid.
2. (6 pts) S waves never arrive at stations on the far side of the earth from an earthquake. What does this tell scientists, and why?
3. (6 pts) A station records an S wave 30 seconds after the P wave. Using the rule of 8 km per second of gap, how far away was the earthquake in km and miles?
4. (6 pts) Give three kinds of evidence Alfred Wegener used in 1912 to argue that the continents had once been joined.
5. (6 pts) Match each place to its kind of plate boundary (spreading, colliding or sliding): (a) San Andreas Fault, (b) Andes, (c) East African Rift.
6. (6 pts) The Pacific Plate near Hawaii moves about 7 cm a year. How far does it move in 60 years, in meters and feet?
7. (6 pts) Explain how two colliding continents build a mountain range like the Himalaya. Use the words fold and root.
8. (6 pts) Mount Everest is 8,849 m tall and the Matterhorn 4,478 m. Find the difference in meters and convert it to feet ( $1 \text{ m} \approx 3.28 \text{ ft}$ ). What evidence near Everest's summit shows its rock was once under the sea?
9. (6 pts) A ship's echo returns 6 seconds after the ping. Sound travels about 1,500 m per second in seawater. How deep is the water, in meters and feet?
10. (6 pts) Describe what Marie Tharp discovered in 1952 and explain why Iceland is the one place where you can walk along the Mid-Atlantic Ridge. Name one way Icelanders use or guard against their moving ground.

### UNIT PROJECT: THE WORLD'S PLATES: VOLCANOES AND EARTHQUAKES ALONG THE EDGES

Draw a large world map showing the edges of the major plates and label at least seven large plates. Using the USGS earthquake map and the Smithsonian volcano catalog, plot at least fifteen recent earthquakes (one symbol) and fifteen volcanoes (another symbol). Mark one example each of a spreading, colliding and sliding boundary, the Himalaya and the Alps, and the Mid-Atlantic Ridge with Iceland. Beside the map, add a photo or drawing of your graham-cracker-and-frosting plate model and write a paragraph explaining why earthquakes and volcanoes gather along the plate edges and how people who live there prepare.

- **Accuracy:** Plates, boundaries, mountains, the ridge and the plotted earthquakes and volcanoes are placed correctly and labeled clearly.
- **Evidence:** Earthquake and volcano locations come from real records, and the map shows how they line up along plate edges.

- **Explanation:** The paragraph correctly explains the three kinds of boundaries, why hazards gather at plate edges, and at least one way people prepare or engineer for them.
- **Care:** The map has a title, key, compass rose and neat lettering, and the model record is clear.

#### Answer key

1. Crust, mantle, outer core, inner core. The outer core is liquid.
2. It tells them that part of the core (the outer core) is liquid, because S waves cannot travel through liquid, so the waves headed through the core are stopped.
3.  $30 \times 8 = 240$  km, about 149 mi (about 150 mi).
4. The matching shapes of the coastlines (such as South America and Africa); the same fossils on continents now far apart (Mesosaurus in Brazil and South Africa, Glossopteris on the southern continents); and matching rock belts and mountain chains across the ocean (the Appalachians and the mountains of Scotland and Norway).
5. (a) sliding (transform), (b) colliding (convergent), (c) spreading (divergent).
6.  $7 \times 60 = 420$  cm = 4.2 m, about 13.8 ft.
7. Continental crust is too thick and light to sink, so when India pushes into Asia the crust crumples. Rock layers fold and slide over one another, stacking up into high mountains, and the thickened crust also pushes down into the mantle as a deep root beneath them.
8.  $8,849 - 4,478 = 4,371$  m, about 14,340 ft. Limestone near the summit contains the remains of sea creatures such as pieces of sea lilies.
9.  $1,500 \times 6 \div 2 = 4,500$  m, about 14,760 ft (almost 2.8 mi).
10. Tharp found a rift valley along the crest of the Mid-Atlantic Ridge, showing that the sea floor is spreading apart there. In Iceland an unusually large supply of hot rock has built the ridge up above sea level, so at places like Þingvellir you can walk in the rift between the North American and Eurasian plates. Icelanders heat about nine of ten homes with geothermal water; in 1973 the people of Heimaey sprayed seawater on the lava to save their harbor.



## VOLCANOES AND EARTHQUAKES

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The psalmist praises the God “Who laid the foundations of the earth, that it should not be removed for ever” (Psalm 104:5). Yet the same psalm speaks of hills that smoke and an earth that trembles. In Unit 2 you learned that the earth’s crust is broken into moving plates. In this unit you will see what happens where those plates meet: magma rises and builds volcanoes, and rocks that have been bent for years suddenly slip and shake the ground.

You will stand with seventeen-year-old Pliny on the shore at Misenum as Vesuvius buries Pompeii in AD 79, and dig through the layers that tell the story. You will watch a volcano born in a Mexican cornfield in 1943 and compare it with Mauna Loa and Mount Fuji. You will walk through San Francisco on the morning of April 18, 1906, and follow the geologists who measured the San Andreas Fault. Then you will become an engineer, testing block and straw buildings on a shake table to learn how bracing, base isolation and wise building codes let people live safely where the ground moves.

On your map you will trace the **Ring of Fire** around the Pacific and learn why so many of the world’s volcanoes and earthquakes lie along it. Throughout, the question is not only what the earth does, but how people can watch, prepare and build well.

### BEFORE YOU BEGIN

- Can name the earth’s layers (crust, mantle, core) and explain that the crust is broken into moving plates (Unit 2)
- Can name the three kinds of plate boundaries: spreading, colliding and sliding
- Can use a map scale and convert between kilometers and miles
- Can divide and multiply to find rates, times and distances

### MASTERY CHECKLIST

- I can tell the story of Vesuvius in AD 79 from Pliny the Younger’s letters and explain how Pompeii was buried.
- I can describe shield volcanoes, cinder cones and composite volcanoes and give a real example of each.
- I can trace the Ring of Fire on a world map and explain why volcanoes and earthquakes gather there.
- I can explain faults, elastic rebound and the main kinds of earthquake waves, using the 1906 San Francisco earthquake.
- I can explain how bracing, flexible frames, base isolation, dampers, building codes and warning systems protect people.
- I can use map scale, rates and wave speeds to solve problems about real volcanoes and earthquakes.

## OPTIONAL BOOKS AND RESOURCES

- **USGS Earthquake Hazards Program** (<https://earthquake.usgs.gov/>): Free. A live map of the world's earthquakes from the past day and week. Have the student check it during the unit and mark recent earthquakes on the Ring of Fire map.
- **Hawai'i Volcanoes National Park (National Park Service)** (<https://www.nps.gov/havo/>): Free. Photographs, maps and explanations of Kilauea and Mauna Loa, the shield volcanoes of Lesson 3.2.

### 3.1 VESUVIUS AND POMPEII ★

#### OBJECTIVES

- Retell the eruption of Vesuvius in AD 79 from the letters of Pliny the Younger and explain how Pompeii and Herculaneum were buried.
- Explain what a volcano is and why sticky, gas-rich magma makes explosive eruptions with pumice, ash and pyroclastic flows.
- Read a map of the Bay of Naples and use scale, direction and rates to reason about distances, burial depths and escape times.

**Warm-up.** Shake a closed bottle of soda water gently, then hold it over the sink and open it slowly. Watch the bubbles rush out. Now open a still bottle of water the same way. Which one foamed? The gas was hiding inside the liquid until the cap came off. Keep that picture in your mind: today you will meet a mountain that did the same thing.

**Watch.** *24th August AD 79: Mount Vesuvius destroys Pompeii and Herculaneum* (HistoryPod, 2:50). [https://www.youtube.com/watch?v=FdbTn\\_RSGCY](https://www.youtube.com/watch?v=FdbTn_RSGCY)

After the story: watch this short account of the AD 79 eruption and listen for Pliny the Younger's letters and the pyroclastic flow that buried Pompeii and Herculaneum.

**Note:** Captions were not available to check; preview it first. It describes how about 1,500 people died from the heat, and it mentions the Roman festival for the god of fire. The video uses August 24; the lesson says that is the traditional date and that newer evidence points to autumn AD 79.

**Backup video.** *24th August 79: Eruption of Mount Vesuvius destroys Pompeii and Herculaneum in the Roman Empire* (HistoryPod, 2:25). <https://www.youtube.com/watch?v=dnBAHVPB4rY>

As review: use this short retelling of the eruption to remember what Pliny saw and how the ash and pyroclastic flow buried the two towns. Note: Captions were not available to check; preview it first. It describes the deaths of about 1,500 people and compares the eruption's energy to the atomic bomb dropped on Hiroshima. The video uses August 24; the lesson says that is the traditional date and that newer evidence points to autumn AD 79.

#### KEY TERMS

##### volcano

An opening in the earth's crust where melted rock, gas and ash come out, and the hill or mountain built up around that opening.

##### magma

Melted rock underground. When it pours out onto the surface it is called lava.

##### pumice

Light, frothy volcanic rock full of gas bubbles, so light that some pieces float on water.

### **volcanic ash**

Tiny bits of shattered rock and glass blown out of a volcano; not soft like wood ash, but gritty and heavy.

### **pyroclastic flow**

A fast avalanche of hot gas, ash and rock that rushes down the side of a volcano, often faster than a car on a highway.

### **Plinian eruption**

A very explosive eruption with a tall column of gas and ash, named after Pliny the Younger, who first described one.

## **CORE IDEAS**

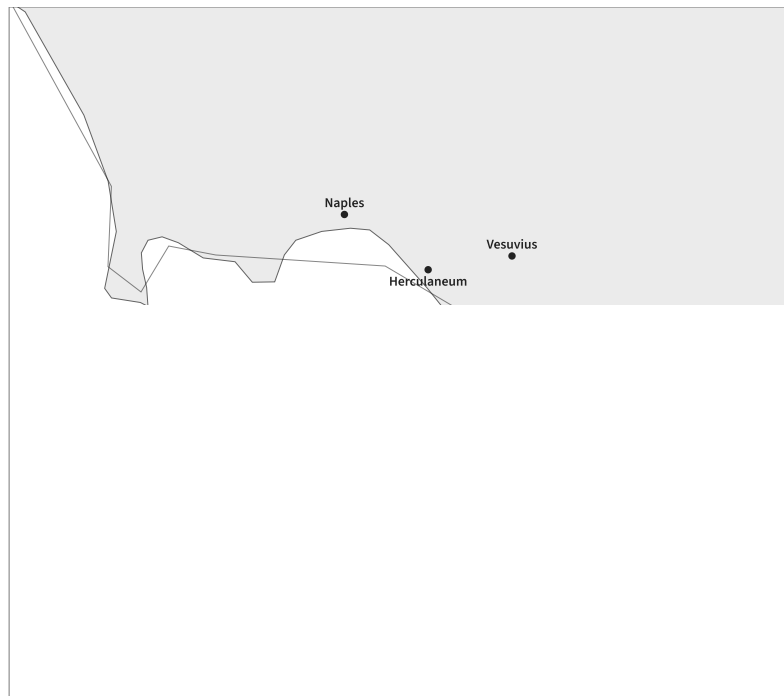
**The story.** Across the Bay of Naples from the mountain called Vesuvius stood the Roman naval base of Misenum. Its commander was the famous scholar Pliny the Elder, and staying with him was his seventeen-year-old nephew, Pliny the Younger. One afternoon in AD 79 (traditionally dated August 24, though some newer evidence points to the autumn of that year), the boy's mother pointed out a cloud of strange size and shape rising over the mountains to the east. Pliny later wrote that it looked most like an umbrella pine: a tall trunk shooting straight up and then spreading out into branches. His uncle ordered the warships launched and sailed toward the danger to rescue friends along the shore. He reached the town of Stabiae, where he calmed his frightened hosts and even slept, while stones and ash piled up in the courtyard. The next day he died on the beach, overcome as the fumes and ash rolled in. Back at Misenum, the young Pliny and his mother fled through a darkness, he wrote, like that of a closed room with the lamp put out.

**What happened to the towns.** For about eighteen hours, pumice and ash rained down on Pompeii, about 10 km (6 miles) southeast of the crater. Roofs gave way under the weight of nearly 3 m (9 feet) of pumice. Many people escaped during those hours. Then, during the night and early the next morning, the great column of ash grew too heavy to hold itself up and collapsed. Glowing **pyroclastic flows** raced down the mountain, burying Herculaneum on the western side under about 20 m (65 feet) of material and sweeping over Pompeii. Anyone still in the towns could not outrun them.

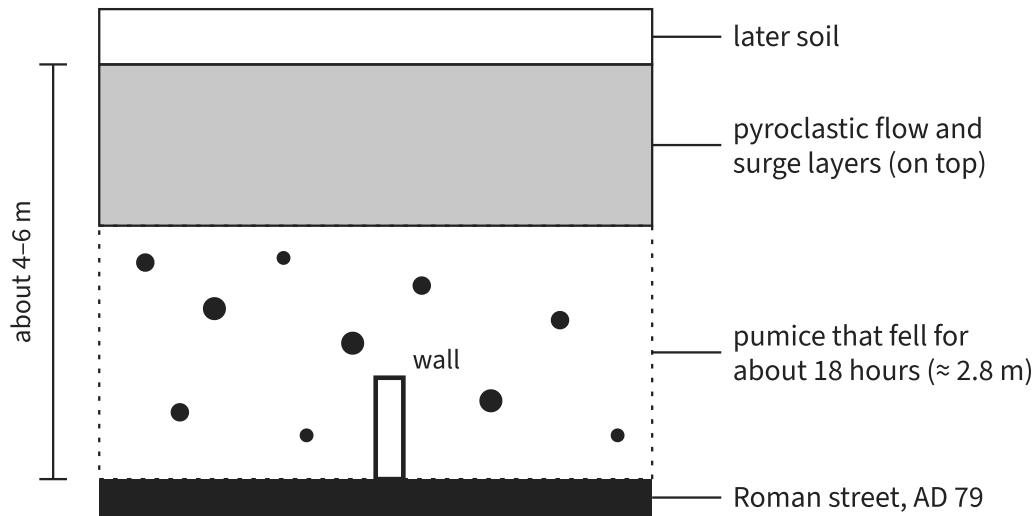
**How they figured it out.** We know this story because, about twenty-five years later, the historian Tacitus asked Pliny the Younger to describe his uncle's death, and Pliny answered in two letters that still survive. Digging at Herculaneum began in 1738 and at Pompeii in 1748. In 1863 the archaeologist Giuseppe Fiorelli noticed hollow spaces in the hardened ash where bodies had decayed. He poured plaster into the hollows and lifted out the shapes of the people of Pompeii in their last moments. Geologists added another kind of reading: the layers. At Pompeii the light pumice lies below and the pyroclastic layers lie above, so the pumice fell first. The order of the layers tells the order of the events, like the pages of a book read from the bottom up.

**The big idea.** A **volcano** is an opening where **magma** from deep below reaches the surface. Magma holds dissolved gas, much as soda water holds bubbles. When magma is runny, gas slips out gently and lava flows quietly. When magma is thick and sticky, the gas is trapped until the pressure blasts the rock apart. The froth hardens into **pumice**, the shattered rock becomes **ash**, and a column of gas and ash can rise many kilometers high. Vesuvius makes this sticky, gas-rich magma. It stands near the meeting of two plates, the African and the Eurasian, where one sinks beneath the other, a process you met in Unit 2. Eruptions like the one Pliny saw are now called **Plinian eruptions** in his honor.

**On the map.** Find Vesuvius at the head of the Bay of Naples, with Herculaneum to its west, Pompeii to its southeast and Misenum about 30 km (19 miles) to the west, across the water. Vesuvius rises to about 1,281 m (4,203 feet) and last erupted in 1944. Today hundreds of thousands of people live on and around its slopes. That is why the Vesuvius Observatory, founded on the mountain in 1841 as the first volcano observatory in the world, still watches it. Scientists measure its small earthquakes, its gases and the swelling of its ground, and Italy keeps evacuation plans for the towns nearby. Pliny's uncle had no warning. Careful watching and planning are how people now live beside a mountain like this one.



*The Bay of Naples in AD 79. Pliny watched from Misenum; his uncle sailed to Stabiae.*



Read from the bottom up: the lowest layer came first.

*The layers at Pompeii, read from the bottom up.*

## PICTURE STUDY



*Vesuvius in Eruption, with a View over the Islands in the Bay of Naples, Joseph Wright of Derby, about 1776-1780 · Oil on canvas · Tate, London*

Joseph Wright was an English painter from the town of Derby who loved to paint light in the dark: candlelight, forge fires and moonlight. In 1773 he set out for Italy, and in 1774 he was in Naples when Vesuvius was active. The sight stayed with him for the rest of his life, and back in England he painted the erupting mountain again and again.

This painting shows Vesuvius at night, glowing from within, with the Bay of Naples stretching away. Wright saw a gentler eruption than the one Pliny saw, but it was the same mountain, and the bay is the same bay across which Pliny's uncle sailed.

### Look closely

- Find the brightest part of the painting. Where does the light come from?
- Follow the lava with your finger from the top of the cone down the slopes. Which way is it flowing?
- Look out across the water to the islands. How does the painter make them look far away?
- Compare the hot red and orange colors with the cool colors of the sky and sea.

### Talk about it

1. Wright painted a mountain that had buried two Roman towns. Does his painting feel frightening, beautiful or both? Why?
2. What could a painter show about a volcano that a scientist's measurements cannot? What could the measurements show that the painting cannot?
3. Where in the painting would you place Pompeii if you could see it?

**Safety first.** Plaster of Paris dust should not be breathed. Mix it outdoors or at a table with an adult, and wash hands afterward. Do not pour leftover plaster down the sink.

## PROJECT: DIG POMPEII: A BURIED-TOWN LAYER JAR

You will bury a little town the way Vesuvius did, layer by layer, and then dig it out like an archaeologist, measuring as you go. If you like, you can also make a plaster cast the way Giuseppe Fiorelli did in 1863.

### You will need

- A clear plastic box or large jar (at least 15 cm, or 6 inches, deep)
- A small toy house, a few plastic figures or LEGO bricks
- Puffed rice cereal or aquarium gravel for pumice
- Flour mixed with a little cocoa powder for ash, and dry sand
- A spray bottle of water, a ruler, a spoon and a soft paintbrush
- Optional: modeling clay, a small toy animal and plaster of Paris

### Steps

1. Set the house and figures on the bottom of the box. This is your Roman street.
2. Use a scale of 1 cm in the box for 1 m at Pompeii. Pour about 3 cm of puffed rice or gravel over the town for the pumice that fell for eighteen hours.
3. Add 1 cm of the flour and cocoa ash, mist it with water, then 1 cm of sand, mist again, then another 1 cm of ash. These are the pyroclastic layers.



4. Top it with a thin layer of soil. Draw a side view of your layers on paper, labeled and measured, before anyone digs.
5. Trade boxes with a partner if you can. Dig from the top down with the spoon and brush. Each time you find something, measure its depth from the top and write it in a dig log.
6. Optional cast: press a toy animal into a slab of clay and lift it out carefully. Fill the hollow with plaster of Paris. When it hardens, peel away the clay. You have made a cast from a hollow, just as Fiorelli did.
7. Write three sentences explaining what your layers tell you about the order of events.

### Tips

- Keep the layers level by pouring slowly and tapping the side of the box.
- Real archaeologists dig slowly and record everything; once a layer is dug away it can never be put back.

### Check your work

- I can name the layers at Pompeii in the order they fell.
- I can explain why the bottom layer is the oldest.
- I can explain how Fiorelli's plaster casts were made.

### MAP NOTEBOOK

1. Draw a map of the Bay of Naples. Mark Vesuvius, Pompeii, Herculaneum, Stabiae, Naples and Misenum, and add a compass rose and a scale bar of 10 km (6 miles).
2. Sketch the umbrella-pine cloud Pliny described next to a drawing of a real umbrella pine tree. Label the trunk and the spreading top.
3. Draw a labeled cross-section of a volcano: magma chamber, vent, crater, eruption column and a pyroclastic flow running down one side.

**From history.** Pompeii had already been badly shaken by a strong earthquake in AD 62, and when Vesuvius erupted seventeen years later, workmen were still repairing some of its buildings. The people did not connect that earthquake to the mountain. Today scientists know that small earthquakes and swelling ground are often the first signs that magma is moving, which is why they are among the first things a volcano observatory watches.

## WORKED EXAMPLES

**Example 1.** On the map of the Bay of Naples, the scale bar shows that 1 cm stands for 5 km. Vesuvius and Pompeii are 2 cm apart on the map. How far apart are they in kilometers and in miles?

*(Use the map or drawing “Measure from the crater to Pompeii.” shown earlier in this lesson.)*

1. Multiply the map distance by the scale:  $2 \text{ cm} \times 5 \text{ km per cm} = 10 \text{ km}$ .
2. Convert to miles. One kilometer is about 0.62 mile:  $10 \times 0.62 = 6.2 \text{ miles}$ .

**Answer:** About 10 km, or about 6 miles.

**Example 2.** About 2.8 m of pumice fell on Pompeii in about 18 hours. What was the average rate in centimeters per hour? About how deep was the pumice after the first 6 hours?

*(Use the map or drawing “The pumice layer is the thick one just above the Roman street.” shown earlier in this lesson.)*

1. Change meters to centimeters:  $2.8 \text{ m} = 280 \text{ cm}$ .
2. Divide by the hours:  $280 \text{ cm} \div 18 \text{ h} \approx 15.6 \text{ cm per hour}$ , about 6 inches an hour.
3. After 6 hours:  $15.6 \text{ cm} \times 6 \approx 93 \text{ cm}$ .

**Answer:** About 15–16 cm (6 inches) an hour; about 93 cm, nearly 1 m (3 feet), after 6 hours.

**Example 3.** Herculaneum is about 7 km from the crater of Vesuvius. A pyroclastic flow moving at 100 km per hour rushes toward the town. How many minutes does it take to arrive? How long would a strong runner going 15 km per hour need to cover the same 7 km?

1. Time = distance  $\div$  speed. For the flow:  $7 \text{ km} \div 100 \text{ km/h} = 0.07 \text{ h}$ .
2. Change hours to minutes:  $0.07 \times 60 = 4.2 \text{ minutes}$ .
3. For the runner:  $7 \text{ km} \div 15 \text{ km/h} \approx 0.47 \text{ h}$ , and  $0.47 \times 60 \approx 28 \text{ minutes}$ .

**Answer:** The flow arrives in about 4 minutes; a runner would need about 28 minutes to go that far. No one can outrun a pyroclastic flow, so people must leave before it comes.

## PRACTICE

1. **EASY** Who wrote the eyewitness account of the eruption of Vesuvius in AD 79, and to whom did he write it?
2. **EASY** What is a pyroclastic flow?

3. **EASY** Vesuvius is about 1,281 m tall. Convert this to feet (1 m  $\approx$  3.28 ft).
4. **MEDIUM** Use the map. Which town lies closer to the crater of Vesuvius, Herculaneum or Pompeii? In what direction from the crater does each lie?  
(Use the map or drawing "Compare the two towns." shown earlier in this lesson.)
5. **MEDIUM** Misenum is about 30 km west of Vesuvius. How far is that in miles? In which direction did Pliny look to see the cloud?
6. **MEDIUM** If pumice fell at 15 cm an hour, how deep would it be after 12 hours, in meters and in feet?
7. **MEDIUM** Explain in two sentences why thick, sticky magma makes more explosive eruptions than runny magma.
8. **HARD** Pliny the Younger was 17 in AD 79 and wrote his letters about 25 years later. About how old was he when he wrote them?
9. **HARD** How did Giuseppe Fiorelli make casts of the people of Pompeii? Why was there a hollow to fill?
10. **CHALLENGE** Digging at Pompeii began in 1748. How many years after the eruption of AD 79 was that? At Pompeii the pumice lies below the pyroclastic layers. What does that tell you about the order of events, and why?

## COMMON MISTAKES

- Thinking Pompeii was buried by red, flowing lava. It was buried by falling pumice and ash and then by pyroclastic flows.
- Calling volcanic ash soft like fireplace ash. Volcanic ash is gritty, heavy rock and glass, heavy enough to collapse roofs.
- Thinking a quiet volcano is a dead one. Before AD 79 most Romans did not even know Vesuvius was an active volcano.

**Make it a game • Layer Detective.** One player secretly stacks five colored paper strips (or books) in a pile, saying nothing. The detective must tell the story of the pile from the bottom up: "First came red, then blue..." Score a point for every layer in the right order. Then switch roles. For a bonus point, name what each color could stand for at Pompeii: street, pumice, pyroclastic layers, soil.

**Scripture.** "Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea; Though the waters thereof roar and be troubled, though the mountains shake with the swelling thereof. Selah." (Psalm 46:2-3, KJV)

The psalmist knew that mountains can shake and swell. He does not pretend they are always safe. He trusts the God who is a refuge and strength, a very present help in trouble, even when the solid ground moves.

## Practice answers

1. Pliny the Younger, in two letters to the historian Tacitus.

2. A fast-moving avalanche of hot gas, ash and rock that rushes down the side of a volcano.
3.  $1,281 \times 3.28 \approx 4,202$  feet (about 4,200 feet).
4. Herculaneum is closer (about 7 km, or 4 miles) and lies to the west. Pompeii is about 10 km (6 miles) away to the southeast.
5.  $30 \times 0.62 \approx 19$  miles. He looked east.
6.  $15 \times 12 = 180$  cm = 1.8 m, about 6 feet.
7. Sticky magma traps its gas so that pressure builds up inside. When the pressure finally breaks free it blasts the rock apart into pumice and ash, while gas escapes gently from runny magma.
8.  $17 + 25 =$  about 42 years old.
9. The ash hardened around the bodies. Over time the bodies decayed and left hollow spaces in the shape of the people. Fiorelli poured plaster into the hollows, let it set and dug out the casts.
10.  $1748 - 79 = 1,669$  years. The pumice fell first and the pyroclastic flows came later, because layers are laid down one on top of another, so lower layers were laid down earlier.

## 3.2 KINDS OF VOLCANOES

### OBJECTIVES

- Describe shield volcanoes, cinder cones and composite volcanoes and explain how the kind of lava builds each shape, using Mauna Loa, Parícutin and Mount Fuji.
- Locate the Ring of Fire on a world map and explain why most of the world's active volcanoes lie around the edges of the Pacific.
- Use heights, slopes and observed growth rates to compare real volcanoes.

**Warm-up.** Pour a spoonful of honey onto a plate, then a spoonful of water next to it, then a spoonful of dry sugar from a little height. Look at each pile from the side. Which spread out flat? Which made the steepest pile? Guess which one is most like lava that builds a tall, steep mountain.

**Watch.** *All About Volcanoes for Children: Introduction to Volcanoes for Kids - FreeSchool* (Free School, 6:36). <https://www.youtube.com/watch?v=V863xR0Y2qk>

With the big idea: watch for the three kinds of volcanoes (shield, cinder cone and composite) and how each one gets its shape.

**Note:** Captions were not available to check; preview it first. Introductions to volcanoes sometimes mention deep-time ages. The video may say "composite volcano" where the lesson says "stratovolcano"; they mean the same thing.

**Backup video.** *Hawaii Volcanoes National Park - UNESCO World Heritage Site* (World Heritage Journey, 8:13). <https://www.youtube.com/watch?v=EeE6CFyZfhY>

With On the map: tour Mauna Loa and Kīlauea on the Big Island of Hawaii to see what broad, gently sloping shield volcanoes look like. Note: Captions were not available to check; preview it first. It is a travel-style tour that will likely give ages for the Hawaiian islands in millions of years; the lesson does not. The video covers only shield volcanoes, not cinder cones or stratovolcanoes.

### KEY TERMS

#### shield volcano

A broad volcano with gentle slopes, built by many thin flows of runny lava, like a warrior's shield laid on the ground.

#### cinder cone

A small, steep cone built of loose cinders and lumps of lava thrown into the air around a single vent.

#### composite volcano

A tall, steep volcano built of alternating layers of lava and ash; also called a stratovolcano.

#### vent

The opening through which lava, gas and ash come out of a volcano.

## Ring of Fire

The horseshoe-shaped belt of volcanoes and earthquakes around the edges of the Pacific Ocean.

### hot spot

A place in the middle of a plate where magma rises from deep below and feeds volcanoes, as under Hawai'i.

## CORE IDEAS

**The story.** On the afternoon of February 20, 1943, a farmer named Dionisio Pulido was working his cornfield near the village of Parícutin in western Mexico. For weeks the ground had rumbled. Now a crack opened in the field. The ground swelled, smoke and a smell of sulfur poured out, and hot stones began to fly. Pulido hurried to the village to tell what he had seen. By the next day a cone of cinders about 50 m (160 feet) tall stood where his corn had been. A year later it was 336 m (1,100 feet) high, and lava had spread across the valley. When the eruption stopped in 1952, the cone stood about 424 m (1,391 feet) above the old field. Lava had buried the villages of Parícutin and San Juan Parangaricutiro. The stone tower of San Juan's church still stands above the black lava today.

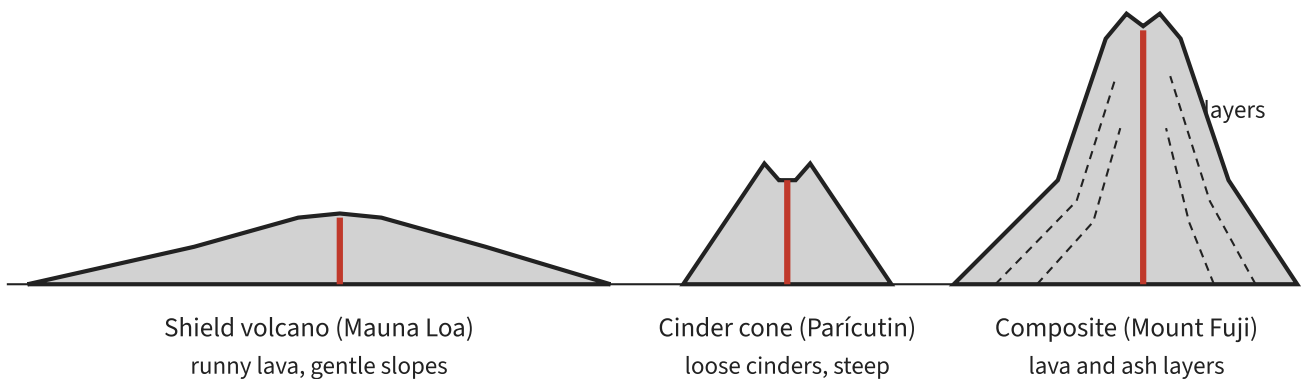
**How they figured it out.** Parícutin gave scientists something they had never had: the chance to watch a volcano from its first day to its last. Geologists from Mexico and the United States measured its height, collected its lava and recorded its explosions for nine years. In Hawai'i, Thomas Jaggar had founded the Hawaiian Volcano Observatory in 1912 to do the same kind of careful watching at Kilauea and Mauna Loa. By comparing many volcanoes, scientists found that the shape of a volcano is written by what comes out of it. Runny lava, sticky lava and flying cinders each build their own kind of mountain.

**The big idea.** There are three main kinds. A **shield volcano** is built by runny basalt lava that flows far before it cools, so the mountain grows wide with gentle slopes. Mauna Loa in Hawai'i is the largest active volcano on earth. It rises 4,169 m (13,679 feet) above the sea, and its flanks reach down about another 5 km (3 miles) to the sea floor. It erupted most recently in 2022, its first eruption since 1984, and its lava came within about 3 km (2 miles) of the main highway across the island. A **cinder cone**, like Parícutin, forms when gassy lava is sprayed into the air, cools into cinders and falls around the vent. Loose cinders pile up only as steeply as they can rest without sliding, about 30 to 35 degrees, so cinder cones are small and steep. A **composite volcano** is built of layer upon layer of sticky lava and ash, so it grows tall and steep. Mount Fuji in Japan, 3,776 m (12,388 feet) high, is one. When it last erupted, in 1707, ash fell on the city of Edo, now Tokyo, about 100 km (60 miles) away. Vesuvius and Mount St. Helens are composite volcanoes too; on May 18, 1980, St. Helens blew away about 400 m (1,300 feet) of its top.

**On the map.** Look at the map of the **Ring of Fire**. It runs about 40,000 km (25,000 miles) around the Pacific: up the Andes and the west coast of North America, across the Aleutian Islands, down through Kamchatka, Japan, the Philippines and Indonesia to New Zealand. About three of every four active volcanoes on land lie along it. Around most of this ring, ocean plates sink beneath other plates, and the melting they cause feeds sticky magma, so

the Ring of Fire is full of composite volcanoes. Mauna Loa is different. It sits in the middle of the Pacific plate over a **hot spot**, which is why it makes runny shield lava instead. Parícutin is one of many cinder cones on the volcanic belt that crosses central Mexico.

**Watching and warning.** Today scientists watch volcanoes with seismometers that feel small earthquakes, GPS stations and tiltmeters that measure the ground swelling as magma rises, and instruments that sample the gases. In the United States, the U.S. Geological Survey announces four alert levels for volcanoes on land: Normal, Advisory, Watch and Warning. Knowing what kind of volcano is nearby tells people what to prepare for: slow lava flows that can be mapped and avoided around a shield, or ash and pyroclastic flows that call for early evacuation around a composite cone.



Not to scale: Mauna Loa is far wider and larger than the other two.

*Three kinds of volcanoes, side by side (not to scale).*



*The Ring of Fire. Mauna Loa and Vesuvius are not part of it.*



## PICTURE STUDY



*Fine Wind, Clear Morning (often called Red Fuji), from Thirty-six Views of Mount Fuji, Katsushika Hokusai, about 1830-1832 · Color woodblock print · Impressions in many museums, including the Metropolitan Museum of Art, New York*

Katsushika Hokusai was a Japanese artist who made thousands of pictures in his long life. When he was past seventy he began a famous series of prints called *Thirty-six Views of Mount Fuji*, showing the mountain from many places and in many seasons. Each print was carved into wooden blocks, one block for each color, and printed by hand on paper, so many copies were made and sold.

In this print Hokusai shows nothing but the mountain and the sky. In early morning light, on a clear day with a gentle south wind, the slopes of Fuji can glow a reddish color. Look at the shape he gives it: the tall, steep, graceful cone of a composite volcano.

### Look closely

- Trace the outline of the mountain with your finger. Is it gentle and wide like Mauna Loa, or steep and tall?
- Find the snow near the top. How does Hokusai show it with only a few streaks?
- Look at the small clouds in the sky. What pattern do they make?
- Find the forest at the foot of the mountain. Where does it stop?

### Talk about it

1. Fuji has not erupted since 1707. Does it look quiet or alive in this print? Why?
2. Why do you think so many Japanese artists painted Fuji again and again?
3. If Hokusai had drawn Mauna Loa from the same distance, how would its outline look different?

## PROJECT: THREE VOLCANOES ON A TRAY

You will build the three kinds of volcanoes from kitchen materials and measure how steep each one is. The point is to see with your own eyes that what comes out of a volcano decides its shape.

### You will need

- A large baking tray lined with wax paper
- Pancake batter made fairly runny (shield lava)
- Thick frosting or peanut butter in a piping bag or zip bag with a corner cut off (sticky lava)
- Dry sand or dry rice and a funnel (cinders); cocoa powder or colored sugar (ash)
- A ruler, a protractor, dental floss and a pencil

### Steps

1. Shield: pour one spoonful of batter onto the tray from the same spot every 30 seconds, ten times. Let each flow spread. Measure the height and the width of the pile.
2. Cinder cone: pour dry sand slowly through a funnel held just above the tray until it stops growing steeper. Measure its height and width, and use the protractor held against the side to measure the angle of its slope.
3. Composite: squeeze a ring of frosting, sprinkle a layer of cocoa ash on it, then another smaller ring of frosting, then more ash, building up five or six layers. Measure height and width.
4. For each volcano, divide the height by half the width. This is the slope ratio: the bigger the number, the steeper the volcano.
5. Slice the composite volcano down the middle with dental floss and look for the layers. Draw what you see.
6. Make a table with the names Mauna Loa, Parícutin and Mount Fuji next to your three models, and write one sentence for each explaining why it has its shape.

### Tips

- Pour the cinders slowly; if you pour fast, the pile slides and you cannot see its true angle.
- Your batter shield will be tiny, but real shields like Mauna Loa are by far the largest of the three kinds.

### Check your work

- I can name the three kinds of volcanoes and give a real example of each.
- I can explain how runny lava, sticky lava and cinders build different shapes.
- I can calculate and compare a slope ratio.

## MAP NOTEBOOK

1. Draw the three kinds of volcanoes side by side as cross-sections and label the vent, the crater and the material that built each one.
2. On a blank world map, trace the Ring of Fire in red. Mark Mount Fuji, Mount St. Helens, Parícutin, Krakatoa and Cotopaxi, then mark Mauna Loa in a different color and write “hot spot” beside it.
3. Draw a timeline of Parícutin from 1943 to 1952 showing its height on the first day, after one year and at the end.

**From history.** Mount Fuji has been climbed by pilgrims for many centuries, and today hundreds of thousands of people climb it every summer. After its 1707 eruption, ash covered the farms around its eastern side so deeply that the rivers filled with it and flooded for years afterward. The farmers had to dig the ash off their fields by hand, one of the first well-recorded struggles of a whole region to recover from a volcano’s ash.

## WORKED EXAMPLES

**Example 1.** Parícutin was about 50 m tall after its first day, 336 m tall after one year and 424 m tall when it stopped erupting in 1952. How much did it grow in its first year, and how much in all the years after? What was its final height in feet?

1. Growth in the first year:  $336 \text{ m} - 0 \text{ m} = 336 \text{ m}$  (it started as a flat field).
2. Growth after the first year:  $424 \text{ m} - 336 \text{ m} = 88 \text{ m}$ .
3. Final height in feet:  $424 \times 3.28 \approx 1,391 \text{ feet}$ .

**Answer:** 336 m in the first year and only 88 m in the eight years after; about 1,391 feet in all. Most of its height was built in the first year.

**Example 2.** In a simple model, a cinder cone is 300 m tall and 1,000 m wide at the base. A shield volcano is 4,000 m tall and 100 km wide. Find the slope ratio (height  $\div$  half the width) of each. About how many times steeper is the cinder cone?

*(Use the map or drawing “Compare the slopes.” shown earlier in this lesson.)*

1. Cinder cone: half the width is 500 m, so  $300 \div 500 = 0.6$ .
2. Shield: 100 km = 100,000 m, and half is 50,000 m, so  $4,000 \div 50,000 = 0.08$ .
3. Compare:  $0.6 \div 0.08 = 7.5$ .

**Answer:** Cinder cone 0.6, shield 0.08; the cinder cone is about  $7\frac{1}{2}$  times steeper, even though the shield is far taller.

**Example 3.** Before May 18, 1980, Mount St. Helens stood about 2,950 m (9,677 feet) high. Afterward its highest point was about 2,549 m (8,363 feet). How much height did it lose in meters and in feet? About what fraction of its height was that?

1. Meters:  $2,950 - 2,549 = 401$  m.
2. Feet:  $9,677 - 8,363 = 1,314$  feet.
3. Fraction:  $401 \div 2,950 \approx 0.14$ , about one-seventh.

**Answer:** About 400 m (1,314 feet), roughly one-seventh of its height, gone in a single morning.

## PRACTICE

1. **EASY** Name the three main kinds of volcanoes and give one real example of each.
2. **EASY** Which kind of volcano is built of alternating layers of lava and ash?
3. **EASY** Mount Fuji is 3,776 m tall. Convert to feet ( $1 \text{ m} \approx 3.28 \text{ ft}$ ).
4. **MEDIUM** Use the Ring of Fire map. Which two volcanoes on the map are NOT part of the Ring of Fire? Explain each.  
*(Use the map or drawing "Look for the volcanoes off the ring." shown earlier in this lesson.)*
5. **MEDIUM** Use the Ring of Fire map. Name the volcanoes on the map that lie in the Andes of South America, and the direction you travel along the ring to go from them to Mount St. Helens.  
*(Use the map or drawing "Follow the ring up the Americas." shown earlier in this lesson.)*
6. **MEDIUM** Parícutin erupted from 1943 to 1952. How many years was that? Mauna Loa erupted in 1984 and next in 2022. How many years apart were those eruptions?
7. **MEDIUM** Ash from Fuji's 1707 eruption fell on Edo, about 100 km away. How far is that in miles? If the wind carried the ash at 25 km per hour, about how many hours would it take to reach Edo?
8. **HARD** A volcano is small and steep, with slopes of about 33 degrees, and made of loose, rough pieces of black rock. Which kind is it, and why can its slopes not get much steeper?
9. **HARD** Mauna Loa rises 4,169 m above sea level, and its flanks go down about another 5,000 m to the sea floor. About how tall is it from the sea floor, in meters and in feet?
10. **CHALLENGE** Write a short paragraph explaining why most volcanoes around the Ring of Fire are composite volcanoes, while Mauna Loa is a shield volcano. Use the words plate, sticky and runny.

## COMMON MISTAKES

- Thinking the steepest volcano is the biggest. Shield volcanoes are gentle but by far the largest.
- Putting Hawai'i on the Ring of Fire. Its volcanoes sit in the middle of the Pacific plate over a hot spot.

- Thinking every volcano looks like a cone with lava pouring out the top. Lava often comes out of cracks on the side, and composite volcanoes may throw out more ash than lava.

**Make it a game • Name That Volcano.** Write twelve clue cards, such as “runny basalt,” “loose cinders,” “layers of lava and ash,” “Hawai‘i,” “a Mexican cornfield,” “ash on Edo,” “hot spot,” “steep and small.” Shuffle them. Players take turns drawing a card and shouting the kind of volcano and a real example that fits. Score one point for the kind and one for a correct example. First to ten wins.

**Scripture.** “He looketh on the earth, and it trembleth: he toucheth the hills, and they smoke.” (Psalm 104:32, KJV)

The psalm that begins with God laying the foundations of the earth also speaks of hills that smoke. The great volcanoes, gentle shields and steep cones alike, are under the hand of the One who made them.

#### Practice answers

1. Shield volcano (Mauna Loa), cinder cone (Parícutin), composite volcano (Mount Fuji; also Vesuvius or Mount St. Helens).
2. A composite volcano (stratovolcano).
3.  $3,776 \times 3.28 \approx 12,385$  feet (the official figure is 12,388 feet).
4. Mauna Loa, which is in the middle of the Pacific plate over a hot spot, and Vesuvius, which is in the Mediterranean where the African and Eurasian plates meet.
5. Cotopaxi and Villarrica. You travel north along the west coast of the Americas.
6.  $1952 - 1943 = 9$  years.  $2022 - 1984 = 38$  years.
7.  $100 \times 0.62 = 62$  miles (about 60 miles).  $100 \div 25 = 4$  hours.
8. A cinder cone. Loose cinders slide down if the pile gets steeper than the angle at which they can rest, about 30 to 35 degrees.
9.  $4,169 + 5,000 \approx 9,170$  m, which is about 30,000 feet ( $9,170 \times 3.28 \approx 30,080$  feet), taller than Mount Everest measured from its base.
10. Around most of the Ring of Fire, ocean plates sink beneath other plates, and the melting this causes makes sticky, gas-rich magma that builds steep composite volcanoes of lava and ash. Mauna Loa sits in the middle of the Pacific plate over a hot spot, where runny basalt lava pours out in thin flows that spread far and build a broad, gentle shield.

## 3.3 THE SAN FRANCISCO EARTHQUAKE OF 1906

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### OBJECTIVES

- Tell the story of the San Francisco earthquake and fire of April 18, 1906, and explain why the fire did more damage than the shaking.
- Explain faults, the elastic rebound of rocks, the three kinds of faults and the main kinds of earthquake waves.
- Use wave arrival times, magnitude steps and map scale to reason about a real earthquake.

**Warm-up.** Hold a plastic ruler or a thin stick by both ends and bend it slowly. Feel it push back against your hands. Keep bending (gently, with a ruler you do not mind losing) and notice how the stress builds before anything happens. If it snapped, what would the two pieces do? Today you will learn that the rocks along a fault behave much the same way.

**Watch.** *1906 San Francisco Earthquake: The Fire That Destroyed 28,000 Buildings* (The Photographed Past, 8:16). <https://www.youtube.com/watch?v=FoyvJ6xdmWg>  
After the story: look through the real 1906 photographs of City Hall stripped to its frame, families cooking in the streets and the refugee camps, and notice how the fires did more damage than the shaking.

**Note:** Captions were not available to check; preview it first. This is a small channel, so check that the narration is a real person and not an AI voice. It says more than 3,000 people died. The video says the shaking lasted about 45 seconds; the lesson says about a minute.

**Backup video.** *The 1906 San Francisco Earthquake and A.P. Giannini* (The History Guy: History Deserves to Be Remembered, 8:17). <https://www.youtube.com/watch?v=TxbZlRuo9MI>

As review: watch The History Guy tell how banker A.P. Giannini helped San Francisco rebuild after the 1906 earthquake and fire. Note: Captions were not available to check, though The History Guy is a trusted channel. Much of the video is about Giannini and banking rather than the earthquake itself, and it may include a short Patreon or merchandise plug.

### KEY TERMS

#### **fault**

A crack in the earth's crust along which the rocks on the two sides have moved past each other.

#### **earthquake**

A sudden shaking of the ground, caused when rocks along a fault slip and release stored energy.



**elastic rebound**

The idea that rocks along a fault bend slowly under stress, then snap and spring back, releasing their energy as an earthquake.

**epicenter**

The point on the surface directly above the place underground where an earthquake starts (the focus).

**seismic waves**

Waves of energy that travel through the earth from an earthquake. P waves come first, then S waves, then the rolling surface waves.

**magnitude**

A number that measures the size of an earthquake. Each whole step means about 10 times more ground motion and about 32 times more energy.

**CORE IDEAS**

**The story.** At 5:12 in the morning on April 18, 1906, most of San Francisco was asleep. The famous Italian singer Enrico Caruso, who had sung in *Carmen* the night before, was in his hotel. Then the ground began to heave. For about a minute the city shook. Chimneys fell, brick walls spilled into the streets, and the dome of City Hall was stripped down to its steel frame. Worse was coming. Broken gas lines and overturned stoves started fires all over the city, and the shaking had broken the water mains, so firefighters opened hydrants and found them dry. The city's fire chief, Dennis Sullivan, was fatally hurt when part of the hotel next door crashed through his firehouse. For three days the fires burned. Soldiers under General Frederick Funston blew up buildings with dynamite to make firebreaks, and the flames were finally stopped along wide Van Ness Avenue. About 28,000 buildings on nearly 500 city blocks were destroyed, more than 200,000 people lost their homes, and historians now estimate that about 3,000 people died.

**How they figured it out.** Eleven years earlier, the Berkeley geologist Andrew Lawson had named a long valley crack the **San Andreas Fault**, after a lake that lies along it. After the earthquake he led a state commission that walked the fault and measured it. They found that the ground had torn along about 477 km (296 miles), from San Juan Bautista in the south to the coast near Shelter Cove in the north. Fences and roads that crossed the fault had been broken and shifted sideways, some by as much as 6 m (20 feet), with the western side moved to the northwest. A geologist named Harry Fielding Reid compared land surveys made before and after the earthquake and saw that the ground near the fault had been slowly bent for years, then had snapped back. He called this **elastic rebound**. Like your bent ruler, the rocks store stress until they suddenly slip.

**The big idea.** A **fault** is a crack where the rocks on either side move. There are three main kinds. Where the crust is pulled apart, one block slides down along a **normal fault**. Where it is pushed together, one block is shoved up over another along a **reverse fault**. Where the blocks slide past each other sideways, it is a **strike-slip fault**. The San Andreas is a strike-slip fault on the boundary between the Pacific plate and the North American plate, which you met in Unit 2. The Pacific side creeps northwest by a few centimeters a year, about as fast as

your fingernails grow. When a stuck part of the fault finally slips, **seismic waves** spread out from the **focus**, the starting point underground; the spot on the surface right above it is the **epicenter**. P waves, which push and pull, travel fastest, about 6 km (4 miles) a second through the crust. S waves, which shake side to side, follow at about 3.5 km (2 miles) a second. Surface waves come last and roll the ground most strongly.

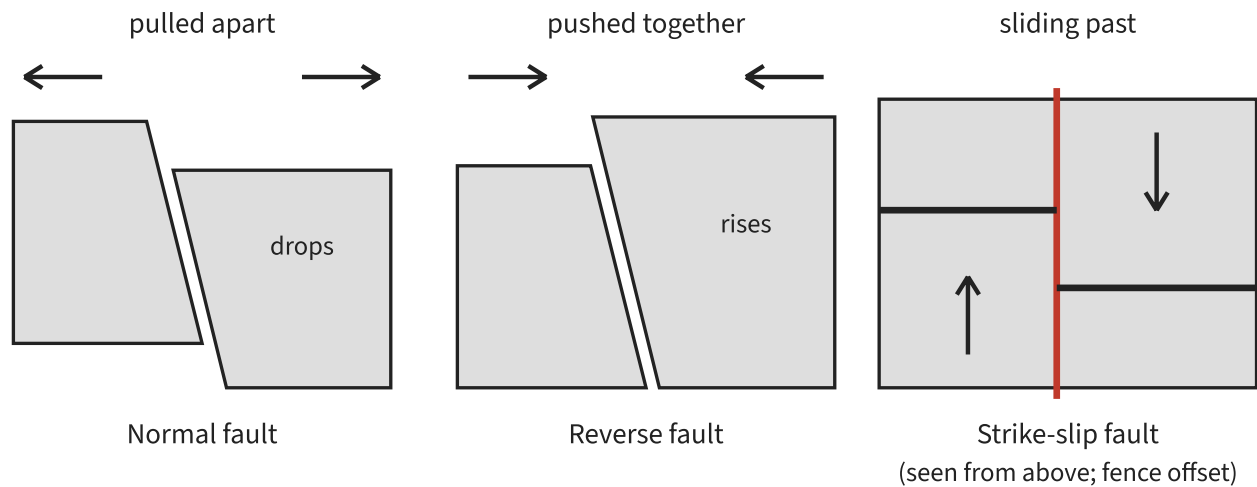
**Measuring a quake.** Scientists describe earthquakes in two ways. **Magnitude** measures the size of the earthquake itself; the 1906 earthquake is estimated at about 7.9. Each whole step on the scale means about 10 times more ground motion and about 32 times more energy. **Intensity** describes how hard the shaking was at one place and what it did to people and buildings. Lawson's commission noticed something important: the shaking was far worse on soft, wet ground and filled-in land along the bay than on solid rock. The same earthquake can be mild on a rocky hill and violent a few blocks away on fill.

**Technology overcoming geography.** San Francisco could not move off the fault, but it could prepare. After 1906 the city built a separate high-pressure water system just for fighting fires, finished in 1913, with its own reservoirs, pump stations, sturdy pipes and special hydrants, and it dug large underground cisterns of water beneath street intersections. In 1915 the rebuilt city welcomed the world to the Panama-Pacific International Exposition. On the map of California, trace the San Andreas Fault from the Salton Sea to the coast north of San Francisco and notice how many cities lie near it. That is why the next lesson asks how people build so that the ground can shake without the buildings falling.



*The San Andreas Fault. In 1906 it tore from San Juan Bautista to Shelter Cove.*





*The three main kinds of faults.*

## PICTURE STUDY



*Looking Down Sacramento Street, San Francisco, April 18, 1906, Arnold Genthe, April 18, 1906 · Photograph · Library of Congress, Arnold Genthe Collection*

Arnold Genthe was a German-born photographer who had a studio in San Francisco. The earthquake wrecked his studio and his own cameras, so he went to a camera shop, borrowed a small camera and walked out into the city to record what was happening.

This is his most famous picture. He stood high on Sacramento Street and looked down the hill toward the fires. The earthquake had already struck. What you see is the calm, strange morning afterward, before the people knew how far the fire would spread.

**Look closely**

- Find the smoke. Where is it rising, and how big is it compared with the buildings?
- Look at the people in the street. What are they doing? Do they look panicked or calm?
- Look at the fronts of the buildings. Can you see damage from the shaking?
- Follow the street downhill with your eyes. What does the steep hill tell you about the shape of the land in San Francisco?

### **Talk about it**

1. Why do you think the people are standing in the street instead of going back inside?
2. This photograph shows the fire, not the shaking. Why did the fire end up destroying more of the city than the earthquake itself?
3. What does a photograph tell us that Lawson's measurements could not?

### **PROJECT: STICK AND SLIP: A FAULT IN A BOX**

You will build a model fault that stores up stress and then slips, just as Reid described, and you will send P and S waves down a spring toy.

### **You will need**

- Two bricks of craft foam, two thick books or two blocks of wood
- Two sheets of coarse sandpaper and tape
- A strong rubber band or a short length of elastic, and a thumbtack or tape
- A ruler, a marker and a strip of paper or a piece of yarn for the "fence"
- A metal or plastic spring toy (a Slinky)

### **Steps**

1. Tape sandpaper to the facing sides of the two blocks. Set them side by side on a table so the sandpaper sides touch. This crack between them is your fault.
2. Lay a paper strip or yarn straight across both blocks and mark it with a line. This is a fence crossing the fault.
3. Hold the left block still. Hook the rubber band to the end of the right block and pull it very slowly along the fault. Watch the rubber band stretch while the block stays stuck.
4. Keep pulling slowly until the block jumps. Measure how far the fence line was offset in that one jump.
5. Repeat five times and record each jump. Are they all the same size? Do they come at regular times?
6. Stretch the spring toy along the floor with a partner. Push one end sharply forward: that is a P wave. Then flick one end quickly side to side: that is an S wave. Which travels to your partner faster?
7. Write a paragraph explaining how your model shows elastic rebound.

### **Tips**

- Pull slowly and steadily. The point is that the pulling is smooth but the slipping is sudden.
- If the block slides smoothly with no jumps, use rougher sandpaper or press the blocks together more firmly.

### Check your work

- I can explain elastic rebound with my model.
- I can show the difference between a P wave and an S wave.
- I can measure and record the offset of a fence across a fault.

### MAP NOTEBOOK

1. Draw the three kinds of faults with arrows showing which way the blocks move. Label them normal, reverse and strike-slip.
2. Trace a map of California and draw the San Andreas Fault in red. Mark San Francisco, Los Angeles, San Juan Bautista and Shelter Cove, and add arrows showing which way each side moves.
3. Draw a fence crossing a fault before and after an earthquake, and label the offset “up to 6 m (20 feet) in 1906.”

**From history.** The 1906 earthquake was recorded by seismographs in many countries, far from California, which helped show scientists that earthquake waves travel through the whole earth. The report of Lawson’s commission, published in 1908 with a second volume in 1910, filled hundreds of pages with maps, photographs and measurements. It became one of the founding works of the science of earthquakes in America, and geologists still study its maps of where the ground shook hardest.

### WORKED EXAMPLES

**Example 1.** A seismograph station records the P waves from an earthquake, and the S waves arrive 10 seconds later. Using the rule that each second of delay means about 8 km (5 miles) of distance, how far away was the earthquake?

1. P waves travel faster than S waves, so the gap between them grows the farther they travel.
2. Distance  $\approx 10 \text{ seconds} \times 8 \text{ km per second} = 80 \text{ km}$ .
3. In miles:  $10 \times 5 = 50 \text{ miles}$  (or  $80 \times 0.62 \approx 50 \text{ miles}$ ).

**Answer:** About 80 km, or about 50 miles, from the station. With three stations, scientists can draw three circles and find the epicenter where they cross.

**Example 2.** The 1906 earthquake had a magnitude of about 7.9. Compare it with a magnitude 6.9 earthquake. How many times more ground motion did it make, and about how many times more energy did it release?

1.  $7.9 - 6.9 = 1$  whole step on the scale.
2. One step means about 10 times more ground motion.
3. One step means about 32 times more energy.

**Answer:** About 10 times the ground motion and about 32 times the energy.

**Example 3.** Suppose a stuck part of a fault has been loaded by the plates moving past each other at 3.5 cm a year. How many years would it take to store up enough motion for a slip of 6 m?

1. Change meters to centimeters:  $6 \text{ m} = 600 \text{ cm}$ .
2. Divide by the yearly rate:  $600 \text{ cm} \div 3.5 \text{ cm per year} \approx 171 \text{ years}$ .

**Answer:** About 170 years. This is why a fault can be quiet for a long time and still be dangerous: it is slowly storing up stress the whole while.

## PRACTICE

1. **EASY** On what date and at what time did the great San Francisco earthquake strike?
2. **EASY** Which kind of fault is the San Andreas Fault, and which two plates does it separate?
3. **EASY** Which kind of seismic wave arrives first at a seismograph, and which comes second?
4. **MEDIUM** The 1906 rupture was about 477 km long. How many miles is that? ( $1 \text{ km} \approx 0.62 \text{ mile}$ )
5. **MEDIUM** Use the map. In which direction does the San Andreas Fault run from Los Angeles to San Francisco? Which side of the fault moves northwest?  
(Use the map or drawing "Follow the red line." shown earlier in this lesson.)
6. **MEDIUM** Use the fault diagrams. In which kind of fault is the crust pushed together so that one block is shoved upward?  
(Use the map or drawing "Look at the arrows." shown earlier in this lesson.)
7. **MEDIUM** The S waves reach a station 25 seconds after the P waves. About how far away is the earthquake in kilometers and in miles?
8. **HARD** Give two reasons why the fire did more damage to San Francisco in 1906 than the shaking did.
9. **HARD** A magnitude 5.9 earthquake and a magnitude 7.9 earthquake are compared. How many times more ground motion and about how many times more energy does the larger one make?

10. **CHALLENGE** Explain elastic rebound in your own words, using the 1906 earthquake and the fences along the fault as your example.

## COMMON MISTAKES

- Thinking the shaking destroyed most of San Francisco. The fires that followed did far more damage.
- Mixing up magnitude and intensity. Magnitude is the size of the earthquake; intensity is how hard it shook at one place.
- Thinking each step on the magnitude scale is just a little bigger. Each whole step is about 32 times more energy.

**Make it a game · Find the Epicenter.** On a large map, a leader secretly picks a city as the epicenter. Three players each choose a different city as their seismograph station. The leader tells each player how far away the epicenter is (using the map scale). Each player draws a circle with a string and pencil around their station at that distance. Where the three circles cross is the epicenter. The first team to name the city wins the round.

**Scripture.** “And he said, Go forth, and stand upon the mount before the LORD. And, behold, the LORD passed by, and a great and strong wind rent the mountains, and brake in pieces the rocks before the LORD; but the LORD was not in the wind: and after the wind an earthquake; but the LORD was not in the earthquake: And after the earthquake a fire; but the LORD was not in the fire: and after the fire a still small voice.” (1 Kings 19:11-12, KJV)

Elijah saw wind, then earthquake, then fire; San Francisco in 1906 saw the earthquake followed by the fire. God rules over all of them, yet He spoke to Elijah in a still small voice. Even in disaster, God draws near to people quietly and personally.

## Practice answers

1. April 18, 1906, at 5:12 in the morning.
2. A strike-slip fault, between the Pacific plate and the North American plate.
3. P waves arrive first; S waves come second (and surface waves last).
4.  $477 \times 0.62 \approx 296$  miles.
5. It runs northwest. The western (Pacific plate) side moves northwest.
6. A reverse fault.
7.  $25 \times 8 = 200$  km, about 125 miles.
8. Broken gas lines and overturned stoves started many fires at once, and the shaking broke the water mains so the hydrants were dry. The fire chief was also fatally injured, and the fires burned for three days.
9. Two steps:  $10 \times 10 = 100$  times the ground motion, and about  $32 \times 32 \approx 1,000$  times the energy.
10. For years the two sides of the San Andreas Fault were moving past each other but the fault was stuck, so the rocks near it bent and stored stress, like a bent ruler. In 1906 the stuck part slipped all at once and the rocks sprang back, releasing the stored energy as an earthquake.

Fences that had crossed the fault in a straight line were left broken and offset by up to about 6 m.

## 3.4 BUILDING AGAINST EARTHQUAKES ⚙️

### OBJECTIVES

- Explain why some buildings fell in the 1989 Loma Prieta earthquake while most stood, and why the kind of ground matters.
- Describe how bracing, flexible steel frames, base isolation and dampers help buildings survive shaking, and how building codes and warning systems protect people.
- Use the sway period of buildings and the speed of seismic waves to reason about resonance and earthquake warning time.

**Warm-up.** Stand a tall stack of six or eight blocks (or books) on a tray, and a short stack of two next to it. Slide the tray quickly back and forth. Which stack falls first? Now set a single block on top of four marbles or round pencils on the tray and slide the tray again. What does the block on rollers do?

**Watch.** *Earthquake-proof Buildings* / *Science Nation* (National Science Foundation News, 4:55). <https://www.youtube.com/watch?v=c25HuZeQsy0>

With the big idea: watch scientists shake a full-size six-story wooden building on a giant shake table, and notice how it is built to bend without falling.

**Note:** Captions were not available to check, though this comes from the National Science Foundation, a trusted source. Preview it first.

### KEY TERMS

#### **building code**

A set of rules, written into law, for how buildings must be designed and built so they are safe.

#### **bracing**

Diagonal beams or walls that turn a frame into triangles, so it cannot be pushed out of shape easily.

#### **base isolation**

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

#### **damper**

A device that soaks up the energy of a building's swaying, like a shock absorber on a car.

#### **resonance**

When shaking matches the natural back-and-forth timing of an object, so each push makes the swaying bigger.

#### **liquefaction**

When strong shaking makes loose, wet, sandy ground act like a thick liquid, so buildings tilt or sink.



## CORE IDEAS

**The story.** At 5:04 in the afternoon on October 17, 1989, more than 60,000 fans sat in Candlestick Park in San Francisco waiting for Game 3 of the World Series, and millions more were watching on television. Then the stadium began to sway. The Loma Prieta earthquake, magnitude 6.9, had broken loose in the Santa Cruz Mountains about 95 km (60 miles) to the south. In Oakland, the upper deck of the double-decker Cypress Street freeway, built on soft bay mud, collapsed onto the lower deck, and 42 people died there. A section of the upper deck of the Bay Bridge fell onto the deck below, closing the bridge for a month. In San Francisco's Marina District, houses built on filled land sank and burned. In all, 63 people died. Yet the stadium held, and so did nearly all the skyscrapers of the city, built under modern codes. Just a year earlier, an earthquake of almost the same size, magnitude 6.8, had struck Spitak in Armenia, where many buildings were made of poorly connected concrete panels. About 25,000 people died there.

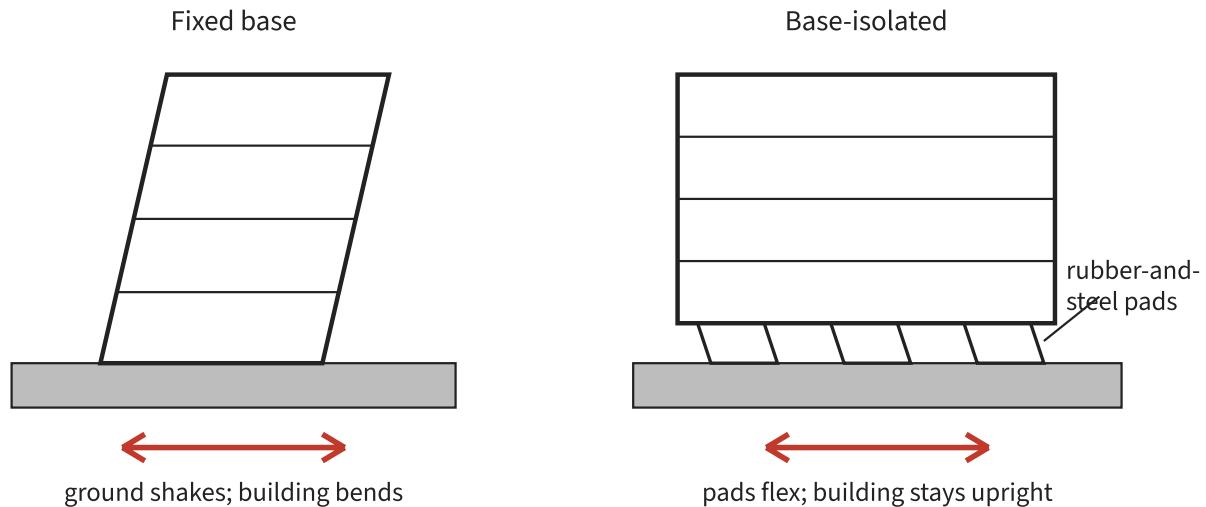
**How they figured it out.** Engineers have a saying: earthquakes rarely kill people directly; falling buildings do. After every great earthquake they study what fell and what stood. They learned that brick and stone walls laid without steel are the most dangerous, because they crack and tumble. They learned that soft ground shakes harder than rock, and that loose, wet fill can turn almost to liquid, which is called **liquefaction**. They learned that every building has its own natural sway, its **period**, the time for one swing back and forth. A rough rule is about 0.1 second for each story, so a 10-story building swings about once a second. If the ground shakes at that same timing, the swaying builds up by **resonance**, like pushing a child on a swing at just the right moment.

**How it works.** Earthquake engineers use several tools. **Bracing** adds diagonal beams or solid shear walls that turn the frame into triangles, which cannot be pushed out of shape. Steel **moment frames** are joined so strongly and made of such tough steel that they bend without snapping; a building that bends a little and stays standing is far better than one that is stiff until it breaks. **Base isolation** sets the whole building on pads of layered rubber and steel, some with a core of lead, a design developed by the New Zealand engineer William Robinson. The pads let the ground slide back and forth beneath while the building above moves slowly and gently. San Francisco's City Hall, damaged in 1989, was lifted onto base isolators and reopened in 1999. **Dampers** soak up energy like a car's shock absorbers. In Taipei 101, a skyscraper in Taiwan, a steel ball weighing about 660 metric tons (about 728 short tons) hangs near the top and swings against the building's sway.

**Old wisdom, new towers.** Japan has a long earthquake history and a long record of wooden pagodas that stood through it. Engineers point to their stacked stories that can sway separately, their flexible wooden joints and the tall central pillar that runs up the middle. The builders of the Tokyo Skytree, a 634 m (2,080 feet) broadcasting tower finished in 2012, gave it a central concrete column inspired by those pagodas.

**Technology overcoming geography.** People cannot move the San Andreas Fault or the Ring of Fire, but they can build wisely beside them. After a 1933 earthquake in Long Beach, California, wrecked many school buildings, the state passed the Field Act, requiring schools

to be built to earthquake standards. Codes have grown stronger after each great earthquake since, and many older buildings have been retrofitted with steel and braces. Warning systems now use the fact that radio and internet signals travel far faster than S waves and surface waves. When sensors near the epicenter feel the first P waves, systems such as ShakeAlert on the West Coast and Japan's warning system can send alerts that arrive seconds before the strong shaking: enough time to slow trains, stop elevators and get under a table.



*Fixed base and base isolation.*

## PICTURE STUDY



*Kinryūzan Temple, Asakusa, from One Hundred Famous Views of Edo*, Utagawa Hiroshige, 1856 · Color woodblock print · Impressions in many museums, including the Metropolitan Museum of Art and the Brooklyn Museum, New York

Utagawa Hiroshige was one of the great Japanese printmakers. Near the end of his life he made a series of more than one hundred prints of famous places in Edo, the city we now call Tokyo. In this winter scene we look through the great gate of Sensō-ji, the oldest temple in the city, past the giant red lantern that hangs in the gate.

Find the tall, slender pagoda rising beyond the gate. Wooden pagodas like this one, built of stacked stories around a central pillar, have a long record of standing through Japan's earthquakes. Modern engineers have studied them to learn how a tall structure can sway without falling.

### Look closely

- Find the giant lantern at the top. How does it frame the scene like a curtain?
- Count the stories of the pagoda. How many roofs can you see?
- Look at the people walking in the snow. What are they carrying?
- Notice how the snow sits on each roof. How does the artist make the scene feel quiet and cold?

### Talk about it

1. Why might a building made of wood with flexible joints survive shaking better than one made of stacked bricks?
2. Hiroshige shows the temple as a peaceful, beautiful place. Why do you think people took such care to build it well?

3. If you were an engineer, what would you want to measure about this pagoda?

## **PROJECT: THE SHAKE-TABLE TEST**

You will build a simple shake table and test buildings of blocks and of straws, then improve them with bracing and base isolation, just as engineers do. Every change you make is an experiment, so change only one thing at a time and record what happens.

### **You will need**

- Two pieces of stiff cardboard or thin plywood about 30 × 40 cm (12 × 16 inches)
- Four tennis balls or six to eight large marbles, and four thick rubber bands
- Wooden blocks or sugar cubes
- Drinking straws, pipe cleaners or paper clips, and masking tape
- A few ping-pong balls or extra marbles and a paper plate (for base isolation)
- A ruler, a timer and a notebook

### **Steps**

1. Build the shake table: set the top board on balls or marbles placed on the bottom board, and loop rubber bands around both boards so the top board springs back when pulled. Tape a ruler to the bottom board so you can pull the top board the same distance each time.
2. Build a block tower six blocks high with no glue. Pull the top board 3 cm (about 1 inch) and let go. Count how many shakes the tower survives. Record it.
3. Build a straw frame of the same height: four straw columns joined at each floor with pipe cleaners or paper clips and tape. Test it the same way.
4. Add diagonal braces of straw to two sides of the frame, making triangles. Test again and compare.
5. Base isolation: set the braced straw building on a paper plate resting on three or four ping-pong balls or marbles on the shake table. Test again. Watch how much the building moves compared with the table.
6. Try a damper: hang a small weight (a washer on a string) from the top of the frame and test once more.
7. Make a results table: building, change made, shakes survived, what you saw. Write a paragraph telling which change helped most and why.

### **Tips**

- Pull the table the same distance each time, or your test is not fair.
- Your block tower is like an old brick building with no steel: notice how it fails. Your straw frame is more like a steel frame that bends.

### **Check your work**

- I can explain why braced frames resist shaking better than unbraced ones.

- I can explain how base isolation lets the ground move while the building moves less.
- I ran a fair test, changed one thing at a time and recorded my results.

## MAP NOTEBOOK

1. Draw two buildings on shaking ground: one fixed to the ground and bending, one on base isolators staying upright. Label the pads.
2. Draw a square frame and a braced frame with a diagonal. Use arrows to show why the triangle keeps its shape.
3. Draw a map of the San Francisco Bay Area. Mark Candlestick Park, the Bay Bridge, Oakland, the Marina District and the Loma Prieta epicenter to the south.

**From history.** After a great earthquake, tsunami and fire destroyed much of Lisbon, Portugal, on November 1, 1755, the city was rebuilt under the direction of the king's chief minister, the Marquis of Pombal. Its new buildings had a hidden wooden frame of crossed timbers, called the *gaiola* or "cage," set inside the stone walls so the building could flex instead of crumbling. Tradition says the design was tested by having soldiers march around a model to shake it. It is one of the first building systems in Europe designed on purpose to resist earthquakes.

## WORKED EXAMPLES

**Example 1.** Using the rule of about 0.1 second of sway period for each story, find the natural period of a 3-story house, a 10-story office building and a 40-story tower.

1.  $3 \text{ stories} \times 0.1 \text{ s} = 0.3 \text{ s}$ .
2.  $10 \text{ stories} \times 0.1 \text{ s} = 1 \text{ s}$ .
3.  $40 \text{ stories} \times 0.1 \text{ s} = 4 \text{ s}$ .

**Answer:** About 0.3 s, 1 s and 4 s. Taller buildings sway more slowly.

**Example 2.** During an earthquake, the ground at one site shakes back and forth twice each second (a period of 0.5 s). Which building is most likely to have trouble with resonance: 2 stories, 5 stories or 20 stories?

1. Find each building's period: 2 stories  $\approx 0.2 \text{ s}$ ; 5 stories  $\approx 0.5 \text{ s}$ ; 20 stories  $\approx 2 \text{ s}$ .
2. Resonance happens when the building's period matches the ground's period.
3. The 5-story building's period (0.5 s) matches the ground's (0.5 s).

**Answer:** The 5-story building. Its swaying would build up with each push of the ground.

**Example 3.** An earthquake starts 100 km (62 miles) from a city. S waves travel about 3.5 km per second. A warning system detects the P waves and sends an alert to phones 8 seconds after the earthquake starts. About how many seconds of warning does the city get before the S waves arrive?

1. Time for S waves to reach the city:  $100 \text{ km} \div 3.5 \text{ km/s} \approx 28.6 \text{ s}$ .
2. The alert arrives at 8 s (radio and internet signals are almost instant).
3. Warning time:  $28.6 \text{ s} - 8 \text{ s} \approx 20.6 \text{ s}$ .

**Answer:** About 20 seconds, enough to drop, cover and hold on, stop elevators and slow trains.

## PRACTICE

1. **EASY** What is base isolation?
2. **EASY** Why do engineers add diagonal braces to a frame?
3. **EASY** What is liquefaction, and in which San Francisco neighborhood did it cause damage in 1989?
4. **MEDIUM** The Loma Prieta earthquake (magnitude 6.9) killed 63 people. The Spitak earthquake in Armenia (magnitude 6.8) killed about 25,000. About how many times more deaths were there at Spitak? What was the main reason for the difference?
5. **MEDIUM** Using the 0.1-second-per-story rule, what is the sway period of a 25-story building? If the ground shakes with a period of 0.3 s, is this building near resonance?
6. **MEDIUM** The damper in Taipei 101 weighs about 660 metric tons. One metric ton is 1,000 kg. How many kilograms is that? About how many 1,500 kg cars would weigh the same?
7. **MEDIUM** Use the diagram. In the base-isolated building, what flexes when the ground moves, and what happens to the building above?  
(Use the map or drawing "Compare the two buildings." shown earlier in this lesson.)
8. **HARD** An earthquake starts 70 km from a city. The S waves travel about 3.5 km a second, and a warning reaches the city 6 seconds after the earthquake begins. How many seconds of warning does the city have?
9. **HARD** What was the Field Act, when was it passed and what event led to it?
10. **CHALLENGE** A town on a fault has an old brick school, a wooden house on rock and a new steel-frame office on filled land by the bay. Rank them from most to least at risk in a strong earthquake and explain your ranking.

## COMMON MISTAKES

- Thinking the strongest building is the stiffest one. Buildings that can bend without breaking often survive better.
- Forgetting the ground. The same building shakes far harder on soft fill or mud than on rock.

- Thinking an earthquake warning predicts earthquakes. It only gives seconds of warning after an earthquake has already started.

**Make it a game · Engineer's Challenge.** Give each player the same small pile of materials: ten straws, a strip of tape and four paper clips. Set a timer for five minutes. Each player builds a tower at least 25 cm (10 inches) tall. Then test every tower on the shake table, pulling the same distance each round and adding 1 cm each round. The last tower standing wins, and its builder must explain which idea from the lesson made it strong.

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

Engineers know that the ground under a building matters as much as the building itself. Jesus used that same truth to teach that a life built on His words stands firm when the storms come.

#### Practice answers

1. Setting a building on flexible pads of rubber and steel so that the ground can move back and forth beneath it while the building moves much less.
2. Diagonals make triangles, and a triangle cannot be pushed out of shape without stretching or crushing one of its sides, so the frame resists sideways shaking.
3. Strong shaking makes loose, wet, sandy ground act like a liquid. It damaged the Marina District, which was built on filled land.
4.  $25,000 \div 63 \approx 400$  times. The main difference was the buildings: the Bay Area mostly had buildings built to modern earthquake codes, while many buildings at Spitak were weak, poorly connected concrete panels.
5. About 2.5 s. No; its period is much longer than 0.3 s, so it is far from resonance with that shaking.
6.  $660 \times 1,000 = 660,000$  kg.  $660,000 \div 1,500 = 440$  cars.
7. The rubber-and-steel pads under the building flex sideways; the building above stays nearly upright and moves much less than the ground.
8.  $70 \div 3.5 = 20$  s for the S waves.  $20 - 6 = 14$  seconds of warning.
9. A California law passed in 1933 requiring school buildings to be built to earthquake-resistant standards. It followed the Long Beach earthquake of 1933, which badly damaged many school buildings.
10. Most at risk: the old brick school, because unreinforced brick cracks and falls. Next: the steel-frame office on fill, because the frame can bend without breaking but the soft fill shakes harder and may liquefy. Least: the wooden house on rock, because wood is light and flexible and rock shakes least. (Other rankings can earn credit if well reasoned.)



## UNIT 3 REVIEW

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Answer each question. Show your work for calculations and use complete sentences for explanations. Give distances in both kilometers and miles where asked. The review is worth 60 points.

1. (6 pts) Who was Pliny the Younger, and why is his account of the eruption of Vesuvius important?
2. (6 pts) Pompeii lies about 10 km from the crater of Vesuvius. How far is that in miles? Name the two kinds of material that buried Pompeii, in the order they came.
3. (6 pts) Explain why sticky magma makes explosive eruptions and runny magma makes quiet ones.
4. (6 pts) Match each volcano to its kind and give one reason for its shape: Mauna Loa, Parícutin, Mount Fuji.
5. (6 pts) Parícutin grew to 336 m in its first year and stopped at 424 m in 1952. How much did it grow after the first year? Give its final height in feet.
6. (6 pts) What is the Ring of Fire? Name four volcanoes on it, and explain why Mauna Loa is not part of it.
7. (6 pts) Explain elastic rebound, using the fences that crossed the San Andreas Fault in 1906.
8. (6 pts) At a seismograph station the S waves arrive 15 seconds after the P waves. Using about 8 km per second of delay, how far away is the earthquake, in kilometers and in miles?
9. (6 pts) Why did fire destroy more of San Francisco in 1906 than the shaking did? Name one thing the city built afterward to fight fires.
10. (6 pts) Describe two ways engineers help buildings survive earthquakes, and use the Loma Prieta (1989) and Spitak (1988) earthquakes to show why building codes matter. Then use the 0.1-second-per-story rule to find the sway period of an 8-story building.

### UNIT PROJECT: MY RING OF FIRE FIELD BOOK

Make a field book about the moving earth. Draw a large map of the Ring of Fire and mark at least eight volcanoes, coloring shield volcanoes, cinder cones and composite volcanoes differently, and add Vesuvius and Mauna Loa with notes explaining why they lie off the ring. Plot at least five real earthquakes from the past month using the USGS earthquake map.

Add your Pompeii layer drawing, your fault-model measurements and your full shake-table report with a results table, photographs or drawings of each building tested, and a paragraph explaining which design survived best and why.

- **Accuracy:** Volcanoes, faults and earthquakes are placed correctly, labeled clearly and matched to the right kind.
- **Records:** Measurements from the layer jar, fault model and shake table are complete, with units, and the tests were fair.

- **Explanation:** Writing explains how magma, plates and faults cause volcanoes and earthquakes and how engineering protects people.
- **Care:** The field book is neat, colorful and easy to read, with a title, a key and a compass rose on each map.

#### Answer key

1. He was the seventeen-year-old nephew of Pliny the Elder, staying at Misenum across the Bay of Naples in AD 79. Years later he described the eruption and his uncle's death in two letters to Tacitus. They are the only eyewitness account of the eruption, and very explosive eruptions are now called Plinian eruptions after him.
2.  $10 \times 0.62 \approx 6.2$  miles. First pumice and ash fell from the sky; then pyroclastic flows swept over the town.
3. Sticky magma traps its gas, so pressure builds until it blasts the rock apart into pumice and ash. In runny magma the gas escapes easily, so the lava flows out quietly.
4. Mauna Loa: shield volcano, built of runny lava that spreads far into gentle slopes. Parícutin: cinder cone, built of loose cinders that pile up steeply around one vent. Mount Fuji: composite volcano, built of layers of sticky lava and ash that make a tall, steep cone.
5.  $424 - 336 = 88$  m.  $424 \times 3.28 \approx 1,391$  feet.
6. The horseshoe-shaped belt of volcanoes and earthquakes around the edges of the Pacific, where plates sink beneath other plates. Examples: Mount St. Helens, Parícutin, Cotopaxi, Villarrica, Mount Fuji, Pinatubo, Krakatoa, Ruapehu. Mauna Loa sits in the middle of the Pacific plate over a hot spot, not at a plate edge.
7. The two sides of the fault were moving but the fault was stuck, so the rocks bent and stored stress. In 1906 they slipped suddenly and sprang back, releasing the energy as an earthquake. Fences that had crossed the fault in straight lines were broken and offset by up to about 6 m (20 feet).
8.  $15 \times 8 = 120$  km, about 75 miles.
9. Broken gas lines and overturned stoves started many fires, and the shaking broke the water mains, so hydrants were dry; the fires burned for three days. Afterward the city built a separate high-pressure water system for firefighting (finished in 1913) and large underground cisterns.
10. Any two of: diagonal bracing or shear walls, flexible steel frames that bend without breaking, base isolation on rubber-and-steel pads, dampers. Loma Prieta (magnitude 6.9) killed 63 people in a region built mostly to modern codes, while Spitak (magnitude 6.8) killed about 25,000 where many buildings were weak concrete panels. Period:  $8 \times 0.1 = 0.8$  second.

## WEATHERING, EROSION AND RIVERS

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The psalmist praised the One “Who laid the foundations of the earth, that it should not be removed for ever” (Psalm 104:5). The earth’s foundations stand firm, yet its surface is never still. Ice pries rock apart, roots split boulders, rain dissolves stone, and rivers and glaciers carry the pieces downhill to build new land somewhere else. In this unit you will study these slow, steady processes as a geographer: **weathering**, which breaks rock where it sits, and **erosion**, which carries it away and lays it down again.

You will stand beneath the Old Man of the Mountain in New Hampshire and learn why his granite face fell on May 3, 2003. You will look down with Thomas Cole on the Connecticut River’s great Oxbow in 1836 and learn how a flood cut it off four years later. You will sail with Herodotus to the Nile delta, trace the Mississippi as it builds and abandons one delta lobe after another, and follow John Muir as he drives stakes into a living glacier in 1872 to show that ice carved Yosemite. Your own paint-tray stream table will let you watch a river cut, carry and drop its load, build a delta and switch its course.

Throughout, you will measure what can be measured: gradients, sinuosity, glacier speeds, waterfall heights, lake depths and the observed rates at which gravestones wear and falls cut back. By the end you will be able to read the story of a landscape from its shape: the V of a mountain stream, the loops of a lowland river, the fan of a delta and the U of a glacial valley.

### BEFORE YOU BEGIN

- Can multiply and divide decimals and find a percent of a number
- Can convert between miles and kilometers and between feet and meters
- Can read a contour map and draw a simple profile (Unit 1)
- Knows the three main rock types or can describe rock as made of mineral grains

### MASTERY CHECKLIST

- I can explain the difference between weathering and erosion and give examples of mechanical and chemical weathering.
- I can explain how a river erodes, transports and deposits its load, and calculate a river’s gradient and sinuosity.
- I can describe the upper, middle and lower course of a river and explain how a meander becomes an oxbow lake.
- I can explain how floodplains, natural levees and deltas form, and why the Mississippi delta has switched its course over time.
- I can explain how glaciers form, move and erode, and tell a V-shaped river valley from a U-shaped glacial valley.
- I can build a stream table that shows erosion, deposition, a delta and a delta switch, and explain what I see.

## OPTIONAL BOOKS AND RESOURCES

- **NASA Earth Observatory** (<https://earthobservatory.nasa.gov/>): Free. Search the image library for “Mississippi River Delta,” “Wax Lake Delta,” “Nile Delta” and “oxbow lakes” to see the landforms of Lessons 4.2 and 4.3 from space, often with before-and-after pairs.
- **Mark Twain, *Life on the Mississippi* (free at Project Gutenberg)** (<https://www.gutenberg.org/ebooks/245>): Free. A parent may read aloud chapters 8 and 9, where the young cub pilot learns to read the face of the water, and chapter 17, on cutoffs and the shifting river (Lesson 4.2).
- **Yosemite National Park (National Park Service)** (<https://www.nps.gov/yose/>): Free. The park’s pages on geology, glaciers and waterfalls include photographs of glacier polish, erratics and hanging valleys for Lesson 4.4.

## 4.1 WEATHERING ★

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### OBJECTIVES

- Explain the difference between weathering and erosion and give a real example of each.
- Describe how ice, roots, rain and air break down rock by mechanical and chemical weathering.
- Tell how frost wedging brought down the Old Man of the Mountain in 2003 and predict where each kind of weathering works fastest.

**Warm-up.** Put a piece of white sidewalk chalk in a clear cup of vinegar and another piece in a cup of plain water. While you watch, rub two rough stones (or two bricks) together over a sheet of dark paper for one minute. What is collecting on the paper? What is happening to the chalk in the vinegar? You have just seen rock broken in two different ways: one by scraping and one by a liquid that changes it.

**Watch.** *What is Weathering?* (Earth Science Classroom, 10:29).

<https://www.youtube.com/watch?v=xvbjTD1I7RQ>

With the big idea: watch for how ice, plant roots and water break down rock, so you can compare it with what happened to the Old Man of the Mountain.

**Note:** Captions were not available to check, and the video details were missing from our data; preview it first. It comes from a small channel ('Earth Science Classroom') and may give ages in millions of years.

### KEY TERMS

#### weathering

The breaking down of rock where it sits, by ice, roots, water, air and other forces.

#### erosion

The carrying away of broken rock and soil by running water, wind, ice or gravity.

#### mechanical weathering

Breaking rock into smaller pieces without changing the minerals it is made of (also called physical weathering).

#### frost wedging

Mechanical weathering in which water freezes in a crack, swells by about 9 percent and pries the rock apart.

#### chemical weathering

Breaking down rock by changing its minerals, as when rainwater dissolves limestone or feldspar turns to clay.

#### oxidation

Chemical weathering in which iron in rock combines with oxygen and rusts, staining rock red, orange or brown.

## CORE IDEAS

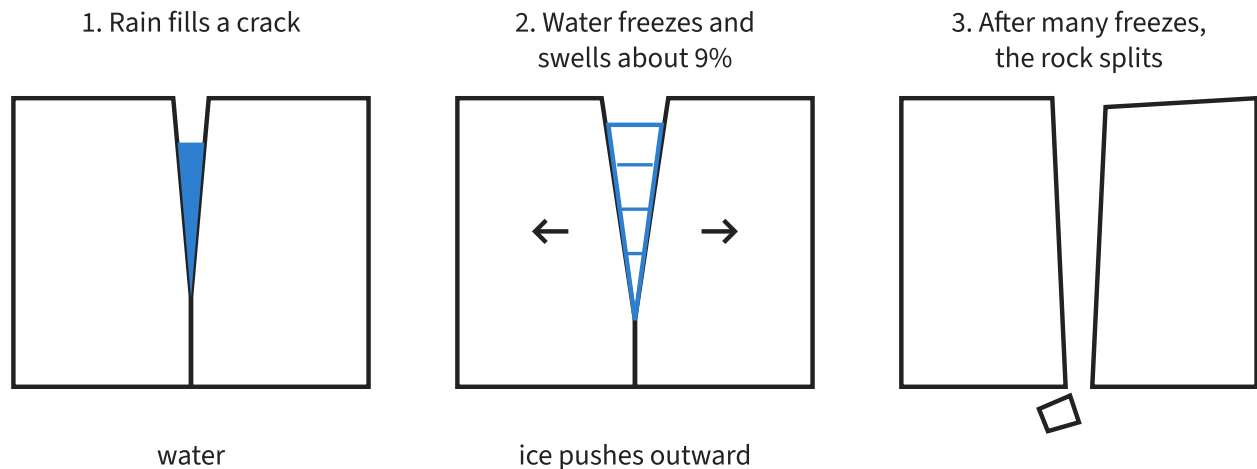
**The story.** For generations, travelers through Franconia Notch in the White Mountains of New Hampshire looked up at a cliff on Cannon Mountain and saw a face. Five ledges of granite, stacked one above another about 1,200 feet (370 m) above Profile Lake, made the profile of an old man with a heavy brow, a sharp nose and a strong chin, about 40 feet (12 m) from top to bottom. People called him the Old Man of the Mountain. Nathaniel Hawthorne wrote a story about him, and New Hampshire put him on its highway signs and, in 2000, on its state quarter. Then, on the morning of May 3, 2003, park workers looked up through the clouds and saw that the face was gone. During the night the ledges had slid down the mountainside in a heap of broken rock.

**How it happened.** The Old Man was not struck by lightning or knocked down by an earthquake. He was pried apart by water. Rain and melting snow trickled into the cracks between the ledges. On cold nights the water froze, and water swells by about 9 percent when it turns to ice. Ice growing in a crack works like a wedge driven by a hammer (see the diagram). Then the sun thawed it, more water ran deeper into the opened crack, and the next freeze pushed again. People noticed the cracks widening early in the twentieth century. Workers climbed onto the stone forehead and fastened the ledges with steel rods and turnbuckles, and for decades caretakers filled the cracks and covered them to keep the water out. The repairs bought many years, but freeze after freeze, the ice won.

**The big idea.** The breaking down of rock where it sits is called **weathering**. Carrying the broken pieces away, by running water, wind, ice or plain gravity, is called **erosion**. Weathering comes in two kinds. **Mechanical weathering** breaks rock into smaller pieces without changing what it is made of. Ice in cracks, called **frost wedging**, is the great mechanical weatherer of cold mountains. Plant roots do the same work more slowly: a seed lodges in a crack, its root thickens year by year, and the crack opens. At Ta Prohm, a temple at Angkor in Cambodia, the roots of giant trees have pried apart stone walls and lifted whole doorways. Salt crystals growing in the pores of desert rock, and sand scraping in wind and rivers, break rock too. **Chemical weathering** changes the minerals themselves. Rainwater is a very weak acid, a little like very weak soda water, and over time it dissolves limestone and marble. Iron in rock combines with oxygen and rusts, staining cliffs red and brown; this is **oxidation**. Even the hard feldspar crystals in granite slowly turn into soft clay.

**On the map.** Where does each kind win? Frost wedging works best where the temperature swings above and below freezing again and again: high mountains such as the Rockies and the Alps, and places like New England, where one winter can bring dozens of freeze-and-thaw days. At the foot of many mountain cliffs lies a slope of sharp-edged broken blocks called talus, pried off by ice. Chemical weathering is fastest where it is warm and wet, so in tropical rain forests rock can rot into deep red clay many feet thick. In limestone country, such as central Kentucky, rainwater soaking underground has dissolved whole passageways; Mammoth Cave there is the longest known cave system in the world, with more than 400 miles (650 km) mapped. In dry deserts both kinds work slowly, and bare rock can keep sharp edges for a very long time.

**Watching it happen.** Weathering is usually too slow to see in a day, but you can measure it within a lifetime. Walk through an old churchyard. Slate gravestones carved two hundred years ago often still have crisp letters, while marble stones of the same age beside them can be so blurred by rain that the names are hard to read. Sidewalks heave where tree roots grow beneath them, and streets in northern cities break into potholes every spring, because water seeps into small cracks in the pavement and freezes. Weathering is not only a destroyer. It is the first step in making **soil**: broken and rotted rock, mixed with the remains of plants and animals, becomes the ground that grows our food. The same slow work that took the Old Man of the Mountain makes the earth fruitful.



*Frost wedging: water fills a crack, freezes and swells, and after many freezes the rock splits.*

## PICTURE STUDY



*Chalk Cliffs on Rügen*, Caspar David Friedrich, about 1818 · Oil on canvas · Museum Oskar Reinhart, Winterthur, Switzerland



Caspar David Friedrich was a German painter who loved mountains, seashores and the quiet light of morning. In 1818 he married Caroline Bommer and took her to the island of Rügen in the Baltic Sea, where he had walked as a young man. Afterward he painted this view of white chalk cliffs plunging toward the sea, framed by trees. Many think the three figures are Friedrich, his wife and his brother.

Chalk is a soft white rock made of countless tiny shells of sea creatures. Rain slowly dissolves it, frost loosens it and waves cut at its foot, so the cliffs of Rügen are always changing. Pieces still crash onto the beach below, most often after wet, frosty winters. Friedrich painted a moment in a long story of weathering and erosion.

### Look closely

- Find the sharp white pinnacles of chalk. What shapes has weathering cut into the cliff?
- Look at the edge where the grass ends and the chalk begins. Where do you think the next piece will break off?
- Find the trees. How might their roots help hold the cliff together, and how might they help break it?
- Look at the three figures. What is each one doing as they look over the edge?

### Talk about it

1. Which kinds of weathering from this lesson would work on a chalk cliff by the sea in a cold northern country?
2. Why might a chalk cliff wear back faster than a granite cliff like Cannon Mountain?
3. Friedrich often painted people looking at the wide world God made. How does this painting make you feel about the size and power of creation?

**Safety first.** Plaster of Paris gets warm as it sets: mix it with a spoon or stick, not your hands, and do not breathe the dry powder. Never pour leftover plaster down a sink; let it harden in the cup and throw it away. Keep vinegar away from eyes.

## PROJECT: BREAKING ROCK IN THE KITCHEN: FOUR WEATHERING TESTS

You will set up four small experiments that copy the four great rock-breakers of this lesson: ice, roots, scraping and acid rain. Some take a few minutes and some take several days, so start them all on the first day and check them during the week. Keep careful notes, just as a geologist would.

### You will need

- A small plastic bottle with a screw cap, and a zip-top bag
- Modeling clay or air-dry clay
- Plaster of Paris, two paper cups and a stirring stick
- Four or five dry beans soaked overnight in water
- Six sugar cubes and a small jar with a lid, plus a handful of small pebbles

- Sidewalk chalk (or a small piece of limestone or a seashell), a clear cup and vinegar
- A pad of steel wool (without soap) and a saucer of water
- Ruler, notebook, pencil and a phone or camera for photos

### Steps

1. **Ice.** Fill the plastic bottle to the very top with water, screw the cap on, seal it in the zip-top bag and freeze it overnight. Next day, look at the bottle's shape. Then make a ball of clay the size of an egg, poke a deep hole in it with a pencil, fill the hole with water, wrap the ball in plastic wrap and freeze it. Thaw it, refill the hole and freeze it again for three or four nights. Record any cracks.
2. **Roots.** Mix plaster of Paris and water in a paper cup to the thickness of pancake batter. Push the soaked beans just under the surface before it sets. Keep the top damp with a few drops of water each day. Over several days, watch for cracks as the seeds sprout and swell.
3. **Scraping.** Put three sugar cubes and the pebbles in the jar and shake hard 100 times. Count how many sharp corners are left and compare with three cubes you did not shake. Shake 100 more times and compare again. This is like stones tumbling in a river or sand blown by wind.
4. **Acid.** Drop the chalk into the cup of vinegar. Watch the bubbles. After 30 minutes and again after a day, measure how much smaller it is than a piece of chalk kept dry.
5. **Rust.** Lay the steel wool in the saucer so it is half in the water and half in the air. Check it after a day and after three days. Where does the orange rust appear first?
6. Make a results table with five rows (ice, roots, scraping, acid, rust) and three columns: what I did, what I saw, mechanical or chemical.
7. Write two sentences: Which test broke the material fastest? Which kind of weathering would win in your own town?

### Tips

- Set the freezing bottle on a tray in the freezer; it may split.
- Vinegar is much stronger than rainwater, so the chalk dissolves in minutes instead of years. Say this in your notes: the experiment speeds up a slow process so you can see it.
- Photograph every test at the start so you can compare later.

### Check your work

- I can tell which of my tests show mechanical weathering and which show chemical weathering.
- I can explain why a full bottle of water bulges or splits when it freezes.
- I can name a place in my town where I have seen each kind of weathering.

## MAP NOTEBOOK

1. Draw a three-panel picture of frost wedging like the diagram, and add a fourth panel of your own showing the broken pieces as talus at the foot of a cliff.
2. Make a two-column chart, Mechanical and Chemical, and list four examples of each that you can find at home or in your neighborhood (cracked sidewalks, rusty nails, roots, blurred gravestones, potholes).
3. Sketch a simple map of your street or yard and mark with symbols every place you find evidence of weathering. Make a key for your symbols.

**From history.** Nathaniel Hawthorne's short story "The Great Stone Face" (1850) was inspired by the Old Man of the Mountain. In it a boy named Ernest grows up in a valley beneath a stone face on the mountainside and waits all his life for a great man who will look like it. In the end the villagers see that Ernest himself, by living humbly and wisely, has come to resemble the face. After the real face fell in 2003, New Hampshire built a memorial beside Profile Lake with steel "profilers" that line up with the cliff so visitors can see where the Old Man once looked out.

## WORKED EXAMPLES

**Example 1.** A crack in a granite ledge holds 200 cubic centimeters (about 12 cubic inches) of rainwater. Water expands by about 9 percent when it freezes. How much room does the ice need, and how much extra room must it push open?

1. Find 9 percent of 200  $\text{cm}^3$ :  $200 \times 0.09 = 18 \text{ cm}^3$ .
2. Add it to the starting volume:  $200 + 18 = 218 \text{ cm}^3$ .
3. In inches: 18  $\text{cm}^3$  is about 1.1 cubic inches (1 cubic inch is about 16.4  $\text{cm}^3$ , and  $18 \div 16.4 \approx 1.1$ ).
4. The ice cannot fit in the old crack, so it presses outward on the rock walls.

**Answer:** The ice needs about 218  $\text{cm}^3$ ; it must push open about 18  $\text{cm}^3$  (about 1.1 cubic inches) of extra space, which is why repeated freezing wedges the crack wider.

**Example 2.** One week of winter weather in a mountain town is shown below (high / low). A freeze-thaw day is a day when the temperature rises above freezing ( $0^{\circ}\text{C}$ ,  $32^{\circ}\text{F}$ ) and also falls below it. How many freeze-thaw days were there?

Mon  $4^{\circ}\text{C}$  /  $-6^{\circ}\text{C}$  ( $39^{\circ}\text{F}$  /  $21^{\circ}\text{F}$ )

Tue  $2^{\circ}\text{C}$  /  $-3^{\circ}\text{C}$  ( $36^{\circ}\text{F}$  /  $27^{\circ}\text{F}$ )

Wed  $-1^{\circ}\text{C}$  /  $-9^{\circ}\text{C}$  ( $30^{\circ}\text{F}$  /  $16^{\circ}\text{F}$ )

Thu  $6^{\circ}\text{C}$  /  $1^{\circ}\text{C}$  ( $43^{\circ}\text{F}$  /  $34^{\circ}\text{F}$ )

Fri  $3^{\circ}\text{C}$  /  $-2^{\circ}\text{C}$  ( $37^{\circ}\text{F}$  /  $28^{\circ}\text{F}$ )

Sat  $8^{\circ}\text{C}$  /  $2^{\circ}\text{C}$  ( $46^{\circ}\text{F}$  /  $36^{\circ}\text{F}$ )

Sun  $5^{\circ}\text{C}$  /  $-4^{\circ}\text{C}$  ( $41^{\circ}\text{F}$  /  $25^{\circ}\text{F}$ )

1. A day counts only if the high is above  $0^{\circ}\text{C}$  *and* the low is below  $0^{\circ}\text{C}$ .
2. Mon: 4 above,  $-6$  below. Yes. Tue: 2 above,  $-3$  below. Yes.
3. Wed: the high,  $-1$ , never got above freezing. No. Thu: the low, 1, never got below freezing. No.
4. Fri: 3 above,  $-2$  below. Yes. Sat: low of 2 stayed above freezing. No. Sun: 5 above,  $-4$  below. Yes.

**Answer:** 4 freeze-thaw days (Monday, Tuesday, Friday and Sunday). On each of those days water in cracks could melt and then freeze again.

**Example 3.** A family measures the letters on two gravestones side by side in an old churchyard. Both were carved in 1820 with letters 6 mm (about  $\frac{1}{4}$  inch) deep. In 2020 the marble stone's letters are only 2 mm deep; the slate stone's letters are 5.5 mm deep. Find the average rate of wearing for each stone. If the marble keeps wearing at the same rate, about when will its letters be gone?

1. Time passed:  $2020 - 1820 = 200$  years.
2. Marble lost  $6 - 2 = 4$  mm. Rate =  $4 \text{ mm} \div 200 \text{ years} = 0.02 \text{ mm per year}$ .
3. Slate lost  $6 - 5.5 = 0.5$  mm. Rate =  $0.5 \div 200 = 0.0025 \text{ mm per year}$ . Marble wore  $0.02 \div 0.0025 = 8$  times faster.
4. Marble has 2 mm left:  $2 \div 0.02 = 100$  more years, so about 2120.

**Answer:** Marble: 0.02 mm a year; slate: 0.0025 mm a year (the marble wears 8 times faster). At that rate the marble letters would be gone around 2120. Rainwater dissolves marble, which is limestone changed by heat and pressure, much faster than it attacks slate.

## PRACTICE

1. **EASY** In one sentence each, define weathering and erosion. What is the key difference?
2. **EASY** Label each as mechanical or chemical weathering: (a) ice in a crack, (b) a rusty red cliff, (c) a tree root splitting a boulder, (d) rain dissolving a limestone cave, (e) sand

blown against a rock, (f) feldspar turning to clay.

3. **EASY** What happened to the Old Man of the Mountain, and on what date was it discovered?
4. **MEDIUM** A full water bottle holds 500 mL (about 17 fluid ounces). About how much space will the water take up after it freezes? (Water expands about 9 percent.)
5. **MEDIUM** Count the freeze-thaw days: Day 1: high 3 °C, low −5 °C. Day 2: high −2 °C, low −10 °C. Day 3: high 7 °C, low −1 °C. Day 4: high 9 °C, low 3 °C.
6. **MEDIUM** Where would chemical weathering work faster: in the hot, rainy Amazon rain forest or in the cold, dry high Arctic? Explain.
7. **MEDIUM** A marble statue in a city park has lost 3 mm of its surface in 150 years. What is the average rate per year? How long would it take to lose 1 cm (10 mm, about 0.4 inch) at that rate?
8. **HARD** Why do streets in cities like Boston and Chicago fill with potholes in late winter and spring more than in midsummer? Use the words frost wedging in your answer.
9. **HARD** Mammoth Cave has more than 400 miles of mapped passages. If the mapped length is 420 miles, how many kilometers is that? (1 mile ≈ 1.61 km.) What kind of weathering made the cave?
10. **CHALLENGE** Write a short paragraph explaining why weathering has to happen before erosion can carry away a mountain, and why weathering is also a gift to farmers.

## COMMON MISTAKES

- Using weathering and erosion as if they meant the same thing. Weathering breaks rock in place; erosion moves the pieces.
- Thinking weathering needs storms. Most weathering is quiet: a freezing night, a growing root, a gentle rain soaking into stone.
- Thinking water shrinks when it freezes. Water is unusual: it expands by about 9 percent as it becomes ice, and that push is what splits rock.

**Make it a game · Break It or Move It?.** One player calls out a happening, such as “ice splits a boulder,” “a river carries sand to the sea,” “a cliff rusts red,” or “wind blows dust across a desert.” The other must shout “Weathering!” or “Erosion!” within five seconds. For weathering, name it mechanical or chemical for a bonus point. Take turns inventing happenings; first to ten points wins.

**Scripture.** “And surely the mountain falling cometh to nought, and the rock is removed out of his place. The waters wear the stones: thou wastest away the things which grow out of the dust of the earth; and thou destroyest the hope of man.” (Job 14:18-19, KJV)

Job, in his grief, noticed what geographers measure: water wears even stone, and mountains crumble. Nothing in creation is so hard that it lasts forever on its own. That is why Scripture points us past the rocks to the Lord, who is called the Rock of His people because He does not wear away.

## Practice answers

1. Weathering is the breaking down of rock where it sits; erosion is the carrying away of the broken pieces by water, wind, ice or gravity. Weathering breaks; erosion moves.
2. (a) mechanical, (b) chemical (oxidation), (c) mechanical, (d) chemical, (e) mechanical, (f) chemical.
3. The granite ledges that formed the face slid down Cannon Mountain during the night; workers saw it was gone on the morning of May 3, 2003. Years of frost wedging had pried the ledges apart.
4.  $500 \times 1.09 = 545$  mL, about 45 mL (1.5 fluid ounces) more than the bottle holds, so the bottle bulges or splits.
5. 2 days (Day 1 and Day 3). Day 2 never thawed and Day 4 never froze.
6. In the Amazon. Chemical weathering works fastest where it is warm and wet, because water is needed for the reactions and warmth speeds them up.
7.  $3 \div 150 = 0.02$  mm per year.  $10 \div 0.02 = 500$  years.
8. In late winter and spring the temperature swings above and below freezing almost every day. Water seeps into small cracks in the pavement, freezes and expands (frost wedging), then melts; the cracks grow until traffic breaks the loosened pieces out. In midsummer there is no freezing, so this does not happen.
9.  $420 \times 1.61 \approx 676$  km. Chemical weathering: rainwater, a weak acid, soaked into the ground and dissolved the limestone.
10. Answers will vary. A good answer explains that water, wind and ice can only carry loose pieces, so solid rock must first be cracked and broken by frost, roots or chemical change; and that weathered rock, mixed with decayed plants and animals, becomes soil, the ground in which crops grow.

## 4.2 RIVERS AT WORK

### OBJECTIVES

- Explain how a river erodes, transports and deposits its load, and why speed controls all three.
- Describe the upper, middle and lower course of a river, from steep V-shaped valleys to wide floodplains with meanders.
- Explain how a meander becomes an oxbow lake, using the Connecticut River's Oxbow (cut off in 1840) as a real example, and calculate a river's gradient and sinuosity.

**Warm-up.** Lay a piece of string on the floor in a wiggly line from one side of the room to the other, then pull it straight. How much longer was the wiggly path than the straight one? Now tilt a cookie sheet a little and pour a slow trickle of water down it. Does the water run straight or start to wiggle? Rivers on gentle slopes love to wiggle, and today you will find out why.

**Watch.** *Why Rivers Move* (Practical Engineering, 17:48).

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

After the story: watch Grady Hillhouse's stream-table model to see how a river cuts away its outside bank and builds up its inside bank, so its loops slowly grow into shapes like the Connecticut River's Oxbow.

**Note:** Captions were not available to check; preview it first. This 18-minute video from a trusted engineering channel may include a short sponsor message (skip it), and the description admits one equation on screen at 11:54 is shown upside down.

**Backup video.** *What types of Landforms are made by Rivers?* (Mr Gedge's Geography Channel, 5:31). [https://www.youtube.com/watch?v=XJ\\_FNS8Z\\_ek](https://www.youtube.com/watch?v=XJ_FNS8Z_ek)

As review: follow a river from its source to the sea and name each landform as it appears: V-shaped valleys, waterfalls, meanders, oxbow lakes, floodplains, levees and deltas. Note: Captions were not available to check; preview it first. This is a British teacher's channel, so expect British terms such as 'upper, middle and lower course'.

### KEY TERMS

#### load

Everything a river carries: dissolved minerals, mud and clay floating in the water, and sand and stones rolled along the bottom.

#### gradient

How steeply a river drops, given as the fall in height for each unit of distance (for example, meters per kilometer or feet per mile).

#### V-shaped valley



A narrow, deep valley cut by a fast, steep river that wears mostly downward; the upper course of a river.

**meander**

A wide, looping bend in a river flowing across gentle, flat land.

**cut bank and point bar**

The steep bank on the outside of a bend, where fast water erodes, and the sloping sand bank on the inside, where slow water deposits.

**oxbow lake**

A curved lake left behind when a river cuts across the neck of a meander and abandons the old loop.

**CORE IDEAS**

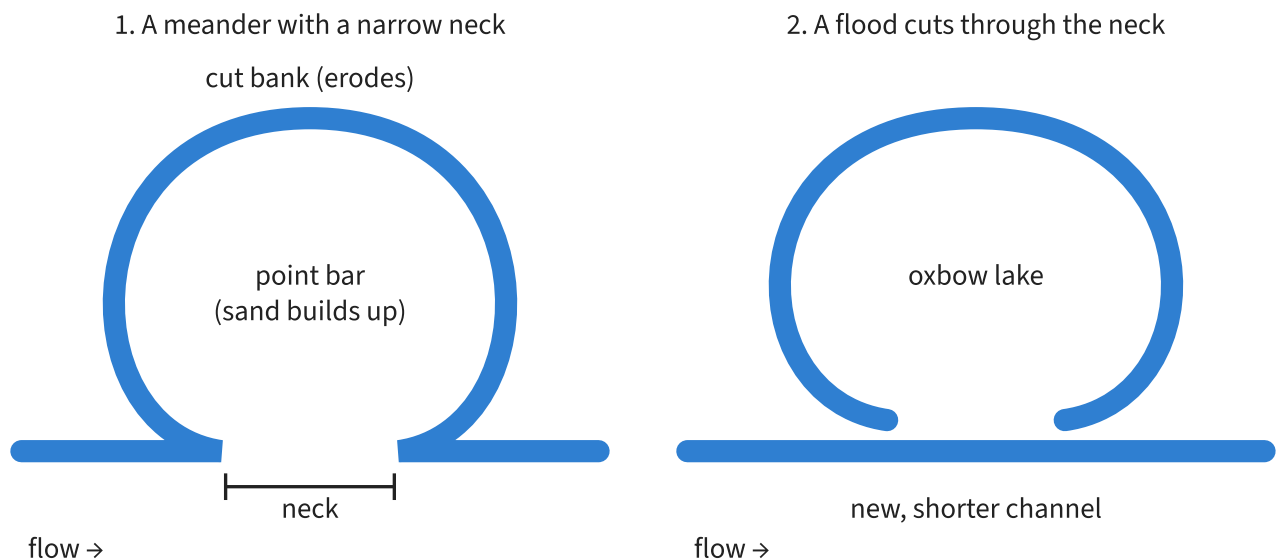
**The story.** In 1836 the painter Thomas Cole climbed Mount Holyoke in western Massachusetts and looked down on the Connecticut River. Below him the river made a huge loop, swinging far out to one side and coming almost all the way back to where it started, around a broad tongue of farmland. People called the loop the Oxbow, because its shape was like the U-shaped wooden collar that went around an ox's neck. Cole painted the view with a thunderstorm passing over the hills, and the picture became one of the most famous American landscapes. Four years later, in 1840, the river did something the painting could not show. During a flood it broke through the narrow neck of land at the start of the loop and took the short way across. The old loop was left behind as a curved lake. You can still find it on a map of Northampton, still called the Oxbow.

**How a river works.** A river does three jobs. It **erodes**, scouring its bed and banks with the sand and pebbles it drags along. It **transports** its **load**: some minerals dissolved in the water, fine mud and clay floating in it (which is why rivers run brown after a storm), and sand and stones rolled and bounced along the bottom. And it **deposits**, dropping its load wherever it slows down. Speed is the key to all three. Fast water can carry big stones; as water slows it drops the pebbles first, then the sand, and last of all the fine mud. A river in flood, fast and deep, can move more material in a few days than in all the rest of the year. The speed depends mostly on the river's **gradient**, how steeply it drops, and on how much water is flowing.

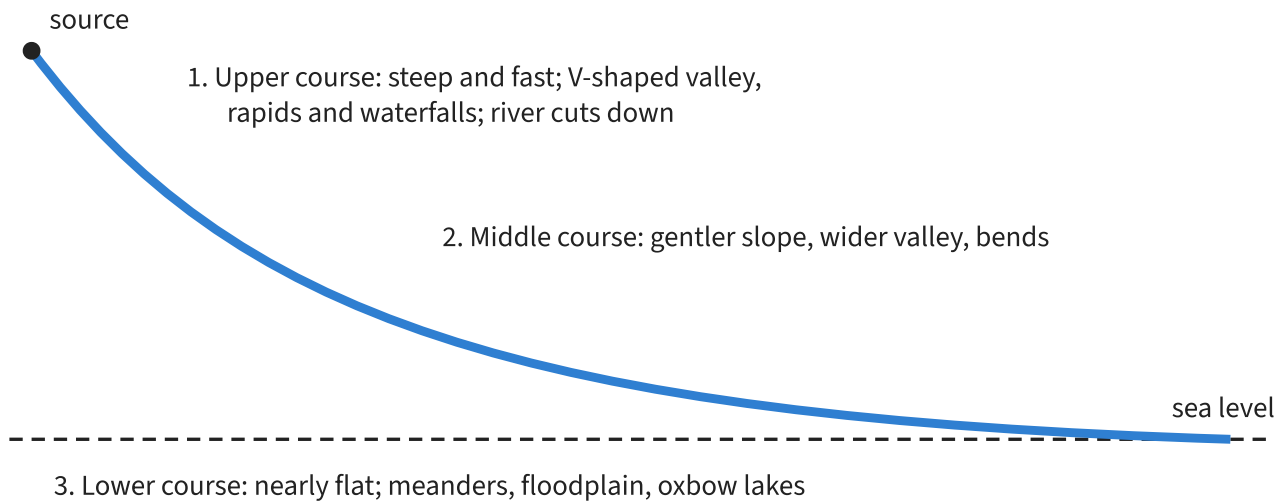
**Youthful valleys.** High in the hills a river runs steep and fast. It spends its strength cutting down into its bed, so its valley is narrow and deep, shaped like the letter V, with rapids and waterfalls. The Grand Canyon of the Yellowstone, where the Lower Falls plunge 308 feet (94 m), is a fine example. Around 1900 the geographer William Morris Davis called such steep V-shaped valleys "youthful," wider valleys with gentle bends "mature," and broad plains with lazy loops "old." His names describe the *shape* of a valley, not its age, so many geographers today simply say the upper, middle and lower course of a river (see the river profile). Waterfalls show cutting in action. Niagara Falls eats backward into its own cliff as the water undercuts soft rock beneath a hard cap layer. In the 1800s the edge of the Horseshoe Falls was wearing back about 3 feet (1 m) a year; today it wears back much more slowly, because much of the river is sent through tunnels to power plants.

**Meanders and oxbow lakes.** Down on the plains the slope is gentle, and a river begins to swing from side to side in loops called **meanders**. (The word comes from the Maeander, a winding river in Turkey now called the Büyük Menderes.) Watch any bend. The water on the outside of the curve runs fastest and deepest, digging into the bank and making a steep **cut bank**. On the inside of the curve the water slows and drops sand, building a gently sloping **point bar**. So each bend is eaten on one side and built up on the other, and slowly the whole loop grows and wanders across the valley. When two bends eat toward each other, the land between them becomes a narrow **neck**. Sooner or later a flood pours across the neck, the river takes the shortcut, and sand seals off the ends of the old loop. What remains is an **oxbow lake**, just like the one at Northampton (see the diagram).

**On the map.** Fly over the lower Mississippi valley and you will see dozens of crescent-shaped lakes, old bends left behind, such as Lake Chicot in Arkansas. Because meanders move, rivers make tricky borders. In 1881 a flood sent the Mississippi into a new channel at Kaskaskia, Illinois, the state's first capital. The river now flows east of the town, so Kaskaskia is still part of Illinois but sits on the Missouri side of the river and is reached by bridge from Missouri. Steamboat pilots knew this restlessness well: they had to keep relearning the river as bends shifted and sandbars moved. Whenever you see a river on a map, read its shape like a story: straight and steep in the hills, looping and wandering across the lowlands.



*How a meander becomes an oxbow lake. The outside of each bend erodes; the inside builds up; a flood cuts the neck.*



*The long profile of a river: steep in the upper course, gentle in the lower course.*

## PICTURE STUDY



*View from Mount Holyoke, Northampton, Massachusetts, after a Thunderstorm (The Oxbow)*, Thomas Cole, 1836 · Oil on canvas · The Metropolitan Museum of Art, New York

Thomas Cole was born in England in 1801 and came to America as a young man. He became the leader of the painters later called the Hudson River School, who painted American mountains, rivers and forests with wonder and care. He painted *The Oxbow* for an exhibition in New York in 1836.

Cole split his picture in two. On the left is wild country: a storm, a shattered tree and dark forest. On the right is the sunny valley, where farmers have cleared fields along the river. In the middle the Connecticut River bends around its great loop. Four years later a flood cut

through the neck of that loop, so the river in this painting no longer flows this way. Look closely and you will find Cole himself, painting at his easel near the bottom of the picture.

### **Look closely**

- Trace the river with your finger. Where does it start its loop, and where does it come back? Find the narrow neck of land the flood later cut through.
- Find a sandy point bar on the inside of the bend. Where would the cut bank be?
- Compare the left and right sides of the painting. What is different about the sky, the trees and the land?
- Find the tiny painter at his easel. Why might Cole have put himself in the picture?

### **Talk about it**

1. If you stood on Mount Holyoke today, what would look different about the river? Why?
2. Why do you think farmers settled on the flat land inside the river's loop?
3. Cole shows wild land and farmed land side by side. What do you think he wanted viewers to think about?

## **PROJECT: A STREAM TABLE IN A PAINT TRAY**

A paint-roller tray is a ready-made river valley: the sloped ridged part is the land, and the deep well at the bottom is the sea or lake. You will build a valley of damp sand, run a steady stream of water down it and watch a river erode, carry and deposit, just as real rivers do. You will keep using this stream table for the rest of the unit, so build it well.

### **You will need**

- A plastic paint-roller tray (a new one, not used for paint)
- Play sand, about 4 cups, mixed with a handful of garden soil or a little fine clay
- A paper or plastic cup with a pencil-point hole in the bottom, or a plastic bottle with a small hole in the cap
- A pitcher of water and a turkey baster or cup to empty the well
- Two or three books to prop up the tray
- Toothpicks with small paper flags, a ruler, a piece of string
- A few small pebbles and a pinch of colored sand or ground coffee to show movement
- Old towels, and a phone or camera for photos

### **Steps**

1. Set the tray on towels. Mix the sand and soil with just enough water that it holds a shape when squeezed. Pack it 3 to 4 cm (about 1½ inches) deep over the sloped part of the tray, and leave the deep well empty. Smooth it flat.
2. Prop the high end of the tray on one book. Press a small hollow at the top of the sand for the river's source.

3. Hold the dripping cup over the source and keep it filled from the pitcher so the flow stays slow and steady. Watch for 5 minutes. Photograph the river every minute.
4. Sprinkle a little colored sand at the top. Watch where it travels and where it settles. Which bits move fastest: pebbles, sand or the fine soil that clouds the water?
5. Look at the bends. Put a toothpick flag on a cut bank (outside of a bend) and another on a point bar (inside of a bend). Check them after 5 more minutes. Which flag falls over first?
6. Measure the river: lay string along the curving channel from source to well, then measure the straight distance. Divide channel length by straight length to find its sinuosity.
7. Make an oxbow: pinch two bends close together with your fingers so only a thin neck of sand separates them. Pour a quick “flood” from the pitcher and see if the river cuts across.
8. Smooth the sand, add a second book to make the slope steeper and run the river again. Compare the shape of the channel and the speed of the water.
9. Empty the well with the baster when it fills. Save the sand damp in a bag for Lesson 4.3.

### Tips

- The slower and steadier the flow, the better the meanders. A fast pour cuts a straight ditch.
- Fine soil in the sand helps the banks hold their shape, as clay does in real riverbanks.
- Write the slope (one book or two) and the time on each photo so you can compare runs.

### Check your work

- I can point to erosion, transport and deposition in my stream table.
- I can find a cut bank and a point bar and explain why each forms.
- I can describe how the river changed when I made the slope steeper.

### MAP NOTEBOOK

1. Draw your stream-table river from above after 10 minutes. Label the source, a cut bank, a point bar and the mouth, and add an arrow showing which way the water flows.
2. Draw the four stages of an oxbow lake in a strip: a gentle bend, a growing loop, a narrow neck, and the cutoff with the oxbow lake.
3. Find a river near your home on a map or satellite view. Trace a section of it in your notebook and mark any meanders or oxbow lakes you can see.

**From history.** Mark Twain (Samuel Clemens) trained as a Mississippi steamboat pilot in 1857 and held a pilot’s license until the Civil War closed the river to trade in 1861. In *Life on the Mississippi* he described how a pilot had to memorize every bend, bar and snag of more than a thousand miles of river, upstream and down, by day and by night, and then learn it all over again as the river changed. His pen name came from the river too: “mark

twain” was the leadsman’s call for a depth of two fathoms, 12 feet (3.7 m), just enough water for a steamboat.

## WORKED EXAMPLES

**Example 1.** The Mississippi River begins at Lake Itasca, Minnesota, about 1,475 feet (450 m) above sea level, and flows about 2,340 miles (3,770 km) to the Gulf of Mexico. What is its average gradient? Compare it with a mountain creek that drops 300 m in 3 km (about 1,000 feet in 1.9 miles).

1. Gradient = fall  $\div$  distance.
2. Mississippi in feet:  $1,475 \text{ ft} \div 2,340 \text{ mi} \approx 0.63 \text{ ft per mile}$ .
3. Mississippi in meters:  $450 \text{ m} \div 3,770 \text{ km} \approx 0.12 \text{ m per km}$ , which is 12 cm per kilometer.
4. Mountain creek:  $300 \text{ m} \div 3 \text{ km} = 100 \text{ m per km}$  (about 530 ft per mile).
5. Compare:  $100 \div 0.12 \approx 830$ .

**Answer:** The Mississippi falls only about 0.63 ft per mile (12 cm per km) on average; the mountain creek is more than 800 times steeper. That is why the creek cuts a V-shaped valley while the lower Mississippi meanders across a flat plain.

**Example 2.** Between two river towns 12 km (7.5 miles) apart in a straight line, a river winds through meanders for 30 km (18.6 miles). What is its sinuosity? Geographers usually call a river meandering if its sinuosity is more than 1.5. Is this river meandering?

1. Sinuosity = channel length  $\div$  straight-line distance.
2.  $30 \text{ km} \div 12 \text{ km} = 2.5$  (in miles:  $18.6 \div 7.5 \approx 2.5$ , the same answer).
3. 2.5 is greater than 1.5.

**Answer:** Sinuosity is 2.5: the water travels two and a half times as far as a crow would fly. Yes, it is a strongly meandering river.



**Example 3.** In *Life on the Mississippi* (1883), Mark Twain, a former river pilot, wrote as a joke: “In the space of one hundred and seventy-six years the Lower Mississippi has shortened itself two hundred and forty-two miles.” What average shortening per year is that, in miles and in kilometers? Why would it be foolish to use this rate to predict the river’s length far into the future?

1. Rate = 242 miles  $\div$  176 years = 1.375 miles per year (Twain called it “a trifle over one mile and a third”).
2. In kilometers: 242 miles  $\times$  1.61  $\approx$  390 km, and 390  $\div$  176  $\approx$  2.2 km per year.
3. Cutoffs happen suddenly in floods, not steadily, and after a cutoff new bends grow and lengthen the river again. Meanders lengthen and cutoffs shorten, so the river stays in a rough balance.

**Answer:** About 1.4 miles (2.2 km) a year. Twain was poking fun at people who stretch a short record far into the future: as he put it, “One gets such wholesale returns of conjecture out of such a trifling investment of fact.” A real river keeps growing new bends, so it does not keep shrinking.

## PRACTICE

1. **EASY** What is a meander?
2. **EASY** On which side of a river bend does the bank erode, and on which side does sand build up? Name each landform.
3. **EASY** What happened to the Connecticut River’s Oxbow, painted by Thomas Cole in 1836?
4. **MEDIUM** A mountain stream falls 600 m in 40 km. What is its gradient in meters per kilometer? In feet per mile? (600 m  $\approx$  1,970 ft; 40 km  $\approx$  24.9 miles.)
5. **MEDIUM** A river flows 45 km (28 miles) along its channel between two bridges that are 15 km (9.3 miles) apart in a straight line. Find its sinuosity.
6. **MEDIUM** Kaskaskia, Illinois, lies on the west side of the Mississippi River, though the rest of Illinois is east of the river. Explain how this happened.
7. **MEDIUM** In the 1800s the Horseshoe Falls at Niagara wore back about 1 m (about 3 feet) a year. At that rate, how far would the edge move in 150 years? Give meters and feet.
8. **HARD** Look at the river profile diagram. In which course would you expect (a) waterfalls and rapids, (b) oxbow lakes, (c) the fastest-moving stones on the river bed? Explain one of your answers.  
(Use the map or drawing “Use the river profile.” shown earlier in this lesson.)
9. **HARD** To measure a river’s speed, you drop a cork into the water and time it: it floats 20 m (about 66 feet) in 25 seconds. What is the speed in meters per second and in feet per second? About how many kilometers per hour is that?
10. **CHALLENGE** William Morris Davis called steep V-shaped valleys “youthful” and wide, looping valleys “old.” Explain why these words describe a valley’s shape rather than its age, and what names many geographers prefer today.



## COMMON MISTAKES

- Thinking the inside of a bend erodes fastest. The fast water swings to the outside, so the outside bank (cut bank) erodes and the inside (point bar) builds up.
- Thinking rivers stay in one place. Meanders migrate across their valleys, and floods can move a river miles in a single night.
- Reading “youthful” and “old” valleys as ages. Davis’s terms describe shapes: steep and V-shaped, or wide and meandering.

**Make it a game • River Pilot.** One player draws a winding river on a large sheet of paper with a few bends, sandbars (point bars) and one narrow neck. The other is the pilot and must steer a toy boat or coin down the deep channel. Rule: the deep water is always on the *outside* of a bend. Each time the pilot strays onto the inside of a bend, they “run aground” and lose a point. At the narrow neck, roll a die: a 6 means a flood cuts the neck, and the pilot may take the shortcut. Switch roles and redraw.

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

Solomon watched the great cycle God built into creation: rain falls on the hills, runs down to the sea, rises again as vapor and falls once more. Every river at work is part of that faithful round.

### Practice answers

1. A wide, looping bend in a river flowing across gentle, flat land.
2. The outside of the bend erodes, forming a steep cut bank. The inside builds up, forming a point bar.
3. In 1840 a flood cut through the narrow neck of the loop; the river took the shortcut, and the old loop was left as an oxbow lake near Northampton, Massachusetts.
4.  $600 \div 40 = 15$  m per km.  $1,970 \div 24.9 \approx 79$  ft per mile.
5.  $45 \div 15 = 3$ . The river is strongly meandering.
6. A flood in 1881 moved the Mississippi into a new channel east of the town. The state border stayed where it was, so Kaskaskia remained in Illinois but ended up on the Missouri side of the river.
7.  $150 \times 1 \text{ m} = 150 \text{ m}$ ;  $150 \times 3.28 \approx 490$  feet (using 3 ft a year gives 450 ft, so about 450 to 490 feet).
8. (a) the upper course, (b) the lower course, (c) the upper course. The upper course is steepest, so water runs fastest and cuts downward, making rapids, falls and V-shaped valleys and moving big stones; the lower course is nearly flat, so the river meanders and leaves oxbow lakes.
9.  $20 \div 25 = 0.8$  m per second;  $66 \div 25 \approx 2.6$  ft per second.  $0.8 \times 3.6 \approx 2.9$  km per hour (about 1.8 miles per hour).
10. Davis’s words describe what a valley looks like: steep, narrow and cutting down, or wide, flat and meandering. A steep valley is not necessarily new; it is steep because of the slope and the

hardness of the rock. Many geographers prefer the plain terms upper course, middle course and lower course.

## 4.3 DELTAS AND FLOODPLAINS

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### OBJECTIVES

- Explain how floods build floodplains and natural levees, and how a river builds a delta where it meets the sea.
- Describe the Nile's yearly flood and the Mississippi's delta lobes, and explain why a delta switches its course over time.
- Read maps of the Nile and Mississippi deltas and use them to estimate areas, gradients and rates of change.

**Warm-up.** Stir two spoonfuls of garden soil into a tall clear jar of water, set it down and start a timer. Watch for five minutes. What sinks first? What is still floating at the end? Leave the jar overnight and look at the layers in the morning. Rivers sort their mud in just the same way when they slow down.

**Watch.** *Why Engineers Can't Control Rivers* (Practical Engineering, 15:52).

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

With On the map: watch how the Mississippi tries to shift toward the Atchafalaya and why engineers built the Old River Control Structure.

**Note:** Captions were not available to check; preview it first. Practical Engineering videos usually include a sponsor message, so skip it. The video runs about 16 minutes. The video does not cover the Nile or the Aswan High Dam.

### KEY TERMS

#### **floodplain**

The wide, flat land beside a river that is built of mud and sand laid down by floods.

#### **natural levee**

A low ridge along a riverbank, built when floodwater slows as it leaves the channel and drops its coarsest sand right beside the river.

#### **silt**

Fine grains of rock, smaller than sand and larger than clay, that rivers carry and drop to make rich soil.

#### **delta**

New land built of river mud where a river slows and drops its load as it enters a sea or lake, named for the Greek letter Δ.

#### **distributary**

A smaller channel that branches off a river and flows away from it, carrying water and mud out across a delta.

#### **delta lobe**

One part of a delta built while the river flowed in one course; when the river switches course, it begins a new lobe.

## CORE IDEAS

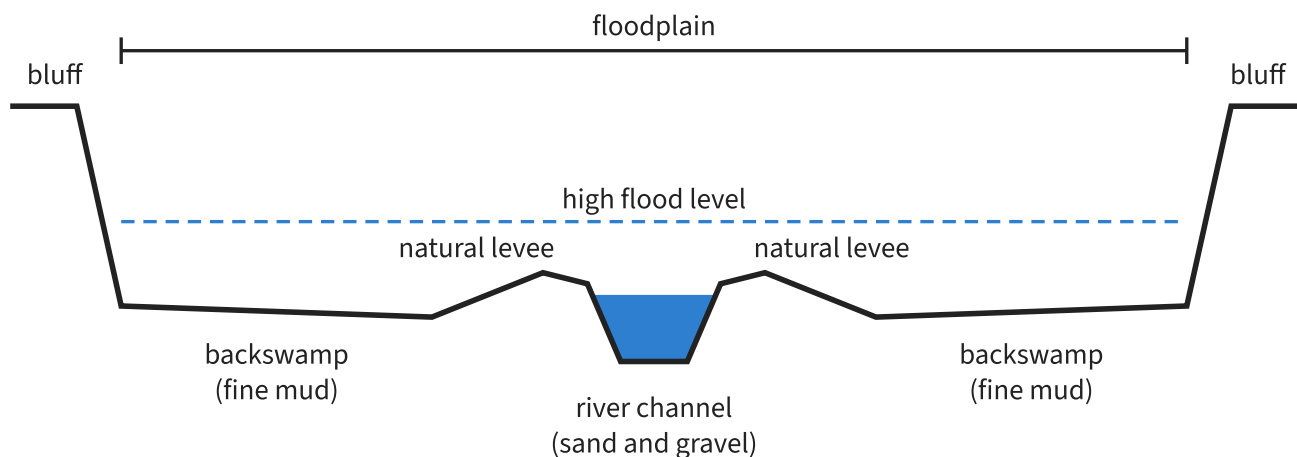
**The story.** Around 450 BC the Greek traveler Herodotus sailed to Egypt and wrote down everything he could learn about it. He noticed that the land near the sea was flat, black and soft, utterly unlike the rocky desert hills on either side. The priests told him that long ago nearly all of Egypt north of Thebes had been a marsh, and Herodotus reasoned that the land had been laid down by the river; Egypt, he wrote, was the gift of the river. He reported that a sailor who let down a weighted line a full day's sail out from shore would still bring up mud, from about 11 fathoms, or 66 feet (20 m), deep. The Greeks gave this land a name we still use. The great triangle where the Nile splits and spreads toward the sea is called the **Delta**, after the Greek letter Δ.

**How the flood worked.** Herodotus puzzled over why the Nile rose every summer, when most rivers in his world ran low. The answer lies far to the south. Each summer heavy rains fall on the highlands of Ethiopia, and the Blue Nile and the Atbara River rush down full of dark mud. The flood reached Egypt in late summer, spread over the valley floor for weeks and then sank back, leaving a fresh layer of rich black **silt** on the fields. Farmers sowed wheat and barley in the wet mud as the water went down. The Egyptians called their country Kemet, "the Black Land," after that dark soil, and the desert beyond it Deshret, "the Red Land." They measured each year's flood with Nilometers, stone stairways or shafts marked in cubits, because the height of the flood told them how good the harvest would be.

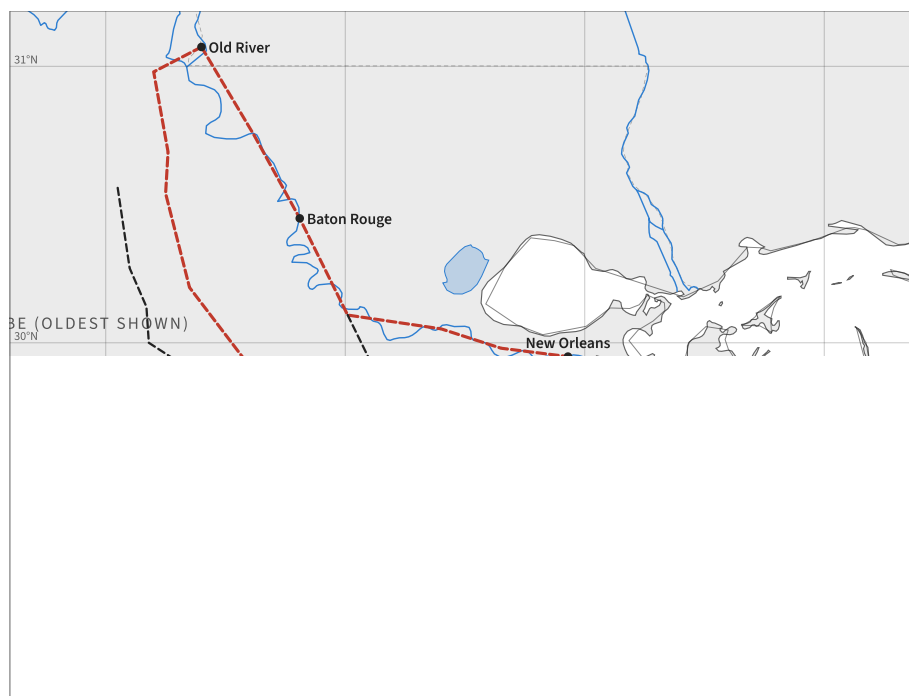
**The big idea.** When a river spills over its banks, the water spreading across the valley slows at once. It drops its coarsest sand right beside the channel, building low ridges called **natural levees**; the finer mud settles farther out in low, wet backswamps. Flood after flood, these layers build a wide, flat **floodplain** (see the cross-section). Where the river reaches the sea, it slows almost to a stop and drops the rest of its load. The mud builds out into the water, and the river splits into smaller channels called **distributaries** that spread the mud into a fan. That new land is a **delta**. A delta's shape shows the contest between river and sea. Strong Mediterranean waves smooth the Nile's delta into a broad arc. The Gulf of Mexico is calmer, so the Mississippi pushes long fingers of mud far out to sea, making a bird's-foot delta.

**On the map: the Mississippi delta through time.** The Mississippi drains about 41 percent of the lower 48 states, and its mud has built all of southern Louisiana. But it does not build in one place forever. As one lobe of the delta grows out into the Gulf, the river's path to the sea gets longer and flatter, and the river slows. Sooner or later, during a flood, it breaks through and takes a shorter, steeper route to the Gulf and starts a new lobe. The old lobe, cut off from fresh mud, settles and is slowly worn back by waves. Geologists, reading the layers of mud and the old channels, have traced the lobes in order: the Teche lobe in the west, the St. Bernard lobe to the east, the Lafourche lobe between them, and today's bird's-foot (see the map). The next switch has already begun: the Atchafalaya River offers the Mississippi a path to the Gulf less than half as long. Since the great flood of 1973, new land has risen out of the water at the mouths of the Atchafalaya and the nearby Wax Lake Outlet, a delta being born within living memory.

**Technology overcoming geography.** People have always wanted the floodplain's rich soil without the danger of the flood. In 1970 Egypt finished the Aswan High Dam. It ended the yearly flood, gave farmers water all year so they could grow two or three crops instead of one, and made electricity for the whole country. But the silt that once fed the fields and the delta now settles in Lake Nasser behind the dam. Egyptian farmers now spread fertilizer, and at the tips of the delta near Rosetta and Damietta the waves began wearing the shore back, so engineers built seawalls and breakwaters to hold it. On the Mississippi, a great control structure at Old River, finished in 1963, keeps the river from switching to the Atchafalaya, and levees protect towns and farms (Unit 8). Yet levees also keep the river's mud off the marshes, and engineers continue to debate how to let some of it reach them again. Good stewardship weighs both sides of every trade.

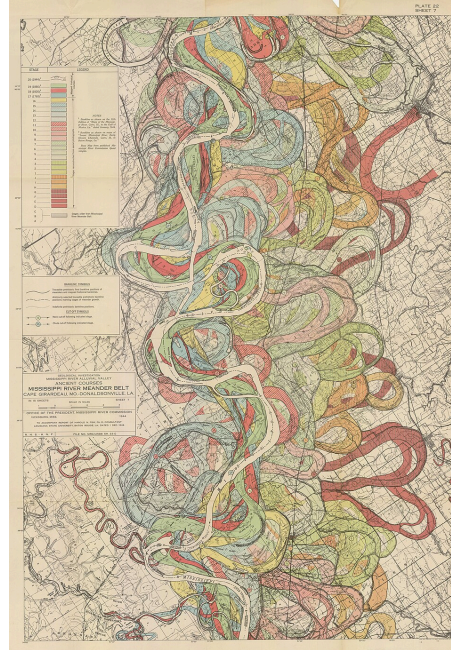


*A floodplain in cross-section. Sand drops beside the channel to build natural levees; fine mud settles in the backswamps.*



*The Mississippi delta through time. Numbers give the order of the lobes from oldest shown (1) to newest (5).*

## PICTURE STUDY



*Ancient Courses, Mississippi River Meander Belt (Plate 22, Sheet 7 of Fisk's report), Harold N. Fisk, for the U.S. Army Corps of Engineers (Mississippi River Commission), 1944 (report dated December 1, 1944) · Color-printed map, one of a set of sheets · Published by the Mississippi River Commission, Vicksburg; copies in many libraries, including the Library of Congress*

In 1944 the geologist Harold N. Fisk published a report on the lower Mississippi valley for the Army Corps of Engineers. Using thousands of borings, aerial photographs and old survey maps, he traced where the river had flowed in earlier times. He drew each older set of channels in its own color and laid them one on top of another, with today's river in white.

Engineers wanted the maps to plan levees and cutoffs. But people have loved them ever since as works of art, because they show something no single photograph can: a river wandering back and forth across its floodplain, leaving loops and oxbows behind like footprints.

### Look closely

- Find the river of the time the map was made, drawn in white. How many older channels cross it?
- Find a complete loop of an old channel. Is it a meander, an oxbow lake or both?
- Look at the edges of the colored area. What do you think lies beyond them, higher than the floodplain?
- Which colors seem to lie on top of others? What might that tell you about which channels came later?

### Talk about it

1. What does this map tell you about building a town right beside the Mississippi?

2. How is Fisk's map like your stream-table photos taken one minute apart?
3. Why might a map be useful to an engineer and beautiful to an artist at the same time?

## **PROJECT: BUILD A DELTA AND WATCH IT MOVE**

Use your paint-tray stream table from Lesson 4.2. This time you will fill the deep well with water to make a sea, let your river build a delta into it, and then force the river to switch course and build a new lobe. By the end you will have drawn your own "delta through time" map.

### **You will need**

- Your paint-tray stream table and damp sand from Lesson 4.2
- Water to fill the well about two-thirds full
- The dripping cup or bottle and a pitcher
- Three small cups of colored sand (or sand mixed with ground coffee, cornmeal or powdered drink mix) in different colors
- Toothpick flags numbered 1, 2 and 3
- Paper, colored pencils, a ruler and a camera

### **Steps**

1. Pack the sand on the slope as before and fill the well about two-thirds full of still water. This is your sea.
2. Carve a short channel from the source down toward the sea. Mix the first colored sand into the top of the channel.
3. Start a slow, steady flow. Watch where the water meets the still sea. Measure how far the new land reaches into the sea every 2 minutes for 10 minutes, and photograph it.
4. Look for the river splitting into distributaries. Count them. Mark the edge of this first lobe with flag 1.
5. Now cause a switch: build a small sand dam across the channel a little above the sea so the water must break out to one side. Add the second color at the source.
6. Let the river build a second lobe for 10 minutes. Mark it with flag 2. Repeat once more with the third color and flag 3.
7. Look at the first lobe now that no river feeds it. Gently make small waves by rocking a ruler in the sea for 30 seconds. What happens to the old lobe compared with the active one?
8. Draw a map from above of your three lobes, each in its own color, with a key and a title: My Delta Through Time. Compare it with the map of the Mississippi delta lobes.

### **Tips**

- A delta builds best into still water. Let the sea settle before you begin.
- If no delta forms, slow the flow or add a little more fine soil to the sand; the river needs mud to carry.



- Measure from the same mark on the tray each time so your growth numbers can be compared.

### Check your work

- I can show where my river slowed and dropped its load.
- I can point to distributaries and explain why the river split.
- I can explain why my river switched course and what happened to the old lobe.

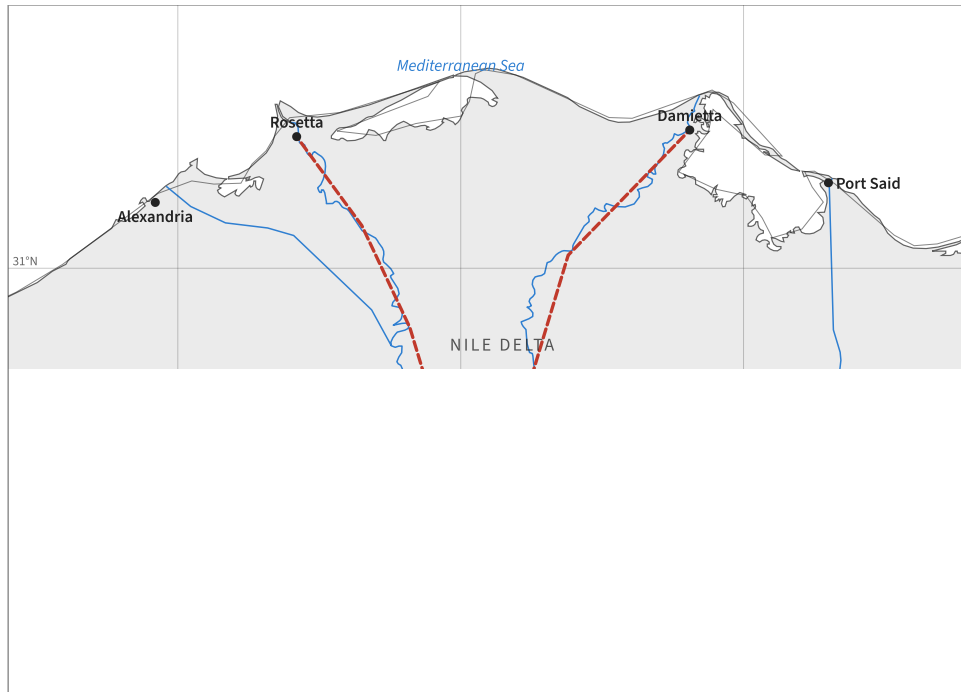
### MAP NOTEBOOK

1. Draw the floodplain cross-section and label the channel, natural levees, backswamps and bluffs. Shade the coarsest sand darker than the fine mud.
2. Trace the Nile delta from the map. Mark Cairo, Alexandria, Rosetta, Damietta and Port Said, and draw the Rosetta and Damietta branches in blue.
3. Copy the Mississippi delta-lobes map in five colors, with a key numbered 1 to 5 from oldest shown to newest. Add an arrow showing where the river would like to go next.

**From history.** In the 1870s the mouths of the Mississippi were choked with sandbars, and big ships often waited days to cross them. The engineer James B. Eads proposed to make the river dig its own channel. Between 1875 and 1879 his crews built long parallel jetties of willow mats and stone at South Pass, narrowing the river so that its faster current scoured the bar away. The channel deepened to about 30 feet (9 m), and New Orleans became a deep-water port again. Eads used the river's own power, the same power that builds deltas, to keep its mouth open.

## WORKED EXAMPLES

**Example 1.** On the map of the Nile delta, the coast from near Alexandria to Port Said is about 240 km (150 miles) long, and the distance from Cairo north to the coast is about 160 km (100 miles). Treat the delta as a triangle and estimate its area in square kilometers and square miles.



*The Nile delta. Use the grid and the cities to estimate distances.*

1. Area of a triangle =  $\frac{1}{2} \times \text{base} \times \text{height}$ .
2. Metric:  $\frac{1}{2} \times 240 \text{ km} \times 160 \text{ km} = 19,200 \text{ km}^2$ .
3. Miles:  $\frac{1}{2} \times 150 \text{ mi} \times 100 \text{ mi} = 7,500 \text{ square miles}$ .
4. Check: 1 square mile  $\approx 2.59 \text{ km}^2$ , and  $7,500 \times 2.59 \approx 19,400 \text{ km}^2$ , which agrees closely.

**Answer:** About 19,000 km<sup>2</sup> (about 7,500 square miles), a little smaller than New Jersey. The real delta bulges outward along the coast, so this triangle is only an estimate.

**Example 2.** From Old River, Louisiana, the Mississippi's own path to the Gulf of Mexico is about 300 miles (480 km) long, while the Atchafalaya's path is about 140 miles (225 km). Suppose the water at Old River stands 15 m (about 50 feet) above the Gulf. Find the average gradient of each path. Which would the water rather take?

1. Mississippi path:  $15 \text{ m} \div 480 \text{ km} \approx 0.031 \text{ m per km}$ , about 3 cm per km ( $50 \text{ ft} \div 300 \text{ mi} \approx 0.17 \text{ ft per mile}$ ).
2. Atchafalaya path:  $15 \text{ m} \div 225 \text{ km} \approx 0.067 \text{ m per km}$ , about 7 cm per km ( $50 \text{ ft} \div 140 \text{ mi} \approx 0.36 \text{ ft per mile}$ ).
3. Compare:  $0.067 \div 0.031 \approx 2$ .

**Answer:** The Atchafalaya path is about twice as steep, so water flows down it faster and more easily. Left alone, more and more of the Mississippi would flow that way; that is why engineers built the Old River Control Structure.

**Example 3.** A river town's gauge shows the top of the natural levee at 12.0 m (39.4 ft). The river now reads 8.5 m (27.9 ft) and is rising 0.7 m (2.3 ft) a day. If it keeps rising at that rate, in how many days will it spill over the levee onto the floodplain?

1. Room left:  $12.0 - 8.5 = 3.5 \text{ m}$  ( $39.4 - 27.9 = 11.5 \text{ ft}$ ).
2. Days:  $3.5 \text{ m} \div 0.7 \text{ m per day} = 5 \text{ days}$  ( $11.5 \div 2.3 = 5 \text{ days}$ ).

**Answer:** In about 5 days. This is how river forecasters warn towns days ahead so people can move livestock, raise goods and prepare sandbags.

## PRACTICE

1. **EASY** What is a delta, and what is a distributary?
2. **EASY** Why did the ancient Egyptians call their land Kemet, "the Black Land"?
3. **EASY** When a river floods, where does it drop its coarsest sand, and what landform does that build?
4. **MEDIUM** Why did the Nile flood every summer even though it almost never rains in Egypt?
5. **MEDIUM** Use the map of the Mississippi delta lobes. (a) Which lobe is the newest? (b) Which abandoned (old) lobe lies farthest east? (c) Which large city sits on the river between Baton Rouge and the bird's-foot?  
(Use the map or drawing "Use the delta-lobes map." shown earlier in this lesson.)
6. **MEDIUM** A new delta grows 50 m (about 165 feet) farther into the sea each year. How far will it grow in 30 years? Give kilometers and miles.
7. **MEDIUM** The Mississippi drains about 1.2 million square miles. About how many square kilometers is that? ( $1 \text{ square mile} \approx 2.59 \text{ km}^2$ .)
8. **HARD** Explain why a river building a delta eventually switches to a new course.

9. **HARD** Name two benefits and two costs of the Aswan High Dam (finished 1970).
10. **CHALLENGE** Herodotus reported that a line let down a day's sail off Egypt brought up mud from 11 fathoms. A fathom is 6 feet. How deep is that in feet and meters? What did the mud far out at sea suggest to him?

## COMMON MISTAKES

- Thinking a levee is always man-made. Rivers build natural levees themselves; engineers later build higher levees on top of them.
- Thinking a delta is always shaped like a neat triangle. Waves, tides and the amount of mud shape it into arcs, fans or a bird's foot.
- Thinking a delta stays in one place. Rivers switch course and build new lobes, while abandoned lobes settle and wear away.

**Make it a game • Delta Builder.** Draw a coastline across a large sheet of paper and a river coming down to it. Players take turns rolling a die and adding that many small squares of new land at the river's mouth with a colored pencil, each player in their own color. On a roll of 1, the river switches: the player draws a new channel breaking out to one side and starts a new lobe there, and the old lobe loses two squares to the waves. After ten rounds, the player who added the most land wins. Then name each lobe like the geologists do.

**Scripture.** "Thou visitest the earth, and waterest it: thou greatly enrichest it with the river of God, which is full of water: thou preparest them corn, when thou hast so provided for it." (Psalm 65:9, KJV)

Egyptian farmers waited on the flood, and Louisiana is built of the Mississippi's mud. The psalmist saw the Lord behind the rivers that water and enrich the land. Floodplains and deltas are some of the most fruitful places on earth because God ordered the rivers to carry soil down to them.

### Practice answers

1. A delta is new land built of river mud where a river slows and drops its load as it enters a sea or lake. A distributary is a smaller channel that branches off the river and carries water and mud out across the delta.
2. Because the Nile's yearly flood left a layer of rich, dark silt on the fields, unlike the red desert (Deshret) beyond.
3. Right beside the channel, where the water first slows; it builds natural levees.
4. Heavy summer rains fell on the highlands of Ethiopia, far to the south. The Blue Nile and the Atbara carried the floodwater and mud north to Egypt, where it arrived in late summer.
5. (a) The Atchafalaya lobe (5). (b) The St. Bernard lobe (2). (c) New Orleans.
6.  $50 \times 30 = 1,500 \text{ m} = 1.5 \text{ km}$ ;  $1.5 \text{ km} \approx 0.93 \text{ mile}$  (about 4,950 feet).
7.  $1.2 \text{ million} \times 2.59 \approx 3.1 \text{ million km}^2$ .
8. As the delta grows into the sea, the river's path gets longer and its slope flatter, so it slows and drops mud in its own channel. During a flood it breaks through to a shorter, steeper route

to the sea and starts building a new lobe.

9. Benefits: it ended dangerous floods, gave farmers water all year for two or three crops, and made electricity. Costs: the silt that fertilized the fields is trapped in Lake Nasser, so farmers must use fertilizer, and the delta coast near Rosetta and Damietta began to wear back, needing seawalls. (Also accept: Lake Nasser flooded Nubian lands, so about 100,000 Nubians had to move and Abu Simbel was relocated; snail-borne schistosomiasis increased along the year-round canals.)
10.  $11 \times 6 = 66$  feet;  $66 \times 0.3048 \approx 20$  m. Finding river mud so far from shore suggested that the Nile carries enormous amounts of mud and has been building the land outward into the sea, so that Egypt's delta is the gift of the river.

## 4.4 GLACIERS

### OBJECTIVES

- Explain how a glacier forms and moves, and how it erodes by plucking and abrasion and deposits moraines and erratics.
- Tell how John Muir measured a living glacier in 1872 and argued that ice carved Yosemite Valley.
- Compare V-shaped river valleys with U-shaped glacial valleys, and explain how ice sheets shaped the Great Lakes, using real heights, depths and rates.

**Warm-up.** Take an ice cube straight from the freezer and press it hard onto a bar of soap or a flat lump of modeling clay, then drag it slowly across. Now sprinkle a pinch of sand on the clay and drag another ice cube over the sand. Compare the two tracks with a magnifying glass. Which one scratched? Ice by itself is soft, but ice armed with rock is a powerful file.

**Watch.** *All About Glaciers for Kids: How Glaciers Form and Erode to Create Landforms* - FreeSchool (Free School, 4:00). <https://www.youtube.com/watch?v=PbYXiJsF5mw>

After the story: watch how snow packs into glacier ice, how the ice slowly flows downhill, and how it carves U-shaped valleys and leaves scratched rock and boulders like the ones John Muir found in Yosemite.

**Note:** Captions were not available to check; preview it first. FreeSchool videos usually suit families, but it may give ice-age dates.

**Backup video.** *Yosemite National Park - UNESCO World Heritage Site* (World Heritage Journey, 5:54). <https://www.youtube.com/watch?v=T72uLA79LcM>

With On the map: tour Yosemite's granite cliffs, waterfalls and valley floor, and look for the smooth, U-shaped valley walls that glaciers left behind. Note: Captions were not available to check; preview it first. This is a general travel tour of the park, so it may say little about glaciers. It works better as a picture of Muir's Yosemite than as a lesson on how glaciers work. The video description puts Yosemite in southern California, but it is in the central Sierra Nevada, as the lesson says.

### KEY TERMS

#### glacier

A thick mass of ice, built from packed snow, that moves slowly under its own weight. A glacier that covers a large part of a continent is an ice sheet.

#### plucking

Glacial erosion in which meltwater freezes onto cracked bedrock and the moving ice tears blocks of rock loose.

#### abrasion

Glacial erosion in which rocks frozen into the bottom of the ice scrape and polish the bedrock, leaving long scratches called striations.

**moraine**

A ridge or heap of mixed clay, sand, gravel and boulders dropped by a glacier where its ice melted.

**U-shaped valley**

A valley with steep walls and a broad, flat floor, carved when a glacier widens and deepens a river valley.

**hanging valley**

A smaller side valley left high above a deeper glacial valley, often with a waterfall pouring from its mouth.

**CORE IDEAS**

**The story.** In 1868 a young Scottish-born wanderer named John Muir walked into Yosemite in California's Sierra Nevada, and it changed his life. He ran a sawmill in the valley, herded sheep in the high country and climbed everywhere with a notebook in hand. He saw granite polished smooth as glass, long scratches running in straight lines across bare rock, and great boulders resting alone on ledges far from any cliff they could have fallen from. Muir became convinced that rivers of ice had once filled Yosemite and carved it. Josiah Whitney, the head of the California Geological Survey, disagreed sharply. He believed the valley floor had simply dropped down between great cracks in the earth, and he waved Muir aside as an untrained shepherd. Muir set out to show that glaciers were more than a guess.

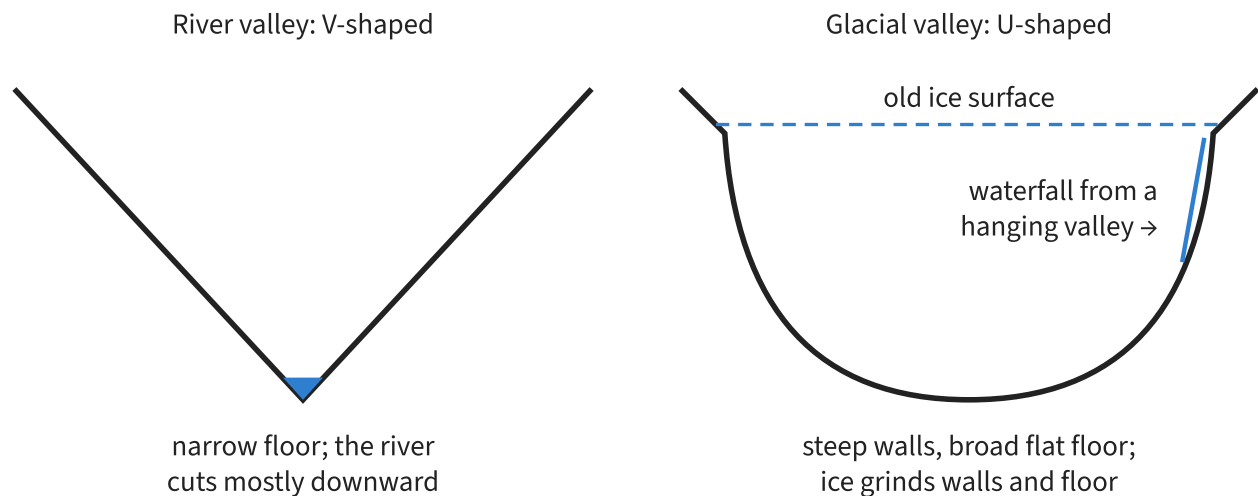
**How he figured it out.** If ice had carved the valley, Muir reasoned, perhaps small glaciers still lived in the shadowed hollows of the high peaks. In the fall of 1871 he found one: below a snowfield on a peak south of the valley, a stream ran milky gray with fine rock flour, the mark of ice grinding stone, and under the snow lay solid blue ice split by cracks. To prove that it moved, in August 1872 he drove a row of stakes across a small glacier on Mount McClure and lined them up with fixed marks. When he returned 46 days later, the stake near the middle had moved 47 inches (about 1.2 m) downhill. The ice was flowing about an inch (2.5 cm) a day. Muir had measured a living glacier with nothing but stakes and patience.

**The big idea.** A **glacier** forms where more snow falls each winter than melts each summer. Year after year the snow piles up, the deep layers are pressed into grainy firn and then into solid ice, and once the ice is thick enough it creeps downhill or spreads outward like thick batter on a griddle. A glacier erodes in two ways. In **plucking**, meltwater freezes onto cracked bedrock under the ice, and the moving glacier tears whole blocks loose. In **abrasion**, the rocks frozen into the bottom of the ice scrape the bedrock like coarse sandpaper, leaving striations and glacier polish and grinding stone into flour. Where the ice melts, it drops everything it carried, from clay to boulders as big as houses, in heaps and ridges called **moraines**. A lone boulder carried far from the rock it came from is called an erratic.



**On the map: Yosemite.** A valley cut by running water is shaped like a V. A glacier is far wider and heavier than a river, so it grinds away the walls as well as the floor and leaves a **U-shaped valley** with steep sides and a broad, flat bottom (see the diagram). Yosemite Valley, about 7 miles (11 km) long and about a mile (1.6 km) wide, is a classic U. El Capitan rises about 3,000 feet (900 m) straight from the valley floor. Side streams whose small valleys were not cut as deep were left hanging high on the walls, and they pour off the edge as waterfalls: Bridalveil Fall drops 620 feet (189 m), and Yosemite Falls, in three steps, 2,425 feet (739 m). Near El Capitan, a moraine left by the melting ice dammed a lake, which later filled with sand and mud to make today's flat meadows. In 1930 François Matthes of the U.S. Geological Survey published a careful study showing that both the river and the ice had done the carving. Muir had been right about the glaciers.

**On the map: the Great Lakes.** Ice once spread far beyond the mountains. A great **ice sheet** covered most of Canada and reached into the northern United States, as ice sheets still cover Greenland and Antarctica today. Long moraines across Ohio, Indiana and Illinois mark where its edge stood, and Long Island in New York is built largely of moraines. Where the ice pushed along lowlands of softer rock, it gouged them deeper and wider into the basins of the five Great Lakes, which together hold about a fifth of all the fresh water on the earth's surface (see the map). The deepest part of Lake Superior lies more than 700 feet (over 200 m) below sea level. The ice was so heavy that it pressed the land down, and the land is still slowly rising back: around Hudson Bay, GPS stations measure the ground rising about 1 centimeter (0.4 inch) a year.



*A river cuts a V; a glacier grinds a U.*



*The Great Lakes, carved and deepened by an ice sheet.*

## PICTURE STUDY



*Yosemite Valley from the Best General View, Carleton E. Watkins, 1866 · Albumen silver print from a glass negative · J. Paul Getty Museum, Los Angeles; other prints in many collections*

Carleton Watkins came to California from New York during the Gold Rush and became one of the first great landscape photographers in America. In 1861 he packed a huge camera onto mules and carried it into Yosemite. His camera used glass plates about eighteen by twenty-two inches, and each one had to be coated, exposed and developed right there on the

mountainside. His photographs helped Americans far away believe that such a place was real, and in 1864 Congress set Yosemite aside to be protected.

Watkins made this picture in 1866 while working with the California Geological Survey, from a spot on the old Mariposa Trail near what is now Tunnel View. Look at it as a geographer as well as an artist. It shows almost the whole U-shaped valley that the glaciers carved and that John Muir and the survey's leader, Josiah Whitney, argued over: El Capitan, Bridalveil Fall in its hanging valley, and Half Dome far up the valley.

### **Look closely**

- Find El Capitan on the left. How do its smooth, steep walls show the work of ice?
- Find Bridalveil Fall on the right. Where does its stream come from, and why does it fall from so high?
- Trace the shape of the valley with your finger from wall to floor to wall. Is it a V or a U?
- Find Half Dome in the distance. How does Watkins make it look far away?

### **Talk about it**

1. What features in this picture would John Muir have pointed to as evidence that glaciers carved the valley?
2. Watkins had to carry a heavy camera and glass plates up the trail. Why do you think he took so much trouble to get this one view?
3. How does a black-and-white photograph help you see shapes and landforms differently from a color one?

## **PROJECT: MAKE A GLACIER AND CARVE A VALLEY**

You will freeze your own small glaciers, one clean and one full of rock, and use them to scratch clay and carve a valley in your stream table. You will see plucking, abrasion and moraines for yourself, and you will turn a river's V into a glacier's U.

### **You will need**

- Two small plastic tubs or a loaf pan (about the size of a stick of butter or larger)
- Gravel, coarse sand and a few small pebbles
- A flat slab of modeling clay about 2 cm ( $\frac{3}{4}$  inch) thick, on a cutting board
- Your paint-tray stream table with damp sand
- A magnifying glass, ruler, towels and a camera

### **Steps**

1. The day before: put a 1 cm ( $\frac{1}{2}$  inch) layer of gravel and sand in the bottom of one tub, add water and freeze it. Freeze the other tub with clean water only. These are your two glaciers.
2. Pop the glaciers out. Turn the gravel one over so the rocks are on the bottom, like a real glacier's base.

3. Press the clean glacier firmly onto the clay and slide it slowly 15 cm (6 inches). Do the same with the gravel glacier on another part of the clay. Compare the two tracks with the magnifying glass. Measure and sketch the striations.
4. Leave the gravel glacier sitting still on the clay at the end of its track until it melts. What is left behind when the ice is gone? That heap is your moraine.
5. In the stream table, press a narrow V-shaped valley into the damp sand with the side of your hand. Photograph it.
6. Push a fresh gravel glacier slowly down the V, pressing downward as you go, three or four times. Photograph the valley again. Has the V become a U?
7. Make a small side valley joining your main valley before you push the glacier, and see whether it is left hanging above the new, deeper floor.
8. Write your results: Which glacier scratched? What shape did the valley become? Where did the moraine form?

### Tips

- Real glaciers move slowly, so push slowly and steadily.
- If the clay is too hard, warm it in your hands first; if the sand slumps, add a little more water.
- Save your clay slab: it is a fine record of striations for your portfolio.

### Check your work

- I can explain why the gravel glacier scratched the clay and the clean one barely did.
- I can show how my glacier changed a V-shaped valley into a U-shaped one.
- I can point to a moraine and say how it formed.

### MAP NOTEBOOK

1. Draw a V-shaped river valley and a U-shaped glacial valley side by side and label each. Add a hanging valley with a waterfall to the U.
2. Sketch the view in *Clearing Winter Storm* from memory as a simple line drawing and label El Capitan, Bridalveil Fall and Half Dome.
3. Trace the Great Lakes from the map. Label each lake, mark Duluth, Chicago, Detroit, Toronto and Buffalo, and draw an arrow showing the ice sheet moving south from Canada.

**From history.** The idea that great sheets of ice once covered much of Europe and North America was championed by the Swiss naturalist Louis Agassiz, who presented it to a scientific society at Neuchâtel in 1837 and published his *Études sur les glaciers* (Studies on Glaciers) in 1840. Agassiz and his helpers camped on the Unteraar Glacier in the Alps, sheltering under a great boulder they nicknamed the “Hôtel des Neuchâtelois,” and measured how the ice moved. Agassiz later moved to America, taught at Harvard and found the same scratched rocks, erratics and moraines across New England and the Great Lakes country.

## WORKED EXAMPLES

**Example 1.** John Muir's central stake on the Mount McClure glacier moved 47 inches in 46 days. What was its average speed in inches and centimeters per day? If it kept that speed all year, how far would it move in a year, in feet and meters?

1. Per day:  $47 \text{ in} \div 46 \text{ days} \approx 1.02 \text{ inches per day}$ .
2. In centimeters:  $1.02 \times 2.54 \approx 2.6 \text{ cm per day}$ .
3. Per year:  $1.02 \times 365 \approx 373 \text{ inches}$ ;  $373 \div 12 \approx 31 \text{ feet}$ .
4. In meters:  $2.6 \text{ cm} \times 365 \approx 950 \text{ cm} \approx 9.5 \text{ m}$ .

**Answer:** About 1 inch (2.6 cm) a day, which would be about 31 feet (9.5 m) in a year. Glaciers move slowly, but they do move, and their speed changes with the seasons.

**Example 2.** Yosemite Falls drops in three steps from its hanging valley: the Upper Fall, 1,430 feet; the middle cascades, 675 feet; and the Lower Fall, 320 feet. What is the total drop in feet and in meters? (1 foot = 0.3048 m.)

1. Total in feet:  $1,430 + 675 + 320 = 2,425 \text{ feet}$ .
2. In meters:  $2,425 \times 0.3048 \approx 739 \text{ m}$ .
3. Check by parts:  $436 \text{ m} + 206 \text{ m} + 98 \text{ m} = 740 \text{ m}$ , which agrees after rounding.

**Answer:** 2,425 feet, about 739 m: one of the tallest waterfalls in North America, pouring from a valley the glacier left hanging.

**Example 3.** The surface of Lake Superior is about 600 feet (183 m) above sea level, and its deepest point is about 1,333 feet (406 m) below the surface. How far below sea level is the deepest part of the lake floor? What does that tell you about how the basin was made?

1. Feet:  $1,333 - 600 = 733 \text{ feet below sea level}$ .
2. Meters:  $406 - 183 = 223 \text{ m below sea level}$ .
3. A river cannot cut its bed below the level of the sea it flows into, but a thick sheet of ice pressing and grinding the land can.

**Answer:** About 733 feet (223 m) below sea level. A basin that deep below the sea points to the gouging power of the ice sheet, not to a river.

## PRACTICE

1. **EASY** What is the difference between plucking and abrasion?
2. **EASY** Describe the shape of a valley carved by a river and one carved by a glacier.
3. **EASY** What is a moraine? What is an erratic?

4. **MEDIUM** A valley glacier in Alaska moves 0.5 m (about 1.64 feet) a day. How far does it move in a year, in meters and feet?
5. **MEDIUM** Bridalveil Fall drops 620 feet. How many meters is that? (1 foot = 0.3048 m.) Why does it fall from such a height?
6. **MEDIUM** Use the map of the Great Lakes. (a) Which lake lies farthest west? (b) Which lake is entirely in the United States? (c) Which city stands at the eastern end of Lake Erie, and which waterfall lies between Lake Erie and Lake Ontario?  
(Use the map or drawing "Use the Great Lakes map." shown earlier in this lesson.)
7. **MEDIUM** The surface of Lake Michigan is about 577 feet (176 m) above sea level, and its greatest depth is about 923 feet (281 m). How far below sea level is its deepest point?
8. **HARD** GPS stations near Hudson Bay show the land rising about 1 cm (0.4 inch) a year. At that rate, how much would it rise in 100 years? Why is the land rising?
9. **HARD** Explain how a hanging valley forms. Name one in Yosemite.
10. **CHALLENGE** Imagine you are John Muir answering Josiah Whitney. List four kinds of evidence you could show that glaciers carved Yosemite Valley, and say what each proves.

## COMMON MISTAKES

- Thinking a glacier is just frozen and still. Glaciers flow downhill or outward under their own weight, as Muir's stakes showed.
- Thinking glaciers carve V-shaped valleys. Rivers cut V's; glaciers widen them into U's.
- Thinking the Great Lakes were dug only by rivers. Rivers cannot cut below sea level, but the lake floors of Superior and Michigan lie far below it; the ice sheet deepened the basins.

**Make it a game • River or Glacier?.** Make cards with landforms and clues: V-shaped valley, U-shaped valley, oxbow lake, moraine, erratic boulder, delta, hanging valley, striations, point bar, rock flour, natural levee, waterfall cutting back. Shuffle and draw. The player must say whether a river or a glacier made it and give one reason. A correct answer with a good reason earns 2 points; a correct guess alone earns 1. Waterfalls are a trick card: both can make them, so the player earns 2 points for explaining both ways.

**Scripture.** "Out of whose womb came the ice? and the hoary frost of heaven, who hath gendered it? The waters are hid as with a stone, and the face of the deep is frozen." (Job 38:29-30, KJV)

In Job 38 the Lord takes Job on a tour of creation and asks him who made the ice. Muir and Agassiz spent their lives studying ice and still marveled at it. The power that carved Yosemite and the Great Lakes belongs to the Creator, who knows every snowflake that ever fell to make a glacier.

## Practice answers

1. In plucking, the ice freezes onto cracked bedrock and tears blocks loose. In abrasion, rocks frozen in the bottom of the ice scrape and polish the bedrock, leaving striations.
2. A river cuts a narrow V-shaped valley. A glacier carves a wide U-shaped valley with steep walls and a flat floor.
3. A moraine is a ridge or heap of mixed clay, sand, gravel and boulders dropped where a glacier's ice melted. An erratic is a lone boulder carried by ice far from the rock it came from.
4.  $0.5 \times 365 = 182.5$  m, about 600 feet ( $182.5 \times 3.28 \approx 599$ ).
5.  $620 \times 0.3048 \approx 189$  m. Its stream flows from a hanging valley: the glacier in the main valley cut far deeper than the small side valley, leaving it high on the cliff.
6. (a) Lake Superior. (b) Lake Michigan. (c) Buffalo; Niagara Falls.
7.  $923 - 577 = 346$  feet;  $281 - 176 = 105$  m below sea level.
8.  $100 \times 1 \text{ cm} = 100 \text{ cm} = 1 \text{ m}$  (about 3.3 feet). The heavy ice sheet once pressed the land down; with the ice gone, the land is slowly springing back up.
9. A large glacier in the main valley cut much deeper than the small glaciers or streams in the side valleys. When the ice melted, the side valleys were left high above the deepened main floor, so their streams pour off the cliff as waterfalls. Examples: the valleys of Bridalveil Fall or Yosemite Falls.
10. Any four, well explained: polished granite and striations (rock dragged under moving ice); erratic boulders far from their source (carried by ice); moraines, including the one near El Capitan (dropped by melting ice); the U shape of the valley (ice grinds walls as well as floor); hanging valleys with waterfalls (the main valley was deepened far more than the side valleys); living glaciers in the high peaks that really move, like the one Muir measured at about an inch a day.



## UNIT 4 REVIEW

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Answer each question. Show your work for calculations, give both metric and U.S. units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (5 pts) Define weathering and erosion, and give one real example of each.
2. (6 pts) Label each as mechanical or chemical weathering: (a) frost wedging, (b) a rusty red cliff, (c) roots lifting the stones of Ta Prohm, (d) rain dissolving a marble gravestone, (e) salt crystals growing in desert rock, (f) feldspar turning to clay.
3. (5 pts) A crack holds 300 mL of water. Water expands about 9 percent when it freezes. What volume will the ice need? Explain how this brought down the Old Man of the Mountain.
4. (6 pts) Draw a meander and label the cut bank and the point bar. Then explain in three or four sentences how a meander becomes an oxbow lake.
5. (6 pts) A river falls 900 m over 60 km. Find its gradient in meters per kilometer and in feet per mile ( $900\text{ m} \approx 2,950\text{ ft}$ ;  $60\text{ km} \approx 37.3\text{ miles}$ ). Would you expect a V-shaped valley or wide meanders? Why?
6. (5 pts) A river winds 36 km (22.4 miles) between two towns that are 12 km (7.5 miles) apart in a straight line. Find its sinuosity. Is it meandering?
7. (6 pts) Explain why the Nile flooded every summer, why the Egyptians called their land Kemet, and one way the Aswan High Dam (1970) changed the delta.
8. (7 pts) Using the map of the Mississippi delta through time, list the lobes in order from oldest shown to newest. Explain why the river switches lobes, and why the Atchafalaya “wants” to capture the Mississippi.
9. (6 pts) A stake on a glacier moves 92 cm in 46 days. Find its speed in cm per day, and how far it would move in a year in meters and feet.
10. (8 pts) Name four features of Yosemite Valley or the Great Lakes that show the work of ice, and explain how ice made each one.

### UNIT PROJECT: STREAM TABLE FIELD REPORT: A LANDSCAPE IN A PAINT TRAY

Assemble a field report of your stream-table work from this unit. Include dated photos or drawings of your river at several stages, your measurements of gradient (slope) and sinuosity, your hand-drawn map “My Delta Through Time” with each lobe in its own color, and your glacier experiment with the striated clay slab or a drawing of it. Add a large hand-drawn map of the real Mississippi delta lobes, numbered from oldest shown to newest, and label Baton Rouge, New Orleans, Morgan City and Old River.

Finish with a one-page explanation, in your own words, of how weathering, rivers and glaciers worked in your models and how the same processes shaped the Old Man of the Mountain, the Connecticut River’s Oxbow, the Nile and Mississippi deltas and Yosemite Valley.

- **Observation:** Photos or drawings are dated and labeled, and they clearly show erosion, deposition, a delta, a delta switch and glacial carving.

- **Measurement:** Gradient, sinuosity and delta growth are measured, calculated correctly and given with units.
- **Maps:** The model delta map and the Mississippi delta-lobes map are accurate, neat, colored and keyed, with lobes in the correct order.
- **Explanation:** The written explanation uses the key terms correctly and links each model to a real place from the unit.

#### Answer key

1. Weathering is the breaking down of rock where it sits (example: ice splitting the ledges of the Old Man of the Mountain). Erosion is the carrying away of broken rock by water, wind, ice or gravity (example: a river carrying sand to the sea).
2. (a) mechanical, (b) chemical, (c) mechanical, (d) chemical, (e) mechanical, (f) chemical. One point each.
3.  $300 \times 1.09 = 327$  mL, 27 mL more than the crack holds. Each freeze pushed the crack wider; meltwater ran deeper and froze again, and after many freeze-thaw cycles the granite ledges were pried loose and fell in 2003.
4. Drawing: cut bank on the outside of the bend, point bar on the inside. The outside of each bend erodes while the inside builds up, so the loop grows until two bends nearly meet at a narrow neck. A flood cuts across the neck, the river takes the shortcut, and sand seals off the old loop, leaving an oxbow lake (as at the Connecticut River's Oxbow in 1840).
5.  $900 \div 60 = 15$  m per km;  $2,950 \div 37.3 \approx 79$  ft per mile. A V-shaped valley, because such a steep river runs fast and cuts downward.
6.  $36 \div 12 = 3$  ( $22.4 \div 7.5 \approx 3$ ). Yes; it is greater than 1.5, so it is strongly meandering.
7. Summer rains on the Ethiopian highlands swelled the Blue Nile and Atbara, which carried the flood and mud north to Egypt in late summer. The flood left dark silt, so Egypt was Kemet, "the Black Land." The dam ended the flood but traps the silt in Lake Nasser, so farmers need fertilizer and the delta coast near Rosetta and Damietta began wearing back (any one change).
8. Teche, St. Bernard, Lafourche, bird's-foot (today), Atchafalaya. As a lobe grows, the river's path gets longer and flatter and it slows, so in a flood it breaks out to a shorter, steeper route. The Atchafalaya offers a path to the Gulf less than half as long, so it is about twice as steep.
9.  $92 \div 46 = 2$  cm per day.  $2 \times 365 = 730$  cm = 7.3 m, about 24 feet.
10. Any four, 2 points each: the U shape of Yosemite Valley (ice ground walls and floor); hanging valleys with waterfalls like Bridalveil and Yosemite Falls (main valley deepened more than side valleys); polish and striations (abrasion by rocks frozen in the ice); erratics (boulders carried by ice); the moraine near El Capitan (dropped by melting ice); Great Lakes basins dug below sea level (gouged by the ice sheet); moraines in Ohio, Indiana, Illinois and Long Island; land still rising near Hudson Bay (pressed down by the ice).

## CLIMATE AS PHYSICAL GEOGRAPHY

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Every place on earth has its own climate: the long pattern of heat and cold, rain and drought, that shapes what grows there and how people live. In this unit you will learn that climate is **physical geography**, as real and as mappable as a river or a mountain range. It is made by causes you can observe and measure: the **latitude** that sets the angle of the sun, the **altitude** that cools the air, the **prevailing winds** that carry moisture from the sea, the **mountains** that wring the rain out of the air and leave dry lands behind them, and the nearness or distance of the **ocean**.

You will start on July 4, 1776, with Thomas Jefferson buying a thermometer in Philadelphia, and learn the difference between one day's weather and a place's climate. You will stand with Eratosthenes beside a well at Syene, sail the trade winds with Edmund Halley, and float down the Columbia with Lewis and Clark from the dry plains east of the Cascades to the soaking rain of Fort Clatsop. Finally you will meet Wladimir Köppen, the botanist-weatherman who used plants as nature's instruments to sort the climates of the world into a system of letters still printed in nearly every atlas.

Along the way you will keep a weather log, measure sunlight on a slant, build a sponge mountain that makes its own rain shadow, and draw climographs of mystery cities. The unit ends with your own Köppen climate map of the world. Units 5 and 7 pair naturally: in Unit 7 you will add the ocean currents that carry heat from the tropics toward the poles.

### BEFORE YOU BEGIN

- Can find the equator, the poles and lines of latitude on a globe (Grades 3-5)
- Can read a bar graph and a line graph and find an average
- Can multiply and divide decimals and convert between inches and millimeters
- Knows the water cycle: evaporation, condensation and precipitation

### MASTERY CHECKLIST

- I can explain the difference between weather and climate and read a climograph.
- I can explain why the tropics are warm and the poles cold, using the angle of the sun's rays, and find the noon sun angle at a given latitude.
- I can estimate how much cooler a mountain is than the lowlands below it.
- I can draw and explain how prevailing winds and mountains make a wet windward side and a dry rain shadow, using the Cascades as an example.
- I can name Köppen's five main climate groups and give a city its Köppen code from its monthly data.
- I can read a Köppen climate map of the world and explain its patterns with latitude, altitude, winds, mountains and the sea.

## OPTIONAL BOOKS AND RESOURCES

- **National Weather Service** (<https://www.weather.gov/>): Free. Look up today's weather and the climate normals (30-year averages) for your own town to compare with your weather log in Lesson 5.1 and to draw your own climographs.
- **NOAA SciJinks** (<https://scijinks.gov/>): Free. Short, clear articles and pictures for students on weather, seasons, wind and climate, from NOAA and NASA.
- **NASA Earth Observatory** (<https://earthobservatory.nasa.gov/>): Free. Satellite images of clouds, snow and deserts. Search for images of the Cascades or the Andes to see rain shadows from space. A parent may want to choose the images.

## 5.1 WEATHER AND CLIMATE ★

### OBJECTIVES

- Tell the difference between weather (the state of the air today) and climate (the long pattern of a place), and name the elements that describe both.
- Read a climograph to find a place's wettest and driest months, its yearly precipitation and its temperature range, in both U.S. and metric units.
- Tell how Thomas Jefferson kept weather records from July 4, 1776, and begin a weather log of your own with a homemade rain gauge and a shaded thermometer.

**Warm-up.** Step outside (or look out a window) for two minutes. Without a phone, write down five things about the air right now: Is it warm or cold? Is it wet or dry? Which way is the wind blowing, and how hard? What do the clouds look like? Then write one sentence answering a different question: "What is the weather usually like here in this month?" Notice that the first list was about today and the sentence was about many years. That is the whole lesson in one minute.

**Watch.** *ESS2D - Weather and Climate* (Bozeman Science, 7:48).

<https://www.youtube.com/watch?v=gLT1J8je5lo>

With the big idea: listen for the difference between weather (today's temperature, wind and rain) and climate (the usual pattern over many years), and what controls each.

**Note:** Captions were not available to check; preview it first. The image credits list a '2000 Year Temperature Comparison' chart, so the video may briefly discuss claims about a changing climate. The last part is a teaching guide for teachers and can be skipped.

**Backup video.** *How climate graphs work* (Geography Lessons, 3:41).

[https://www.youtube.com/watch?v=faEVT\\_48ZK8](https://www.youtube.com/watch?v=faEVT_48ZK8)

Before the project: learn to read a climate graph, with temperature shown as a line and rainfall as bars for each month, and use the graph to work out whether a place is near the equator, near the poles, in a desert or by the coast. Note: Captions were not available to check; preview it first. The graphs probably use Celsius and millimeters, and the narrator may not be a native English speaker. The lesson calls this a climograph; the video calls it a climate graph.

### KEY TERMS

#### weather

The condition of the air at one place and one time: its temperature, precipitation, humidity, wind, air pressure and clouds.

#### climate

The long-term pattern of weather in a place, measured by averages and ranges over many years, including how it changes through the seasons.

**precipitation**

Water that falls from the sky as rain, snow, sleet or hail, measured as a depth in inches or millimeters.

**climate normal**

An official average for a weather station, worked out from 30 years of records and updated every ten years.

**climograph**

A graph of a place's climate showing average precipitation for each month as bars and average temperature for each month as a line.

**annual temperature range**

The difference between the average temperature of the warmest month and that of the coldest month.

**CORE IDEAS**

**The story.** On July 4, 1776, Thomas Jefferson was in Philadelphia while the Continental Congress approved the Declaration of Independence he had drafted. That same busy day he did something small: he bought a new thermometer from a Philadelphia shopkeeper named John Sparhawk, and he began writing down the temperature. His notes say it was 68°F (20°C) at six in the morning and 76°F (24°C) at one in the afternoon. A few days later he bought a barometer to measure air pressure. Those numbers describe the **weather** on one famous day: how warm the air was, hour by hour, in one city.

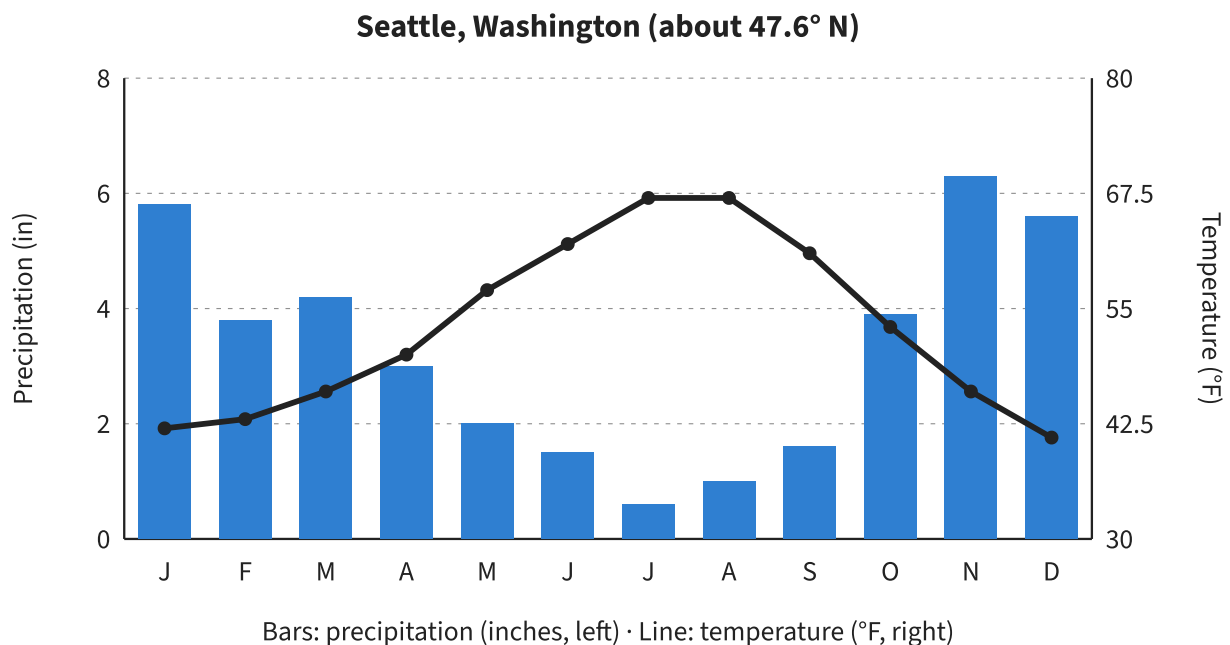
**How they figured it out.** Jefferson did not stop with one day. For decades he wrote down temperatures, winds and rain, at home at Monticello in Virginia and wherever he traveled. He urged friends to do the same, and James Madison kept a weather journal at his home, Montpelier. Jefferson knew that one day's numbers tell you very little about a place, but years of numbers side by side reveal its pattern: when the last frost comes, which months are wet, how hot summer usually gets. In 1870 Congress set up a national weather service, and from 1890 thousands of volunteer observers began sending in daily readings, just as Jefferson had dreamed. Today the government averages 30 years of those records for each station. These averages are called **climate normals**, and they are updated every ten years.

**The big idea.** **Weather** is what the air is doing now: its temperature, **precipitation**, humidity, wind, air pressure and clouds. It can change in an hour. **Climate** is the long pattern of weather in one place: the averages, the usual highs and lows, and the rhythm of the seasons. An old saying puts it simply: climate is what you expect, weather is what you get. A cold week in July does not change a place's climate, any more than one bad grade changes a student's whole report card. Geographers draw climate on a **climograph**: bars show the average precipitation of each month, and a line shows the average temperature. One glance tells you whether a place is hot or cold, wet or dry, and whether its rain comes in summer or winter.

**On the map.** Look at the climograph of Seattle, Washington (figure). Seattle gets about 39 inches (about 1,000 mm) of precipitation a year, but almost none of it falls in July and

August. Its coldest month averages about 41°F (5°C) and its warmest about 67°F (19°C), a mild, small range. Now look at Fargo, North Dakota, at almost the same latitude in the middle of the continent: its January averages only about 10°F (−12°C), more than 30°F colder than Seattle’s. Why? In the rest of this unit you will meet the physical causes that give each place its climate: **latitude** and the angle of the sun, **altitude**, the **prevailing winds**, **mountains** that block rain, nearness to the **ocean** and the currents in it. Climate is physical geography, as real and as mappable as rivers and mountains.

**Why it matters.** Because climate is a pattern, people can plan by it. Farmers choose crops by the length of the frost-free season; builders design roofs for the usual snow; cities size their storm drains for the usual heavy rains. The Bible promises this kind of steady order: after the Flood, God said that “cold and heat, and summer and winter” would not cease while the earth remains. The weather of a single day may surprise us, but the faithful round of the seasons is something we can count on, measure and map.



*Seattle’s climate at a glance: bars show average monthly precipitation (left scale, inches); the line shows average monthly temperature (right scale, °F). Values are rounded normals for Seattle-Tacoma Airport.*



## PICTURE STUDY



*Cloud Study*, John Constable, 1822 · Oil on paper laid on panel · Yale Center for British Art, New Haven, Connecticut (Paul Mellon Collection)

John Constable was an English landscape painter who loved the open sky. In the summers of 1821 and 1822, at Hampstead Heath on a hill north of London, he painted dozens of quick oil sketches of nothing but clouds. On the backs of many of them he wrote the date, the time of day and the direction of the wind, almost like a weather observer filling in a log.

Constable called the sky the “chief organ of sentiment” in a landscape. He painted fast, because clouds change in minutes. Each sketch is a picture of *weather*: one sky at one moment. Laid side by side, his many sketches begin to show the *pattern* of an English summer sky.

### Look closely

- Find the brightest part of the clouds. Where is the sun shining from?
- Look at the edges of the clouds. Are they sharp or soft? What does that tell you about the moisture in the air?
- Is there any land in the picture? Why do you think Constable left it out?
- Look for brushstrokes that show movement. Which way do you think the wind was blowing?

### Talk about it

1. Constable wrote the date, time and wind on his sketches. Why would a painter want to record the weather like a scientist?
2. Is one cloud sketch a record of weather or of climate? What would you need to describe the climate of Hampstead?

3. Which kinds of clouds do you see most often where you live?

## **PROJECT: MY BACKYARD WEATHER STATION**

Like Jefferson, you will measure the weather every day at the same times and keep a careful log. After two weeks you will compare your numbers with the climate normals for your town and see the difference between weather and climate for yourself.

### **You will need**

- A straight-sided clear jar or plastic bottle with the top cut off (a rain gauge)
- A ruler with inches and millimeters, and waterproof tape
- An outdoor thermometer
- A drinking straw, a pin, a pencil with an eraser, and a card (for a wind vane), plus a compass or phone compass
- A notebook ruled into a weather log with columns: Date, Time, Temperature, Precipitation, Wind direction, Clouds, Notes

### **Steps**

1. Make the rain gauge: tape the ruler to the outside of the jar so that zero is exactly at the inside bottom. Set it in an open place, away from roofs and trees, and wedge it with stones so it cannot tip.
2. Hang the thermometer in the shade about 5 feet (1.5 m) above the ground, out of direct sun. Air temperature is always measured in the shade.
3. Make the wind vane: cut a card arrowhead and tail, slide them into the ends of a straw, and pin the straw at its balance point to the pencil eraser. Mark N, E, S and W around the base with a compass. Remember that a wind is named for the direction it comes *from*.
4. Every day for two weeks, read your instruments at the same two times (for example, 7 a.m. and 4 p.m.). Record temperature in °F and °C, rain in inches and mm, wind direction and a word for the clouds. Empty the rain gauge after each reading.
5. At the end, find your average temperature and your total rain for the two weeks.
6. With a parent, look up your town's climate normals for this month from the National Weather Service. Compare: Was your fortnight warmer or colder, wetter or drier than normal?
7. Write three sentences: one about the weather you measured, one about your town's climate, and one explaining why the two are not the same.

### **Tips**

- A thermometer in the sun can read many degrees too high. Shade is everything.
- If it snows, bring the gauge inside, let the snow melt, and measure the water.
- Reading at the same times every day makes your numbers fair to compare.

### **Check your work**

- I measured the weather at the same times for two weeks and kept a neat log.
- I found an average temperature and a total precipitation.
- I can explain why two weeks of weather do not tell me my town's climate.

## MAP NOTEBOOK

1. Copy Seattle's climograph into your map notebook. Label the wettest month, the driest month and the warmest month.
2. Draw a two-column chart titled "Weather or Climate?" and write five examples in each column.
3. Draw a small outline map of the United States and mark Seattle and Fargo. Beside each, write its January average temperature and one reason you think they differ.

**From history.** On February 9, 1870, President Ulysses S. Grant signed the act that created the first national weather service in the United States. It was run by the Army Signal Corps, which used the telegraph to collect weather reports from many cities at the same hour and send out warnings of storms. In 1891 it became the civilian Weather Bureau, and in 1970 it was renamed the National Weather Service. Its volunteer Cooperative Observers, who have sent in daily readings since 1890, are the reason we know the climate of thousands of American towns today.

## WORKED EXAMPLES

**Example 1.** Use the Seattle climograph. The monthly precipitation (inches) is: Jan 5.8, Feb 3.8, Mar 4.2, Apr 3.0, May 2.0, Jun 1.5, Jul 0.6, Aug 1.0, Sep 1.6, Oct 3.9, Nov 6.3, Dec 5.6. Find the yearly total in inches and in millimeters, and name the wettest and driest months.

*(Use the map or drawing "Read the height of each bar on the left scale." shown earlier in this lesson.)*

1. Add the twelve months:  $5.8 + 3.8 + 4.2 + 3.0 + 2.0 + 1.5 + 0.6 + 1.0 + 1.6 + 3.9 + 6.3 + 5.6 = 39.3$  inches.
2. Convert to millimeters: 1 inch = 25.4 mm, so  $39.3 \times 25.4 \approx 998$  mm, about 1,000 mm.
3. The tallest bar is November (6.3 in). The shortest bar is July (0.6 in).

**Answer:** About 39.3 inches (about 1,000 mm) a year. Wettest: November. Driest: July.

**Example 2.** On the Seattle climograph the warmest months average about  $67^{\circ}\text{F}$  and the coldest month (December) about  $41^{\circ}\text{F}$ . Find the annual temperature range in  $^{\circ}\text{F}$ , and change both temperatures to  $^{\circ}\text{C}$ .

1. Range in  $^{\circ}\text{F}$ :  $67 - 41 = 26^{\circ}\text{F}$ .
2. To change  $^{\circ}\text{F}$  to  $^{\circ}\text{C}$ , subtract 32 and multiply by  $5/9$ .
3.  $67^{\circ}\text{F}$ :  $(67 - 32) \times 5/9 = 35 \times 5/9 \approx 19.4^{\circ}\text{C}$ .
4.  $41^{\circ}\text{F}$ :  $(41 - 32) \times 5/9 = 9 \times 5/9 = 5^{\circ}\text{C}$ .
5. Range in  $^{\circ}\text{C}$ :  $19.4 - 5 = 14.4^{\circ}\text{C}$ . (Check:  $26 \times 5/9 \approx 14.4$ .)

**Answer:** The annual range is  $26^{\circ}\text{F}$  (about  $14^{\circ}\text{C}$ ). Warmest about  $19^{\circ}\text{C}$ , coldest  $5^{\circ}\text{C}$ .

**Example 3.** Jefferson's readings in Philadelphia on July 4, 1776 were  $68^{\circ}\text{F}$  at 6 a.m.,  $72\frac{1}{4}^{\circ}\text{F}$  at 9 a.m.,  $76^{\circ}\text{F}$  at 1 p.m. and  $73\frac{1}{2}^{\circ}\text{F}$  at 9 p.m. Find the average of his four readings and the range for the day. Is this weather or climate?

1. Add:  $68 + 72.25 + 76 + 73.5 = 289.75$ .
2. Divide by 4:  $289.75 \div 4 \approx 72.4^{\circ}\text{F}$ . In Celsius:  $(72.4 - 32) \times 5/9 \approx 22.4^{\circ}\text{C}$ .
3. Range for the day: highest 76 minus lowest 68 =  $8^{\circ}\text{F}$  (about  $4.4^{\circ}\text{C}$ ).
4. These numbers describe one day in one city, so they are weather. To learn Philadelphia's July climate you would need the average of many Julys.

**Answer:** Average about  $72.4^{\circ}\text{F}$  (about  $22^{\circ}\text{C}$ ); range  $8^{\circ}\text{F}$ . These are weather readings, not climate.

## PRACTICE

1. **EASY** Weather or climate? (a) It is snowing in Denver this morning. (b) Phoenix usually gets less than 10 inches of rain a year. (c) A thunderstorm knocked out the power last night. (d) Seattle's summers are usually dry.
2. **EASY** Name four elements that a weather observer measures or records.
3. **EASY** Change  $86^{\circ}\text{F}$  to degrees Celsius.
4. **EASY** A storm drops 2 inches of rain. How many millimeters is that?
5. **MEDIUM** Using the Seattle climograph values (Jan 5.8, Feb 3.8, Mar 4.2, Apr 3.0, May 2.0, Jun 1.5, Jul 0.6, Aug 1.0, Sep 1.6, Oct 3.9, Nov 6.3, Dec 5.6 inches), how many months get less than 2 inches of precipitation? Which are they?  
(Use the map or drawing "Count the bars that stay below the 2-inch line." shown earlier in this lesson.)
6. **MEDIUM** A student recorded these daily high temperatures for one week: 70, 74, 79, 81, 77, 72 and  $73^{\circ}\text{F}$ . Find the average high, to the nearest tenth of a degree.
7. **MEDIUM** Climate normals are averages of 30 years, not 1 year. Why use so many years?

8. **HARD** Seattle's yearly precipitation is about 39.3 inches. November, December and January together get  $6.3 + 5.6 + 5.8$  inches. What percent of the year's precipitation falls in those three months?
9. **HARD** Chicago's coldest month averages about  $-4^{\circ}\text{C}$  and its warmest about  $24^{\circ}\text{C}$ . Find the annual range in  $^{\circ}\text{C}$  and in  $^{\circ}\text{F}$ . Is the range larger or smaller than Seattle's  $26^{\circ}\text{F}$ ?
10. **CHALLENGE** A family visits Seattle for a sunny, dry week in August and goes home saying, "Seattle is a dry place." Using the climograph, write two or three sentences explaining their mistake.

## COMMON MISTAKES

- Using "weather" and "climate" as if they mean the same thing. Weather is now; climate is the long pattern.
- Judging a place's climate by a single day, week or season you happened to experience.
- Reading a thermometer in the sun, or forgetting that a wind is named for the direction it blows from.

**Make it a game • Weather or Climate Lightning Round.** A parent reads quick statements, such as "It is foggy this morning" or "Alaska has long, cold winters." Shout "Weather!" or "Climate!" as fast as you can. Score a point for each right answer and a bonus point if you can turn a weather statement into a climate statement for the same place (for example, "It is foggy this morning" becomes "San Francisco often has summer fog"). Play to ten points.

**Scripture.** "While the earth remaineth, seedtime and harvest, and cold and heat, and summer and winter, and day and night shall not cease." (Genesis 8:22, KJV)

Weather changes from day to day, but God promised a steady round of seasons. That faithful order is what makes climate something we can measure, map and plan by.

### Practice answers

1. (a) weather, (b) climate, (c) weather, (d) climate.
2. Any four of: temperature, precipitation, humidity, wind direction, wind speed, air pressure, cloud cover or cloud type.
3.  $(86 - 32) \times 5/9 = 54 \times 5/9 = 30^{\circ}\text{C}$ .
4.  $2 \times 25.4 = 50.8$  mm, about 51 mm.
5. Four months: June (1.5), July (0.6), August (1.0) and September (1.6). May is exactly 2.0, not less.
6.  $\text{Sum} = 526$ .  $526 \div 7 \approx 75.1^{\circ}\text{F}$ .
7. Any single year can be unusually wet, dry, hot or cold. Averaging 30 years smooths out those odd years so the number shows what is usual for the place.
8.  $6.3 + 5.6 + 5.8 = 17.7$  inches.  $17.7 \div 39.3 \approx 0.45$ , so about 45%, nearly half the year's total in just three months.
9.  $24 - (-4) = 28^{\circ}\text{C}$ . A difference of  $28^{\circ}\text{C}$  is  $28 \times 9/5 \approx 50^{\circ}\text{F}$ . That is nearly twice Seattle's range of  $26^{\circ}\text{F}$ .

10. They judged the climate by one week of weather. August is one of Seattle's driest months (about 1 inch), but Seattle gets about 39 inches (1,000 mm) a year, mostly from October to March. Its climate is wet in winter and dry in summer, not dry all year.

## 5.2 LATITUDE AND THE SUN'S ANGLE

### OBJECTIVES

- Explain why sunlight striking the earth at a high angle heats the ground more than sunlight at a low angle, and why that makes the tropics warm and the poles cold.
- Find the noon sun angle at a given latitude on the equinoxes and solstices, and locate the Tropics of Cancer and Capricorn and the Arctic and Antarctic Circles.
- Tell how Eratosthenes used shadows at Syene and Alexandria to show that the sun's angle changes with latitude, and how Edmund Halley linked the sun's heat to the trade winds.

**Warm-up.** In a dark room, hold a flashlight straight down about 30 cm (1 foot) above a sheet of paper and trace the circle of light with a pencil. Now, keeping the flashlight the same distance away, tilt it to a low slant and trace the light again. Which shape is bigger? Which one looks brighter? The flashlight gave out the same amount of light both times. Where did the difference come from?

**Watch.** *Why Is The Equator Hot & The Polar Regions Cold?* (Earth Science Classroom, 5:44). [https://www.youtube.com/watch?v=ZTIV\\_OB-YBY](https://www.youtube.com/watch?v=ZTIV_OB-YBY)

With the big idea: watch how the sun's rays hit the equator straight on but strike the poles at a low slant, spreading the same light over more ground, and how that uneven heating drives winds and climate.

**Note:** Captions were not available to check; preview it first. 'Earth Science Classroom' is a smaller channel, so listen to make sure the narration is a real teacher and not a computer voice.

### KEY TERMS

#### latitude

Distance north or south of the equator, measured in degrees from 0° at the equator to 90° at the poles.

#### sun angle

How high the sun stands above the horizon, in degrees. At 90° it is straight overhead; at 0° it is on the horizon.

#### Tropic of Cancer and Tropic of Capricorn

The lines of latitude about 23.4° north and 23.4° south. Between them, the noon sun is straight overhead on at least one day each year.

#### Arctic and Antarctic Circles

The lines of latitude about 66.6° north and south. Poleward of them there is at least one day a year when the sun does not set and one when it does not rise.

#### solstice



One of the two days each year (about June 21 and December 21) when the noon sun is overhead at one of the tropics and the day is longest in one hemisphere.

### **equinox**

One of the two days each year (about March 20 and September 22) when the noon sun is overhead at the equator and day and night are nearly equal everywhere.

## **CORE IDEAS**

**The story.** More than two thousand years ago, Eratosthenes, the head of the great library at Alexandria in Egypt, heard a curious report. Far up the Nile at Syene (today Aswan), at noon on the longest day of the year, the sun shone straight down to the bottom of a deep well, and upright posts cast almost no shadow. The sun was straight overhead, or very nearly so. Yet on the same day at noon in Alexandria, far to the north, a pointer still cast a short shadow. Eratosthenes measured the angle of that shadow and found it was about one-fiftieth of a full circle, about 7.2 degrees. The same sun, at the same moment, stood at different heights in the sky in two places, only because one was farther north.

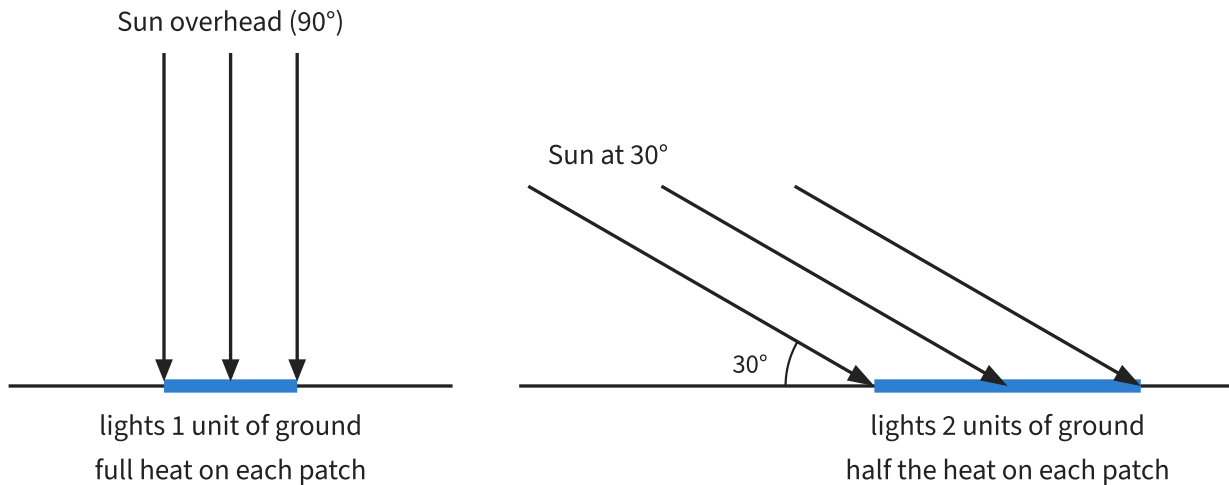
**How they figured it out.** Eratosthenes reasoned that the sun is so far away that its rays arrive parallel. If the ground at Alexandria was tilted 7.2° away from the ground at Syene, then the two cities must sit on a curved earth, one-fiftieth of the way around it. The distance between them was reckoned at about 5,000 stadia, so the whole earth must be about  $50 \times 5,000 = 250,000$  stadia around, a very good estimate. Greek geographers already divided the world into belts by the slant of the sun. Their word for a slope or slant was *klima*, and it is where our word **climate** comes from. To the Greeks, a place's climate was literally its slant toward the sun.

**The big idea.** Sunlight heats the ground best when it strikes straight on. When the sun is high, a beam of sunlight falls on a small patch of ground and all its energy is packed into that patch. When the sun is low, the very same beam is smeared out over a much larger area, so each square meter gets less heat (see the figure). At a sun angle of 30°, the beam covers twice the ground it covers at 90°, so each square gets only half as much. Low sunlight also travels a longer, slanting path through the air, which scatters and absorbs some of it. Near the equator the noon sun is always high, so the tropics stay warm all year. Near the poles the sun never climbs high, so even long summer days stay cool, and in winter the sun may not rise at all.

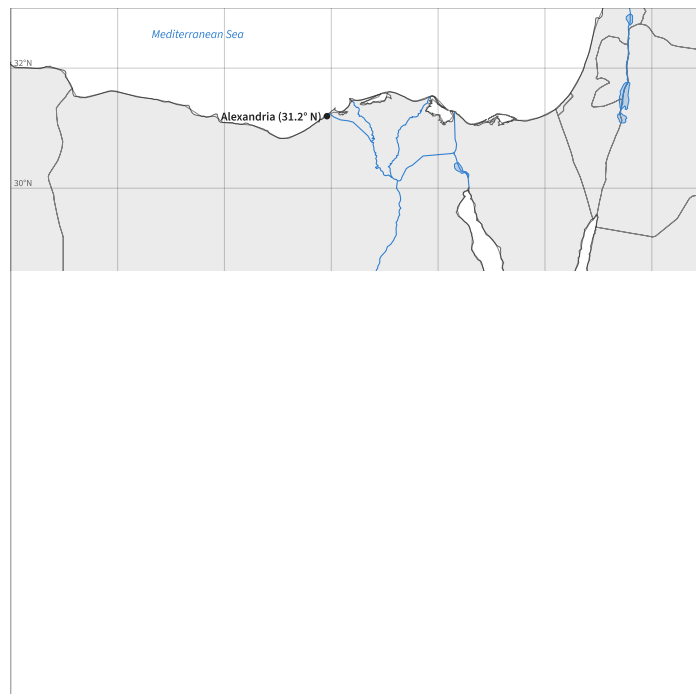
**On the map.** The earth's axis is tilted about 23.4° from upright, and it keeps pointing the same way as the earth travels around the sun. So the place where the noon sun is straight overhead moves north and south through the year: to the **Tropic of Cancer** (23.4° N) at the June **solstice**, back to the equator at the **equinoxes**, and to the **Tropic of Capricorn** (23.4° S) at the December solstice. This gives us the seasons and three great belts. The *tropics* lie between the two Tropic lines. The *polar regions* lie beyond the **Arctic and Antarctic Circles** (66.6°), where there is at least one day of midnight sun and one of polar night. The *middle latitudes* lie between, with warm summers and cold winters. Follow the temperatures down a globe: Singapore, near the equator, averages about 27°C (81°F) for the year; London, at about 51.5° N, about 11°C (52°F); Utqiagvik, Alaska, at about 71° N, about -11°C (12°F).

**Heat on the move.** Latitude is the first and strongest control on climate, but not the only one. Quito, Ecuador, sits almost on the equator, yet because it stands about 2,850 m (9,350 ft) high, it averages only about 14°C (57°F), and you will see why in the next lesson. The extra heat of the tropics also sets the air and sea in motion. In 1686 the astronomer Edmund Halley drew the first map of the world's winds and argued that the sun's heat near the equator makes the air rise, so cooler air flows in from north and south to take its place. Those steady winds are the trade winds, and they carry the sun's gift of heat around the world. The psalmist saw the same sun and wrote that "there is nothing hid from the heat thereof."

### The same beam of sunlight

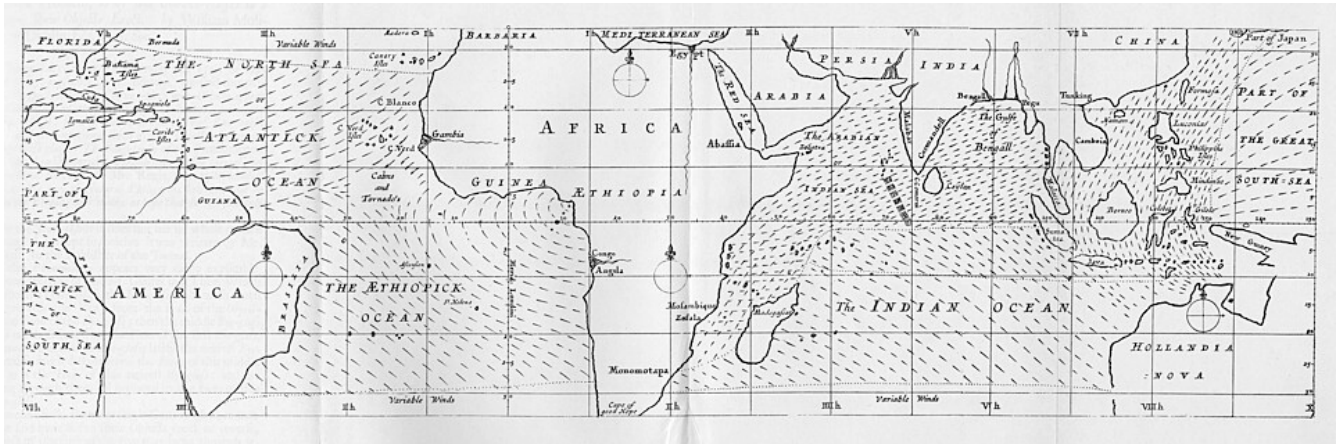


*The same beam of sunlight heats a small patch when the sun is overhead and is spread over twice the area when the sun is 30° above the horizon.*



*Alexandria and Syene (Aswan): about 7° of latitude apart along the Nile.*

## PICTURE STUDY



*A chart of the trade winds and monsoons, from "An Historical Account of the Trade Winds, and Monsoons, Observable in the Seas between and near the Tropicks", Edmund Halley, 1686 · Engraved map, printed in the Philosophical Transactions of the Royal Society, vol. 16 · Published by the Royal Society, London; copies in many libraries*

Edmund Halley, the English astronomer remembered for the comet that bears his name, sailed as a young man to the island of St. Helena in the South Atlantic to map the stars of the southern sky. On the long voyage he felt the steady trade winds for himself. Back in England he gathered reports from sailors and in 1686 published this chart with a paper on the trade winds and monsoons. It is often called the first meteorological map: the first map to show weather patterns over the whole world.

Halley needed a way to draw something invisible. He covered the oceans with rows of little tapering strokes, and explained that the sharp end of each stroke points toward the direction the wind comes from. Where the winds change with the seasons, as in the monsoon seas of the Indian Ocean, he drew them differently.

### Look closely

- Find the equator and the belt of ocean on either side of it. Which way do the strokes point north of the equator, and which way south of it?
- Find the band near the equator where the strokes are few or confused. Sailors called the calm there the doldrums.
- Find the Indian Ocean. How are the winds drawn differently there, where they reverse with the seasons?
- Look at the edges of the chart. About how far north and south of the equator do the steady winds reach?

### Talk about it

1. Why would sailors in the age of sail have valued this map so much?
2. Halley thought the sun's heat near the equator drives these winds. How does that connect to what you learned about the sun's angle?

3. How did Halley show something you cannot see? Can you think of another way to draw wind on a map?

## **PROJECT: SUNLIGHT ON A SLANT**

You will measure, with a flashlight and graph paper, how much the same beam spreads out at different angles, and then test it with real sunlight and two thermometers. You will be repeating, at your kitchen table, the reason the tropics are warm and the poles cold.

### **You will need**

- A flashlight with a narrow beam, and a tube of paper taped around the end to make the beam's edge sharp
- Graph paper with 1 cm squares
- A protractor and a ruler
- Two identical thermometers and two pieces of black construction paper
- Two pieces of stiff cardboard and some books or clay for propping

### **Steps**

1. Darken the room. Hold the flashlight straight down ( $90^\circ$ ) with the end of the tube 15 cm above the graph paper. Trace the spot of light and count the whole squares inside it.
2. Keeping the end of the tube 15 cm from the center of the spot, tilt the flashlight to  $60^\circ$  and then  $30^\circ$  from the paper, using the protractor to check. Trace and count the squares each time.
3. Make a table: Angle, Squares lit. Divide the  $90^\circ$  count by each count to see how much the light spread.
4. On a sunny day, glue black paper to both pieces of cardboard and lay a thermometer on each. Prop one so that it faces the sun squarely (its shadow is as short as possible). Lay the other flat on the ground or tilt it away from the sun.
5. Read both thermometers at the start and every 5 minutes for 20 minutes. Record the readings in  $^\circ\text{F}$  and  $^\circ\text{C}$ .
6. Write a conclusion: Which card warmed faster? Which one is like the equator, and which like the Arctic?

### **Tips**

- Hold the flashlight steady by resting it on a stack of books.
- At  $30^\circ$  you should find roughly twice as many squares as at  $90^\circ$ . Small differences come from the fuzzy edge of the beam.
- Never look at the sun, even for a moment.

### **Check your work**

- I measured how a beam spreads at  $90^\circ$ ,  $60^\circ$  and  $30^\circ$ .
- I tested two cards in real sunlight and recorded the temperatures.

- I can explain why the poles are cold even though the sun shines all day in their summer.

## MAP NOTEBOOK

1. Draw a large circle for the earth. Draw and label the equator, the Tropics of Cancer and Capricorn, and the Arctic and Antarctic Circles with their latitudes, and color the tropical, middle-latitude and polar belts.
2. Copy the sun-angle figure and write under it, in your own words, why the same sunbeam heats a small patch more than a large one.
3. Draw Eratosthenes' two cities: a well at Syene with the sun straight overhead, and a pointer at Alexandria with its shadow. Label the  $7.2^\circ$  angle.

**From history.** Halley's explanation of the trade winds was only half right. He saw that heated air near the equator rises and that air flows in to replace it, but he could not explain why the trade winds blow from the northeast and southeast instead of straight from the north and south. In 1735 a London lawyer named George Hadley gave the answer: because the earth spins, the ground near the equator moves eastward faster than the ground farther north or south, so air flowing toward the equator lags behind and arrives as an east wind. The great loop of rising tropical air is still called the Hadley cell.

## WORKED EXAMPLES

**Example 1.** Seattle is at about  $47.6^\circ$  N. How high is the noon sun there on the March equinox, the June solstice and the December solstice?

1. Rule: noon sun angle =  $90^\circ$  minus the number of degrees between your latitude and the latitude where the sun is overhead.
2. Equinox (sun over the equator,  $0^\circ$ ):  $47.6 - 0 = 47.6^\circ$ , so  $90 - 47.6 = 42.4^\circ$ .
3. June solstice (sun over  $23.4^\circ$  N):  $47.6 - 23.4 = 24.2^\circ$ , so  $90 - 24.2 = 65.8^\circ$ .
4. December solstice (sun over  $23.4^\circ$  S): the gap is  $47.6 + 23.4 = 71.0^\circ$ , so  $90 - 71.0 = 19.0^\circ$ .

**Answer:** About  $42^\circ$  in March,  $66^\circ$  in June and only  $19^\circ$  in December. The low winter sun is one reason Seattle's winters are cool.

**Example 2.** Eratosthenes found the noon shadow at Alexandria to be about  $7.2^\circ$  when the sun was overhead at Syene, and he took the distance between them as 5,000 stadia. (a) What fraction of a circle is  $7.2^\circ$ ? (b) How big did he find the earth? (c) Check his angle with modern latitudes: Alexandria  $31.2^\circ$  N, Aswan  $24.1^\circ$  N. (d) Using 111 km (69 miles) per degree of latitude, about how far apart are the cities?

*(Use the map or drawing “Syene lies just north of the Tropic of Cancer, so the noon sun stands almost over” shown earlier in this lesson.)*

1. (a)  $360 \div 7.2 = 50$ , so  $7.2^\circ$  is  $1/50$  of a circle.
2. (b) If 5,000 stadia is  $1/50$  of the way around, the whole earth is  $50 \times 5,000 = 250,000$  stadia.
3. (c)  $31.2 - 24.1 = 7.1^\circ$ , very close to his  $7.2^\circ$ .
4. (d)  $7.1 \times 111 \approx 790$  km;  $7.1 \times 69 \approx 490$  miles.

**Answer:** (a)  $1/50$ ; (b) 250,000 stadia; (c)  $7.1^\circ$ , almost the same; (d) about 790 km (490 miles).

**Example 3.** A beam of sunlight 1 m wide shines straight down and lights 1 square meter of ground. The same beam then arrives at a sun angle of  $30^\circ$  and lights a strip 1 m wide and 2 m long. How many square meters does it light now, and what fraction of the overhead heat does each square meter receive?

*(Use the map or drawing “Count the lit ground under each beam.” shown earlier in this lesson.)*

1. Area at  $30^\circ$ :  $1 \text{ m} \times 2 \text{ m} = 2$  square meters.
2. The beam carries the same energy as before, now shared among 2 square meters.
3. Each square meter gets  $1 \div 2 =$  one half as much as when the sun was overhead.

**Answer:** 2 square meters; each gets about half the heat it would get from an overhead sun (before even counting the longer path through the air).

## PRACTICE

1. **EASY** Give the latitudes of the Tropic of Cancer, the Tropic of Capricorn and the Arctic Circle.
2. **EASY** What did the Greek word *klima* mean, and why is it a good root for our word “climate”?
3. **EASY** In one sentence, explain why the noon sun heats the ground more at the equator than at the North Pole.
4. **MEDIUM** Find the noon sun angle at Quito, Ecuador (about  $0^\circ$ ), on the March equinox and on the June solstice.

5. **MEDIUM** Miami is at about  $25.8^{\circ}$  N. Find its noon sun angle on the September equinox and on the June solstice.
6. **MEDIUM** Utqiagvik, Alaska, is at about  $71.3^{\circ}$  N. Find its noon sun angle on the June solstice. Then try the December solstice. What does your second answer mean?
7. **MEDIUM** Singapore is at about  $1.3^{\circ}$  N and London at about  $51.5^{\circ}$  N. How many degrees of latitude apart are they, and about how many km and miles north-south is that? (Use 111 km or 69 miles per degree.)
8. **HARD** Suppose Eratosthenes had measured a shadow angle of  $6^{\circ}$  instead of  $7.2^{\circ}$ , with the same 5,000 stadia between the cities. What size would he have found for the earth?
9. **HARD** In June and July, Utqiagvik has daylight for 24 hours, yet its warmest month averages only about  $4^{\circ}\text{C}$  ( $40^{\circ}\text{F}$ ). Give two reasons.
10. **CHALLENGE** Using what you know about the sun's angle, explain in three or four sentences Halley's idea about why the trade winds blow toward the equator.

## COMMON MISTAKES

- Thinking the poles are cold because they are farther from the sun. The whole earth is about the same distance from the sun; the difference is the angle of the rays.
- Thinking the sun is straight overhead at noon everywhere, or that it is ever overhead in the fifty states outside Hawaii. Overhead sun happens only between the tropics.
- Thinking long summer days must make a place hot. Many hours of low, slanting sun can still bring little heat.

**Make it a game • Human Sundial.** On a sunny day, stand on pavement at the same time (near noon) once a week for a month while a partner traces your shadow with chalk and writes the date. Before each tracing, predict whether the shadow will be longer or shorter than last time. Score a point for each correct prediction. In the fall the shadows grow longer as the noon sun sinks lower; in the spring they shrink.

**Scripture.** "His going forth is from the end of the heaven, and his circuit unto the ends of it: and there is nothing hid from the heat thereof." (Psalm 19:6, KJV)

The sun's daily circuit reaches every land, yet it falls on each at its own slant. That ordered slant, set by God when He made the earth and its tilt, is the first cause of every climate on the map.

### Practice answers

1. Tropic of Cancer about  $23.4^{\circ}$  N; Tropic of Capricorn about  $23.4^{\circ}$  S; Arctic Circle about  $66.6^{\circ}$  N.
2. It meant a slope or slant. A place's climate depends first on its slant toward the sun, which is set by its latitude.
3. At the equator the sun is high, so its rays strike nearly straight down and pack their energy into a small area; near the pole the low sun spreads the same energy over a much larger area (and through more air).



4. Equinox:  $90 - 0 = 90^\circ$ , straight overhead. June solstice:  $90 - 23.4 = 66.6^\circ$ .
5. Equinox:  $90 - 25.8 = 64.2^\circ$ . June solstice:  $25.8 - 23.4 = 2.4^\circ$ , so  $90 - 2.4 = 87.6^\circ$ , nearly overhead.
6. June:  $71.3 - 23.4 = 47.9^\circ$ , so  $90 - 47.9 = 42.1^\circ$ . December:  $71.3 + 23.4 = 94.7^\circ$ , so  $90 - 94.7 = -4.7^\circ$ . A negative angle means the sun stays below the horizon even at noon: the polar night.
7.  $51.5 - 1.3 = 50.2^\circ$ .  $50.2 \times 111 \approx 5,570$  km;  $50.2 \times 69 \approx 3,460$  miles north to south.
8.  $360 \div 6 = 60$ , so the earth would be  $60 \times 5,000 = 300,000$  stadia around.
9. Even at noon the sun is never higher than about  $42^\circ$ , so its rays are spread out and pass through a long path of air. Also, snow, sea ice and the cold Arctic Ocean reflect much of the light or use the heat for melting instead of warming the air.
10. The noon sun is high all year near the equator, so the ground and sea there are heated more than at higher latitudes. The heated air expands, becomes lighter and rises. Cooler, heavier air from north and south flows in near the surface to take its place, and these steady flows are the trade winds. (Later George Hadley showed that the earth's spin turns them so they blow from the northeast and southeast.)

## 5.3 ALTITUDE, WINDS AND RAIN SHADOWS

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### OBJECTIVES

- Explain why air grows colder with altitude and use an average rate to estimate the temperature on a mountain.
- Describe how prevailing winds and mountains make a wet windward side and a dry leeward rain shadow, using the Cascade Range of Washington as the example.
- Tell how Lewis and Clark crossed from the dry country east of the Cascades to the rain-soaked coast in 1805, and build a sponge-mountain model of a rain shadow.

**Warm-up.** Breathe on a cold spoon or a mirror. Tiny drops of water appear. Now blow on the back of your hand with your lips pursed tight, then breathe on it slowly with your mouth wide open. Which feels cooler? (The fast, narrow stream pulls in cooler room air as it goes.) High in the sky, air that rises expands and cools down, and cool air cannot hold as much water vapor, so the vapor turns into drops. Keep those two facts in mind: they are the secret of every mountain rain shadow.

**Watch.** *Rain Shadow* (University of Illinois Extension, 2:40).

<https://www.youtube.com/watch?v=iMu4dShS74w>

After the story: watch how moist air rises up a mountain, cools and drops its rain on one side, then sinks dry down the other side, which is why Lewis and Clark found dry sagebrush east of the Cascades and soaking rain on the west.

**Note:** Captions were not available to check; preview it first. This short video comes from University of Illinois Extension, a trusted source.

### KEY TERMS

#### **altitude**

Height above sea level. On average the air cools about  $6.5^{\circ}\text{C}$  for every 1,000 m you climb (about  $3.6^{\circ}\text{F}$  for every 1,000 feet).

#### **prevailing winds**

The winds that blow most often from one direction in a region. Across most of the United States the prevailing winds blow from the west.

#### **windward**

The side of a mountain range that faces the oncoming wind. Rising air there makes clouds and heavy rain or snow.

#### **leeward**

The side of a mountain range sheltered from the wind, where air sinks, warms and dries.

#### **rain shadow**

A dry region on the leeward side of mountains, where the air has already dropped most of its moisture on the windward side.

#### **orographic precipitation**

Rain or snow caused when wind pushes moist air up the slope of a mountain, cooling it until its water vapor condenses.

## CORE IDEAS

**The story.** In October 1805, the explorers Meriwether Lewis and William Clark floated down the Columbia River in dugout canoes, racing to reach the Pacific before winter. East of the Cascade Mountains they passed through open, dry country of grass and sagebrush, so short of trees that they bought firewood from the Indians along the river or burned driftwood and willow. Then the Columbia carried them through its great gorge, the only near-sea-level passage through the Cascades. Within days the land changed: tall, dark forests of fir and spruce, ferns and moss, and rain. On November 7, Clark wrote in his journal, “Oceania in view! O! the joy.” That winter, at Fort Clatsop near the mouth of the Columbia, it rained on all but about a dozen days of their stay. Their clothes rotted and their elk meat spoiled. In a few days of paddling they had crossed one of the sharpest climate lines in North America.

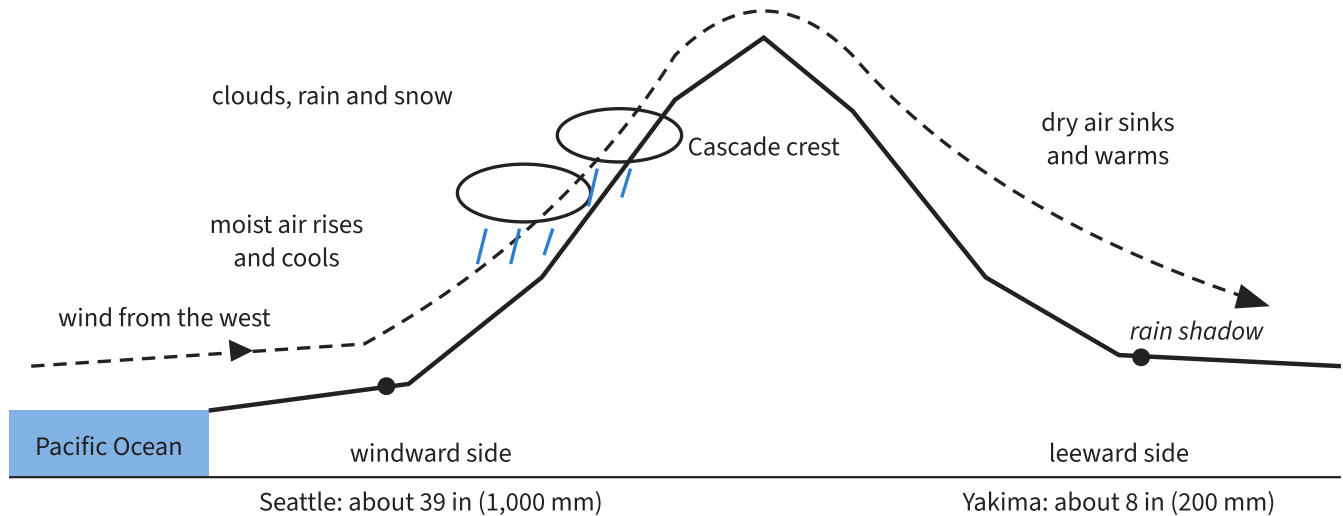
**How it works: altitude.** Air near the ground is warmed by the sunlit land beneath it. Higher up, the air is thinner and farther from that warm ground, so it is colder. On average the temperature falls about 6.5°C for every 1,000 m you climb (about 3.6°F per 1,000 ft). That is why Mount Rainier, at 14,410 ft (4,392 m), wears snow and glaciers all summer while Seattle, at sea level, enjoys July days in the 70s. Altitude can even beat latitude: Mount Kilimanjaro in Africa stands only about 3° south of the equator, yet its summit has ice.

**How it works: wind and mountains.** Across the middle latitudes, the **prevailing winds** blow from the west. Off the Pacific they carry air full of water vapor. When that air meets the Cascades, it has nowhere to go but up. As it rises, the air pressure on it drops, so it expands and cools, about 10°C per 1,000 m (5.5°F per 1,000 ft) at first. Cool air cannot hold as much vapor, so the vapor condenses into clouds, and rain and snow pour down on the **windward** slopes. This is **orographic precipitation**, from the Greek word for mountain. When the air finally spills over the crest and sinks down the **leeward** side, it is squeezed by the heavier air below, warms up, and soaks up moisture instead of dropping it. The land in its lee lies in a **rain shadow**.

**On the map.** Follow the numbers across Washington State (see the map). On the Pacific side of the Olympic Mountains, Forks gets about 120 inches (3,050 mm) of rain a year, and the nearby Hoh valley grows one of the few temperate rain forests on earth. Seattle, partly sheltered by the Olympics, gets about 39 inches (1,000 mm). High on Mount Rainier, more than 50 feet (15 m) of snow falls in an average winter at the Paradise ranger station. But cross the Cascade crest and drop to Yakima, only about 180 km (110 miles) from Seattle, and the yearly total is just 8 inches (200 mm), about one-fifth as much. The forests give way to sagebrush, and farmers must bring water from the mountains to grow apples and hops. Even Sequim, in the lee of the Olympics, gets only about 16 inches (400 mm). The same pattern repeats around the world: the Sierra Nevada and the Great Basin, the Andes and the deserts of Argentina, the Himalaya and the high, dry plateau of Tibet.

**The big idea.** A mountain range is a climate machine. It forces air up, wrings it out, and sends it down dry. Wherever you find steady winds and a wall of mountains, look for a wet windward side and a dry leeward side. What Lewis and Clark felt on their skin, soaking at Fort Clatsop after the dusty plains of the Columbia, was physical geography: the wind, the water and the mountains working exactly as God made them to work.

### The Cascade rain shadow (not to scale)



*How a rain shadow forms: moist air rises and cools on the windward side, drops its rain and snow, then sinks and warms on the leeward side.*



*Washington's rain shadow: yearly precipitation drops from about 120 inches at Forks to about 8 inches at Yakima.*

## PICTURE STUDY

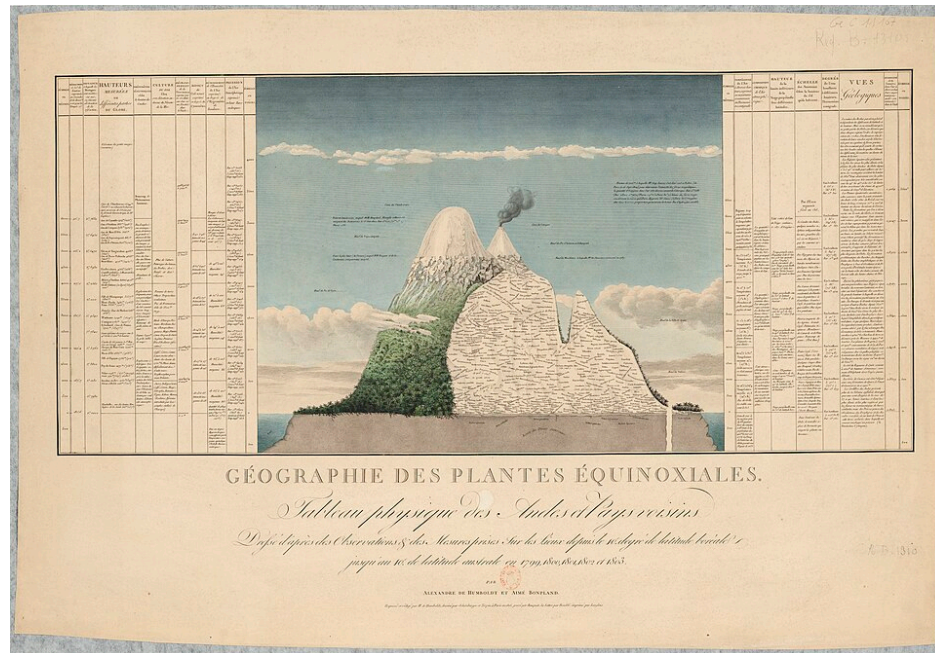


*Tableau physique des Andes et pays voisins (Physical Profile of the Andes and Neighboring Lands), from Essai sur la géographie des plantes, Alexander von Humboldt and Aimé Bonpland, dated 1805; published 1807 · Engraving, printed in color and finished by hand · Published in Paris; copies in many libraries*

In 1802 the German naturalist Alexander von Humboldt and his French companion, the botanist Aimé Bonpland, climbed high on Chimborazo, the great volcano of Ecuador, reaching about 19,000 feet (about 5,800 m) before a ravine and the thin air turned them back. All the way up they measured the temperature, the air pressure and the boiling point of water, and they wrote down which plants grew at each height.

Back in Europe, Humboldt turned their notes into this picture. The mountain is cut open like a slice of cake. Palms and tropical plants grow at its foot, then forests, then grasses, then mosses and lichens, then bare rock and permanent snow. Columns of numbers at the sides give the temperature and other measurements at each height. In one image Humboldt showed that climbing a mountain near the equator is like traveling from the tropics toward the poles.

### Look closely

- Find the snow line. About how far up the mountain does the permanent snow begin?
- Find the plant names written on the mountain. Are they spread out evenly, or do they change in bands?
- Look at the columns of numbers at the sides. What do you think they measure?
- Find the smoking volcano in the background. (It is Cotopaxi.)

### Talk about it

1. Why would plants change in bands as you climb a mountain?

2. How is climbing a tall mountain near the equator like traveling north from the equator to the Arctic?
3. Humboldt measured everything he could. Which measurement would you most want to take on a mountain climb?

## **PROJECT: A SPONGE-MOUNTAIN RAIN SHADOW**

You will build a mountain from sponges in a baking pan, blow “ocean air” at it with a spray bottle, and measure how much water lands on each side. Your model will show in a few minutes what the Cascades do every winter.

### **You will need**

- A large baking pan or plastic storage-box lid
- An upside-down bowl or a block of wood about 10 cm (4 in) high to shape the mountain
- Three or four dry kitchen sponges (or a thick sponge cloth) to drape over the bowl
- A spray bottle filled with water, set to a fine mist, and blue food coloring (optional)
- A small battery fan or a piece of cardboard for fanning
- Six strips of paper towel of the same size, a kitchen scale that reads in grams, and a ruler

### **Steps**

1. Set the bowl in the middle of the pan and cover it with sponges to make a long ridge running north to south. Mark the west side with a card that says “Pacific” and the east side with one that says “Yakima.”
2. Weigh the six paper towel strips and write down their dry weights. Lay three on the floor of the pan on the west side, at 5, 10 and 15 cm from the mountain’s foot, and three on the east side at the same distances.
3. Stand on the west side. Hold the spray bottle level with the base of the mountain, about 30 cm (1 ft) away, and spray 20 fine mists toward the mountain while a helper fans gently from the west so the mist drifts up and over the ridge.
4. Carefully lift each paper towel and weigh it again. Subtract the dry weight to find how many grams of water landed on it.
5. Press the sponge on each side of the ridge. Which side is wetter?
6. Make a bar graph with six bars, west to east, of the water each strip caught.
7. Repeat with the mountain made twice as tall (stack another bowl or block). Does the rain shadow get stronger?

### **Tips**

- Spray from the same spot and the same number of times in every trial so the test is fair.
- A drop of food coloring in the bottle makes it easy to see where the “rain” landed.
- The model shows the pattern, not every cause: real mountains also cool the air as it rises. Explain that part in your own words.

### Check your work

- I built a model mountain and measured the water on both sides.
- My bar graph shows more water on the windward side than in the rain shadow.
- I can explain how rising air makes rain and sinking air makes a desert.

### MAP NOTEBOOK

1. Draw the rain-shadow cross-section. Label the ocean, the prevailing wind, the windward side, the clouds, the crest, the leeward side and the rain shadow.
2. Trace an outline of Washington State. Mark Forks, Seattle, Mount Rainier and Yakima, and write each place's yearly precipitation in both inches and millimeters.
3. Draw a tall mountain in three bands from bottom to top: forest, meadow and snow. Beside each band, write an estimated temperature using  $3.6^{\circ}\text{F}$  per 1,000 feet.

**From history.** In the winter of 1971–1972, the Paradise ranger station on Mount Rainier measured 1,122 inches (about 93 feet, or 28.5 m) of snowfall, a world record for one season at the time. All that snow was lifted out of the Pacific air by the same windward slopes that leave Yakima dry. Mount Rainier's snow and glaciers feed rivers that run down both sides of the range, so the mountain that makes the rain shadow also helps water the farms within it.

### WORKED EXAMPLES

**Example 1.** In July, Seattle at sea level averages about  $67^{\circ}\text{F}$  ( $19.4^{\circ}\text{C}$ ). Using the average rate of cooling with height, estimate the temperature at the summit of Mount Rainier, 14,410 ft (4,392 m) high, in both units.

1. In feet: 14,410 ft is about 14.4 thousand feet.  $14.4 \times 3.6^{\circ}\text{F} \approx 51.9^{\circ}\text{F}$  colder.  $67 - 51.9 \approx 15^{\circ}\text{F}$ .
2. In meters: 4,392 m is about 4.4 thousand meters.  $4.392 \times 6.5^{\circ}\text{C} \approx 28.5^{\circ}\text{C}$  colder.  $19.4 - 28.5 \approx -9^{\circ}\text{C}$ .
3. Check:  $15^{\circ}\text{F} = (15 - 32) \times 5/9 \approx -9.4^{\circ}\text{C}$ . The two answers agree.

**Answer:** About  $15^{\circ}\text{F}$  (about  $-9^{\circ}\text{C}$ ), well below freezing, which is why the summit keeps its snow and glaciers all summer.



**Example 2.** A simple model of air crossing the Cascades: Air leaves the coast at sea level at 15°C. It cools 10°C per 1,000 m as it rises until clouds form at 1,000 m. Inside the cloud it cools only 6°C per 1,000 m (because condensing water gives off heat) up to the crest at 2,000 m. It then sinks back to sea level on the east side, warming 10°C per 1,000 m. What is its temperature at the cloud base, at the crest, and on the east side?

*(Use the map or drawing “Follow the dashed arrow from the ocean over the crest into the rain shadow.” shown earlier in this lesson.)*

1. Sea level to cloud base: 1,000 m at 10°C per 1,000 m  $\rightarrow 15 - 10 = 5^\circ\text{C}$ .
2. Cloud base to crest: another 1,000 m at 6°C per 1,000 m  $\rightarrow 5 - 6 = -1^\circ\text{C}$ . Snow falls on the windward slope.
3. Crest down to sea level: 2,000 m at 10°C per 1,000 m  $\rightarrow -1 + 20 = 19^\circ\text{C}$ .
4. Compare: the air ends 4°C warmer than it started, and it has lost the water it dropped as rain and snow.

**Answer:** 5°C at the cloud base,  $-1^\circ\text{C}$  at the crest, and 19°C on the leeward side: warmer and much drier than when it started.

**Example 3.** Seattle is at about 47.6° N, 122.3° W, and Yakima at about 46.6° N, 120.5° W. (a) Estimate the straight-line distance between them. Use 111 km per degree of latitude and, at this latitude, about 76 km per degree of longitude. (b) Seattle gets about 39 inches of precipitation a year and Yakima about 8 inches. What fraction of Seattle’s total does Yakima get?

*(Use the map or drawing “The Cascade crest lies between Seattle and Yakima.” shown earlier in this lesson.)*

1. (a) North-south:  $47.6 - 46.6 = 1.0^\circ$ ,  $\times 111 \approx 111$  km.
2. East-west:  $122.3 - 120.5 = 1.8^\circ$ ,  $\times 76 \approx 137$  km.
3. Straight line (Pythagorean theorem):  $\sqrt{(111^2 + 137^2)} = \sqrt{(12,321 + 18,769)} = \sqrt{31,090} \approx 176$  km, about 110 miles.
4. (b)  $8 \div 39 \approx 0.21$ , about one-fifth.

**Answer:** (a) About 176 km (about 110 miles). (b) Yakima gets only about one-fifth (about 21%) of Seattle’s precipitation.

## PRACTICE

1. **EASY** Define windward and leeward. On which side of the Cascades is Seattle? On which side is Yakima?
2. **EASY** From which direction do the prevailing winds usually blow across Washington State, and where do they pick up their moisture?

3. **EASY** Forks, Washington, gets about 120 inches of rain a year. How many millimeters is that? How many feet?
4. **MEDIUM** Denver, Colorado, is about 1,600 m (one mile, 5,280 ft) above sea level. Using the average rate, how much cooler would you expect it to be than a sea-level place at the same latitude with the same air? Give °C and °F.
5. **MEDIUM** Paradise, on Mount Rainier, is about 5,400 ft (1,650 m) above sea level. If it is 70°F in Seattle at sea level, estimate the temperature at Paradise.
6. **MEDIUM** Mount Kilimanjaro is 5,895 m (19,341 ft) high, only about 3° south of the equator. If the plains at its foot, about 1,000 m high, are at 25°C, estimate the temperature at the summit.
7. **MEDIUM** Use the Washington map. Which town lies in the rain shadow of the Olympic Mountains, and which lies in the rain shadow of the Cascades?  
*(Use the map or drawing "Look for the towns on the side of each range away from the Pacific." shown earlier in this lesson.)*
8. **HARD** Forks gets about 120 inches of precipitation a year and Yakima about 8 inches. How many times as much does Forks get? Give both amounts in millimeters.
9. **HARD** Dry air at the Cascade crest, 2,000 m high, is at -2°C. It sinks to Yakima, about 300 m high, warming 10°C for every 1,000 m it descends. What is its temperature when it reaches Yakima?
10. **CHALLENGE** Lewis and Clark burned driftwood east of the Cascades in October 1805, and a few weeks later they were soaked almost every day at Fort Clatsop. Explain both experiences in a short paragraph using the words prevailing winds, windward, leeward and rain shadow.

## COMMON MISTAKES

- Thinking mountaintops are cold because they are closer to the sun. A few kilometers make no difference to the sun's distance; the air is colder because it is thinner and farther from the warm ground.
- Putting the rain shadow on the wrong side. First find the direction the prevailing wind comes from; the rain shadow is on the far side of the mountains.
- Thinking a rain shadow is dry because no clouds ever reach it. Clouds often drift over, but the sinking air warms and dries, so they seldom give much rain.

**Make it a game · Find the Rain Shadow.** Spread a world physical map or globe on the table. One player names a mountain range (Sierra Nevada, Andes, Himalaya, Rocky Mountains, Great Dividing Range in Australia, Olympic Mountains). The other must point to the direction of the prevailing wind there, then put a finger on the rain shadow. Score a point for each correct rain shadow and a bonus point for naming a desert or dry land that lies in it.

**Scripture.** "The wind goeth toward the south, and turneth about unto the north; it whirleth about continually, and the wind returneth again according to his circuits."  
(Ecclesiastes 1:6, KJV)

Solomon saw that the winds are not random but follow their circuits. The prevailing westerlies that water the Cascades and leave a rain shadow behind them follow the same faithful pattern year after year.

#### Practice answers

1. Windward is the side facing the oncoming wind; leeward is the sheltered side. Seattle is on the windward (west) side; Yakima is on the leeward (east) side.
2. From the west, off the Pacific Ocean.
3.  $120 \times 25.4 = 3,048$  mm (about 3 m).  $120 \div 12 = 10$  feet of water.
4.  $1.6 \times 6.5 \approx 10.4^\circ\text{C}$  cooler. In feet:  $5.28 \times 3.6 \approx 19^\circ\text{F}$  cooler. ( $10.4^\circ\text{C} \times 9/5 \approx 19^\circ\text{F}$ , so they agree.)
5.  $5.4 \times 3.6 \approx 19.4^\circ\text{F}$  cooler, so about  $70 - 19 = 51^\circ\text{F}$  (about  $10.5^\circ\text{C}$ ). (In meters:  $1.65 \times 6.5 \approx 10.7^\circ\text{C}$  cooler than  $21^\circ\text{C}$ , about  $10^\circ\text{C}$ .)
6. The climb is  $5,895 - 1,000 \approx 4,900$  m.  $4.9 \times 6.5 \approx 32^\circ\text{C}$  colder, so about  $25 - 32 = -7^\circ\text{C}$  (about  $19^\circ\text{F}$ ). Altitude makes the summit freezing even near the equator.
7. Sequim lies in the rain shadow of the Olympics (about 16 in, 400 mm). Yakima lies in the rain shadow of the Cascades (about 8 in, 200 mm).
8.  $120 \div 8 = 15$  times as much. Forks: about 3,050 mm. Yakima: about 200 mm.
9. It descends  $2,000 - 300 = 1,700$  m.  $1.7 \times 10 = 17^\circ\text{C}$  warmer, so  $-2 + 17 = 15^\circ\text{C}$ .
10. The prevailing winds blow from the west off the Pacific, carrying moist air. At Fort Clatsop, on the coast and the windward side of the mountains, that moist air is pushed up, cools, and drops heavy rain all winter. By the time the air crosses the Cascades it has lost most of its water, and as it sinks down the leeward side it warms and dries. So the Columbia Plateau east of the mountains lies in a rain shadow, too dry for many trees, which is why the explorers had to burn driftwood.

## 5.4 KÖPPEN'S CLIMATE ZONES ★

### OBJECTIVES

- Name Köppen's five main climate groups (A, B, C, D, E) and the temperature and rainfall rules that define them.
- Use monthly temperature and precipitation data to give a city its Köppen letters, such as Af, BWh, Csb or Dfa.
- Tell how Wladimir Köppen used plants as nature's instruments to build his system (1884, revised 1918–1936), and read a Köppen map of the world.

**Warm-up.** Think of five places you have visited or read about: a beach, a desert, a snowy mountain town, a jungle, a big northern city. Sort them into groups any way you like, using only two clues: how warm they are and how wet they are. How many groups did you need? What rule did you use to decide the borders between groups? You have just done what Wladimir Köppen spent fifty years perfecting.

**Watch.** *Köppen climate classification* (Geography Lessons, 5:46).

<https://www.youtube.com/watch?v=pJoRTHt3lbw>

With the big idea: watch how Köppen starts at the equator and moves toward the poles, and listen for what each letter (A, B, C, D, E) stands for.

**Note:** Captions were not available to check; preview it first. The video uses metric units (18 °C, 400 mm of rain a year). The description spells the name 'Wladimir Koppen' instead of Wladimir Köppen.

**Backup video.** *The Koppen-Geiger Climate Classification System* (Geodiode, 11:38).

<https://www.youtube.com/watch?v=BsOL9Fafo2w>

With On the map: use the chapters to pause on each climate code (Af, BWh, Cfa, Dfb and so on) and find where that climate is on the world map. Note: Captions were not available to check; preview it first. This is a detailed 11-minute reference video, so older students may get more from it than younger ones. It calls the system 'Köppen-Geiger' and credits Rudolf Geiger with refining it. Check this against how the lesson names the system.

### KEY TERMS

#### climate classification

A system for sorting the world's climates into types by clear rules, so that places with similar climates get the same name.

#### Köppen system

The climate classification of Wladimir Köppen, which names each climate with letters based on monthly temperature and precipitation and the plants that can grow there.

#### dryness line

In the Köppen system, the amount of yearly precipitation below which a place counts as dry (group B). It is higher for hotter places, because heat evaporates more water.

### **continental climate**

A climate far from the moderating sea, with hot summers and cold winters (Köppen's group D).

### **climograph**

A graph of a place's monthly temperatures and precipitation, the data you need to give it Köppen letters.

## **CORE IDEAS**

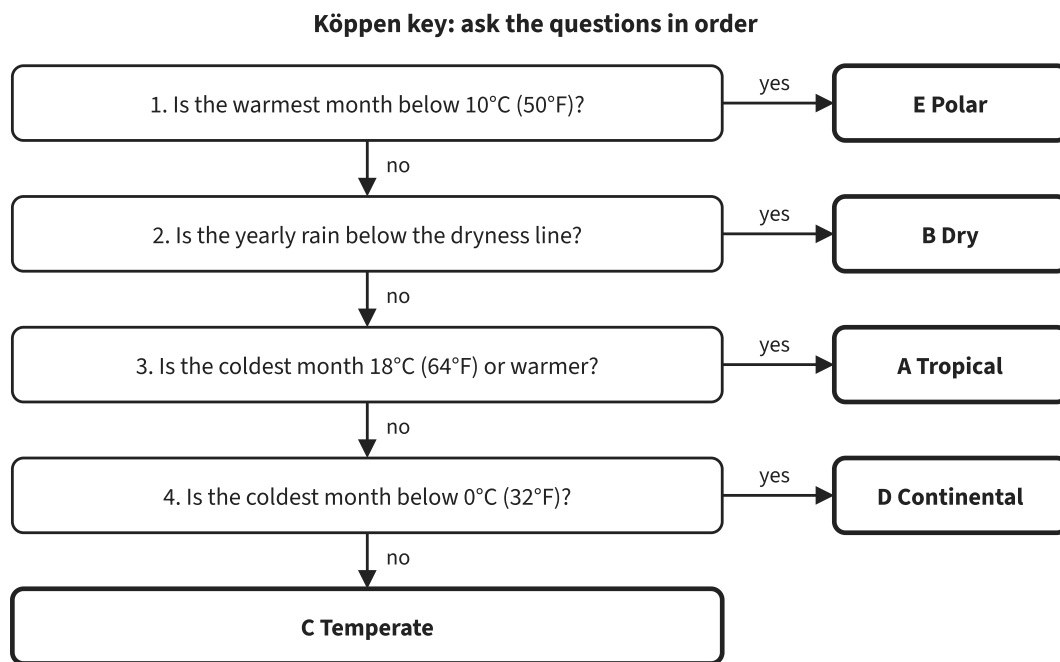
**The story.** Wladimir Köppen was born in St. Petersburg, Russia, in 1846. He went to school in the Crimea, on the Black Sea, and on the long journeys between the Crimea and St. Petersburg he watched the land change outside the window: southern orchards and grasslands, then broad-leaved woods, then dark northern forests of pine and spruce. He studied botany, the science of plants, and then became a weatherman. For many years he worked at the German Naval Observatory in Hamburg, studying the winds and sending storm warnings to ships. But he never forgot the plants. In 1884 he published a map of the earth's "heat zones," sorting the world by how many months each year are hot, moderate or cold. It was the first step toward the climate map in nearly every atlas today.

**How he figured it out.** In Köppen's day there were few weather stations in the jungles, deserts and Arctic lands. But plants grow everywhere, and every plant has its needs. Palms will not survive a hard frost; trees will not grow where the warmest month stays below about 10°C (50°F); cactus thrives where grasses wither. The Swiss botanist Alphonse de Candolle had already sorted plants into groups by the heat and water they need. Köppen realized that the plants were nature's own instruments, recording the climate year after year. He chose his temperature and rainfall boundaries so that they matched the edges of the great plant regions. He published a full system in 1900, revised it in 1918, and finished his last version in 1936, four years before he died. His son-in-law was Alfred Wegener, whose puzzle of the continents you met in Unit 2, and his younger colleague Rudolf Geiger carried on the work, so you will often see the name Köppen-Geiger.

**The big idea.** Köppen named climates with letters. The first capital letter gives the main group. **A** (tropical): every month averages 18°C (64°F) or warmer. **B** (dry): the yearly precipitation is below the **dryness line**; BW is desert and BS is steppe or semi-desert. **C** (temperate): the coldest month is between 0°C (32°F) and 18°C (64°F). **D** (continental): the coldest month is below 0°C (32°F) but the warmest is above 10°C (50°F). **E** (polar): even the warmest month is below 10°C (50°F), too cold for trees; ET is tundra and EF is ice cap. (Köppen himself set the C/D line at -3°C, about 27°F; many modern maps use 0°C.) A second letter tells when the rain falls: **f** for rain in every season, **s** for a dry summer, **w** for a dry winter, and **m** for a monsoon. A third letter tells how hot the summer is: **a** hot (warmest month 22°C, 72°F, or more), **b** warm, **c** cool and short. For B climates, **h** means hot and **k** means cold.

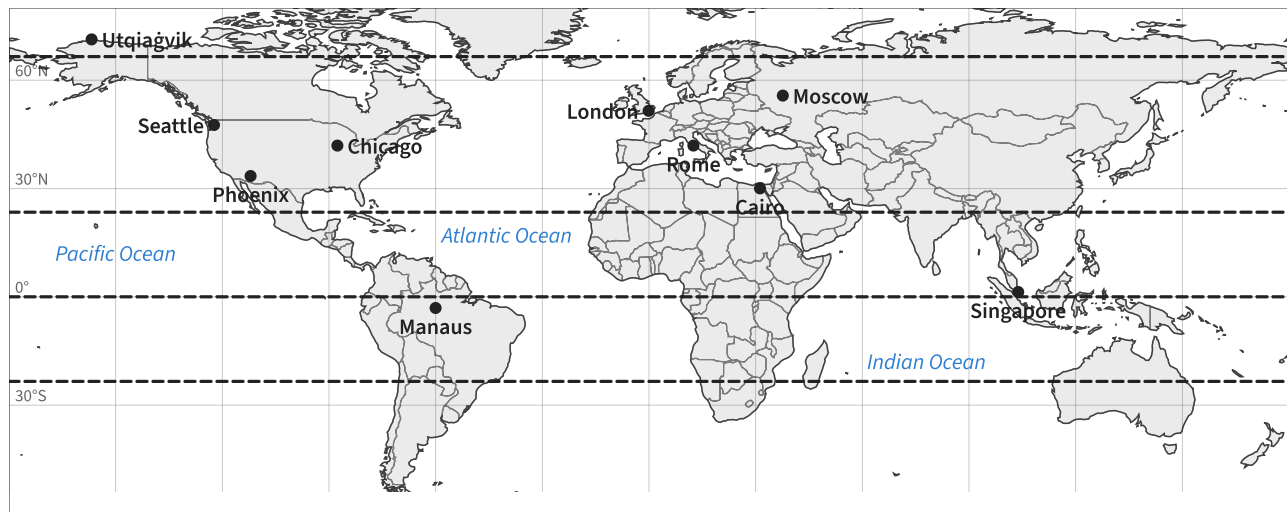
**On the map.** A Köppen map of the world is a summary of everything in this unit. Find the A climates in a belt along the equator, where the high sun of Lesson 5.2 keeps every month warm. Find the great B deserts near 20° to 30° north and south, the Sahara and the Australian outback, and the smaller deserts hiding in rain shadows like the one behind the Cascades in Lesson 5.3. Find C climates along coasts in the middle latitudes, where the sea keeps winters mild: Seattle and London. Find the D climates in the interiors of the big northern continents, Chicago and Moscow, far from the sea’s moderating hand. There is almost no D climate in the Southern Hemisphere, because there is no wide land at those latitudes there. Find E around the poles and on the highest mountains. Each color on the map is a pattern that latitude, altitude, winds, mountains and the sea have painted together.

**Why it matters.** A Köppen code is a short sentence about a place. “Csa” means mild, rainy winters and hot, dry summers, the climate of Rome and Jerusalem, of olives, grapes and figs. “Dfb” means snowy winters, warm summers and rain all year, the climate of Moscow and much of southern Canada. Farmers, foresters and engineers use these codes to know what will grow and how to build. When the Apostle Paul told the Athenians that God “hath determined the times before appointed, and the bounds of their habitation,” he was speaking of nations, but the same Creator set the sun’s angle, the winds and the mountains that give each land its climate.



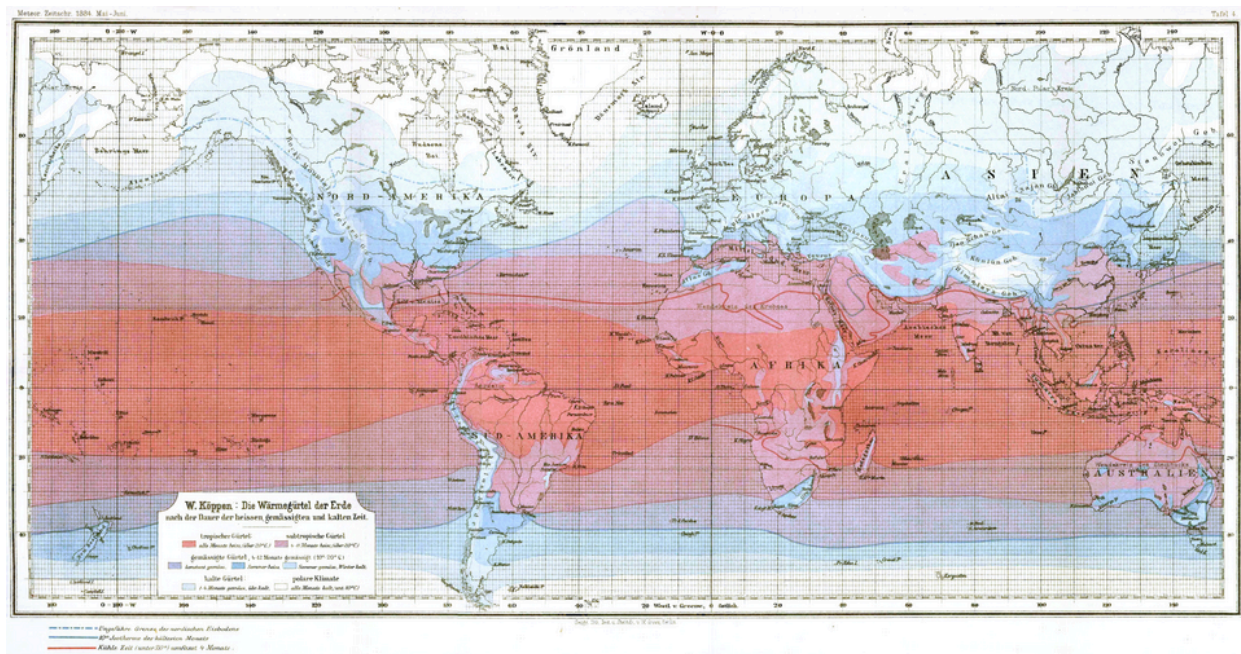
*A simple key to Köppen’s five main groups. Ask the questions in order from the top.*





Ten cities to classify. Compare their places on this map with a Köppen climate map in an atlas.

## PICTURE STUDY



*Die Wärmezonen der Erde (The Heat Zones of the Earth), Wladimir Köppen, 1884 · Color-printed map in the Meteorologische Zeitschrift · Published in the first volume of the Meteorologische Zeitschrift (1884); copies in many libraries*

This is Köppen's first climate map, made more than thirty years before his famous letters. He sorted every part of the world by how many months of the year are hot, how many moderate and how many cold, and colored the zones on a world map. Instead of neat stripes following the lines of latitude, the zones bend and wander.

Those bends are the whole point. If climate depended only on latitude, every zone would follow the lines of latitude exactly. Köppen's map showed that oceans, winds, mountains and the size of the continents push the zones north and south. Out of this map grew the system you are learning today.



### Look closely

- Find the equator. Is the hottest zone centered exactly on it everywhere?
- Look at the west coast of Europe and the east coast of North America at the same latitude. Do they have the same color?
- Find the interiors of Asia and North America. How do their zones differ from the coasts?
- Find a place where a zone bends sharply. What feature of the land or sea might cause the bend?

### Talk about it

1. Why don't the climate zones follow the lines of latitude exactly?
2. Köppen had far fewer weather stations than we have today. How could plants help him fill in the empty places?
3. Compare this map with a modern Köppen map. What stayed the same, and what is more detailed?

## PROJECT: MYSTERY CITY CLIMOGRAPHS

You will draw climographs for four cities from their monthly data, give each one its Köppen code with the key, and then find them on a Köppen map of the world. This is the beginning of your unit portfolio map.

### You will need

- Graph paper, a ruler, a pencil, and blue and red colored pencils
- The Köppen key (figure g6-koppen-key)
- Monthly temperature and precipitation data for four cities, from the National Weather Service or an atlas (a parent can print them), or the data in this lesson's practice problems
- An atlas or a printed Köppen climate map of the world

### Steps

1. Ask a parent to copy the monthly data for four cities onto cards without the city names, labeled Mystery City 1 to 4. Choose cities in different groups, for example Singapore, Phoenix, London and Moscow.
2. For each city, draw a climograph: twelve blue bars for precipitation (mm, left scale) and a red line for temperature (°C, right scale).
3. Under each climograph, find the coldest month, the warmest month and the yearly total precipitation.
4. Work through the Köppen key from the top. Write the first letter, then the second and third letters.
5. Guess which part of the world each mystery city is in, and why. Then turn over the card to see its name.

6. Find each city on a Köppen map. Does the color match your code? If not, find your mistake.

### Tips

- Always ask the E question first and the B question second, before deciding between A, C and D.
- In the Southern Hemisphere the coldest month is July and the warmest is January.
- Use the same scales on all four climographs so you can compare them at a glance.

### Check your work

- I drew four climographs with correct scales and labels.
- I gave each city a Köppen code and checked it against a map.
- I can explain which physical causes give each city its climate.

### MAP NOTEBOOK

1. Copy the Köppen key into your notebook in your own handwriting and decorate each group with a small drawing of a plant that grows there (palm, cactus, oak, spruce, moss).
2. Make a table of the five main groups with three columns: Letter, Rule, Example city.
3. On a blank world outline map, shade a rough belt for each main group in a different color and add a legend. You will improve it into your portfolio map.

**From history.** Köppen and his son-in-law Alfred Wegener worked together closely, and Köppen's climate maps helped Wegener argue that the continents had once been joined. Wegener died in 1930 on the Greenland ice cap, crossing the EF climate he had studied, while trying to bring supplies to a research station far inland. Köppen, by then in his eighties, kept working on the great *Handbuch der Klimatologie* (Handbook of Climatology), which he edited with Rudolf Geiger and in which the final 1936 version of his system appeared.

## WORKED EXAMPLES

**Example 1.** Singapore (about 1.3° N): every month averages between about 26°C and 28°C (79–82°F), and every month gets more than 100 mm (4 in) of rain. The yearly total is about 2,300 mm (about 90 in). Give its Köppen code.

*(Use the map or drawing “Answer the questions from the top: E, then B, then A.” shown earlier in this lesson.)*

1. E? The warmest month is far above 10°C. No.
2. B? The yearly mean is about 27°C, so the dryness line is about  $20 \times 27 + 140 = 680$  mm. Singapore gets about 2,300 mm. Not dry. No.
3. A? The coldest month is about 26°C, at least 18°C. Yes: group A.
4. Second letter: every month is wet (60 mm or more), so f.

**Answer:** Af, tropical rain forest climate.

**Example 2.** Seattle: coldest month about 5°C (41°F), warmest about 19°C (67°F), yearly mean about 12°C (53°F), yearly precipitation about 1,000 mm (39 in). July gets only about 15 mm, while the wettest winter month gets about 160 mm. Give its Köppen code.

1. E? Warmest month 19°C is above 10°C. No.
2. B? Dryness line  $\approx 20 \times 12 + 140 = 380$  mm. Seattle gets 1,000 mm. No.
3. A? Coldest month 5°C is below 18°C. No.
4. D? Coldest month 5°C is not below 0°C. No, so it is C.
5. Second letter: summer is very dry (15 mm, less than a third of 160 mm and under 40 mm), so s.
6. Third letter: warmest month 19°C is under 22°C, and more than four months are above 10°C, so b.

**Answer:** Csb, a warm-summer Mediterranean climate. (Seattle lies close to the border with Cfb, the marine west coast climate of London, so some maps show it as Cfb.)

**Example 3.** Yakima, in the rain shadow of the Cascades: yearly mean about 10°C (50°F), yearly precipitation about 200 mm (8 in), coldest month about −2°C, warmest about 22°C. Give its Köppen group, its second letter (desert or steppe) and its third letter (hot or cold).

1. E? Warmest month 22°C. No.
2. B? Dryness line  $\approx 20 \times 10 + 140 = 340$  mm. Yakima gets 200 mm, less than 340.  
Yes: group B.
3. Desert or steppe? Half the dryness line is 170 mm. 200 mm is more than 170, so it is steppe: S.
4. Hot or cold? Yearly mean 10°C is below 18°C, so k (cold).

**Answer:** BSk, cold steppe. The rain shadow has made it a dry climate even though Seattle, about 180 km (110 mi) away, is a wet C climate.

## PRACTICE

1. **EASY** Name Köppen's five main climate groups by letter and name.
2. **EASY** A place's warmest month averages 6°C (43°F). Which main group is it in, and what kind of plants would you expect there?
3. **EASY** What does the second letter s mean in a Köppen code? What does w mean?
4. **MEDIUM** Chicago: coldest month about −4°C (25°F), warmest about 24°C (75°F), yearly mean about 10°C, precipitation about 950 mm (37 in) spread through the year. Give its Köppen code.
5. **MEDIUM** Rome: coldest month about 8°C (46°F), warmest about 25°C (77°F), yearly precipitation about 800 mm (31 in), with July nearly dry. Give its Köppen code.
6. **MEDIUM** London: coldest month about 5°C (41°F), warmest about 19°C (66°F), yearly mean about 11°C, precipitation about 600 mm (24 in) spread fairly evenly through the year. Give its Köppen code.
7. **MEDIUM** Phoenix: yearly mean about 24°C (75°F), yearly precipitation about 200 mm (8 in). Is it B? Desert or steppe? Hot or cold?
8. **HARD** Moscow: coldest month about −6°C (21°F), warmest about 19°C (66°F), yearly mean about 6°C, precipitation about 700 mm (28 in) spread through the year. Give its code, and explain why London, at about the same latitude, is C while Moscow is D.
9. **HARD** Utqiagvik, Alaska, gets only about 120 mm (5 in) of precipitation a year, as little as many deserts, and its warmest month averages about 4°C. Why do we call it E and not B? Give its full code.
10. **CHALLENGE** Köppen set the boundary of group E at a warmest month of 10°C (50°F). In two or three sentences, explain why this number makes sense if plants are nature's instruments.

## COMMON MISTAKES

- Deciding A, C or D before checking E and B. A cold desert like Yakima or a polar place like Utqiagvik will be mislabeled if you skip the first two questions.
- Using the same dryness amount for every place. A hot place needs much more rain than a cool one to escape group B, because heat evaporates the water.
- Forgetting that the seasons are reversed in the Southern Hemisphere when looking for the coldest and warmest months, or the dry summer and dry winter.

**Make it a game · Köppen Code Breaker.** Write the letters A, B, C, D, E, f, s, w, m, a, b, c, h, k, W and S on small cards. A parent describes a climate in plain words, such as “hot all year with rain every month” or “mild, rainy winters and hot, dry summers.” Race to lay down the right cards in order (Af, Csa). Score a point for each correct code and a bonus point for naming a real city with that climate.

**Scripture.** “And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation;” (Acts 17:26, KJV)

God made people to dwell on “all the face of the earth,” from the Af rain forest to the ET tundra. Köppen’s map shows how varied that face is, and how families and nations have learned to live, farm and build in every kind of climate.

### Practice answers

1. A tropical, B dry, C temperate, D continental, E polar.
2. E (polar), and since the warmest month is above 0°C it is ET, tundra: mosses, lichens, grasses and low shrubs, but no trees.
3. s means a dry summer; w means a dry winter.
4. Not E (24°C > 10). Dryness line  $\approx 340$  mm, and 950 mm is more, so not B. Coldest month is below 18°C (not A) and below 0°C, so D. Rain all year: f. Warmest month 24°C  $\geq$  22°C: a. Code: Dfa.
5. Not E, not B (800 mm is far above the dryness line of about  $20 \times 16 + 140 = 460$  mm). Coldest month between 0°C and 18°C: C. Dry summer: s. Warmest month 25°C  $\geq$  22°C: a. Code: Csa.
6. Not E. Dryness line  $\approx 20 \times 11 + 140 = 360$  mm; 600 mm is more, so not B. Coldest month between 0 and 18°C: C. No dry season: f. Warmest under 22°C with more than four months above 10°C: b. Code: Cfb.
7. Dryness line  $\approx 20 \times 24 + 140 = 620$  mm. 200 mm is less, so B. Half the line is 310 mm; 200 is less than half, so W (desert). Mean 24°C  $\geq$  18°C, so h. Code: BW h.
8. Not E; dryness line  $\approx 20 \times 6 + 140 = 260$  mm, so not B; coldest month below 0°C: D; rain all year: f; warmest under 22°C: b. Code: Dfb. London sits beside the Atlantic, and the westerly winds bring mild sea air that keeps its winters above freezing. Moscow lies deep inside a huge continent, far from the sea, so its winters are much colder (continentality).
9. The E question comes first in the key: if even the warmest month is below 10°C, the place is polar no matter how little precipitation it gets. Its warmest month is above 0°C, so it is ET, tundra.

10. Trees do not grow where the warmest month stays below about 10°C, so the 10°C line matches the tree line, the edge between forest and tundra. By drawing his boundary there, Köppen made his climate map agree with what anyone could see on the ground: forests on one side and treeless tundra on the other.

## UNIT 5 REVIEW

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Answer each question. Show your work for calculations, give both U.S. and metric units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (5 pts) Weather or climate? (a) Fog closed the airport this morning. (b) Miami is warm all year. (c) It hailed during the ball game. (d) The Sahara gets very little rain. (e) Seattle's winters are usually wet.
2. (6 pts) A town's climograph shows these monthly precipitation amounts in inches: 3, 3, 4, 4, 5, 4, 3, 3, 3, 3, 4, 3. Find the yearly total in inches and in millimeters, and name the wettest month.
3. (5 pts) Change 50°F to °C and 30°C to °F. Then explain in one sentence what a climate normal is.
4. (6 pts) Chicago is at about 41.9° N. Find the noon sun angle there on the September equinox and on the June solstice (sun overhead at 23.4° N).
5. (6 pts) A beam of sunlight lights 1 square meter of ground when the sun is straight overhead. When the sun is 30° above the horizon, the same beam lights 2 square meters. How much heat does each square meter receive now compared with before? Use this to explain why the poles are cold.
6. (5 pts) Eratosthenes found a noon shadow of 7.2° at Alexandria when the sun was overhead at Syene, 5,000 stadia away. Show how he found the size of the earth. What Greek word gave us "climate," and what did it mean?
7. (6 pts) Colorado Springs is about 6,035 ft (1,839 m) above sea level, and the summit of Pikes Peak above it is 14,115 ft (4,302 m). On a summer afternoon it is 80°F (27°C) in Colorado Springs. Using 3.6°F per 1,000 ft (6.5°C per 1,000 m), estimate the temperature on the summit in both units.
8. (7 pts) Draw and label a cross-section of the Cascade Range showing the Pacific Ocean, the prevailing wind, the windward side, clouds and rain, the crest, the leeward side and the rain shadow. Then explain in two or three sentences why Seattle gets about 39 inches (1,000 mm) of precipitation a year and Yakima only about 8 inches (200 mm).
9. (7 pts) Cairo, Egypt: yearly mean about 22°C (72°F), yearly precipitation about 25 mm (1 in), coldest month about 14°C, warmest about 28°C. Use the Köppen key and the dryness line ( $20 \times \text{yearly mean } ^\circ\text{C} + 140 \text{ mm}$ ) to give its full code. Show each step.
10. (7 pts) Atlanta, Georgia: coldest month about 7°C (44°F), warmest about 27°C (81°F), yearly mean about 17°C, precipitation about 1,270 mm (50 in) spread through the year. (a) Give its Köppen code. (b) Name the five main Köppen groups. (c) Why is there almost no D climate in the Southern Hemisphere?

## UNIT PROJECT: MY KÖPPEN CLIMATE MAP OF THE WORLD

Make a large hand-drawn or traced world map colored by Köppen's five main groups (A, B, C, D, E), with a clear legend. Draw and label the equator, the Tropics of Cancer and Capricorn, and the Arctic and Antarctic Circles. Mark at least eight cities, including Seattle and Yakima, and write each one's Köppen code beside it. Around the edge of the map, mount



four climographs of mystery cities you classified, the photographs or drawings and bar graph from your sponge-mountain rain-shadow model, and a summary of your two-week weather log.

Finish with a paragraph of 150 to 200 words explaining the patterns on your map: why the A climates hug the equator, why deserts appear near 20° to 30° and in rain shadows, why the west coasts of the middle latitudes are mild, and why the interiors of the northern continents have cold winters. Use the words latitude, sun angle, altitude, prevailing winds, rain shadow and continentality.

- **Accuracy:** Climate groups, lines of latitude and cities are placed correctly, and each city's Köppen code matches its data.
- **Evidence:** The climographs, rain-shadow results and weather log are complete, labeled in both U.S. and metric units, and correctly calculated.
- **Explanation:** The paragraph explains the map's patterns with the physical causes of climate: latitude and sun angle, altitude, winds, mountains and the sea.
- **Care:** The map is neat, colorful, and easy to read, with a clear legend and title.

#### Answer key

1. (a) weather, (b) climate, (c) weather, (d) climate, (e) climate. One point each.
2. Total = 42 inches.  $42 \times 25.4 \approx 1,067$  mm (about 1,070 mm). Wettest month: May (5 inches). (2 points each.)
3.  $50^{\circ}\text{F} = (50 - 32) \times 5/9 = 10^{\circ}\text{C}$ .  $30^{\circ}\text{C} = 30 \times 9/5 + 32 = 86^{\circ}\text{F}$ . A climate normal is an average of 30 years of weather records for a station, updated every ten years.
4. Equinox:  $90 - 41.9 = 48.1^{\circ}$ . June solstice:  $41.9 - 23.4 = 18.5^{\circ}$ , so  $90 - 18.5 = 71.5^{\circ}$ . (3 points each.)
5. Each square meter receives half as much. Near the poles the sun is always low, so its energy is spread over a large area (and passes through more air), while near the equator the high sun concentrates its energy. So the poles receive much less heat per square meter.
6.  $360 \div 7.2 = 50$ , so the earth's circumference is  $50 \times 5,000 = 250,000$  stadia. The word is *klima*, meaning a slope or slant (the slant toward the sun).
7. Difference:  $14,115 - 6,035 = 8,080$  ft.  $8.08 \times 3.6 \approx 29^{\circ}\text{F}$  colder, so about  $51^{\circ}\text{F}$ . In meters:  $4,302 - 1,839 = 2,463$  m.  $2.463 \times 6.5 \approx 16^{\circ}\text{C}$  colder, so about  $11^{\circ}\text{C}$ . ( $51^{\circ}\text{F} \approx 10.6^{\circ}\text{C}$ , so the answers agree.)
8. Drawing labeled with all seven parts (4 points). Explanation (3 points): The prevailing westerly winds carry moist Pacific air to the Cascades. The air is forced up the windward (western) slopes, expands and cools, and its water vapor condenses into clouds that drop rain and snow. After crossing the crest, the dried-out air sinks down the leeward side, warms and dries further, so Yakima lies in a rain shadow.
9. E? Warmest  $28^{\circ}\text{C} > 10^{\circ}\text{C}$ , no. B? Dryness line =  $20 \times 22 + 140 = 580$  mm; 25 mm is less, so B. Half the line is 290 mm; 25 mm is less, so W (desert). Mean  $22^{\circ}\text{C} \geq 18^{\circ}\text{C}$ , so h. Code: BWh, hot desert.
10. (a) Not E; dryness line  $\approx 20 \times 17 + 140 = 480$  mm, so not B; coldest month below  $18^{\circ}\text{C}$ , so not A; coldest month above  $0^{\circ}\text{C}$ , so C; rain all year, f; warmest month  $\geq 22^{\circ}\text{C}$ , a. Code: Cfa (3 points). (b) A tropical, B dry, C temperate, D continental, E polar (2 points). (c) D climates form in the interiors of large continents in the middle and high latitudes, far from the sea; the

Southern Hemisphere has almost no wide land at those latitudes, so the ocean keeps winters milder (2 points).

## BIOMES

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In Unit 5 you learned how latitude, altitude, winds, rain shadows and distance from the sea give every place its climate, and how Wladimir Köppen sorted those climates into a map. In this unit you will see that map come alive. A **biome** is a great region where the climate shapes a whole community of plants and animals: the layered rain forest of the Amazon, the bare rock and sand of the Sahara, the grass seas of the prairie and the steppe, the oaks and maples of the temperate lands, the spruce and fir of the taiga, and the treeless tundra and ice of the far north.

You will travel with Henry Walter Bates up the Amazon in 1848, ride with Stephen Long's expedition across the "Great Desert" of 1820, climb Mount Katahdin with Henry David Thoreau in 1846, and follow the engineers who built the Trans-Alaska Pipeline across frozen ground in the 1970s. In each place you will ask the same questions: **How much rain falls, and when? How warm is the warmest month, and how cold the coldest? And how are the living things built to fit?**

By the end you will be able to lay a biome map beside a Köppen map and explain why they match so closely, and you will have made your own biome boxes or biome field guide. As the psalmist wrote, "O LORD, how manifold are thy works! in wisdom hast thou made them all" (Psalm 104:24).

### BEFORE YOU BEGIN

- Can explain how latitude and the sun's angle make the tropics warm and the poles cold (Lesson 5.2)
- Can explain how altitude, prevailing winds and rain shadows change climate (Lesson 5.3)
- Knows the main Köppen groups A, B, C, D and E (Lesson 5.4)
- Can convert between metric and U.S. units and use  $1^\circ$  of latitude  $\approx$  111 km (69 mi)

### MASTERY CHECKLIST

- I can name the layers of a tropical rain forest and explain why it rains there almost every day.
- I can tell a desert from a grassland by yearly rainfall and explain why the Sahara, the steppe and the prairie are dry.
- I can explain why oaks and maples drop their leaves and why spruce and fir keep their needles, and where the taiga lies.
- I can describe permafrost, the active layer and the midnight sun, and explain how engineers build on frozen ground.
- I can match each biome to its Köppen climate group and show the biomes in order of latitude and altitude.

- I can calculate distances by latitude, temperature ranges and rainfall differences, in both metric and U.S. units.

## OPTIONAL BOOKS AND RESOURCES

- ***The Naturalist on the River Amazons* by Henry Walter Bates (free at Project Gutenberg)** (<https://www.gutenberg.org/ebooks/search/?query=Naturalist+on+the+River+Amazons>): Free. Bates's own account of eleven years in the Amazon (Lesson 6.1). A parent can choose short passages on the forest at Pará, the flooded forest and his collecting walks to read aloud.
- ***The Maine Woods* by Henry David Thoreau (free at Project Gutenberg)** (<https://www.gutenberg.org/ebooks/search/?query=Thoreau+Maine+Woods>): Free. The first essay, "Ktaadn," tells of his 1846 climb through hardwoods, spruce and fir to the treeless heights near the summit of Katahdin (Lesson 6.3).
- **Gates of the Arctic National Park and Preserve (National Park Service)** (<https://www.nps.gov/gaar/index.htm>): Free. Photographs and pages on the Brooks Range, tundra, permafrost and caribou, in the region the Trans-Alaska Pipeline crosses (Lesson 6.4).

## 6.1 TROPICAL RAIN FORESTS ★

### OBJECTIVES

- Name and describe the four layers of a tropical rain forest and explain why so little light reaches the forest floor.
- Explain with latitude, rising air and the trade winds why the Amazon is hot and rainy in every month, and classify a rain forest climate with Köppen's rules (Af).
- Tell how Henry Walter Bates explored the Amazon from 1848 to 1859 and locate the world's great rain forests on a map.

**Warm-up.** Hold your hand flat under a lamp and look at its shadow on the table. Now hold a leafy houseplant, a kitchen sieve or a sheet of tissue paper between the lamp and the table. Then stack two or three layers. How dark does the table get under three layers? Guess how much of the sun's light reaches the ground under a forest that is four layers deep.

**Watch.** *Layers of the Amazon rainforest.* (Geography Lessons, 2:27).

<https://www.youtube.com/watch?v=SYiv0JJ4Ko4>

After the story: watch how the canopy, understory and forest floor each get different amounts of sunlight and rain, and think about which layers Bates would have explored on his forest walks.

**Note:** Captions were not available to check; preview it first. The description suggests a short, plain explanation of the forest layers. The description calls Brazil's divisions "provinces"; Brazil is divided into states.

**Backup video.** *The Tropical Rainforest Climate - Secrets of World Climate #1* (Geodiode, 8:57). <https://www.youtube.com/watch?v=wq0asIXcW7w>

With the big idea: watch the "Causes and Dynamics" part (about 2:09 to 3:42) to see why it is hot and rainy near the equator all year, with thunderstorms almost every afternoon.

Note: Captions were not available to check; preview it first. It has a section on "Ecosystem Threats" (about 6:55) that may cover deforestation or claims about a changing climate, and the pace and vocabulary are aimed at older viewers.

### KEY TERMS

#### biome

A large region of the earth with a similar climate, plants and animals, such as a rain forest, desert or tundra.

#### tropical rain forest

A thick, evergreen forest near the equator where it is warm all year and rain falls in nearly every month.

#### canopy

The thick, continuous roof of treetops, roughly 30 to 45 m (100 to 150 ft) above the ground in the Amazon.

**emergent layer**

The scattered giant trees that poke up above the canopy into full sun and wind.

**understory**

The dim layer of young trees, palms and shrubs below the canopy.

**transpiration**

The giving off of water vapor by the leaves of plants.

**CORE IDEAS**

**The story.** In May 1848 two young English naturalists stepped off a sailing ship at Pará, the port city we now call Belém, near the mouth of the Amazon. Their names were Henry Walter Bates and Alfred Russel Wallace. Wallace went home after four years, but Bates stayed for eleven, traveling upriver by canoe and trading boat and living for years at the village of Ega (today Tefé), far up the river. He walked the forest paths every morning with a net and collecting boxes. By the time he sailed home in 1859 he had sent back specimens of 14,712 species of animals, mostly insects, and about 8,000 of them were new to science. In his book *The Naturalist on the River Amazons* (1863) he admitted that much of the forest's life lived high in the treetops, where he could only watch it from below.

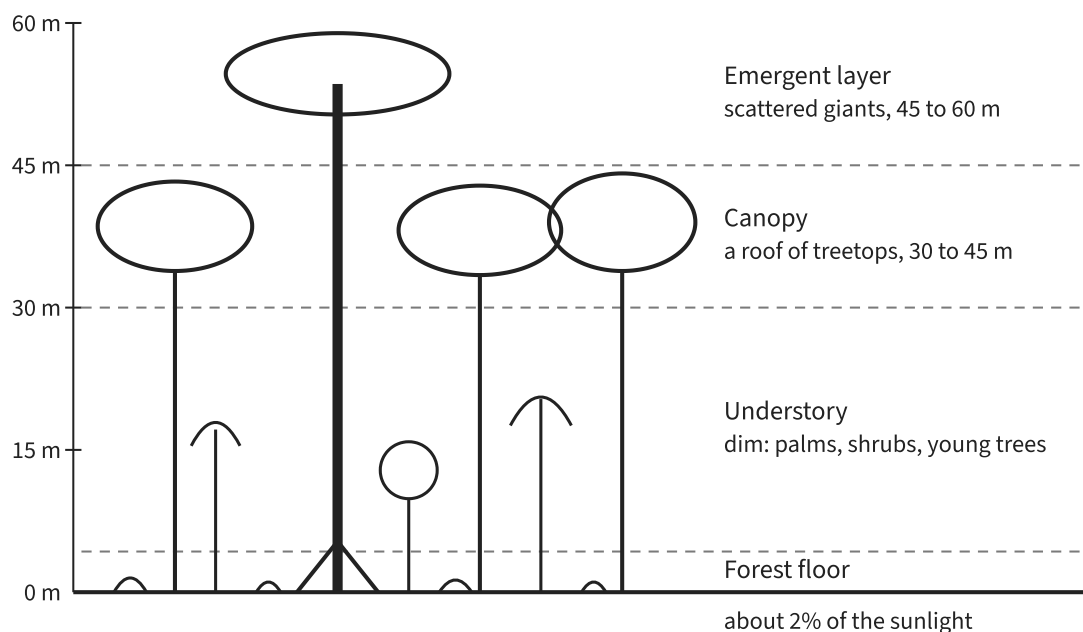
**How it is built.** A rain forest is not one forest but several, stacked on top of each other. At the top is the **emergent layer**: scattered giants such as the kapok and the Brazil nut tree, often 45 to 60 m (150 to 200 ft) tall, standing in full sun and wind. Below them is the **canopy**, a nearly unbroken roof of crowns about 30 to 45 m (100 to 150 ft) up. Here live most of the forest's monkeys, birds, frogs and insects, along with *epiphytes*, plants such as orchids and bromeliads that grow perched on branches. Woody vines called lianas climb from the ground to the light. Below the canopy is the **understory**, a dim, still world of palms, shrubs and young trees waiting for a gap. At the bottom is the **forest floor**. So many leaves catch the light on the way down that only about 2 percent of the sunlight reaches it, which is why the floor is surprisingly open and dark.

**Why it rains every day.** The Amazon lies right on the equator, where the noon sun stands nearly overhead all year (Lesson 5.2). The strong sun heats the ground and the wet leaves, the warm, moist air rises, and as it rises it cools until its water vapor condenses into towering clouds. By afternoon the thunder rolls and the rain pours. The trade winds blow steadily from the Atlantic, carrying ocean moisture westward over the forest. The trees then pump much of the fallen rain back into the air through their leaves (**transpiration**), so the same water can fall again and again farther west, until the air reaches the wall of the Andes. That is why Manaus, in the middle of the forest, receives about 2,300 mm (about 90 inches) of rain a year, and its temperature stays near 27°C (81°F) in every month. In Köppen's system (Lesson 5.4) most of the Amazon rain forest has an **Af** climate (Manaus, with a short, drier season around August, sits right at the edge of Af): every month averages at least 18°C (64°F), and even the driest month has at least 60 mm (about 2.4 in) of rain.

**Soil and river.** You might expect such a forest to stand on rich, deep soil, but most rain forest soil is thin and poor. Heavy rain washes the minerals downward, and dead leaves rot within weeks in the warm, damp air, so the forest keeps most of its nourishment in living plants rather than in the ground. Roots spread wide and shallow to catch every fallen leaf, and many giant trees stand on flaring *buttress roots* like the fins of a rocket. The rivers rise and fall with the rainy seasons. At Manaus the river often rises about 10 m (33 ft) between low water and high water, and huge areas of forest stand in water for months. Bates watched fish swim among the tree trunks and eat fruits and seeds that dropped into the flood.

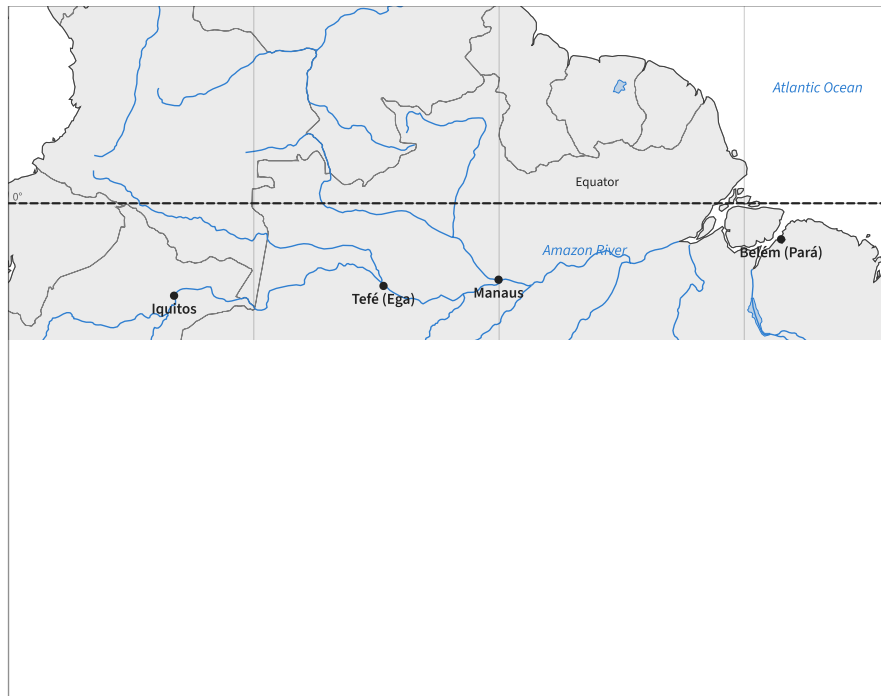
**On the map.** Tropical rain forests form a broken belt within about 10° of the equator: the Amazon basin of South America, the Congo basin of Africa, and the islands and peninsulas of Southeast Asia, such as Borneo, Sumatra and New Guinea. The Amazon River drains about 7 million square kilometers (about 2.7 million square miles), and it carries more water to the sea than any other river on earth, roughly a fifth of all the river water that reaches the oceans. On a Köppen map, the dark green Af areas and the biome map's rain forest areas line up closely. That is the big idea of this unit: **climate draws the map, and the plants and animals fill it in.**

**The big idea.** A **biome** is a great region of the earth where the climate shapes a whole community of living things. In the rain forest, steady warmth and steady rain allow plants to grow all year, and the competition for light builds a forest in layers. Bates found more kinds of butterflies within an hour's walk of Pará than in all of Britain. It is a living picture of the psalmist's words: "O LORD, how manifold are thy works!"



*The four layers of a tropical rain forest. Only about 2 percent of the sunlight reaches the floor.*





*The Amazon basin and the towns of Bates's travels. The river runs almost along the equator.*

## PICTURE STUDY



*Surprised! (Tiger in a Tropical Storm)*, Henri Rousseau, 1891 · Oil on canvas · National Gallery, London

Henri Rousseau was a toll collector in Paris who taught himself to paint. People sometimes called him “Le Douanier,” the customs officer. He never traveled to a tropical forest. He painted his jungles from the palm houses and greenhouses of the Jardin des Plantes in Paris, from animal statues and from pictures in books and magazines. *Surprised!* was his first jungle painting, shown in Paris in 1891.

Rousseau worked very slowly, leaf by leaf, building the jungle out of many shades of green. He even painted silvery streaks of rain slanting across the whole picture. Some critics laughed at him at first, but later painters admired the bold, dreamlike way he saw the world.

### **Look closely**

- Find the streaks of rain and the bending plants. Which way is the wind blowing?
- Count how many different greens you can see. How did Rousseau make the jungle look thick and layered?
- Look at the tiger's eyes and mouth. Is it hunting, or is it frightened by the storm?
- Find the lightning. Where does the light in the picture come from?

### **Talk about it**

1. Tigers live in the forests of Asia, not the Amazon. Which big cat would Bates have met in the Amazon? (The jaguar.)
2. Rousseau painted a storm in a jungle. From what you learned in this lesson, why are thunderstorms so common in a tropical rain forest?
3. How is a painter who has never seen a place like a student studying it from a map and a book? What can each one get right, and what might each one miss?

## **PROJECT: A RAIN FOREST IN A JAR**

You will build a small closed terrarium and watch it make its own "weather" for two weeks. Water will rise from the soil and leaves, collect on the glass like clouds, and fall back like rain, just as the Amazon's trees recycle the rain westward. You will also build the forest in layers, from floor to canopy.

### **You will need**

- A large clear glass jar or plastic bottle with a lid (a 2-liter soda bottle cut in half and taped back together works)
- Small pebbles or aquarium gravel
- Potting soil
- Two or three small leafy plants that like damp shade (a small fern, moss, a baby's tears or a small pothos cutting)
- A spray bottle of water
- A notebook, ruler and pencil

### **Steps**

1. Spread 2 to 3 cm (about 1 in) of pebbles in the bottom of the jar for drainage.
2. Add 5 to 8 cm (2 to 3 in) of potting soil on top.
3. Plant the tallest plant toward the back as your "emergent," a medium plant as your "canopy," and moss or a low plant in front as your "forest floor." Add a few dead leaves on the soil as leaf litter.

4. Spray the soil and leaves until they are damp but not soggy. Close the lid.
5. Set the jar in bright light but not in hot direct sun.
6. Every day for two weeks, record: Is there fog or drops on the glass? Where (top, sides)? At what time of day is it heaviest? Do drops run back down?
7. On day 14, draw your jar as a cross-section and label the four layers and the arrows of the water cycle: rain, soaking in, transpiration, condensation.

### Tips

- If the glass stays completely fogged all day, open the lid for an hour to let some water out. If no drops ever form, add a little more water.
- Watch in the morning and again after the jar has been in the light for a few hours. Like the Amazon, the jar often makes the most “cloud” after the sun has warmed it.

### Check your work

- I can point to the water coming from the leaves and soil and explain transpiration.
- I can label the layers of my jar forest and the real forest they stand for.
- I can explain how the trees of the Amazon help make rain fall again farther west.

### MAP NOTEBOOK

1. Draw the four layers of a rain forest as a tall cross-section with a height scale in meters and feet. Put at least two animals or plants in each layer.
2. On a world outline map, shade the three great rain forest regions (Amazon, Congo, Southeast Asia) and draw the equator and the lines at 10°N and 10°S.
3. Draw a weather cartoon of one Amazon day in four frames: morning sun, rising warm air, piling clouds, afternoon rain.

**From history.** Henry Walter Bates noticed something strange while he was collecting butterflies. Some kinds that birds refused to eat, because they tasted bad, had harmless, good-tasting look-alikes from a completely different family, flying in the same places. In 1862 he explained that the harmless butterflies were protected because birds mistook them for the bad-tasting ones. Naturalists still call this kind of copying “Batesian mimicry.”

## WORKED EXAMPLES

**Example 1.** At the top of the Amazon forest, call the sunlight 100 units. Suppose the canopy catches 90 percent of the light that reaches it, and the understory catches 80 percent of what gets through the canopy. How many units reach the forest floor? What percent is that?

*(Use the map or drawing “Each layer catches part of the light left by the layer above.” shown earlier in this lesson.)*

1. The canopy lets through  $100\% - 90\% = 10\%$  of 100 units:  $0.10 \times 100 = 10$  units reach the understory.
2. The understory lets through  $100\% - 80\% = 20\%$  of those 10 units:  $0.20 \times 10 = 2$  units reach the floor.
3. 2 units out of 100 is 2 percent.

**Answer:** 2 units, or about 2 percent of the sunlight, reach the forest floor. Layers multiply: each one takes its share of what is left.

**Example 2.** You want to draw an emergent tree 60 m tall and a canopy from 30 m to 45 m in your sketchbook, using the scale 1 cm = 5 m. How tall is the tree in your drawing, where does the canopy go, and how tall is the tree in feet (1 m  $\approx$  3.28 ft)?

1. Tree:  $60 \text{ m} \div 5 \text{ m per cm} = 12 \text{ cm}$  tall in the drawing.
2. Canopy bottom:  $30 \div 5 = 6 \text{ cm}$  above the ground line. Canopy top:  $45 \div 5 = 9 \text{ cm}$  above the ground line.
3. Feet:  $60 \times 3.28 = 196.8$ , about 197 ft.

**Answer:** Draw the tree 12 cm tall and the canopy band from 6 cm to 9 cm above the ground line. The real tree is about 197 ft, close to 200 ft.

**Example 3.** Here are rounded monthly figures from a rain gauge and thermometer in a river town of the western Amazon: the coolest month averages 25°C (77°F) and the warmest 27°C (81°F). The driest month gets 110 mm (4.3 in) of rain, and the year totals 2,500 mm (98 in). Use Köppen’s rules to classify the climate.

1. Group A (tropical) needs every month to average at least 18°C (64°F). The coolest month is 25°C, so every month passes. It is an A climate.
2. Af (rain forest) needs the driest month to have at least 60 mm (2.4 in). The driest month has 110 mm, which passes.
3. Check the temperature range:  $27 - 25 = 2^{\circ}\text{C}$ . The seasons hardly change in temperature; the year is steady.

**Answer:** Af, a tropical rain forest climate: hot in every month (only a 2°C range) and wet in every month.

## PRACTICE

1. **EASY** Name the four layers of a tropical rain forest from top to bottom.
2. **EASY** Who explored the Amazon from 1848 to 1859 and wrote *The Naturalist on the River Amazons*? Which naturalist traveled out with him?
3. **EASY** Manaus gets about 2,300 mm of rain a year. Convert this to inches (1 in = 25.4 mm).
4. **MEDIUM** A canopy tree is 40 m tall. How tall is it in feet (1 m  $\approx$  3.28 ft)?
5. **MEDIUM** Bates sent home 14,712 species, and about 8,000 were new to science. About what percent were new?
6. **MEDIUM** A tropical town’s coolest month averages 24°C, but its driest month gets only 20 mm of rain. Is it an Af climate? Explain.
7. **MEDIUM** Use the map. Manaus lies at about 3°S. One degree of latitude is about 111 km (69 mi). How far is Manaus from the equator?  
(Use the map or drawing “Find Manaus and the equator.” shown earlier in this lesson.)
8. **HARD** The rain forest has more plants than any other biome, yet its soil is usually poor. Explain why.
9. **HARD** Rousseau painted a tiger in a jungle. If you set his picture in the Amazon, what would you change, and why?
10. **CHALLENGE** Write three or four sentences explaining how the trees of the eastern Amazon help bring rain to the western Amazon.

## COMMON MISTAKES

- Thinking a rain forest floor is a tangled jungle everywhere. Under a full canopy the floor is dark and fairly open; thick tangles grow mainly along rivers and in gaps where light gets in.

- Thinking rich plant life means rich soil. Rain forest soil is usually thin and poor; the nutrients are in the living plants.
- Mixing up the canopy and the emergent layer. The canopy is the continuous roof; emergents are the scattered giants that stick up above it.

**Make it a game · Layer Leap.** Mark four zones on the floor or stairs: forest floor, understory, canopy, emergent. A caller names a plant or animal (jaguar, howler monkey, orchid, leaf-cutter ant, harpy eagle, toucan, buttress root, young palm, kapok tree top). Players jump to the layer where it mostly lives or grows and must give one reason (light, food, safety). A correct layer and reason earns a point. Then switch callers.

**Scripture.** “O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches.” (Psalm 104:24, KJV)

“Manifold” means many and varied. A single acre of rain forest can hold more kinds of trees than a whole country in the cooler north. The more Bates collected, the more he found that no one had ever named. The variety of creation is one of the ways it shows the wisdom of its Maker.

#### Practice answers

1. Emergent layer, canopy, understory, forest floor.
2. Henry Walter Bates. He sailed out with Alfred Russel Wallace.
3.  $2,300 \div 25.4 \approx 90.6$ , about 90 inches.
4.  $40 \times 3.28 = 131.2$ , about 131 ft.
5.  $8,000 \div 14,712 \approx 0.54$ , so about 54 percent, a little more than half.
6. No. It is an A (tropical) climate because every month is above  $18^{\circ}\text{C}$ , but Af needs at least 60 mm in the driest month. With a dry month of 20 mm it is a tropical climate with a dry season (a monsoon or savanna type), not a rain forest climate.
7.  $3 \times 111 = 333$  km, or  $3 \times 69 = 207$  mi. About 330 km (about 210 mi) south of the equator.
8. Heavy rain washes minerals down out of reach, and dead leaves rot very quickly in the warm, damp air, so the nutrients are taken up again by roots almost at once. Most of the forest’s nourishment is stored in the living plants, not in the soil.
9. Replace the tiger with a jaguar. Tigers are native to Asia; the jaguar is the great spotted cat of the Amazon. Rousseau never visited a jungle and painted from greenhouses and pictures.
10. The trade winds carry moist air from the Atlantic westward over the forest, and rain falls. The trees draw that water up through their roots and give much of it back to the air as water vapor through their leaves (transpiration). The winds carry this vapor farther west, where it rises, cools and falls as rain again. So the same water can fall several times on its way toward the Andes.

## 6.2 DESERTS AND GRASSLANDS

### OBJECTIVES

- Use yearly rainfall to tell a desert from a grassland and a forest, and explain why the Sahara lies where the sinking air of the subtropics keeps clouds away.
- Explain how continentality and the rain shadow of the Rockies make the steppe of Eurasia and the prairie of North America too dry for most trees.
- Tell how Stephen Long's expedition of 1820 labeled the Great Plains a "Great Desert" and judge, with rainfall numbers, whether that label was right.

**Warm-up.** Fill one cup with dry sand (or dry soil) and another with water, and set both in a sunny window or under a lamp for 15 minutes. Touch each one. Which warmed faster? Now set both in a shady spot for 15 minutes. Which cooled faster? Guess what this tells you about nights in a desert.

**Watch.** *The Grassland Biome - Biomes #5* (Geodiode, 10:51).

<https://www.youtube.com/watch?v=Yy191KVBNP0>

With the big idea: listen for the different names for grasslands (prairie, steppe, pampas, veldt) and look for the North American Great Plains on the map.

**Note:** Captions were not available to check; preview it first. A section near the end (9:11) on threats to grasslands may touch on environmental concerns.

### KEY TERMS

#### desert

A region that gets very little rain or snow, usually less than about 250 mm (10 in) a year, so that plants are few and widely spaced.

#### grassland

A biome covered mostly by grasses and flowers, with few trees, where rain is too scanty or uncertain for forest. In North America it is called prairie; in Eurasia, steppe.

#### subtropical high

A belt of high pressure near 20° to 30° latitude where air sinks, warms and dries out, so clouds rarely form.

#### continentality

The effect of being far from the ocean: drier air, hot summers and very cold winters.

#### oasis

A place in a desert where groundwater reaches the surface, so that palms and crops can grow.

#### sod

The top layer of grassland soil, tightly bound together by a dense mat of grass roots.



## CORE IDEAS

**The story.** In the summer of 1820 Major Stephen H. Long of the U.S. Army led a small expedition up the Platte River across what is now Nebraska and Colorado to the foot of the Rocky Mountains. His botanist, Edwin James, made the first recorded climb of Pikes Peak that July. For weeks the men rode across a sea of grass with hardly a tree except along the rivers, short of water and shade. When the expedition's map was published in 1823, the plains east of the Rockies were labeled "Great Desert," and Long wrote that the land was almost wholly unfit for farming. Zebulon Pike had compared the same plains to the sandy deserts of Africa after his journey of 1806–1807. For a generation, schoolbooks showed a "Great American Desert" in the middle of the continent. Were they right?

**How to tell them apart.** Geographers sort dry lands by how much water falls in a year. A **desert** usually gets less than about 250 mm (10 in). A **grassland** usually gets roughly 250 to 750 mm (10 to 30 in), enough for a thick cover of grass but often not enough, or not steady enough, for a forest. Cairo, at the edge of the Sahara, gets only about 25 mm (1 in) a year. Western Kansas gets about 480 mm (19 in), and eastern Kansas about 1,000 mm (40 in). So Long's "desert" was really a **grassland**: dry, windy and treeless, but covered with grass whose roots held some of the richest soil on earth. Once settlers had steel plows to cut the tough **sod** and windmills to pump groundwater, the plains became one of the world's great wheat and cattle lands.

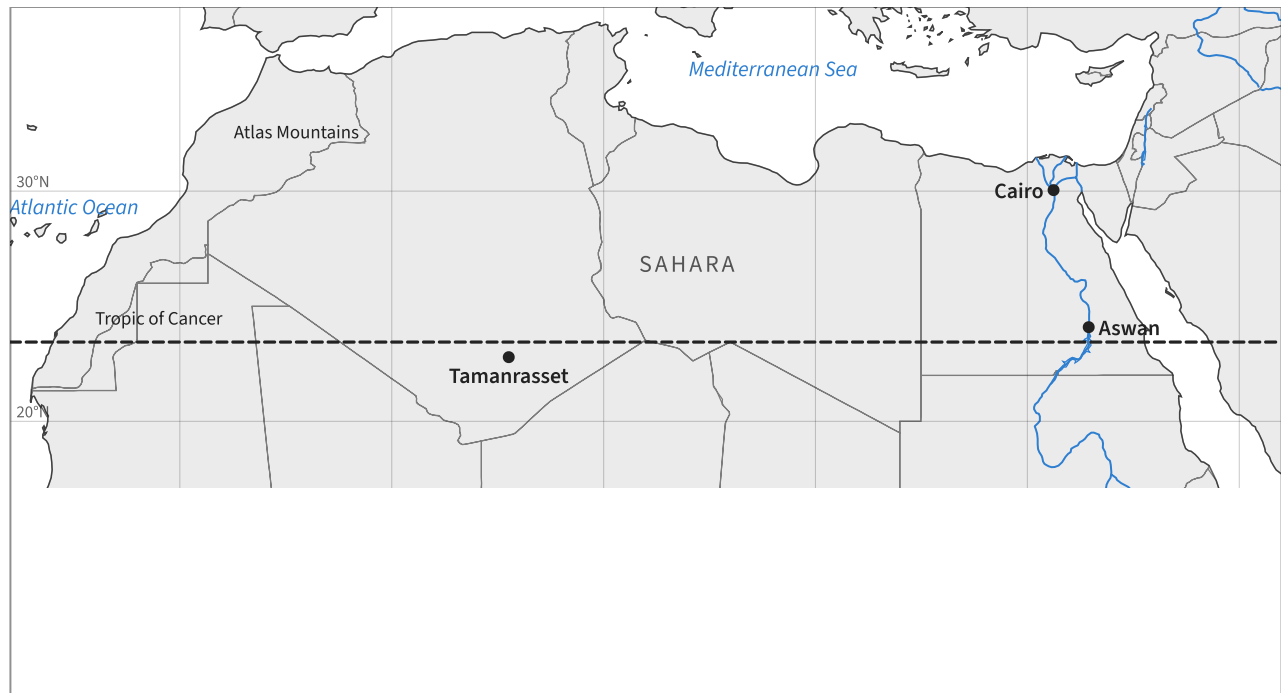
**Why the Sahara is dry.** The Sahara is a true desert, the largest hot desert on earth, about 9.2 million square kilometers (about 3.6 million square miles), a little larger than the 48 connected states of the U.S. It stretches roughly 4,800 km (3,000 mi) from the Atlantic to the Red Sea. Its dryness comes from the same circulation that soaks the rain forest. The air that rises over the equator and drops its rain flows away toward the north and south and sinks again near 20° to 30° latitude. Sinking air is squeezed and warmed, and warm sinking air does not form clouds. This belt of **subtropical high** pressure lies over the Sahara, Arabia, the Kalahari and the deserts of Australia and Mexico. Under clear skies the ground heats fiercely by day and loses its heat fast at night, so a summer day of 40°C (104°F) can be followed by a night of 20°C (68°F) or less. Most of the Sahara is bare rock plateau and gravel plain; the great sand seas cover only part of it. Wind piles the sand into dunes, and small crescent dunes can creep many meters in a single year. People live where water is found: along the Nile and in **oases**, where groundwater reaches the surface.

**Why grasslands lie inland.** The grasslands of the middle latitudes lie deep inside the continents. The Eurasian **steppe** runs about 8,000 km (5,000 mi) from Hungary and Ukraine across Kazakhstan to Mongolia, farther from the sea than almost any other land. Winds that reach it have dropped most of their ocean moisture long before. This is **continentality**: dry air, hot summers and bitter winters. The North American **prairie** adds a rain shadow. Pacific air loses its moisture on the western mountains and the Rockies (Lesson 5.3), so the western plains are dry, while moist air from the Gulf of Mexico waters the eastern plains. That is why tallgrass prairie, with big bluestem taller than a man, grew in Illinois and eastern Kansas, and shortgrass prairie only ankle-high grew near the Rockies. John Wesley Powell pointed

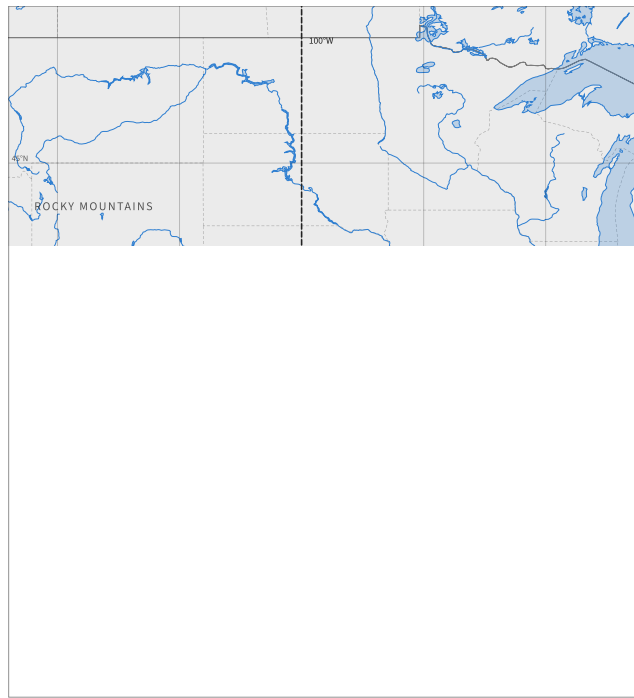
out in 1878 that the line of about 20 inches (510 mm) of yearly rain runs close to the 100th meridian, and that farming west of it would need irrigation or careful dry farming.

**Why grass and not trees.** Grasses grow from the base, not the tip, so they can be grazed, trampled or burned and grow right back. Their roots reach deep and form a thick sod that holds water through a dry summer. Tree seedlings are killed by drought, by the hooves and teeth of bison or wild horses, and by the fires that swept the prairie. Grassland plants are built for a land of drought, wind, fire and grazing, and the prairie bloomed with flowers among the grasses each spring and summer.

**On the map.** Find the deserts in two belts near 20° to 30° north and south, and on the west coasts where cold ocean currents chill the air, such as the Atacama and the Namib. Find the grasslands between the deserts and the forests: the prairie of North America, the steppe of Eurasia, the pampas of Argentina, and the tropical savannas of Africa. On the Köppen map they are the B climates: BW for desert, BS for steppe.

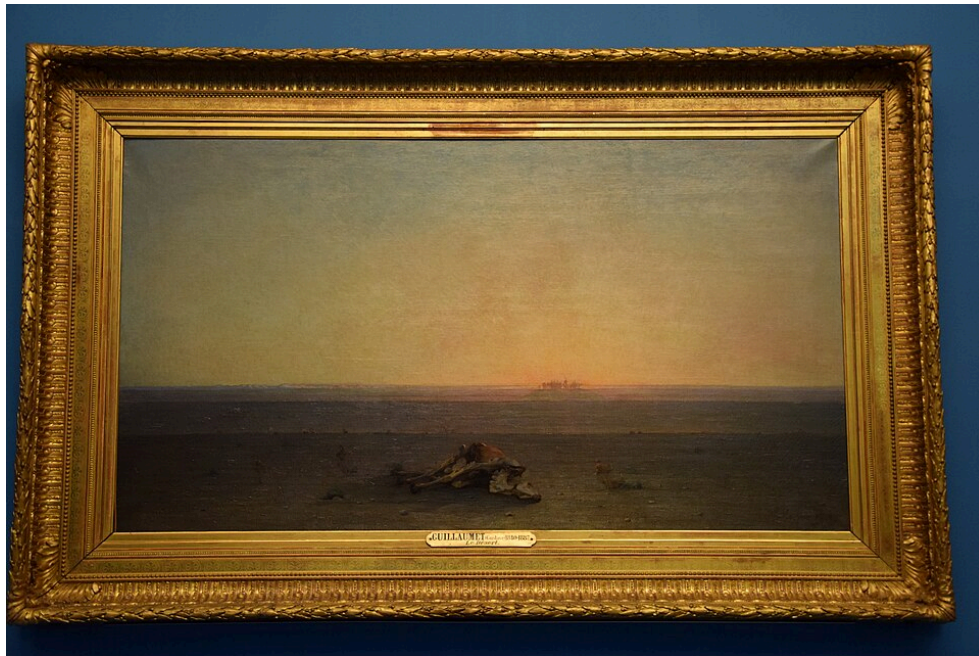


*The Sahara lies under the subtropical high, across the Tropic of Cancer.*



*The Great Plains. Rain decreases from the Gulf-watered east to the rain shadow of the Rockies in the west.*

## PICTURE STUDY



*The Sahara (also called The Desert), Gustave Guillaumet, 1867 · Oil on canvas · Musée d'Orsay, Paris*

Gustave Guillaumet was a French painter who traveled to Algeria many times and spent long months at the edge of the Sahara. Unlike many painters of his day who filled their desert pictures with bright costumes and exciting scenes, Guillaumet wanted to show the desert as it felt: huge, silent, hot and empty.

In this painting almost nothing happens. The ground runs flat to the horizon, the sky is hazy with heat, and in front of us lie the bones of a camel that did not finish its journey. It is one of the most honest pictures ever painted of what a true desert is like.

### **Look closely**

- Find the horizon. How much of the painting is sky and how much is ground?
- Look at the colors. Can you find any green at all? What does that tell you about rainfall?
- Find the camel skeleton. Why do you think the painter placed it so close to us?
- Look far into the distance. Can you see any sign of people or a caravan?

### **Talk about it**

1. How is this desert different from the prairie that Long's men crossed in 1820? What would have to change to make it a grassland?
2. Why did the caravans of the Sahara travel from oasis to oasis instead of in a straight line?
3. How does this painting make you feel? How did the painter make a picture of almost nothing so powerful?

## **PROJECT: SAND, SOIL AND SOD**

In two short experiments you will discover why desert days are hot and nights are cold, and why prairie grass survives drought and fire. Scientists learn by measuring, so you will record numbers, not just impressions.

### **You will need**

- Two small identical containers (yogurt cups or jar lids)
- Dry sand and damp potting soil
- Two kitchen or outdoor thermometers (or one, used in turn)
- A desk lamp with an incandescent or halogen bulb, or a sunny window
- A clear plastic bottle or tall clear cup, potting soil and grass seed (or a clump of lawn grass dug up with its roots)
- Notebook, ruler and pencil

### **Steps**

1. Experiment 1: Fill one container with dry sand and the other with damp soil. Push a thermometer about 1 cm into each. Record both temperatures.
2. Set both under the lamp, the same distance away, or in the same sunny spot. Record the temperatures every 5 minutes for 20 minutes.
3. Turn off the lamp (or move both to the shade) and record every 5 minutes for another 20 minutes.

4. Make a line graph with time across the bottom and temperature up the side, with one line for sand and one for damp soil. Which heated faster? Which cooled faster?
5. Experiment 2: Fill the clear bottle with soil, sprinkle grass seed along the side against the plastic, and keep it damp. (Or plant a clump of lawn grass, roots and all, against the side.)
6. After two to three weeks, measure the longest root and the tallest blade. Then cut the grass down to 1 cm with scissors, as a grazing bison or a fire would, and watch for a week. Record how fast it grows back.
7. Write a short paragraph: How do your results explain a desert night and the survival of the prairie?

### Tips

- Keep the lamp at least 30 cm (12 in) from the containers and do not leave it unattended. The bulb gets hot.
- Grass roots will often grow longer than the leaves above them. That hidden half is what holds prairie soil together.

### Check your work

- I can explain from my graph why dry desert ground heats and cools quickly.
- I can explain why grass grows back after being cut or burned.
- I can tell a desert from a grassland by yearly rainfall.

### MAP NOTEBOOK

1. On a world outline map, shade the desert belts near 20° to 30° N and S in one color and the grasslands (prairie, steppe, pampas, savanna) in another. Label the Sahara, the steppe and the prairie.
2. Draw a cross-section of the prairie from the Rockies to the Mississippi, with short grass in the west and tall grass in the east, and arrows showing dry air from the west and moist air from the Gulf.
3. Draw a prairie grass plant with its roots, to scale, next to a drawing of yourself. Label the depth of the roots.

**From history.** Settlers on the treeless prairie of Nebraska and Kansas in the 1870s and 1880s often had no timber to build with, so they built houses of the prairie itself. They plowed long strips of sod, cut them into bricks about a foot by two feet, and stacked them grass side down into thick walls. These “soddies” were cool in summer and warm in winter, because the thick earth walls held the temperature steady. The tough sod that made the bricks was the same root mat that let the prairie survive drought and fire.

## WORKED EXAMPLES

**Example 1.** Classify each place as desert, grassland or forest using yearly precipitation: Cairo, about 25 mm (1 in); Goodland in western Kansas, about 480 mm (19 in); Kansas City, about 1,000 mm (40 in).

1. Rule of thumb: desert under about 250 mm (10 in); grassland about 250 to 750 mm (10 to 30 in); above that, forest is possible.
2. Cairo: 25 mm is far below 250 mm, so desert.
3. Goodland: 480 mm is between 250 and 750 mm, so grassland (shortgrass prairie).
4. Kansas City: 1,000 mm is above 750 mm, enough for forest. Here tallgrass prairie met the eastern woodlands, with trees along every stream.

**Answer:** Cairo: desert. Goodland: grassland. Kansas City: wet enough for forest, at the eastern edge of the prairie.

**Example 2.** The Sahara runs from about 30°N at its northern edge (near the Mediterranean and the Atlas Mountains) to about 16°N at its southern edge (the Sahel). One degree of latitude is about 111 km (69 mi). About how wide is the Sahara from north to south?

*(Use the map or drawing “Measure from the northern edge to the Sahel.” shown earlier in this lesson.)*

1. Subtract the latitudes:  $30^\circ - 16^\circ = 14^\circ$ .
2. Kilometers:  $14 \times 111 = 1,554$  km.
3. Miles:  $14 \times 69 = 966$  mi.

**Answer:** About 1,550 km (about 970 mi) from north to south, roughly a third of its 4,800 km (3,000 mi) width from west to east.

**Example 3.** Kansas City gets about 1,000 mm (40 in) of precipitation a year and Goodland about 480 mm (19 in). Goodland lies about 610 km (380 mi) west of Kansas City. How fast does rainfall drop as you travel west, per 100 km and per 100 mi?

*(Use the map or drawing “Kansas City in the east and Goodland near the 100th meridian in the west.” shown earlier in this lesson.)*

1. Difference:  $1,000 - 480 = 520$  mm, or  $40 - 19 = 21$  in.
2. Per 100 km:  $520 \div 610 \times 100 \approx 85$  mm less for every 100 km west.
3. Per 100 mi:  $21 \div 380 \times 100 \approx 5.5$  in less for every 100 mi west.

**Answer:** Rainfall drops about 85 mm per 100 km (about 5.5 in per 100 mi) going west, which is why tallgrass gives way to shortgrass across Kansas.



## PRACTICE

1. **EASY** About how much yearly precipitation marks a desert? Give it in millimeters and inches.
2. **EASY** What is the grassland of North America called? Of Eurasia? Of Argentina?
3. **EASY** The Sahara covers about 9.2 million km<sup>2</sup> and the 48 connected U.S. states about 8.1 million km<sup>2</sup>. How many times larger is the Sahara?
4. **MEDIUM** A Sahara day reaches 40°C (104°F) and the night falls to 14°C (57°F). What is the daily range in °C and °F? Why is the range so large?
5. **MEDIUM** Explain in two sentences why so many of the world's deserts lie near 20° to 30° latitude.
6. **MEDIUM** Long's map of 1823 labeled the Great Plains a "Great Desert." Using rainfall, explain whether that label was accurate.
7. **MEDIUM** Use the Great Plains map. Is the land just west of the 100th meridian usually wetter or drier than the land just east of it? Why?  
(Use the map or drawing "Find the 100th meridian." shown earlier in this lesson.)
8. **HARD** Explain why the Eurasian steppe is dry even though it is not in the subtropical high-pressure belt.
9. **HARD** A small crescent dune moves 15 m (about 50 ft) a year toward a road 150 m (about 490 ft) away. If it keeps that pace, how many years until it reaches the road?
10. **CHALLENGE** Give three reasons grasses, not trees, covered the natural prairie.

## COMMON MISTAKES

- Thinking every desert is hot and sandy. Most of the Sahara is rock and gravel, and some deserts, such as the Gobi and interior Antarctica, are very cold.
- Thinking a treeless land must be a desert. The prairie and steppe are grasslands with far more rain than a desert and some of the richest soil in the world.
- Forgetting that the same circulation explains both the rain forest and the Sahara: air rises and rains at the equator, then sinks and dries in the subtropics.

**Make it a game • Desert or Grassland?.** Make cards with a place and its yearly precipitation (Cairo 25 mm; Goodland 480 mm; Ulaanbaatar, Mongolia, about 270 mm; Timbuktu about 200 mm; Lincoln, Nebraska, about 740 mm; Phoenix about 200 mm). A player draws a card and must call desert, grassland or forest edge, then give one reason from the lesson (subtropical high, continentality or rain shadow). A correct call scores 1 point, and a correct reason scores 1 more.

**Scripture.** "The wilderness and the solitary place shall be glad for them; and the desert shall rejoice, and blossom as the rose." (Isaiah 35:1, KJV)

Anyone who has seen a desert after a rare rain knows how quickly seeds that waited in the dry ground spring up and bloom. Isaiah uses that picture to describe God's power to bring life where there was none.



## Practice answers

1. Less than about 250 mm (10 in) a year.
2. Prairie; steppe; pampas.
3.  $9.2 \div 8.1 \approx 1.14$ , so about 1.1 times as large, a little larger than the 48 states.
4.  $40 - 14 = 26^{\circ}\text{C}$ ;  $104 - 57 = 47^{\circ}\text{F}$ . Dry air and clear skies let the sun heat the ground strongly by day, and with no clouds or moisture to hold the heat, it escapes quickly at night.
5. Air that rises and rains over the equator flows poleward and sinks near  $20^{\circ}$  to  $30^{\circ}$  latitude. Sinking air is warmed and dried, so clouds and rain rarely form there (the subtropical high).
6. Not really. Most of the plains get about 380 to 750 mm (15 to 30 in) a year, which is grassland, not desert (under 250 mm). The land was treeless and dry, which is why it looked like a desert to travelers, but it had deep, rich soil held by grass roots and later became great farming land.
7. Drier. It is farther from the Gulf of Mexico's moist air and deeper in the rain shadow of the Rockies. Powell noted that the 20-inch (about 510 mm) rainfall line runs near the 100th meridian.
8. It lies deep inside the largest continent, thousands of kilometers from the oceans (continentality). Winds lose most of their moisture before they reach it, and mountains to the south block moist air from the Indian Ocean. So it gets only grassland amounts of rain, with hot summers and very cold winters.
9.  $150 \div 15 = 10$  years.
10. Any three: there was too little and too uncertain rain for most trees; grasses grow from the base and recover after grazing and fire while tree seedlings are killed; frequent prairie fires burned young trees; bison trampled and grazed seedlings; deep, dense grass roots took the water first and formed a tough sod.

## 6.3 FORESTS OF THE TEMPERATE LANDS AND THE TAIGA

### OBJECTIVES

- Describe the temperate deciduous forest and the taiga (boreal forest), and explain how broad leaves that fall and needles that stay suit each climate.
- Use Köppen's rules and a city's coldest and warmest months to recognize a continental (D) climate, and explain why the taiga lies in the interiors of the northern continents.
- Tell how Henry David Thoreau climbed Mount Katahdin in 1846 through hardwoods, spruce and fir to the treeless heights near the summit, and explain why climbing a mountain is like traveling north.

**Warm-up.** Find a leaf from a broadleaf tree (maple, oak or any houseplant) and a sprig of needles from an evergreen (pine, spruce, fir or a Christmas wreath). Feel both. Which is thicker and waxier? Which has more surface? Bend each one. Guess which would lose its water faster on a dry, frozen winter day.

**Watch.** *Why Do Leaves Change Color? What Makes the Leaves Fall?* FreeSchool (Free School, 3:39). <https://www.youtube.com/watch?v=UuTrDnzmMxY>

With the big idea: watch why the leaves of maples, birches and beeches like the ones Thoreau walked through turn color and drop in fall, and compare them with the evergreen spruce and fir.

**Note:** Captions were not available to check; preview it first. FreeSchool videos usually suit families.

**Backup video.** *The Taiga Biome (Boreal Forest) - Biomes #7* (Geodiode, 12:22).

<https://www.youtube.com/watch?v=OUmHWrF8MnY>

With On the map: watch from "What is the Taiga?" (1:31) through "Taiga Fauna" (about 10:30) to see where the boreal forest stretches across Canada, Alaska and Siberia and why conifers grow best there. Note: Captions were not available to check; preview it first. The last chapter, "Relationship to Global Climate" (10:30), probably covers carbon and claims about a changing climate, so you may want to stop before it. The video is long and fairly technical.

### KEY TERMS

#### temperate deciduous forest

A forest of broadleaf trees such as oak, maple, beech and hickory that drop their leaves each autumn, found where there are four seasons and rain all year.

#### deciduous

Shedding leaves for part of the year.

#### conifer

A cone-bearing tree, usually with needles, such as spruce, fir, pine or larch. Most are evergreen.

**taiga**

The great northern forest of conifers (also called the boreal forest) that crosses Alaska, Canada, Scandinavia and Russia; the largest land biome on earth.

**tree line**

The edge, toward the poles or up a mountain, beyond which it is too cold for trees to grow.

**krummholz**

A German word meaning “crooked wood”: the low, twisted, wind-pruned trees found just below the tree line.

**CORE IDEAS**

**The story.** In early September 1846, while he was still living in his cabin at Walden Pond near Concord, Massachusetts, Henry David Thoreau traveled north into the wild woods of Maine to climb Mount Katahdin, the highest mountain in the state at 1,605 m (5,267 ft). He walked first through forests of maple, birch and beech, then through dark, close-packed spruce and fir. Higher up, the spruce grew so short and so dense that he described walking on top of the treetops instead of under them. Near the summit there were no trees at all, only rocks, mosses and low plants, wrapped in racing clouds. He wrote about the climb in essays later gathered in *The Maine Woods* (1864). In a climb of just a few miles, Thoreau had passed through three biomes.

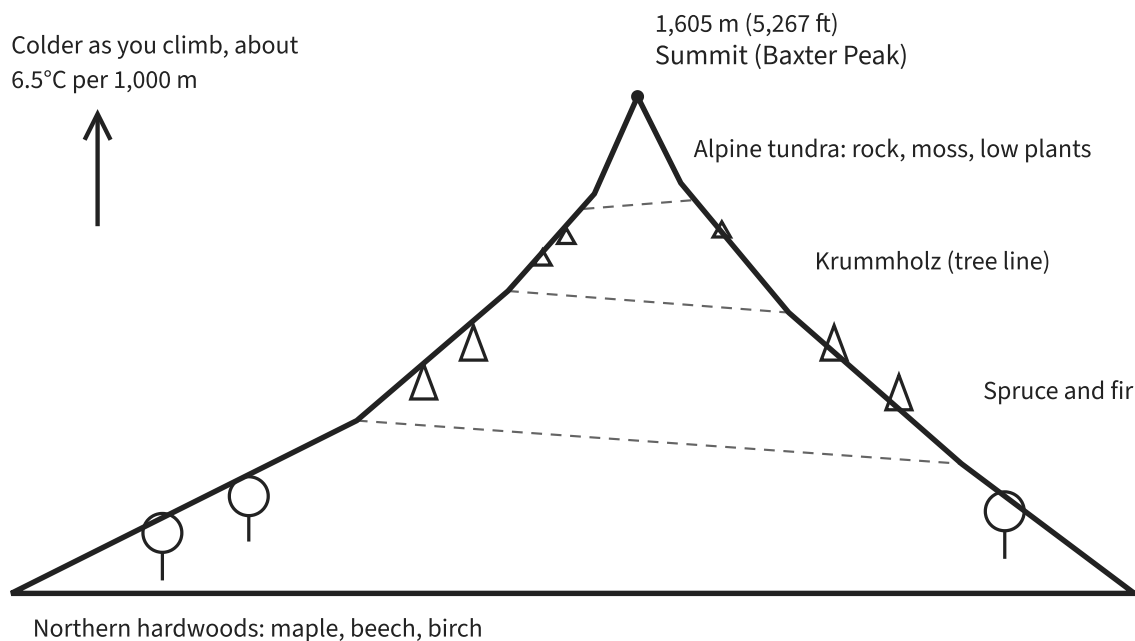
**The temperate deciduous forest.** Around Concord, and across the eastern United States, western and central Europe and eastern China, grows the **temperate deciduous forest**. Its climate has four clear seasons and rain or snow in every month, often 750 to 1,500 mm (30 to 60 in) a year. Its trees are oaks and maples, beech, hickory, ash and tulip trees, with broad, thin leaves that catch a great deal of light in summer. But broad leaves lose a great deal of water, and in winter the ground freezes, so the roots cannot replace it. So each autumn the trees stop making green chlorophyll, the yellows and oranges that were hidden in the leaf show through (and some trees, like red maples, make new reds), and the leaves fall. The fallen leaves rot into rich brown soil. In early spring, before the trees leaf out, wildflowers such as trillium and bloodroot race to bloom in the sunlight on the forest floor. Thoreau kept careful notes for years of the dates when each plant in Concord first flowered, and scientists still use his records today.

**The taiga.** North of the broadleaf forests, from Alaska across Canada and from Norway across all of Russia to the Pacific, lies the **taiga**, or boreal forest, the largest land biome on earth. Its winters are long and bitter and its summers short and cool. Spruce, fir, pine and larch are built for it. Their needles are thin and coated with wax, so they lose little water when the ground is frozen. Most stay on the tree all winter, ready to start making food on the first warm day of the short summer. Their cone shape and bending branches shed heavy snow. The soil is thin and acid because needles rot slowly in the cold, and water collects in countless lakes and bogs. Moose, lynx, snowshoe hares, wolves and bears live in it. In

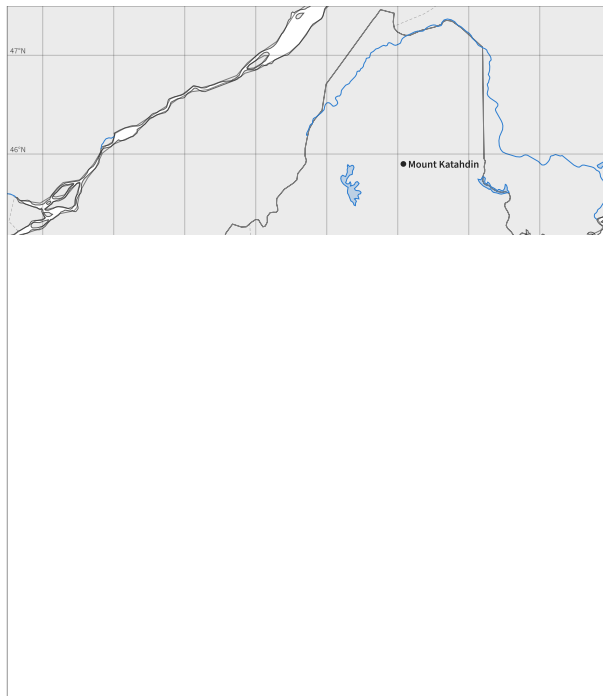
eastern Siberia the larch, a conifer that drops its needles each fall, takes over where even spruce cannot stand the cold.

**Why the taiga lies inland.** The taiga lies mostly between about 50° and 65° north, in the interiors of North America and Eurasia, and its climate is the strongest example of **continentality** on earth. Yakutsk in Siberia, in the heart of the taiga, averages about  $-39^{\circ}\text{C}$  ( $-38^{\circ}\text{F}$ ) in January and about  $19^{\circ}\text{C}$  ( $66^{\circ}\text{F}$ ) in July, a range of  $58^{\circ}\text{C}$  ( $104^{\circ}\text{F}$ ). Compare Concord, much nearer the ocean, at about  $-2^{\circ}\text{C}$  ( $28^{\circ}\text{F}$ ) in January and about  $23^{\circ}\text{C}$  ( $73^{\circ}\text{F}$ ) in July. Land heats and cools far faster than water, so places far from the sea swing between extremes. In Köppen's system these are the **D** climates: the coldest month is below  $-3^{\circ}\text{C}$  ( $27^{\circ}\text{F}$ ) but at least one month reaches  $10^{\circ}\text{C}$  ( $50^{\circ}\text{F}$ ), the warmth trees need to grow. There is almost no such climate in the Southern Hemisphere, because there is no wide land at those latitudes to make it.

**On the map: up is like north.** On Katahdin, Thoreau saw the map of a continent in a few thousand feet. Air cools about  $6.5^{\circ}\text{C}$  for every 1,000 m you climb (Lesson 5.3), so the mountainside is stacked in the same order as the lands from Massachusetts to the Arctic: hardwoods at the bottom, then spruce and fir like the taiga, then twisted **krummholz** at the **tree line**, then treeless alpine tundra at the top, like the Arctic coast you will visit in the next lesson. On a biome map, notice how the belts of forest bend: they reach farther north on the mild west coasts of the continents and dip south in the cold interiors.



*Climbing Katahdin is like traveling north: the same belts of plants appear in the same order.*



*From Concord to Katahdin, the forests change from oak and maple toward spruce and fir.*

## PICTURE STUDY



*Morning in a Pine Forest*, Ivan Shishkin and Konstantin Savitsky, 1889 · Oil on canvas · State Tretyakov Gallery, Moscow

Ivan Shishkin was the great forest painter of Russia. He studied trees as carefully as a botanist, and people said they could tell the kind of every tree in his paintings. For this picture he painted the misty northern pine forest and the fallen tree, and his friend Konstantin Savitsky painted the bears. When the collector Pavel Tretyakov bought the

painting, he had Savitsky's signature removed, saying that everything in it was Shishkin's style, so only Shishkin's name remains.

The painting became so loved in Russia that its bears were printed on the wrappers of a famous chocolate candy, and many Russians still call the picture "Three Bears," though there are four.

### **Look closely**

- Find the light. Where is it coming from, and what does the mist tell you about the time of day?
- Count the bears. What is each one doing?
- Look at the fallen tree. What might have knocked it down, and what will happen to it over the coming years?
- Look at the trunks in the background. Are they broadleaf trees or conifers? How can you tell?

### **Talk about it**

1. How is this northern forest different from the Amazon forest in Lesson 6.1? Think about light, layers and the floor.
2. Why do needles rot more slowly on a taiga floor than leaves on a rain forest floor?
3. Shishkin studied trees closely before painting them. What can an artist and a geographer learn from each other?

## **PROJECT: THE LEAF AND NEEDLE WATER TEST**

Trees "breathe out" water through their leaves. In this test you will catch that water and compare a broadleaf tree with a conifer, to see why one drops its leaves for winter and the other does not. You will also start a small field collection for your biome field guide.

### **You will need**

- Two clear plastic sandwich or produce bags
- Two twist ties or string
- Access to one broadleaf tree or shrub and one conifer (pine, spruce, fir, juniper or arborvitae) in sun
- Measuring spoons or a small measuring cup marked in milliliters
- Paper, pencil, a hand lens if you have one, and a heavy book for pressing

### **Steps**

1. On a sunny morning, choose a leafy twig on the broadleaf tree and a twig of about the same size on the conifer, both in the sun.
2. Slip a bag over each twig and tie it tightly around the stem so no air gets in. Do not pick the twigs.
3. Leave the bags for 4 to 6 hours. Then look: which bag has more fog and drops inside?



4. Remove the bags carefully, shake the water into a corner, and measure or estimate each amount.
5. Count the leaves on the broadleaf twig and estimate the needles on the conifer twig. Which has more surface facing the sun?
6. Collect one fallen leaf of each of five broadleaf trees and one sprig and cone of each conifer you can find. Press the leaves, and label each with its name, place and date.
7. Write: Which twig lost more water? How does this help explain why oaks and maples drop their leaves before the ground freezes, while spruce and fir keep their needles?

### Tips

- Ask permission before tying bags on a neighbor's tree. Use only fallen leaves and cones, or a single sprig from your own tree.
- A hot, sunny, still day gives the clearest result. Repeat on a cloudy day if you can and compare.

### Check your work

- I can explain transpiration and show my measured results.
- I can give two reasons needles suit the taiga.
- I can identify at least three broadleaf trees and two conifers from my collection.

### MAP NOTEBOOK

1. Draw Mount Katahdin as a cross-section with its four zones labeled, and beside it a north-to-south strip from Massachusetts to the Arctic coast with the same four zones.
2. Draw a climate chart (bars for each month) comparing January and July temperatures for Concord and Yakutsk. Label the ranges.
3. Sketch a maple leaf and a spruce sprig side by side, and list three differences that help each survive its climate.

**From history.** Thoreau's neat notes of when Concord's wildflowers first bloomed, and when its trees first leafed out, filled pages of his journal through the 1850s. Long after his death, botanists working in Concord compared their own observations of the same plants with his lists. His journal shows that patient, careful recording of ordinary things, done year after year in one place, can become valuable science.



## WORKED EXAMPLES

**Example 1.** Yakutsk averages about  $-39^{\circ}\text{C}$  ( $-38^{\circ}\text{F}$ ) in January and about  $19^{\circ}\text{C}$  ( $66^{\circ}\text{F}$ ) in July. Find its yearly temperature range in  $^{\circ}\text{C}$  and  $^{\circ}\text{F}$ , and use Köppen's rules to find its climate group.

1. Range in  $^{\circ}\text{C}$ :  $19 - (-39) = 19 + 39 = 58^{\circ}\text{C}$ .
2. Range in  $^{\circ}\text{F}$ :  $66 - (-38) = 66 + 38 = 104^{\circ}\text{F}$ .
3. Köppen: the coldest month,  $-39^{\circ}\text{C}$ , is below  $-3^{\circ}\text{C}$ , so it is not an A or C climate. The warmest month,  $19^{\circ}\text{C}$ , is above  $10^{\circ}\text{C}$ , so it is not an E (polar) climate. It is not dry enough to be B.
4. Coldest month below  $-3^{\circ}\text{C}$  with a warmest month of at least  $10^{\circ}\text{C}$ : group D, a continental climate.

**Answer:** A range of  $58^{\circ}\text{C}$  ( $104^{\circ}\text{F}$ ); a D (continental, subarctic) climate, the climate of the taiga.

**Example 2.** Thoreau started his climb near the foot of Katahdin, at about 300 m (about 1,000 ft), and climbed toward the summit at 1,605 m (5,267 ft). If air cools about  $6.5^{\circ}\text{C}$  for every 1,000 m of height (about  $3.5^{\circ}\text{F}$  per 1,000 ft), about how much cooler is the summit than his starting point?

*(Use the map or drawing "Each zone is cooler than the one below it." shown earlier in this lesson.)*

1. Height gained:  $1,605 - 300 = 1,305$  m, or  $5,267 - 1,000 = 4,267$  ft.
2. In  $^{\circ}\text{C}$ :  $1,305 \div 1,000 \times 6.5 = 1.305 \times 6.5 \approx 8.5^{\circ}\text{C}$ .
3. In  $^{\circ}\text{F}$ :  $4,267 \div 1,000 \times 3.5 = 4.267 \times 3.5 \approx 14.9^{\circ}\text{F}$ , about  $15^{\circ}\text{F}$ .

**Answer:** About  $8.5^{\circ}\text{C}$  (about  $15^{\circ}\text{F}$ ) cooler, enough to change the forest from hardwoods to spruce and fir and then to treeless tundra.

**Example 3.** Sugar maples of the temperate forest are tapped in late winter, when nights freeze and days thaw. It takes about 40 gallons of sap to make 1 gallon of maple syrup. If one tap gives about 10 gallons (about 38 liters) of sap in a season, how much syrup does it make?

1. Syrup = sap  $\div$  40 =  $10 \div 40 = 0.25$  gallon.
2. 0.25 gallon = 1 quart (4 quarts make a gallon).
3. In liters:  $38 \div 40 \approx 0.95$  liter.

**Answer:** About 1 quart (about 0.95 liter) of syrup per tap per season. The rest of the sap is water boiled away.

## PRACTICE

1. **EASY** Name three trees of the temperate deciduous forest and three of the taiga.
2. **EASY** What is the largest land biome on earth, and on which continents is it found?
3. **EASY** What does “deciduous” mean? Name the conifer that is deciduous.
4. **MEDIUM** Give two reasons needles help taiga trees survive.
5. **MEDIUM** Why do oaks and maples drop their leaves in autumn?
6. **MEDIUM** Use the map. Concord is at about 42.5°N and Katahdin at about 45.9°N. How far north is Katahdin from Concord, in km and miles? (1° of latitude ≈ 111 km ≈ 69 mi.)  
(Use the map or drawing “Find Concord and Katahdin,” shown earlier in this lesson.)
7. **MEDIUM** Concord averages about –2°C in January and 23°C in July. What is its range? Compare it with Yakutsk’s 58°C range and explain the difference.
8. **HARD** A town’s coldest month averages –12°C and its warmest month 8°C. Can trees grow there? Which Köppen group is it?
9. **HARD** Why are there no taiga forests in the Southern Hemisphere?
10. **CHALLENGE** In three or four sentences, explain why Thoreau’s climb up Katahdin was like a journey from Massachusetts to the Arctic coast.

## COMMON MISTAKES

- Thinking all conifers are evergreen. The larch drops its needles each fall, and in eastern Siberia it is the main tree of the taiga.
- Thinking leaves change color because of frost. The colors come as the trees stop making green chlorophyll in the shortening, cooler days of autumn; frost is not needed.
- Thinking the taiga stops at a fixed latitude. Its edges bend with ocean, wind and altitude, reaching farther north on mild coasts and climbing up mountains only as high as the warmth allows.

**Make it a game • Climb the Mountain.** Make a staircase or a line of four chairs labeled hardwood forest, spruce and fir, krummholz and alpine tundra. The caller reads a clue (“I see sugar maples and trillium,” “the trees are knee-high and twisted,” “only lichens and moss,” “dark close-packed firs”). The player climbs to the matching step and names the matching biome you would reach by traveling north instead (temperate deciduous forest, taiga, tree line, tundra). Both answers right earns 2 points.

**Scripture.** “The trees of the LORD are full of sap; the cedars of Lebanon, which he hath planted; Where the birds make their nests: as for the stork, the fir trees are her house.” (Psalm 104:16–17, KJV)

The psalmist calls the trees “the trees of the LORD,” planted by Him and full of sap. Every spring the sap rising in a sugar maple and the new needles on a fir are reminders of the Creator who provides for trees, and for the birds that make their homes in them.

### Practice answers

1. Temperate deciduous: any three of oak, maple, beech, hickory, ash, birch, tulip tree. Taiga: any three of spruce, fir, pine, larch (also birch and aspen in places).
2. The taiga (boreal forest), found in North America (Alaska and Canada), Europe (Scandinavia and Russia) and Asia (Siberia).
3. Shedding its leaves for part of the year. The larch is a conifer that drops its needles each fall.
4. Any two: thin, waxy needles lose little water when the ground is frozen; evergreen needles are ready to make food as soon as the short summer begins; the cone shape and bending branches shed snow; dark needles absorb sunlight.
5. Broad, thin leaves lose a lot of water. In winter the ground freezes and roots cannot replace that water, and heavy snow on leaves would break branches. So the trees pull back what they can, let the leaves fall and rest until spring.
6.  $45.9 - 42.5 = 3.4^\circ$ .  $3.4 \times 111 \approx 377$  km;  $3.4 \times 69 \approx 235$  mi. About 380 km (235 mi) farther north.
7.  $23 - (-2) = 25^\circ\text{C}$ . Yakutsk's range is more than twice as large because it lies deep inside Asia, far from the sea, while Concord is near the Atlantic. Water warms and cools slowly and keeps coastal climates milder (continentality).
8. Probably not. Trees need at least one month averaging  $10^\circ\text{C}$  or more. With a warmest month of only  $8^\circ\text{C}$  it is an E (polar) climate, tundra (ET), beyond the tree line.
9. The taiga needs a D climate, which forms only in the interiors of large continents at about  $50^\circ$  to  $65^\circ$  latitude. In the Southern Hemisphere there is almost only ocean at those latitudes, and the ocean keeps the few lands there (such as southern South America) from having such cold winters.
10. Air cools as you climb, about  $6.5^\circ\text{C}$  per 1,000 m, just as it gets colder as you travel toward the pole. So the plant zones on the mountain appear in the same order as the biomes from south to north. Thoreau climbed through hardwoods, like the forests near Concord, then spruce and fir, like the taiga, then stunted krummholz at the tree line, and finally treeless alpine tundra like the Arctic. He crossed in a few miles of climbing what would take well over a thousand miles of northward travel.

## 6.4 TUNDRA AND ICE

### OBJECTIVES

- Describe the tundra and the ice caps, define permafrost and its active layer, and classify polar climates with Köppen's rules (ET and EF).
- Explain the midnight sun and polar night by latitude, and calculate how long the sun stays up at a high-latitude place.
- Tell how the builders of the Trans-Alaska Pipeline (finished in 1977) engineered around permafrost, and explain why heat is the enemy of frozen ground.

**Warm-up.** Put an ice cube on a plate and a second ice cube on two toothpicks or a bottle cap laid across the plate so it is raised a little. Set a small cup of hot water on top of a third ice cube for one minute. Which ice melts fastest? What would happen to frozen ground under a warm house sitting right on it?

**Watch.** *The Tundra Biome and Ice Biome - Biomes#8* (Geodiode, 8:46).

<https://www.youtube.com/watch?v=II15uUa1on0>

With the big idea: watch for why the weak sun keeps the tundra cold all year, and which plants (mosses and lichens) can survive there.

**Note:** Captions were not available to check; preview it first. Videos on tundra and ice sheets often mention melting ice or a warming climate, so listen for that.

**Backup video.** *The Tundra Climate - Secrets of World Climate #11* (Geodiode, 7:17).

<https://www.youtube.com/watch?v=pNxgY4Ru3gs>

As review: watch for the long cold winters, short summers and frozen ground that make the tundra climate. Note: Captions were not available to check; preview it first.

### KEY TERMS

#### tundra

A cold, treeless biome of low plants (mosses, lichens, sedges, dwarf shrubs) beyond the tree line, in the Arctic or high on mountains.

#### permafrost

Ground that stays frozen for at least two years in a row; in the far north it can be hundreds of meters deep.

#### active layer

The top layer of soil above permafrost that thaws each summer and freezes again each winter.

#### ice cap

A thick sheet of ice covering land all year, such as the ice sheets of Greenland and Antarctica.

#### midnight sun

The summer days north of the Arctic Circle (or south of the Antarctic Circle) when the sun does not set.

### **heat pipe**

A sealed pipe filled with a fluid that carries heat up out of the ground and lets it escape into cold air, keeping the ground frozen.

## **CORE IDEAS**

**The story.** In 1968 oil was found at Prudhoe Bay, on the Arctic coast of Alaska. The nearest harbor that stays free of ice all year was at Valdez, on the southern coast, about 1,287 km (800 mi) away by the route the pipe would take, across three mountain ranges and hundreds of rivers. Between them lay the tundra and the taiga, and under nearly all of the northern route lay **permafrost**. Engineers knew that oil comes out of the ground warm. A warm pipe buried in frozen ground would thaw the soil around it, and thawed permafrost turns to mud that cannot hold anything up. So when the Trans-Alaska Pipeline was built, from 1975 to 1977, about half of it, roughly 420 miles (about 680 km), was raised above the ground on tens of thousands of steel supports. Many of the supports carry **heat pipes**, with aluminum fins on top like a radiator. In winter they draw heat up out of the ground and give it off to the frigid air, so the ground stays frozen. Oil began to flow in June 1977.

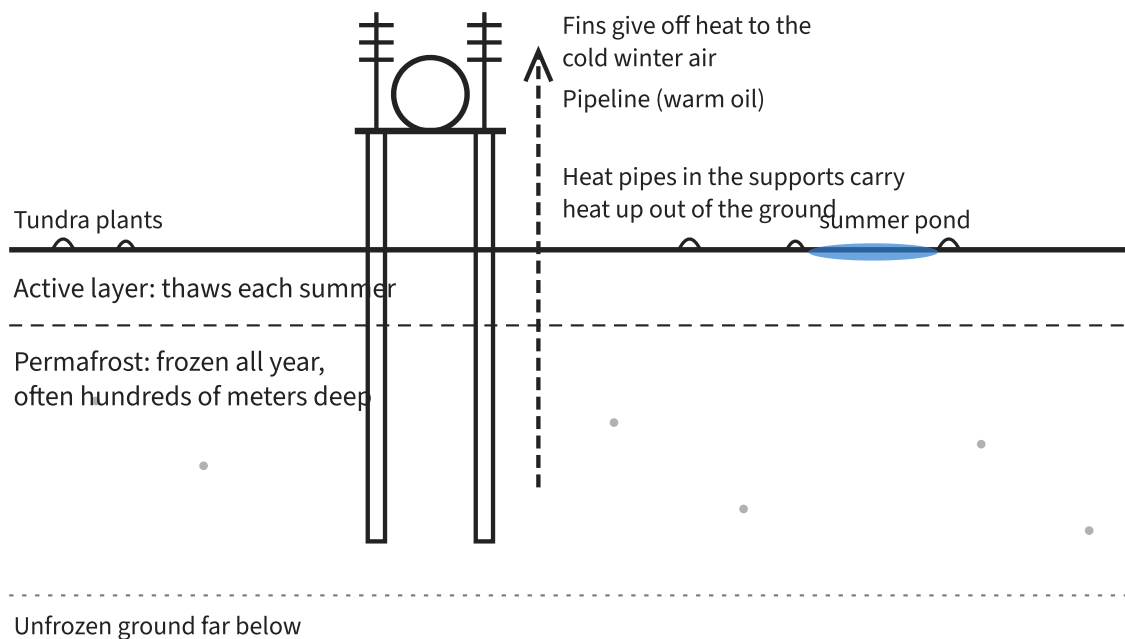
**How the ground works.** Permafrost is ground that stays frozen year after year. Under Prudhoe Bay it reaches down hundreds of meters. Each summer only the top part, the **active layer**, thaws, often 30 cm to 1 m (1 to 3 ft) deep, then freezes again in the fall. Because water cannot soak down through the frozen ground beneath, the summer tundra becomes a land of puddles, ponds, bogs and clouds of mosquitoes, even though it gets very little precipitation. Utqiagvik (formerly Barrow), on the northern tip of Alaska, gets less than 150 mm (6 in) a year, as little as many deserts, yet it is soggy all summer because the cold air evaporates little water and the ground below cannot drain. The freezing and thawing push and crack the ground into patterns you can see from an airplane: polygons outlined by wedges of ice, and in some places round hills with cores of solid ice called *pingos*.

**The Arctic summer.** North of the Arctic Circle (about 66.6°N), the sun stays up for at least one whole day at midsummer, because the North Pole is tilted toward the sun (Lesson 5.2). The farther north, the longer the **midnight sun**. At Utqiagvik, at about 71.3°N, the sun does not set from about May 11 to about August 1, and in winter it does not rise for about two months. The summer sun is low, so the air stays cool. The warmest month averages only a few degrees above freezing. The growing season lasts only about two months. Tundra plants grow low and close to the ground, out of the wind, often in cushions or mats: mosses, lichens, sedges, cotton grass, Arctic poppies, and willows and birches only ankle-high. Many have dark or fuzzy parts that soak up warmth. When summer comes, caribou herds move north to calve, and millions of geese, ducks and shorebirds fly in to nest and feed on the insects. Musk oxen, Arctic foxes, lemmings and snowy owls stay all year.

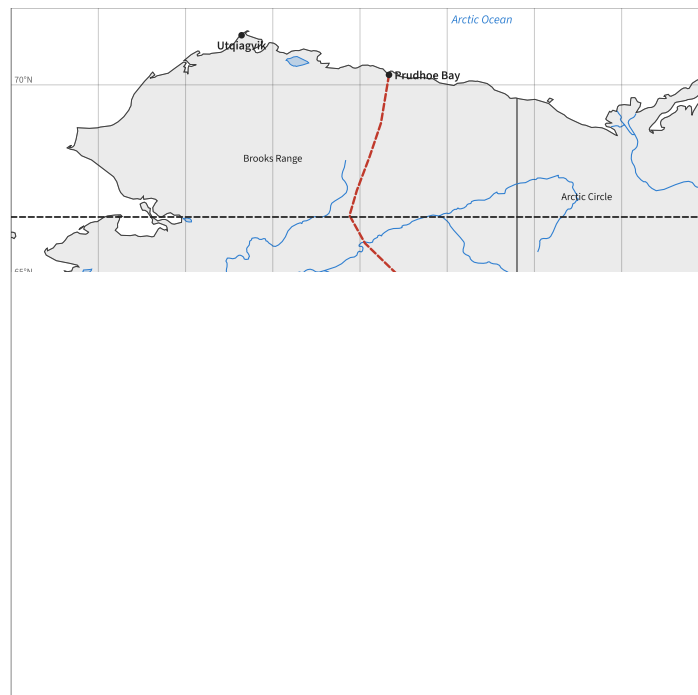
**Ice.** Where even the warmest month stays below freezing, snow piles up year after year and packs into ice. Greenland is buried under an ice sheet up to about 3 km (almost 2 mi) thick, and Antarctica under ice more than 4 km (2.5 mi) thick in places, holding most of the world's

fresh water. The coldest temperature ever measured by a thermometer on earth,  $-89.2^{\circ}\text{C}$  ( $-128.6^{\circ}\text{F}$ ), was recorded at Russia's Vostok Station in Antarctica in July 1983. In Köppen's system, a place whose warmest month averages between  $0^{\circ}\text{C}$  and  $10^{\circ}\text{C}$  ( $32^{\circ}\text{F}$  and  $50^{\circ}\text{F}$ ) is **ET**, tundra. A place whose warmest month stays below  $0^{\circ}\text{C}$  is **EF**, ice cap. Notice that  $10^{\circ}\text{C}$  is also about the warmth trees need, so the Köppen line and the tree line lie close together on the map.

**On the map.** The Arctic tundra rings the Arctic Ocean across northern Alaska, Canada, Greenland's coasts, Scandinavia and Siberia. Alpine tundra appears on high mountains, as Thoreau found on Katahdin, and even on the highest peaks of the tropics. Now look at the whole unit at once: from the rain forests of the equator through the deserts of the subtropics, the grasslands and forests of the middle latitudes, the taiga, the tundra and the ice, the biomes follow the climate belts that latitude, altitude, winds and the oceans create. The Inuit and other northern peoples learned to live well in the Arctic long before pipelines, with skin clothing, kayaks, dog sleds and snow houses. Modern engineers have added gravel pads, insulated foundations, buildings on piles and heat pipes, so that towns, roads and runways can stand safely on frozen ground.



*Permafrost and the active layer. Heat pipes on the pipeline's supports keep the ground frozen.*



*The Trans-Alaska Pipeline crosses tundra, the Brooks Range, the taiga and the Alaska Range.*

|            |                                               |                                                                                          |
|------------|-----------------------------------------------|------------------------------------------------------------------------------------------|
| 90°N Pole  | Ice and polar sea (EF)                        | Boundaries are approximate:<br>mountains, coasts, winds and<br>currents bend every belt. |
| 75°N       | Tundra (ET)                                   |                                                                                          |
| 65°N       | Taiga (D)                                     | Lesson 6.4                                                                               |
| 50°N       | Grassland (BS) and<br>temperate forest (C, D) | Lesson 6.3                                                                               |
| 30°N       | Hot desert (BW)                               | Lessons 6.2, 6.3                                                                         |
| 20°N       | Savanna (Aw)                                  | Lesson 6.2                                                                               |
| 10°N       | Tropical rain forest (Af)                     | Lesson 6.1                                                                               |
| 0° Equator |                                               |                                                                                          |

*The biomes in order of latitude in the Northern Hemisphere. The boundaries are approximate; mountains, coasts and winds bend them.*



## PICTURE STUDY



*The Sea of Ice*, Caspar David Friedrich, about 1823–1824 · Oil on canvas · Hamburger Kunsthalle, Hamburg, Germany

Caspar David Friedrich was a German painter of the Romantic age who loved mountains, mists, moonlight and the sea. He never went to the Arctic. He made careful oil sketches of ice floes on the Elbe River near Dresden during a hard winter and used them to build this frozen scene. The painting is often linked to the British voyages searching for a Northwest Passage in those years, such as William Edward Parry's.

No one bought the painting in Friedrich's lifetime. Today it is one of the most famous pictures of the polar world ever made.

### Look closely

- Find the ship. How much of it can you see, and what is happening to it?
- Look at the slabs of ice. How are they arranged? What forces could stack ice like this?
- Look at the colors. Where do you see blue, green or gold in the ice and sky?
- Look at the distance. Is the sky stormy or calm? How does that make you feel?

### Talk about it

1. Friedrich painted Arctic ice from river ice he had studied. What did he get right about the power of ice?
2. Why was sea ice such a danger to explorers' ships, and why did Valdez matter so much to the pipeline builders?
3. Read Job 38:29–30. How does this painting show that "the waters are hid as with a stone"?

**Safety first.** Use the lamp with an adult nearby, keep it at least 30 cm (12 in) from the pan and paper, and unplug it when you finish.

## PROJECT: PERMAFROST IN A PAN

You will make your own frozen ground, give it an active layer, and test three ways of building a “house” on it. Engineers in Alaska, Canada, Norway and Russia face this same problem every day.

### You will need

- A small metal or plastic baking pan or a large freezer-safe container
- Potting soil or garden soil and water
- Three small identical jars or cups with lids (baby food jars or small cups)
- Hot tap water (not boiling)
- Craft sticks or wooden blocks, and a small square of foam or several folded layers of cardboard
- A desk lamp, a ruler, a kitchen timer and a notebook

### Steps

1. Mix soil and water until it is like thick mud. Pack it 5 cm (2 in) deep in the pan and freeze it overnight. This is your permafrost.
2. Take out the pan and shine the lamp on the surface for 20 to 30 minutes. Press a toothpick in: how deep has the top thawed? This is your active layer. Record the depth.
3. Fill the three jars with hot tap water and close them. These are your heated houses.
4. House A: set it directly on the soil. House B: set it on a pad of foam or folded cardboard (insulation). House C: set it on craft-stick stilts or small blocks so air flows underneath.
5. After 20 minutes, lift each house and measure how far the soil under it has thawed or sunk. Feel the soil with a toothpick.
6. Make a table of your results and rank the three foundations from best to worst.
7. Write a paragraph: Why did the pipeline builders raise the pipe on supports with heat pipes? Which of your houses was most like the pipeline?

### Tips

- Work quickly once the pan is out of the freezer, and do all three houses at the same time so the test is fair.
- Real buildings in Utqiagvik and Fairbanks often stand on piles with an open space underneath, so the cold winter air can keep the ground frozen.

### Check your work

- I can explain the difference between the active layer and the permafrost below it.
- I can show from my measurements which foundation kept the ground frozen best.
- I can explain how heat pipes protect permafrost.

## MAP NOTEBOOK

1. Draw a cross-section of the tundra in summer: active layer, permafrost, a pond on top, and low plants. Label the depths.
2. Draw a 24-hour clock face and shade the hours the sun is up at Utqiagvik on June 21 and on December 21.
3. Trace a map of Alaska and draw the Trans-Alaska Pipeline. Color the tundra, the taiga and the mountains it crosses.

**From history.** From 1903 to 1905 the Norwegian explorer Roald Amundsen and his small crew wintered their ship *Gjøa* in a sheltered harbor on King William Island in the Canadian Arctic, now called Gjoa Haven. They traded and lived near the Netsilik Inuit, and Amundsen carefully learned how they dressed in loose caribou-skin clothing, drove dogs and built snow houses. He later said that this knowledge helped him on his journey to the South Pole in 1911. The peoples of the Arctic had long ago worked out how to live safely in the tundra, and the wisest explorers learned from them.

## WORKED EXAMPLES

**Example 1.** The Arctic Circle lies at about  $66.6^{\circ}\text{N}$ . Utqiagvik lies at about  $71.3^{\circ}\text{N}$ . How far north of the Arctic Circle is Utqiagvik, in km and miles? ( $1^{\circ}$  of latitude  $\approx 111\text{ km} \approx 69\text{ mi.}$ )

*(Use the map or drawing “Find the Arctic Circle and Utqiagvik.” shown earlier in this lesson.)*

1. Difference in latitude:  $71.3^{\circ} - 66.6^{\circ} = 4.7^{\circ}$ .
2. Kilometers:  $4.7 \times 111 = 521.7\text{ km}$ .
3. Miles:  $4.7 \times 69 = 324.3\text{ mi}$ .

**Answer:** About 520 km (about 325 mi) north of the Arctic Circle.

**Example 2.** At Utqiagvik the sun stays above the horizon from about May 11 to about August 1. How many days of midnight sun is that, and about how many weeks?

1. May 11 through May 31:  $31 - 11 + 1 = 21$  days.
2. June: 30 days. July: 31 days. August 1: 1 day.
3. Total:  $21 + 30 + 31 + 1 = 83$  days.  $83 \div 7 \approx 11.9$  weeks.

**Answer:** About 83 days, nearly 12 weeks, without a sunset.

**Example 3.** Classify two places with Köppen’s rules: Utqiagvik, whose warmest month (July) averages about 5°C (41°F), and a research station high on the Greenland ice sheet, whose warmest month averages about –10°C (14°F).

1. Both warmest months are below 10°C (50°F), so both are group E (polar).
2. Utqiagvik’s warmest month, 5°C, is between 0°C and 10°C, so it is ET, tundra.
3. The ice-sheet station’s warmest month, –10°C, is below 0°C, so it is EF, ice cap: even in summer the snow does not melt away.

**Answer:** Utqiagvik: ET (tundra). The Greenland ice-sheet station: EF (ice cap).

## PRACTICE

1. **EASY** What is permafrost? What is the active layer?
2. **EASY** Give the Köppen letters for tundra and for ice cap, and the rule for each.
3. **EASY** Name four plants or animals of the Arctic tundra.
4. **MEDIUM** About 420 of the pipeline’s 800 miles are above ground. What percent is that, and how many kilometers (1 mi  $\approx$  1.609 km)?
5. **MEDIUM** Use the map. Prudhoe Bay is at about 70.3°N and Valdez at about 61.1°N, nearly due south. How far apart are they in latitude, in km and miles? Why is the pipeline, 1,287 km (800 mi) long, longer than that?  
*(Use the map or drawing “Compare the straight north-south distance with the pipeline’s route.” shown earlier in this lesson.)*
6. **MEDIUM** Utqiagvik gets less than 150 mm (6 in) of precipitation a year, as little as many deserts. Why is the tundra there soggy all summer?
7. **MEDIUM** Convert the Vostok record of –89.2°C to °F ( $^{\circ}\text{F} = ^{\circ}\text{C} \times 1.8 + 32$ ).
8. **HARD** Greenland’s ice sheet is up to about 3 km thick. How thick is that in miles and in feet (1 km  $\approx$  0.621 mi  $\approx$  3,281 ft)?
9. **HARD** Explain how a heat pipe on a pipeline support keeps the ground frozen. In which season does it work?
10. **CHALLENGE** In three or four sentences, explain why tundra plants are small and low and grow so quickly in summer.

## COMMON MISTAKES

- Thinking the tundra is frozen solid all year. The top layer thaws every summer and the tundra fills with flowers, insects and birds.
- Thinking the tundra must be wet because it has lots of rain. It gets very little; it is wet because the frozen ground beneath will not let the water drain away.
- Thinking the midnight sun makes the Arctic summer hot. The sun stays low in the sky, so its light is spread thin and the air stays cool.

**Make it a game · Biome Ladder Race.** Make eight cards: rain forest, savanna, hot desert, grassland, temperate forest, taiga, tundra and ice cap. Shuffle them. Race to lay them in order from the equator to the North Pole and name one plant or animal for each. Then race again, this time going up a tall tropical mountain from base to snowy top: which cards fit the mountain? A correct ladder in under one minute scores a point.

**Scripture.** “Out of whose womb came the ice? and the hoary frost of heaven, who hath gendered it? The waters are hid as with a stone, and the face of the deep is frozen.” (Job 38:29–30, KJV)

In Job 38 God takes Job on a tour of the earth, its foundations, seas, snow and ice, and asks who made them and who rules them. Ice that turns water hard as stone and ground that stays frozen all year are part of that tour. The God who made the rain forest also made the ice.

#### Practice answers

1. Permafrost is ground that stays frozen for at least two years in a row. The active layer is the top layer of soil above it that thaws every summer and freezes again every winter.
2. ET: warmest month between 0°C and 10°C (32°F and 50°F). EF: warmest month below 0°C (32°F).
3. Any four: mosses, lichens, sedges, cotton grass, Arctic poppy, dwarf willow, dwarf birch, caribou, musk ox, Arctic fox, lemming, snowy owl, geese, shorebirds.
4.  $420 \div 800 = 0.525$ , so 52.5 percent, about half.  $420 \times 1.609 \approx 676$  km.
5.  $70.3 - 61.1 = 9.2^\circ$ .  $9.2 \times 111 \approx 1,021$  km;  $9.2 \times 69 \approx 635$  mi. The pipeline is longer because it cannot go in a straight line: it follows river valleys and passes through three mountain ranges, and it zigzags so the pipe can bend and shift with heat, cold and earthquakes.
6. The permafrost below the active layer does not let water soak down, and the cool air evaporates very little water. So the snowmelt and the little rain that falls stay at the surface in ponds and bogs.
7.  $-89.2 \times 1.8 = -160.56$ ;  $-160.56 + 32 = -128.56$ , about  $-128.6^\circ\text{F}$ .
8.  $3 \times 0.621 \approx 1.86$  mi, almost 2 miles.  $3 \times 3,281 = 9,843$  ft, nearly 10,000 ft.
9. The sealed pipe holds a fluid that takes up heat from the ground at the bottom and turns to vapor. The vapor rises to the fins at the top, where the cold air takes the heat away and the fluid turns back to liquid and runs down. This works in winter, when the air is colder than the ground. It chills the ground so deeply in winter that it stays frozen through the summer.
10. The summer is short and cool, and strong cold winds blow across the open land. Growing low keeps the plants close to the ground, where it is warmer and out of the wind, and snow covers and protects them in winter. Because the growing season lasts only about two months, they must leaf out, flower and set seed quickly. The midnight sun gives them light around the clock to do it.

## UNIT 6 REVIEW

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Answer each question. Show your work for calculations, give both metric and U.S. units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (6 pts) Name the four layers of a tropical rain forest from top to bottom. About what percent of the sunlight reaches the bottom layer, and why so little?
2. (6 pts) A town's coolest month averages 26°C and its warmest 28°C. Its driest month gets 90 mm of rain and its yearly total is 2,600 mm (about 102 in). Classify it with Köppen's rules and name the biome you would expect there.
3. (6 pts) Explain how latitude, rising air and the trade winds give the Amazon rain almost every day.
4. (6 pts) Classify each place by its yearly precipitation as desert, grassland or wet enough for forest: (a) 120 mm (5 in); (b) 450 mm (18 in); (c) 1,200 mm (47 in).
5. (6 pts) Why is the Sahara a desert while the Amazon, also in the tropics, is a rain forest?
6. (6 pts) Use the Great Plains map. Stephen Long's 1823 map called the plains a "Great Desert." Which side of the 100th meridian is drier, why, and was Long's label correct?
7. (6 pts) A Siberian town averages -35°C (-31°F) in January and 18°C (64°F) in July. Find its yearly range in °C and °F, give its Köppen group, and name its biome.
8. (6 pts) Give one reason oaks and maples drop their leaves in autumn and two reasons spruce and fir keep their needles.
9. (6 pts) A hiker climbs from 400 m to 1,600 m. If air cools about 6.5°C for every 1,000 m, about how much cooler is the top? Name the zones of plants the hiker would pass on a New England mountain like Katahdin.
10. (6 pts) Fairbanks lies at about 64.8°N and Prudhoe Bay at about 70.3°N. How far apart are they in latitude, in km and miles (1° ≈ 111 km ≈ 69 mi)? Explain why the Trans-Alaska Pipeline was raised on supports with heat pipes over much of the route between them.

### UNIT PROJECT: MY BIOME FIELD GUIDE (OR BIOME BOXES)

Make a field guide of at least six biomes: tropical rain forest, desert, grassland, temperate deciduous forest, taiga and tundra (add ice cap or savanna for extra credit). Give each biome a two-page spread with: a small world map shading where it is found; a climate box with typical yearly precipitation, warmest and coldest month (in °C and °F) and its Köppen letters; a labeled drawing or cross-section (rain forest layers, prairie roots, permafrost and active layer); three plants and three animals with one way each is built to fit; and one real place and person from this unit. Instead of a book, you may build six shoebox biome boxes with the same information on a card attached to each.

Finish with a large world map on which you color the biomes and lay a Köppen map beside it. Write a paragraph explaining three places where the two maps match and one place where altitude or an ocean current bends the pattern.



- **Accuracy:** Each biome is placed correctly on the map, and its climate numbers, Köppen letters, plants and animals are correct.
- **Explanation:** Each spread explains why the biome has its climate (latitude, rising or sinking air, rain shadow, continentality, altitude) and how living things fit it.
- **Maps and drawings:** The world biome map and the Köppen comparison are clear, keyed and labeled; diagrams are labeled with correct terms.
- **Care:** The guide or boxes are neat, colorful and complete, with both metric and U.S. units, and the closing paragraph is thoughtful.

#### Answer key

1. Emergent layer, canopy, understory, forest floor. Only about 2 percent of the sunlight reaches the floor, because the leaves of the layers above catch nearly all of it.
2. Every month is above 18°C, so it is group A. The driest month has more than 60 mm, so it is Af. Expect tropical rain forest.
3. Near the equator the sun is nearly overhead all year and heats the ground and wet leaves. Warm, moist air rises, cools and forms thunderclouds that rain in the afternoon. The trade winds carry moisture from the Atlantic westward, and the trees give much of the rain back to the air by transpiration, so it can fall again farther west.
4. (a) Desert (under about 250 mm). (b) Grassland (about 250 to 750 mm). (c) Wet enough for forest (over about 750 mm).
5. Air rises and drops its rain near the equator over the Amazon. That air flows away and sinks near 20° to 30° latitude, where the Sahara lies. Sinking air is warmed and dried, so clouds rarely form (the subtropical high), and the Sahara gets almost no rain.
6. The west side is drier, because it is in the rain shadow of the Rockies and farther from the moist air of the Gulf of Mexico. Long's label was not correct: the plains get grassland amounts of rain (roughly 380 to 750 mm, 15 to 30 in), not desert amounts, and had deep, rich soil held by grass roots.
7.  $18 - (-35) = 53^{\circ}\text{C}$ ;  $64 - (-31) = 95^{\circ}\text{F}$ . Coldest month below  $-3^{\circ}\text{C}$  and warmest month above  $10^{\circ}\text{C}$ : group D (continental). Biome: taiga (boreal forest).
8. Oaks and maples: broad, thin leaves lose too much water when the ground is frozen and roots cannot replace it (or: heavy snow on leaves would break branches). Spruce and fir: thin, waxy needles lose little water; evergreen needles can start making food as soon as the short summer begins; cone shape and bending branches shed snow.
9.  $1,600 - 400 = 1,200\text{ m}$ ;  $1.2 \times 6.5 = 7.8^{\circ}\text{C}$ , about  $8^{\circ}\text{C}$  (about  $14^{\circ}\text{F}$ ) cooler. Northern hardwoods, then spruce and fir, then stunted krummholz at the tree line, then treeless alpine tundra.
10.  $70.3 - 64.8 = 5.5^{\circ}$ ;  $5.5 \times 111 \approx 611\text{ km}$ ;  $5.5 \times 69 \approx 380\text{ mi}$ . The oil in the pipe is warm, and a buried warm pipe would thaw the permafrost into mud that could not hold it up. Raising the pipe lets cold air pass beneath, and heat pipes carry heat out of the ground in winter, so the ground stays frozen and solid.



## OCEANS AND CURRENTS

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The sea looks restless on top and still underneath, but the whole ocean is on the move. Great rivers without banks run through it, carried by the winds and turned by the spinning of the earth. Twice a day the sea climbs up the shore and slides back, pulled by the moon. And the moving water carries the warmth of the tropics far to the north, so that London stays mild while Labrador, at nearly the same latitude, is locked in ice. In this unit you will learn to read the **paths of the seas**.

You will start in London around 1768 with Benjamin Franklin, who wanted to know why the mail ships were so slow, and his cousin Timothy Folger, a Nantucket whaler who knew the answer. You will drift across the Arctic with Fridtjof Nansen's *Fram*, follow Isaac Newton's explanation of the tides to the Bay of Fundy, where the sea rises about 16 meters (more than 50 feet), and sail with the Moravian mission ships from London to the icy coast of Labrador. Along the way you will race corks with and against a current, draw a straight line on a spinning plate, graph a real harbor's tides and make a convection current in a pan.

This unit pairs naturally with Unit 5 (Climate as Physical Geography). The winds you met there drive the currents you meet here, and together they explain much of the world's climate map.

### BEFORE YOU BEGIN

- Can find places on a world map by latitude and longitude
- Knows the prevailing wind belts (trade winds and westerlies) from Unit 5
- Can multiply and divide to find speed, time and distance, and convert between km and miles
- Knows the phases of the moon

### MASTERY CHECKLIST

- I can tell the story of Franklin and Folger's Gulf Stream chart and find a ship's speed with and against a current.
- I can explain how winds and the Coriolis effect make the great gyres, and say which way they turn in each hemisphere.
- I can name and locate at least eight major ocean currents and sort them into warm and cold.
- I can explain why there are two high tides a day, what spring and neap tides are, and why the Bay of Fundy's tides are so high.
- I can use tide times and heights to plan when a ship can enter a harbor.
- I can explain why London is mild and Labrador is cold at nearly the same latitude.

## OPTIONAL BOOKS AND RESOURCES

- **NOAA Tides and Currents** (<https://tidesandcurrents.noaa.gov/>): Free. Official U.S. tide predictions and water-level records for harbors all along the coasts. Use it for the tide-graph project in Lesson 7.3.
- **NOAA SciJinks** (<https://scijinks.gov/>): Free. Short, clear articles and images from NOAA and NASA on weather, oceans and tides, written for students. A parent should preview pages first.
- **NOAA Ocean Service** (<https://oceanservice.noaa.gov/>): Free. Plain explanations of currents, tides and the Gulf Stream, with diagrams and maps.

## 7.1 THE GULF STREAM ★ ⚙️

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### OBJECTIVES

- Tell how Benjamin Franklin and Captain Timothy Folger charted the Gulf Stream to speed up the mail ships between England and America.
- Describe the Gulf Stream: where it starts, where it flows, how fast it moves and how sailors can find it with a thermometer.
- Calculate a ship's speed over the ground when it sails with or against a current, in both km/h and mph.

**Warm-up.** Walk the length of a moving walkway in your mind (or on a real one at an airport or mall). If you walk at 3 miles per hour and the walkway moves at 2 miles per hour, how fast do you pass the wall when you walk with it? When you walk against it? Write both answers. Sailing ships on the sea faced exactly this problem, but the “walkway” was invisible.

**Video.** Coming soon. The Gulf Stream and Benjamin Franklin's chart; ocean surface currents from space: search NASA and NASA Earth Observatory (the “Perpetual Ocean” visualization), Smithsonian, Library of Congress; NOAA and NOAA SciJinks (candidates, need vetting); Homeschool Pop (Alternate).

### KEY TERMS

#### **ocean current**

A steady stream of seawater moving in one direction, like a river within the ocean.

#### **Gulf Stream**

A strong, warm current that flows out of the Gulf of Mexico through the Florida Straits, up the coast of North America and then east across the Atlantic.

#### **packet ship**

A ship that sailed on a regular schedule carrying mail, passengers and small freight. The British mail packets sailed from Falmouth, England.

#### **speed over the ground**

How fast a ship actually moves past the sea floor or the land, after the current is added or taken away from its speed through the water.

#### **nautical chart**

A map made for sailors that shows coasts, depths, dangers and, on some charts, currents.

### CORE IDEAS

**The story.** Around 1768 Benjamin Franklin was living in London. Besides being a printer and scientist, he was one of the two deputy postmasters general for the American colonies, so the mail was his business. Customs officials in Boston had complained to the Treasury in

London: the government mail packets sailing from Falmouth, England, to New York took about two weeks longer to cross than ordinary merchant ships sailing from London to Rhode Island, even though London was farther away. Franklin asked his cousin, Captain Timothy Folger of Nantucket, a whaling captain who happened to be in London. Folger explained the puzzle at once. The Nantucket whalers knew of a great warm current running along the American coast and then east across the ocean. The Rhode Island captains knew of it and stayed out of it on the way west. The English packet captains did not, and they sailed straight up against it, sometimes losing in a day of light wind more than they had gained. Folger said the whalers had even met packets in the middle of the stream and told them so, but the English captains would not take advice from American fishermen.

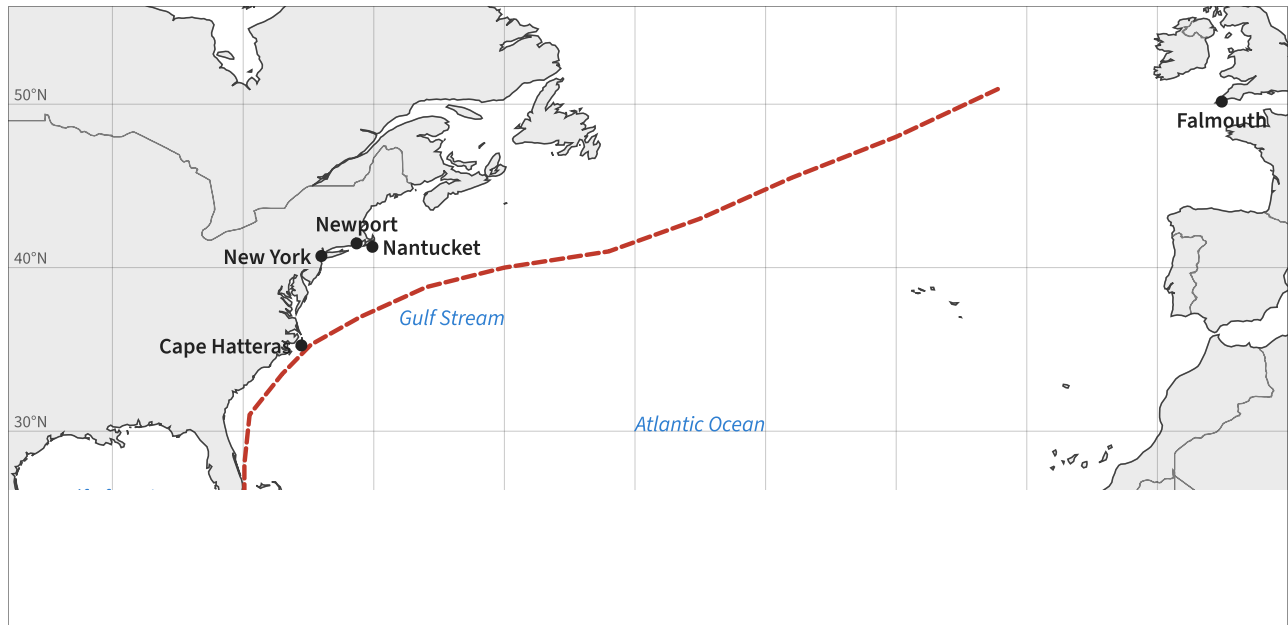
**How they figured it out.** Franklin asked Folger to draw the stream on a chart. Folger sketched its path, its width and its speed, and added advice on how to cross it quickly. Franklin had the chart engraved and printed in London about 1769 or 1770 and sent copies to the packet captains in Falmouth. They mostly ignored it. Franklin did not give up. On his voyages across the Atlantic in 1775, 1776 and 1785 he lowered a thermometer over the side again and again and wrote down the temperature of the water. He found that the stream was clearly warmer than the sea on either side, so a captain with a thermometer could tell when he had entered it, even at night or in fog. He also noticed that the stream's water had a different color and carried floating gulfweed. In 1786 he published the chart again with his notes in Philadelphia.

**The big idea.** The ocean is not still. Great **currents** move through it like rivers without banks. The Gulf Stream begins where warm water pours out of the Gulf of Mexico through the narrow Florida Straits between Florida and Cuba. It runs north along the coast of the Carolinas, leaves the coast near Cape Hatteras, and swings northeast and east across the Atlantic toward Europe. It is about 100 km (60 miles) wide and often flows at 3 to 4 miles per hour (5 to 6.5 km/h), faster in the Florida Straits. That may sound slow, but a sailing ship of Franklin's day might sail at only 5 or 6 miles per hour. Off Florida the stream carries more water every second than all the rivers of the world put together.

**How it worked.** A ship's **speed over the ground** is its speed through the water plus or minus the speed of the current. A ship making 8 km/h (5 mph) through the water against a 5 km/h (3 mph) current moves forward only 3 km/h (2 mph). Turn around and ride the current, and the same ship moves 13 km/h (8 mph). Over a day the difference is huge: 72 km (48 miles) against the stream, 312 km (192 miles) with it. Franklin's advice was simple: going east to Europe, ride the stream; going west to America, cross it quickly and stay north or south of it.

**Technology overcoming geography.** The Gulf Stream is a piece of geography no one can move. But a chart, a thermometer and good records let sailors turn it from an enemy into a helper. Franklin's chart is one of the first maps of an ocean current ever printed. Later, Matthew Fontaine Maury of the U.S. Navy collected thousands of ship logbooks and published wind and current charts in the 1840s and 1850s that cut days off voyages. Today ships and racing yachts still plan their routes around the Gulf Stream, using satellite maps of

sea-surface temperature that show the warm stream as a bright ribbon, the same clue Franklin found with his thermometer.



*The Gulf Stream and the ports in Franklin's story. The packets sailed west from Falmouth to New York; the Rhode Island merchant ships sailed to Newport.*

## PICTURE STUDY



*The Franklin-Folger Chart of the Gulf Stream, Benjamin Franklin and Captain Timothy Folger, drawn about 1768; printed in London about 1769-1770; reprinted in Philadelphia, 1786 · Engraved and printed chart · Copies of the first London printing are in the Bibliothèque nationale de France, Paris, and the Library of Congress, Washington; the 1786 version appeared in the Transactions of the American Philosophical Society, Philadelphia*

This is one of the first printed charts of an ocean current. Captain Timothy Folger, a Nantucket whaler, sketched the path of the stream from what whalers had seen for years, and his cousin Benjamin Franklin had it engraved in London. The original printing was so rare that for a long time scholars thought no copy had survived, until an oceanographer from Woods Hole, Philip Richardson, found copies in a Paris library in 1980.

Notice that the chart does not show waves or depths. It shows something sailors cannot see from the deck: a river of warm water inside the sea.

### **Look closely**

- Find Florida and follow the shaded band north. Where does the stream leave the coast and head out to sea?
- Compare the stream on this chart with a modern map of the Gulf Stream (Figure g6-gulf-stream-map). How close did the whalers come?
- Look for notes or writing on the chart. What kind of advice would a sea captain want written on a chart like this?
- Find Nantucket. Why would whalers from that island know the stream so well?

### **Talk about it**

1. Why did the English packet captains ignore advice that would have saved them two weeks?
2. How could a thermometer help a captain find something invisible?
3. What knowledge do ordinary working people in your town have that experts might overlook?

## **PROJECT: RIDING AND FIGHTING THE STREAM**

You will make a working model of a current and race a paper boat with it and against it, then draw your own Franklin-Folger chart.

### **You will need**

- A bathtub or a long plastic storage bin with 5–8 cm (2–3 inches) of water
- A small battery fan or a sturdy piece of cardboard for fanning (to make a steady wind)
- A plastic cup or pitcher for pouring a steady current
- Two corks or small paper boats
- A stopwatch, a ruler or tape measure, and a pencil
- A copy of a blank North Atlantic outline map and colored pencils

### **Steps**

1. Make a “current”: hold a pitcher at one end of the tub and pour slowly and steadily along one side, or fan the surface steadily from one end. Drop a pinch of pepper on the water to see which way it moves.
2. Mark a 50 cm (20 inch) course along the side where the water moves.

3. Push a cork with one gentle puff of a straw *with* the current and time how long it takes to cover the course. Repeat three times.
4. Now give the cork the same puff *against* the current and time it. Repeat three times.
5. Find the average time for each direction. Divide the distance by the time to get the speed in cm per second for each.
6. On the outline map, draw the Gulf Stream in red from the Florida Straits to the middle of the Atlantic. Mark Falmouth, New York, Newport and Nantucket.
7. Draw two routes from Falmouth to New York: one that fights the stream and one that stays north of it. Write a sentence of advice to a packet captain on your chart, as Folger did.

### Tips

- Keep the “wind” or the pouring the same for every trial, or your race is not fair.
- If the cork drifts to the side, use a straight strip of tape on the bottom as a guide line and watch it from above.

### Check your work

- I made a steady current and measured speed with and against it.
- My chart shows the Gulf Stream and two routes, with advice written on it.
- I can explain why the packets were two weeks slower.

### MAP NOTEBOOK

1. Trace the Gulf Stream from Figure g6-gulf-stream-map and label the Florida Straits, Cape Hatteras and the open Atlantic.
2. Draw Franklin’s thermometer being lowered over the side in a bucket, with a little chart of water temperatures you might record as a ship enters the stream.
3. Write Franklin’s rule for captains in your own words: which way to ride the stream and which way to avoid it.

**From history.** Franklin was not the first to notice the current. In 1513 the Spanish explorer Juan Ponce de León and his pilot Antón de Alaminos found that off Florida their ships were carried backward even with a fair wind. Spanish treasure fleets soon learned to leave Havana, ride the current north through the Florida Straits and then sail east for Spain. What Franklin and Folger added was a printed chart that showed the stream’s whole path for any captain willing to read it.



## WORKED EXAMPLES

**Example 1.** A packet ship sails at 8 km/h (5 mph) through the water. The Gulf Stream flows at 5 km/h (3 mph). How far does the ship travel over the ground in 24 hours (a) against the stream and (b) with the stream?

1. Against the current, subtract:  $8 - 5 = 3$  km/h ( $5 - 3 = 2$  mph).
2. In 24 hours:  $3 \times 24 = 72$  km ( $2 \times 24 = 48$  miles).
3. With the current, add:  $8 + 5 = 13$  km/h ( $5 + 3 = 8$  mph).
4. In 24 hours:  $13 \times 24 = 312$  km ( $8 \times 24 = 192$  miles).

**Answer:** (a) 72 km (48 miles) a day; (b) 312 km (192 miles) a day, about four times as far.

**Example 2.** Two captains sail west to America. Captain A takes a 5,600 km (3,500 mile) route that fights the Gulf Stream for part of the way and averages 120 km (75 miles) a day. Captain B takes a longer 6,000 km (3,750 mile) route that avoids the stream and averages 160 km (100 miles) a day. Who arrives first, and by how many days?

1. Captain A:  $5,600 \div 120 \approx 46.7$  days ( $3,500 \div 75 \approx 46.7$ ), about 47 days.
2. Captain B:  $6,000 \div 160 = 37.5$  days ( $3,750 \div 100 = 37.5$ ), about 38 days.
3. Difference:  $46.7 - 37.5 \approx 9$  days.

**Answer:** Captain B arrives about 9 days sooner, even though his route is 400 km (250 miles) longer.

**Example 3.** Franklin's style of record: a ship sailing south toward the Gulf Stream measures the sea every two hours: 15°C, 15°C, 16°C, 22°C, 24°C, 24°C. (a) Between which two readings did the ship enter the stream? (b) Convert 24°C to °F.

1. Look for the sudden jump: 16°C to 22°C is a rise of 6 degrees in two hours, much bigger than any other change.
2. So the ship entered the warm stream between the third and fourth readings.
3.  $^{\circ}\text{F} = ^{\circ}\text{C} \times 9 \div 5 + 32 = 24 \times 9 \div 5 + 32 = 43.2 + 32 = 75.2^{\circ}\text{F}$ .

**Answer:** (a) Between the third (16°C) and fourth (22°C) readings. (b) 24°C is about 75°F.

## PRACTICE

1. **EASY** Where does the Gulf Stream begin, and through what narrow passage does it flow?
2. **EASY** Who was Timothy Folger, and what did he tell Franklin?
3. **EASY** What instrument did Franklin use on his voyages to find the Gulf Stream, and what did it show?

4. **MEDIUM** A ship sails at 10 km/h (6 mph) through the water against a current of 4 km/h (2.5 mph). What is its speed over the ground?
5. **MEDIUM** The same ship turns and rides the 4 km/h current for 12 hours. How far does it go?
6. **MEDIUM** Use Figure g6-gulf-stream-map. After it leaves the coast near Cape Hatteras, in which general compass direction does the Gulf Stream flow?  
(Use the map or drawing “Follow the line of the Gulf Stream from Florida.” shown earlier in this lesson.)
7. **MEDIUM** Convert the Gulf Stream’s typical width of 100 km into miles (1 km  $\approx$  0.62 mile).
8. **HARD** A sailing ship makes 6 mph through the water. In very light wind it makes only 2 mph through the water while stemming a 3 mph current. What happens to the ship, and how far does it move in 10 hours?
9. **HARD** Why would a captain sailing east from New York to England want to be *in* the Gulf Stream, but a captain sailing west want to be *out* of it?
10. **CHALLENGE** Write three or four sentences: Franklin’s chart was printed in 1769–1770, yet the packet captains ignored it. What does this story teach about knowledge, pride and listening to ordinary working people?

## COMMON MISTAKES

- Thinking a current only matters if it is fast. Even a current of 3 to 4 mph is more than half the speed of a sailing ship.
- Adding the current when sailing against it. Against the current, subtract; with the current, add.
- Thinking the Gulf Stream stays along the coast all the way to Maine. It leaves the coast near Cape Hatteras and turns out to sea.

**Make it a game • Current Captain.** One player is the captain and names a ship speed (for example, 6 mph). The other names a current (for example, 2 mph) and a direction: “with” or “against.” The captain has five seconds to give the speed over the ground. Then switch. Bonus point if you can say how far the ship goes in 10 hours. Play to ten points.

**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)

The whalers of Nantucket did their business in great waters and learned one of the wonders of the deep. Careful watching of God’s works is the beginning of good geography.

## Practice answers

1. It begins with warm water flowing out of the Gulf of Mexico and passes through the Florida Straits, between Florida and Cuba.
2. A Nantucket whaling captain and Franklin’s cousin. He told Franklin that the packet ships were sailing against the Gulf Stream, a current the whalers and Rhode Island captains knew well, and he sketched it on a chart.

3. A thermometer. It showed that the water in the stream was warmer than the sea on either side.
4.  $10 - 4 = 6$  km/h ( $6 - 2.5 = 3.5$  mph).
5.  $(10 + 4) \times 12 = 168$  km. In miles:  $(6 + 2.5) \times 12 = 102$  miles.
6. Northeast, then east across the Atlantic toward Europe.
7.  $100 \times 0.62 = 62$  miles, about 60 miles.
8. Its speed over the ground is  $2 - 3 = -1$  mph, so it is carried backward. In 10 hours it loses 10 miles (about 16 km). This is what happened to packets in calm weather.
9. The stream flows east across the Atlantic. Going east, it adds its speed to the ship's; going west, it subtracts from the ship's speed and can even carry the ship backward.
10. Answers will vary. A good answer notes that the whalers had real knowledge from experience, that the packet captains' pride kept them from learning, and that good science listens to careful observations no matter who makes them.

## 7.2 GYRES AND CURRENTS

### OBJECTIVES

- Explain how steady winds and the turning of the earth set the surface of the sea moving in great loops called gyres.
- Name the five great ocean gyres and tell which way each turns in the Northern and Southern Hemispheres.
- Read a map of the world's major ocean currents and sort them into warm and cold currents.

**Warm-up.** Fill a pie pan or shallow bowl with water and sprinkle a little pepper on it. Blow gently and steadily across the top through a straw, always from the same side. Watch the pepper for one minute. Does the water only move straight away from you, or does it start to circle? Draw what you see.

**Watch.** *Ocean currents and circulation* (Geography Lessons, 3:55).

<https://www.youtube.com/watch?v=C0ck2njRe9Y>

With the big idea: watch how warm water moves from the equator toward the poles, cools, and sinks, and how wind drives the surface currents.

**Note:** Captions were not available to check; preview it first. This small channel may use text-on-screen or computer-voice narration, so make sure it suits your student. The video is mostly about thermohaline (density-driven) circulation; the lesson's focus on gyres and the Coriolis effect may get only a brief mention or none.

**Backup video.** *An Ocean in Motion: NASA's Mesmerizing View of Earth's Underwater Highways* (NASA Goddard, 5:26). <https://www.youtube.com/watch?v=R5-s6O8qyvE>

With On the map: watch the swirling currents and pick out the big loops (gyres) in each ocean basin, plus the Gulf Stream along the U.S. East Coast.

### KEY TERMS

#### gyre

A huge ring of ocean currents that circles an entire ocean basin.

#### Coriolis effect

Because the earth turns, anything moving freely over its surface (wind, water, a long-range shell) is turned to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

#### prevailing winds

Winds that blow from the same direction most of the time, such as the trade winds and the westerlies.

#### warm current

A current that flows from the tropics toward the poles, carrying warm water into cooler seas.

**cold current**

A current that flows from cold, high latitudes toward the equator, carrying cool water along a coast.

**upwelling**

Cold water rising from the deep to the surface, often where winds push coastal water out to sea.

**CORE IDEAS**

**The story.** In June 1881 the American ship *Jeannette* was crushed by sea ice north of Siberia and sank. Three years later, in 1884, clothing and papers from the wreck were found frozen in an ice floe off the southwest coast of Greenland, on the other side of the Arctic. A young Norwegian scientist named Fridtjof Nansen read the report and reasoned that the ice must drift right across the polar sea. So he built a ship to ride it. The *Fram* had a rounded hull so that the ice would squeeze it upward instead of crushing it. In September 1893 Nansen let the *Fram* freeze into the ice north of Siberia. For almost three years the ship drifted with the ice until it broke free near Spitsbergen in August 1896. Nansen's guess was right: the sea and its ice were moving.

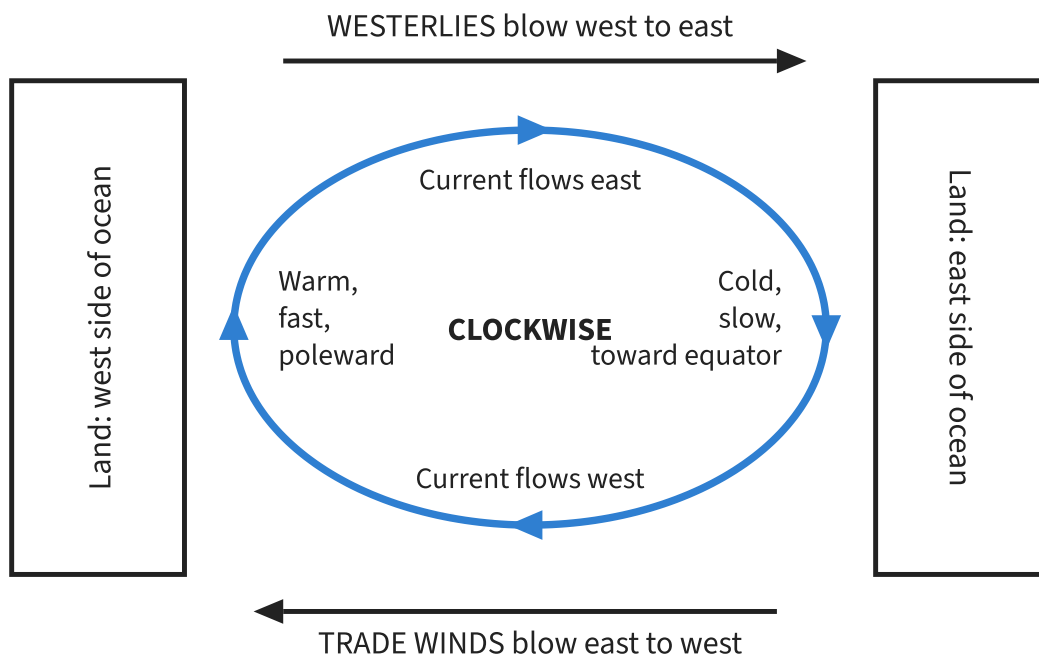
**How they figured it out.** On the drift Nansen noticed something strange. The ice did not move straight downwind. It drifted at an angle of about 20 to 40 degrees to the *right* of the wind. Back home he gave this puzzle to scientists, and in 1905 a young Swedish student, Vagn Walfrid Ekman, worked out the reason. Wind drags the surface of the sea along, but the earth is turning underneath. In the Northern Hemisphere, anything moving freely over the earth is turned to the right; in the Southern Hemisphere, to the left. This is called the **Coriolis effect**, after the French engineer Gaspard-Gustave de Coriolis, who described the mathematics in 1835. It happens because the ground near the equator is carried around the earth's axis much faster (about 1,670 km/h, or 1,040 mph) than the ground near the poles.

**The big idea.** Two steady belts of wind blow across every ocean. Near the tropics the **trade winds** blow from the east toward the west. In the middle latitudes the **westerlies** blow from the west toward the east. The trades push surface water west; the westerlies push it east. When the water reaches a continent, it turns along the coast. The result is a great loop of currents around each ocean called a **gyre**. There are five large ones: the North Atlantic, South Atlantic, North Pacific, South Pacific and Indian Ocean gyres. Because of the Coriolis effect, the gyres in the Northern Hemisphere turn **clockwise** and those in the Southern Hemisphere turn **counterclockwise**.

**On the map.** Follow the North Atlantic gyre clockwise. The Canary Current runs south past Portugal and West Africa. The North Equatorial Current carries water west toward the Caribbean. The Gulf Stream runs north along America, and the North Atlantic Drift carries water back east toward Europe. Every gyre has the same plan. On the *west* side of each ocean a narrow, fast, **warm current** flows toward the pole: the Gulf Stream, the Kuroshio off Japan, the Brazil Current, the East Australian Current and the Agulhas Current off South

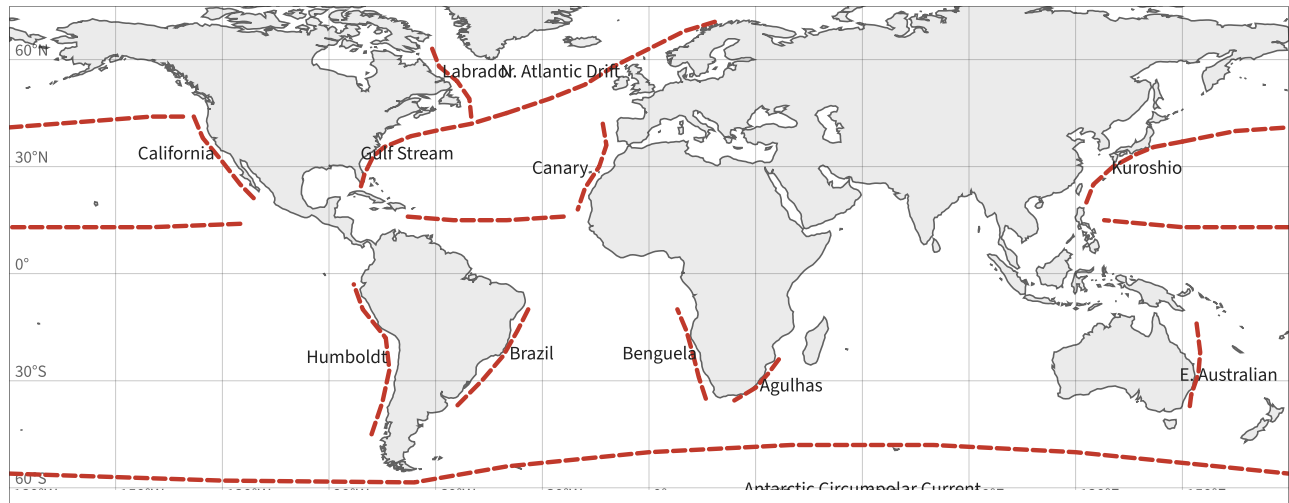
Africa. On the *east* side a broad, slow, **cold current** flows toward the equator: the Canary, the California, the Humboldt (Peru) and the Benguela currents. Around Antarctica, where no continent blocks the way, the westerlies drive the Antarctic Circumpolar Current all the way around the world.

**Why it matters.** Where the wind pushes coastal water out to sea, cold water rises from the deep to take its place. This **upwelling** brings up the food that tiny sea creatures need, so the cold currents off Peru, California and southwest Africa are among the richest fishing grounds on earth. Currents also carry anything that floats. A bottle, a log or a coconut can ride a gyre for years and land on a beach thousands of miles from where it started. The paths of the sea, as the psalmist called them, are not random. They follow the winds and the turning of the earth that God set in place.



*How winds make a Northern Hemisphere gyre: the trades push water west, the westerlies push it east, and the coasts turn it into a clockwise loop.*





*The world's major surface currents. Warm currents run poleward on the west sides of the oceans; cold currents run toward the equator on the east sides.*

## PICTURE STUDY



*The Gulf Stream*, Winslow Homer, 1899 · Oil on canvas · Metropolitan Museum of Art, New York

Winslow Homer was an American painter who spent his later years on the coast of Maine and made winter trips to Florida and the Bahamas. In this painting a sailor lies on the deck of a small boat whose mast has snapped. With no sail, he can only drift wherever the current carries him. Stalks of sugar cane spill from the boat, sharks circle in the water, and a waterspout twists on the horizon.

Homer titled the painting after the current itself. The boat is in the grip of the great stream that leaves the Florida Straits and runs north, and the man cannot steer out of it.

**Look closely**



- Find the broken mast. Why does a boat without a sail go wherever the current goes?
- Look at the color of the water. How did Homer show that this is deep, warm, tropical sea?
- Find the ship on the far horizon. Can it see the man? Will the current carry him toward it or away?
- Look at the man's face and body. What is he feeling?

### Talk about it

1. If this boat drifted with the Gulf Stream for many weeks, where might it end up? Use the gyre map to trace its path.
2. Nansen let his ship drift on purpose. This sailor drifts against his will. How are the two stories alike and different?

## PROJECT: THE TURNING PLATE AND THE WIND-BLOWN GYRE

You will see the Coriolis effect for yourself by drawing a straight line on a turning plate, then make a gyre with wind in a pan.

### You will need

- A paper plate and a pushpin or pencil for the center
- A piece of cardboard to put under the plate, and a marker
- A ruler
- A rectangular baking pan, water, ground pepper or tiny paper bits
- Two straws, and blocks or books to stand for continents
- A blank world outline map and red and blue colored pencils

### Steps

1. Pin the paper plate through its center to the cardboard so it can spin. Mark the center "North Pole."
2. Hold the ruler still over the plate from the center outward. While a helper turns the plate slowly *counterclockwise* (the way the earth turns seen from above the North Pole), draw a line along the ruler from the center to the edge.
3. Stop and look. The ruler was straight, but the line on the plate curves. Which way does it bend, as seen by someone moving outward along it? (To the right.)
4. Fill the pan with about 2 cm (1 inch) of water and sprinkle pepper on it. Place a block at each end as continents.
5. Blow steadily through one straw across the bottom half of the pan from right to left (the trade winds) while a partner blows across the top half from left to right (the westerlies).
6. Watch the pepper. Draw the loop it makes, with arrows. Which way does it turn?
7. On the world map, draw the five gyres with arrows. Color the warm currents red and the cold currents blue, using Figure g6-world-currents as your guide.

## Tips

- Blow gently and steadily; hard puffs make splashes, not currents.
- The pan only shows the push of the winds. The turning plate shows the Coriolis effect. The real ocean has both at once.

## Check your work

- I drew a curving line on a turning plate and can say which way it bent.
- I made a wind-driven loop of water in a pan.
- My map shows five gyres turning the correct way, with warm and cold currents colored.

## MAP NOTEBOOK

1. Draw the *Fram* frozen in the ice with an arrow for the wind and another for the drift, about 30 degrees to the right of the wind.
2. Copy Figure g6-gyre-diagram and label the trade winds, the westerlies and the four currents of the North Atlantic gyre.
3. Make a two-column table, “Warm currents” and “Cold currents,” and list at least four of each with the ocean they are in.

**From history.** In January 1992 a storm in the North Pacific knocked shipping containers off a cargo ship, and one of them spilled about 29,000 plastic bath toys: ducks, frogs, turtles and beavers. In November 1992 the first of them washed ashore near Sitka, Alaska. Oceanographer Curtis Ebbesmeyer asked beachcombers to report every toy they found, and for years the reports showed how the North Pacific gyre carried them around in a great loop. The little ducks became an accidental experiment in how currents move.

## WORKED EXAMPLES

**Example 1.** In the Northern Hemisphere a steady wind blows from the north toward the south over the sea. Nansen found that the surface ice and water drift to the right of the wind. Which way does the surface water drift?

*(Use the map or drawing “In the Northern Hemisphere, moving water is turned to the right.” shown earlier in this lesson.)*

1. The wind blows toward the south.
2. Face south, the way the wind is going. Your right hand points west.
3. So the water is turned to the west of south.

**Answer:** Toward the southwest (to the right of the wind’s direction).

**Example 2.** A floating buoy drifts in a current at an average of 0.5 km/h (about 0.3 mph). How far does it drift in 30 days?

1. Hours in 30 days:  $30 \times 24 = 720$  hours.
2. Distance:  $0.5 \times 720 = 360$  km.
3. In miles:  $0.3 \times 720 = 216$  miles (or  $360 \times 0.62 \approx 223$  miles).

**Answer:** About 360 km, or about 220 miles.

**Example 3.** A bottle is dropped into the sea off Portugal. Using Figure g6-world-currents, list in order the currents it would ride around the North Atlantic gyre, and say which way it turns.

*(Use the map or drawing “Trace the North Atlantic loop.” shown earlier in this lesson.)*

1. Off Portugal the water flows south: the Canary Current.
2. Near the tropics the trade winds carry it west: the North Equatorial Current, toward the Caribbean.
3. Along America it turns north: the Gulf Stream.
4. In the westerlies it is carried east: the North Atlantic Drift, back toward Europe.
5. South, west, north, east: that is a clockwise loop.

**Answer:** Canary Current, North Equatorial Current, Gulf Stream, North Atlantic Drift; the gyre turns clockwise.

## PRACTICE

1. **EASY** What is a gyre?
2. **EASY** Name the five great ocean gyres.
3. **EASY** Which way do gyres turn in the Northern Hemisphere? In the Southern Hemisphere?
4. **EASY** Which two belts of wind drive the gyres, and which way does each blow?
5. **MEDIUM** Sort these into warm and cold currents: Kuroshio, California, Brazil, Benguela, Humboldt, Agulhas.
6. **MEDIUM** In the Southern Hemisphere a wind blows toward the east. Which way is the surface water turned?
7. **MEDIUM** The *Fram* was frozen in from September 1893 until it broke free in August 1896. About how many months did the drift last?
8. **HARD** The ground at the equator is carried around the earth’s axis at about 1,670 km/h (1,040 mph). At 60° latitude the circle around the axis is half as long. How fast does the ground move there? Why does this difference cause the Coriolis effect?

9. **HARD** Use Figure g6-world-currents. Why is there a current that flows all the way around Antarctica, but no current that circles the whole earth at the latitude of the United States?  
*(Use the map or drawing “Compare the Southern Ocean with the northern oceans.” shown earlier in this lesson.)*
10. **CHALLENGE** Explain in three or four sentences why the cold current off Peru is one of the richest fishing grounds in the world.

## COMMON MISTAKES

- Thinking currents flow straight downwind. Because of the Coriolis effect, surface water drifts at an angle to the wind.
- Mixing up the hemispheres. Clockwise is the Northern Hemisphere; counterclockwise is the Southern.
- Believing the Coriolis effect makes bathtubs and sinks drain in opposite directions in the two hemispheres. A sink is far too small; its swirl comes from the shape of the basin and how the water was moving. The effect matters for things that move over long distances, like winds and ocean currents.

**Make it a game · Clockwise or Counter?.** One player names an ocean (North Pacific, South Atlantic, Indian Ocean and so on). The other must stand and turn in the direction that ocean’s gyre spins, clockwise or counterclockwise, and name one current in it. A correct turn and current earns 2 points. Play until someone reaches 10. For a harder round, name a current and the other player must say whether it is warm or cold.

**Scripture.** “The fowl of the air, and the fish of the sea, and whatsoever passeth through the paths of the seas.” (Psalm 8:8, KJV)

A story often told about Matthew Fontaine Maury, the American navy officer who charted the winds and currents in the 1800s, is that this verse set him searching for the “paths of the seas.” Whether or not the story is exact, the currents really are paths, laid down by the winds and the turning of the earth.

### Practice answers

1. A huge ring of ocean currents that circles a whole ocean basin.
2. North Atlantic, South Atlantic, North Pacific, South Pacific and Indian Ocean gyres.
3. Clockwise in the Northern Hemisphere; counterclockwise in the Southern Hemisphere.
4. The trade winds blow from east to west near the tropics; the westerlies blow from west to east in the middle latitudes.
5. Warm: Kuroshio, Brazil, Agulhas. Cold: California, Benguela, Humboldt.
6. To the left of the wind. Facing east, your left is north, so the water drifts toward the northeast.
7. From September 1893 to August 1896 is 35 months, almost three years.
8. About 835 km/h (520 mph). Because the ground at different latitudes moves at different speeds, air or water moving north or south keeps its old eastward speed and seems to curve

compared with the ground beneath it.

9. Around Antarctica (about 55° to 60° S) no continent blocks the water, so the westerlies push it around the whole globe. At the latitude of the United States, North America, Europe and Asia block the way and turn the water into separate gyres.
10. Winds push the coastal surface water away from shore, and cold water from the deep rises (upwells) to replace it. This deep water carries nutrients that feed tiny plants and animals at the surface. Small fish such as anchovies feed on them in huge numbers, and bigger fish and birds feed on the anchovies.

## 7.3 TIDES

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### OBJECTIVES

- Explain how the pull of the moon (and, less strongly, the sun) raises two bulges of water that make the tides rise and fall about twice a day.
- Describe the great tides of the Bay of Fundy and explain spring tides and neap tides.
- Use tide times and heights to plan when a ship can safely enter a harbor, and explain how engineers design harbors for large tides.

**Warm-up.** Look at a calendar that shows the phases of the moon, or look up tonight's moon. Write down the dates of the next new moon and full moon. Then guess: on which of those days might the tides at the seashore be highest? Keep your guess and check it at the end of the lesson.

**Watch.** *What Causes Tides?* (NOAA SciJinks, 3:33). [https://www.youtube.com/watch?v=tcGEjzt\\_4is](https://www.youtube.com/watch?v=tcGEjzt_4is)

After the story: watch how the moon's gravity, which Newton explained, makes two bulges of ocean water, so most coasts get two high tides and two low tides each day.

**Note:** Captions were not available to check, but this is a short animation from NOAA's SciJinks science site and is very likely fine; a quick preview is still wise.

### KEY TERMS

#### **tide**

The regular rise and fall of the sea level along the shore, caused mainly by the pull of the moon and the sun.

#### **high tide and low tide**

The highest and lowest water levels reached during one rise and fall of the tide.

#### **tidal range**

The difference in height between high tide and the low tide that follows it.

#### **spring tide**

An extra-large tide that comes at new moon and full moon, when the sun, moon and earth are in a line. (It has nothing to do with the season of spring.)

#### **neap tide**

A smaller tide that comes at the first and last quarter moon, when the sun and moon pull at right angles.

#### **tide table**

A printed or online list of the times and heights of high and low tide for a place, worked out in advance.

## CORE IDEAS

**The story.** People who live by the sea have always known that the water rises and falls about twice a day, and that the tides grow and shrink with the moon. But no one could explain why until Isaac Newton. In 1687, in his great book the *Principia*, Newton showed that the same force of gravity that makes an apple fall also holds the moon in its path, and that the pull of the moon and the sun on the oceans raises the tides. For the first time, the rising sea at the harbor wall and the moon in the night sky were explained by one law.

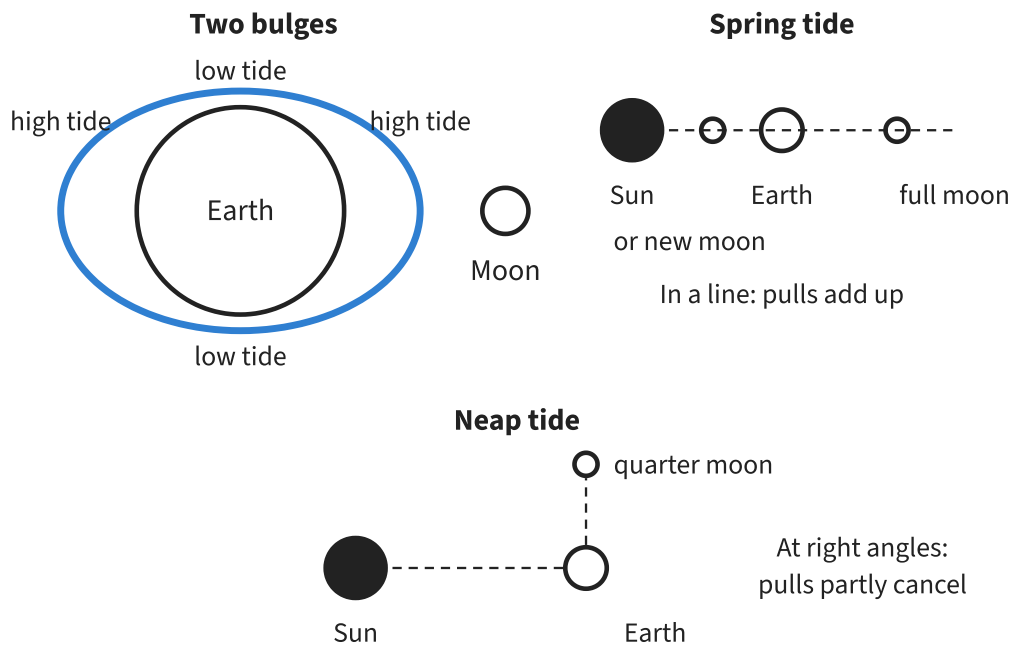
**How it works.** The moon pulls on every part of the earth, but it pulls hardest on the side nearest to it and weakest on the far side. The ocean on the near side is pulled toward the moon a little more than the earth's center, so it heaps up in a bulge. The ocean on the far side is pulled a little *less* than the earth's center, so it is left behind in a second bulge. As the earth turns, a harbor passes through both bulges each day, giving two high tides and two low tides. Because the moon moves along its orbit while the earth turns, the harbor needs about 24 hours and 50 minutes to come back under the moon. So high tides come about 12 hours and 25 minutes apart, and each day they arrive about 50 minutes later than the day before.

**The big idea.** The sun pulls on the oceans too, but because it is so far away its tide-raising pull is a little less than half the moon's. At **new moon** and **full moon**, the sun, moon and earth line up, the two pulls work together, and the tides are extra high and extra low. These are **spring tides**, from an old word meaning to leap up. At the **first and last quarter**, the sun and moon pull at right angles and partly cancel, giving gentle **neap tides**. In the open ocean the tide is only about 1 meter (3 feet) high. But when it runs into a bay of the right shape and length, it can grow enormous.

**On the map.** The **Bay of Fundy** lies between New Brunswick and Nova Scotia in Canada. It is long, and it narrows and grows shallower toward its head, so the tide is squeezed as it rushes in. Even more important, the water in the bay sloshes back and forth in a rhythm of about 13 hours, very close to the 12 hours and 25 minutes of the tide, like a child on a swing pushed at just the right moment. At Burntcoat Head in the Minas Basin, the tidal range at the biggest spring tides reaches about 16 meters (more than 50 feet), the highest in the world. About 100 billion tonnes of seawater flow in and out of the bay with each tide. At Hopewell Rocks you can walk on the sea floor at low tide around tall rock "flowerpots" that stand in deep water six hours later.

**Technology overcoming geography.** Big tides are a problem for a harbor. A ship that floats at the dock at high tide may sit on the mud at low tide. In the Fundy fishing village of Hall's Harbour, boats rest on the harbor floor twice a day. Engineers answer with several tools. They build very tall wharves, or **floating docks** that rise and fall with the water. They dredge deep channels. And in ports with large tides they build **wet docks** closed by lock gates that keep ships afloat while the tide runs out. Liverpool opened one of the first enclosed commercial wet docks in 1715, and in 1809 the engineer William Jessop finished Bristol's Floating Harbour by damming the tidal river so ships in the city never touched bottom. Harbor masters still plan every arrival with a **tide table**, worked out in advance from the motions of the moon and sun.





*Two tidal bulges, and why spring tides come at new and full moon while neap tides come at the quarter moons. (Not to scale.)*



*The Bay of Fundy narrows into the Minas Basin, where the world's highest tides are measured.*

## PICTURE STUDY



*Fishermen at Sea*, Joseph Mallord William Turner, 1796 · Oil on canvas · Tate, London

This was the first oil painting J. M. W. Turner showed at the Royal Academy in London, when he was only twenty-one. It shows fishermen at night off the Needles, the chalk rocks at the western tip of the Isle of Wight in the English Channel. A full moon breaks through the clouds and lights the waves.

Fishermen along the Channel lived by the moon and the tides. A full moon meant light to work by, but it also meant spring tides, with strong currents racing through narrow passages like the one beside the Needles.

### Look closely

- Find the moon. What phase is it? What kind of tides would the fishermen expect that night?
- Compare the cold moonlight with the warm glow of the lantern in the boat. Which one did Turner make stronger?
- Find the rocks in the shadows. Why would sailors fear rocks most at low tide?
- Look at the shape of the waves. Is the sea calm or rough?

### Talk about it

1. Why would a fisherman need to know the time of high and low tide before setting out?
2. Turner painted the moon as the brightest thing in the picture. In what way is the moon also the most powerful thing in the scene?

## PROJECT: TIDE WATCH AND A MODEL HARBOR

You will follow the real tides at a harbor for a week and graph them, then build a model harbor that works at both high and low tide.

### You will need

- Internet access to NOAA Tides and Currents ([tidesandcurrents.noaa.gov](http://tidesandcurrents.noaa.gov)) or a printed local tide table
- Graph paper, a ruler and two colored pencils
- A clear plastic bin, sand or modeling clay, a cup for adding and removing water
- Craft sticks, a small sponge or cork, string and tape
- A small toy boat or bottle cap

### Steps

1. Choose a harbor on the NOAA site, such as Boston, Massachusetts, or Eastport, Maine, at the mouth of the Bay of Fundy. Write down the times and heights of each high and low tide for seven days.
2. Graph one day: time across the bottom (midnight to midnight), water height up the side. Join the points with a smooth wavy line.
3. From your list, find how many minutes later the first high tide comes each day. Average your answers. Is it close to 50 minutes?
4. Mark the moon's phase for each day. Do the biggest ranges fall near new or full moon?
5. Build a harbor in the bin: a sloping sand or clay shore and a wharf made of craft sticks standing upright.
6. Add water for "high tide" and float the boat at the wharf. Remove water for "low tide." What happens to the boat?
7. Now build a floating dock: tape a cork or sponge under a craft-stick platform and tie it loosely to two upright sticks so it slides up and down. Test it at high and low tide. Write two sentences on which dock works better and why.

### Tips

- Tide heights on NOAA tables are measured from a fixed mark called a datum, so low tides can show as 0 or even a small negative number. That is normal.
- Keep the strings on your floating dock loose so it can rise and fall freely.

### Check your work

- I graphed a real harbor's tides and measured how much later they come each day.
- I compared the tides to the phases of the moon.
- I built a dock that works at both high and low tide and can explain it.

## MAP NOTEBOOK

1. Copy the tide-bulge diagram (Figure g6-tide-bulges) and label the moon, the two bulges and a harbor at high tide.
2. Draw the moon phases for a month in a row and mark “spring” under new and full moon and “neap” under the quarter moons.
3. Sketch Hopewell Rocks twice, at high tide and low tide, with a person standing at the base in the low-tide picture.

**From history.** Where the Saint John River meets the Bay of Fundy at Saint John, New Brunswick, the river runs through a narrow rocky gorge. At low tide the river pours out to sea over rapids. At high tide the bay rises higher than the river, and the water at the gorge runs *upstream*. People call it the Reversing Falls. For safe passage, boats wait for “slack water,” the short calm time between, when the river and the sea are at the same level.

## WORKED EXAMPLES

**Example 1.** At a harbor, high tide comes at 5:40 a.m. Using 12 hours 25 minutes between high tides, find (a) the next high tide, (b) the next morning’s high tide, and (c) the low tide between the first two high tides (halfway).

1. (a)  $5:40 \text{ a.m.} + 12 \text{ h } 25 \text{ min} = 5:40 \text{ p.m.} + 25 \text{ min} = 6:05 \text{ p.m.}$
2. (b)  $6:05 \text{ p.m.} + 12 \text{ h } 25 \text{ min} = 6:05 \text{ a.m.} + 25 \text{ min} = 6:30 \text{ a.m.}$  the next day. That is 50 minutes later than the first morning’s high tide.
3. (c) Half of 12 h 25 min is about 6 h 12 min.  $5:40 \text{ a.m.} + 6 \text{ h } 12 \text{ min} = 11:52 \text{ a.m.}$

**Answer:** (a) 6:05 p.m.; (b) 6:30 a.m. the next day; (c) about 11:52 a.m.

**Example 2.** On a spring tide at Burntcoat Head, the tide table gives high tide at 15.6 m and low tide at 0.2 m. Find the tidal range in meters and in feet ( $1 \text{ m} \approx 3.28 \text{ ft}$ ).

*(Use the map or drawing “Burntcoat Head is in the Minas Basin at the head of the bay.” shown earlier in this lesson.)*

1.  $\text{Range} = \text{high} - \text{low} = 15.6 - 0.2 = 15.4 \text{ m.}$
2. In feet:  $15.4 \times 3.28 \approx 50.5 \text{ ft.}$

**Answer:** 15.4 m, about 50 feet: as tall as a five-story building.

**Example 3.** A harbor channel is 3.0 m (about 10 ft) deep at low tide. A cargo ship needs 5.5 m (about 18 ft) of water to float, plus 1.0 m (about 3 ft) of safety room under the hull. How much must the tide rise before the ship can enter? If the tidal range that day is 6.0 m (about 20 ft), can the ship enter at high tide?

1. Water needed:  $5.5 + 1.0 = 6.5$  m ( $18 + 3 = 21$  ft).
2. Extra depth needed above low tide:  $6.5 - 3.0 = 3.5$  m ( $21 - 10 = 11$  ft).
3. At high tide the channel is  $3.0 + 6.0 = 9.0$  m deep ( $10 + 20 = 30$  ft), which is more than 6.5 m.

**Answer:** The tide must rise at least 3.5 m (about 11 ft). Yes, the ship can enter near high tide, but it must not arrive near low tide.

## PRACTICE

1. **EASY** Which pulls more strongly on the tides, the moon or the sun? About how strong is the other one?
2. **EASY** In what year did Isaac Newton explain the tides by gravity, and in what book?
3. **EASY** At which moon phases do spring tides come? At which do neap tides come?
4. **MEDIUM** High tide at a beach is at 9:15 a.m. on Monday. About what time will the morning high tide be on Tuesday? On Wednesday?
5. **MEDIUM** High tide is 4.8 m and low tide is 0.6 m. What is the tidal range in meters and in feet?
6. **MEDIUM** Use Figure g6-tide-bulges. Why are there two high tides a day and not just one? (*Use the map or drawing “Find both bulges.” shown earlier in this lesson.*)
7. **MEDIUM** Give two reasons the Bay of Fundy has such large tides.
8. **HARD** At Burntcoat Head the tide rises about 15 m (50 ft) in about 6 hours. What is the average rise per hour, in meters and feet? About how many minutes does it take to rise the height of a 1.5 m (5 ft) tall person?
9. **HARD** Name three ways engineers make a harbor usable where the tides are large.
10. **CHALLENGE** Write a short plan (3–4 sentences) for a captain bringing a ship into a Fundy port at night. What would the captain look up, and when would the captain choose to arrive?

## COMMON MISTAKES

- Thinking spring tides happen only in springtime. They happen twice every month, at new and full moon.
- Thinking the moon pulls water only on the side facing it. There is a second bulge on the far side, which is why there are two high tides a day.
- Thinking high tide comes at the same time every day. It comes about 50 minutes later each day because the moon moves along its orbit.

**Make it a game • Tide Clock.** Make a paper clock face. One player names a high tide time (for example, 3:20 a.m.). The other moves the hands to the next high tide (add 12 hours 25 minutes) and then to the same tide the next day (add 50 minutes to the first time). Each correct answer earns a point. Bonus point: say whether the tide would be spring or neap if the moon is full.

**Scripture.** “And said, Hitherto shalt thou come, but no further: and here shall thy proud waves be stayed?” (Job 38:11, KJV)

In Job 38, God reminds Job that He set the bounds of the sea. Even the mighty Fundy tide rises to its mark and turns back on time, so faithfully that its height can be printed in a table a year ahead.

#### Practice answers

1. The moon. The sun's tide-raising pull is a little less than half of the moon's.
2. 1687, in the *Principia*.
3. Spring tides at new moon and full moon; neap tides at the first and last quarter moons.
4. About 50 minutes later each day: about 10:05 a.m. Tuesday and about 10:55 a.m. Wednesday.
5.  $4.8 - 0.6 = 4.2$  m;  $4.2 \times 3.28 \approx 13.8$  ft, about 14 feet.
6. There are two bulges of water, one on the side facing the moon and one on the far side. As the earth turns, a place passes through both bulges each day.
7. (1) The bay is long and narrows and shallows toward its head, squeezing the incoming tide higher. (2) The water in the bay naturally sloshes back and forth in about 13 hours, close to the 12 hour 25 minute tide, so each tide pushes the sloshing higher, like pushing a swing in rhythm.
8.  $15 \div 6 = 2.5$  m per hour ( $50 \div 6 \approx 8.3$  ft per hour). 1.5 m takes  $1.5 \div 2.5 = 0.6$  hour, about 36 minutes.
9. Any three: very tall wharves; floating docks that rise and fall with the water; dredged deep channels; wet docks or floating harbors closed by lock gates that hold water in at low tide; tide tables to schedule ships.
10. Answers will vary. A good plan looks up the tide table for the port, finds the time and height of high tide, checks the ship's depth against the channel depth, and arrives on the rising tide near high water, leaving before the water falls too low or tying up in a dock that stays afloat. It might also note that spring tides at new and full moon bring the strongest currents.

## 7.4 CURRENTS AND CLIMATE

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### OBJECTIVES

- Explain why London is mild in winter while the coast of Labrador, at nearly the same latitude, is locked in ice.
- Describe how warm currents, cold currents and prevailing winds carry heat and shape the climate of coasts around the world.
- Make and explain a convection current in a pan of warm and cold water.

**Warm-up.** Fill one cup with hot tap water and one with cold, and put both on the counter with a thermometer (or your fingertip) for 5 minutes. Now hold a metal spoon in the hot water for 30 seconds and touch it. Which cools faster in the air, the spoon or the water? Write a guess: why might a coast next to a big sea have milder winters than a place far inland?

**Watch.** NASA / *The Ocean: A Driving Force for Weather and Climate* (NASA Goddard, 6:00). <https://www.youtube.com/watch?v=6vgvTeuoDWY>

With the big idea: watch the satellite maps of sea-surface temperature and see how currents carry warm water from the tropics toward the poles.

**Note:** Captions were not available to check; preview it first. NASA climate videos sometimes include a short line about a changing climate.

### KEY TERMS

#### North Atlantic Drift

The warm current that carries water of the Gulf Stream northeast across the Atlantic toward the British Isles and Norway.

#### Labrador Current

A cold current that flows south from the Arctic along the coasts of Labrador and Newfoundland, carrying sea ice and icebergs.

#### maritime climate

The mild climate of places where winds blow in from the sea: cool summers, mild winters and rain in all seasons.

#### continental climate

The climate of places far from the sea or where winds blow from the land: hot summers and very cold winters.

#### convection current

A flow in a liquid or gas set up when warm, lighter fluid rises and cool, heavier fluid sinks.

#### heat capacity

How much heat something must take in to warm up. Water has a very high heat capacity, so it warms and cools slowly.



## CORE IDEAS

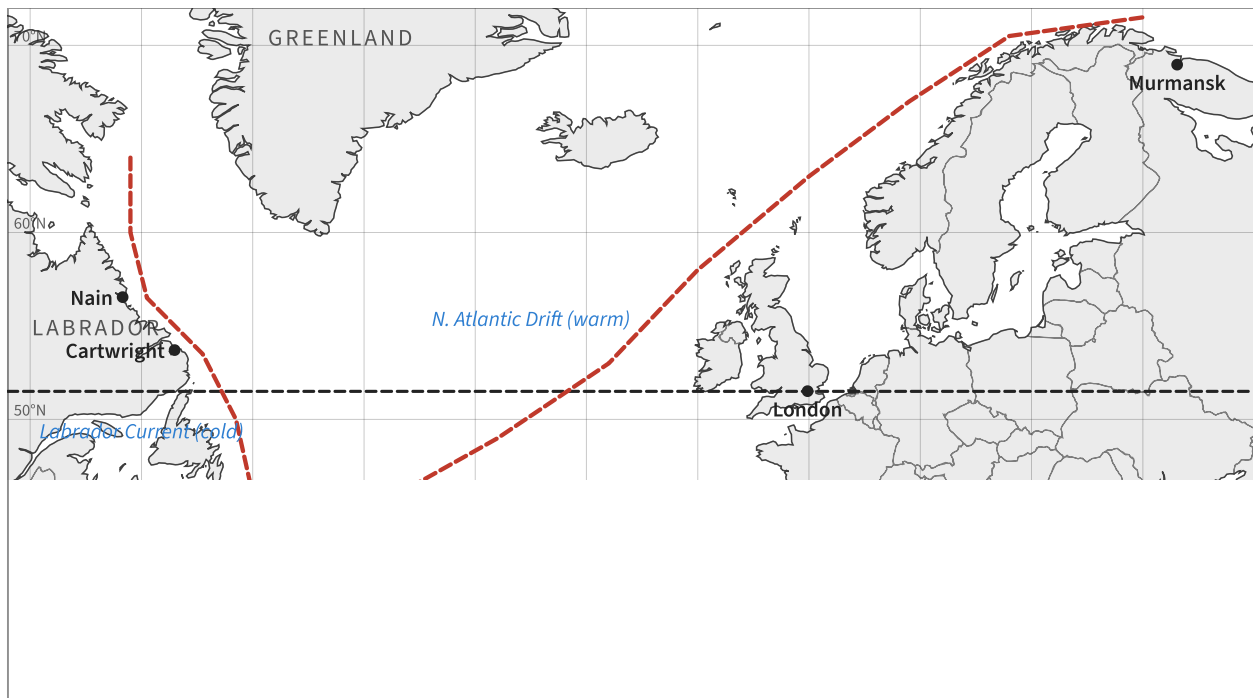
**The story.** In 1771 a small band of Moravian missionaries, among them Jens Haven, a Danish carpenter who had learned the Inuit language in Greenland, built a mission station at Nain on the coast of Labrador. For well over a century afterward, a mission ship sailed each summer from London to the Labrador stations with supplies, letters and new workers. The two ends of that voyage were very different worlds. London sits at about  $51.5^{\circ}$  N, and its river rarely freezes. Labrador lies at about  $52^{\circ}$  to  $60^{\circ}$  N, hardly farther north, yet its harbors are locked in sea ice for much of the year and icebergs drift down its coast. The mission ship could reach Labrador only in the short weeks of summer when the ice opened.

**The big idea.** Latitude tells you how high the sun climbs, but it does not tell the whole story of a place's climate. Compare London ( $51.5^{\circ}$  N) with Cartwright, Labrador (about  $53.7^{\circ}$  N). In January, London averages about  $5^{\circ}\text{C}$  ( $41^{\circ}\text{F}$ ); Cartwright averages about  $-14^{\circ}\text{C}$  (about  $7^{\circ}\text{F}$ ). In July, London averages about  $19^{\circ}\text{C}$  ( $66^{\circ}\text{F}$ ) and Cartwright only about  $13^{\circ}\text{C}$  ( $55^{\circ}\text{F}$ ). Two things make the difference: the **ocean currents** beside each coast, and the **winds** that blow across them.

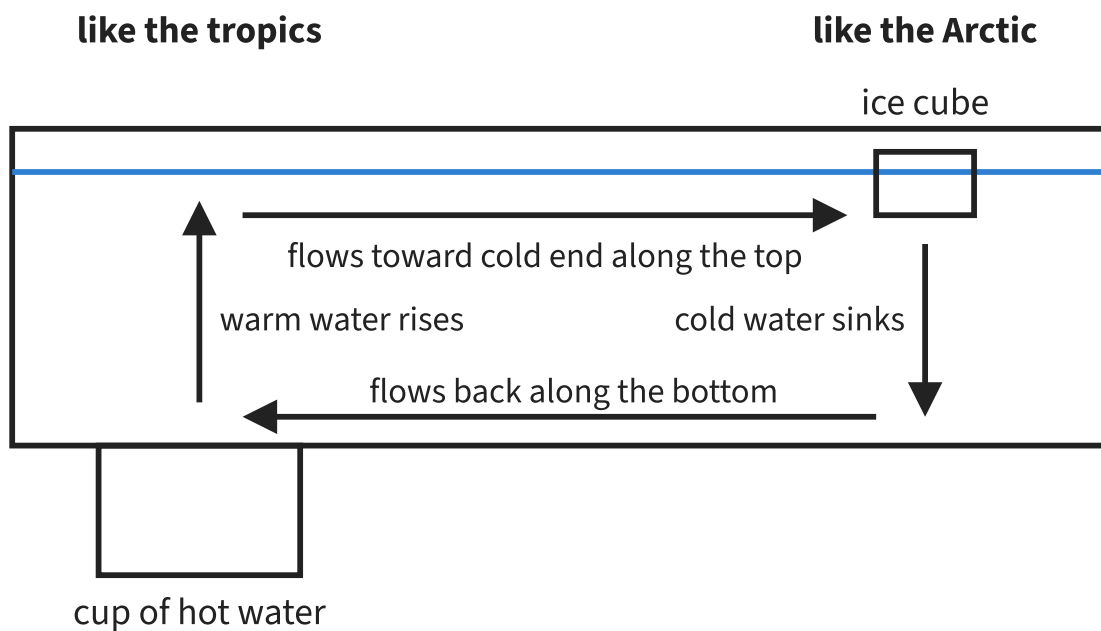
**How it works.** Water has a very high **heat capacity**. It soaks up a great deal of the sun's heat in the tropics and gives it back slowly. The Gulf Stream and the **North Atlantic Drift** carry warm water northeast across the Atlantic, so the sea off Ireland, Britain and Norway stays far warmer in winter than the latitude alone would allow. Then the **westerlies**, the prevailing winds of the middle latitudes, blow from the ocean onto Europe and carry that mildness ashore. Britain has a **maritime climate**: mild winters, cool summers and rain all year. Labrador sits on the *west* side of the ocean. Its westerlies blow out of the frozen heart of Canada, bringing a **continental** cold, and offshore runs the cold **Labrador Current**, carrying sea ice and icebergs south from the Arctic and the glaciers of Greenland.

**On the map.** The same pattern appears all over the world. The warm North Atlantic Drift keeps the Russian port of Murmansk, north of the Arctic Circle at about  $69^{\circ}$  N, free of ice all winter, while ports on the Baltic Sea far to the south freeze over. On the Isles of Scilly, off southwest England, gardeners grow palms and other plants from warmer lands. Cold currents do the opposite. Along the east side of the oceans, cold currents chill the air above them. Cool air does not rise to make rain clouds, so it brings fog instead of rain. That is why some of the driest deserts on earth lie right beside the sea: the Atacama Desert of Chile and Peru beside the cold Humboldt Current, and the Namib Desert of southwest Africa beside the cold Benguela Current. San Francisco's cool summer fog comes from the cold California Current just offshore.

**How they figured it out.** Sea water also moves up and down. When water cools near the poles, it becomes heavier and sinks; warmer, lighter water flows in at the surface to take its place. Scientists call a flow like this a **convection current**, and you can make one in a pan in your kitchen. In the real ocean, convection works together with the winds to keep the great currents turning, carrying heat from the tropics toward the poles and cold water back toward the equator. God set the sun, the sea and the winds in their courses so that the warmth of the tropics is shared across the earth.



*London and Cartwright lie at nearly the same latitude, but a warm current and sea winds warm one, while a cold current and land winds chill the other.*



*A convection current in a pan: warm water rises, cold water sinks, and the water turns in a loop.*

## PICTURE STUDY



*The Icebergs*, Frederic Edwin Church, 1861 · Oil on canvas · Dallas Museum of Art, Dallas, Texas

In the summer of 1859 the American landscape painter Frederic Edwin Church sailed north to the waters off Newfoundland and Labrador to sketch icebergs. His friend, the minister Louis Legrand Noble, went along and wrote a book about the trip. Back in his New York studio Church turned his sketches into this enormous painting, about 1.6 by 2.9 meters (5½ by 9½ feet).

The icebergs Church saw had broken from the glaciers of Greenland and were carried south by the cold Labrador Current. In 1863, before showing the painting in London, Church added a broken ship's mast on the ice in the foreground: a quiet reminder of what these waters can do.

### Look closely

- Find the broken mast. What story does it suggest?
- Look at the colors in the ice. Where do you see white, and where do you see blue and green?
- Notice how calm the water is. Is this a peaceful scene or a dangerous one? Why might it be both?
- Find the sky. What time of day or kind of weather did Church paint?

### Talk about it

1. Where did these icebergs come from, and what carried them to where Church painted them?
2. Why would no one see icebergs like these off the coast of England at the same latitude?

**Safety first.** Use hot tap water, not boiling water. An adult should pour the hot water. Food coloring stains, so cover the table.

## PROJECT: A CONVECTION CURRENT IN A PAN

You will make the ocean's hidden up-and-down currents visible with warm water, cold water and food coloring, and then connect what you see to the currents of the North Atlantic.

### You will need

- A clear glass baking dish or clear plastic storage box
- Room-temperature water to fill it about 5 cm (2 inches) deep
- Two mugs or small heatproof cups, one filled with hot tap water
- Ice cubes made with blue food coloring (freeze them the day before)
- Red food coloring and a dropper
- A white sheet of paper to set under or behind the dish, and a timer

### Steps

1. Set the clear dish across two supports: the mug of hot water under one end and an empty mug (or a block) under the other end, so the dish is level. Put white paper behind it so you can see from the side.
2. Fill the dish with room-temperature water and let it sit still for two minutes.
3. Gently drop a blue ice cube into the end *away* from the hot mug.
4. With the dropper, place a few drops of red food coloring on the bottom of the dish just above the hot mug. Let them sink and settle, then watch.
5. Watch from the side for 5 minutes. Draw what the red water does over the heat and what the blue meltwater does under the ice.
6. Draw arrows on your sketch to show the whole loop. Label "warm water rises," "cold water sinks," and the flow along the top and bottom.
7. Write three sentences comparing your pan to the North Atlantic: which end is like the tropics, which is like the Arctic, and which way the warm surface water flows.

### Tips

- Keep the dish very still. Bumping it mixes the colors and hides the current.
- If the red coloring floats at the top right away, the water in the dish may be too warm. Start again with cooler water.

### Check your work

- I saw warm red water rise and cold blue water sink.
- My drawing shows a complete loop with arrows.
- I can explain how this models the way the ocean carries heat from the tropics toward the poles.

## MAP NOTEBOOK

1. Draw a line of latitude at  $51.5^{\circ}$  N across the North Atlantic. Put London on one end and Labrador on the other, and draw the warm and cold currents in red and blue.
2. Make a side-by-side bar graph of January and July average temperatures for London and Cartwright, Labrador.
3. Sketch a desert coast (the Atacama or the Namib) with a cold current offshore and a bank of fog rolling in instead of rain.

**From history.** On the night of April 14, 1912, the liner *Titanic* struck an iceberg south of the Grand Banks of Newfoundland and sank early the next morning. The iceberg had almost certainly broken from a Greenland glacier and drifted south in the Labrador Current to where that cold current meets the Gulf Stream. After the disaster, the nations that sailed the North Atlantic set up the International Ice Patrol in 1914. Run by the U.S. Coast Guard, it still watches the iceberg season each year and warns ships where the ice has drifted.

## WORKED EXAMPLES

**Example 1.** London's January average is about  $5^{\circ}\text{C}$  ( $41^{\circ}\text{F}$ ). Cartwright, Labrador's is about  $-14^{\circ}\text{C}$  ( $7^{\circ}\text{F}$ ). How much warmer is London, in  $^{\circ}\text{C}$  and in  $^{\circ}\text{F}$ ?

1. In Celsius:  $5 - (-14) = 5 + 14 = 19^{\circ}\text{C}$ .
2. In Fahrenheit:  $41 - 7 = 34^{\circ}\text{F}$ .
3. Check: a difference of 19 Celsius degrees  $\times 1.8 \approx 34$  Fahrenheit degrees.

**Answer:** London is about  $19^{\circ}\text{C}$  ( $34^{\circ}\text{F}$ ) warmer in January.

**Example 2.** London is at about  $51.5^{\circ}$  N and Cartwright at about  $53.7^{\circ}$  N. Each degree of latitude is about 111 km (69 miles). How far apart are they north to south?

(Use the map or drawing "Compare the latitude lines." shown earlier in this lesson.)

1. Difference in latitude:  $53.7 - 51.5 = 2.2^{\circ}$ .
2. In km:  $2.2 \times 111 \approx 244$  km.
3. In miles:  $2.2 \times 69 \approx 152$  miles.

**Answer:** Only about 244 km (152 miles) apart north to south, yet their winters are very different.

**Example 3.** On the world currents map from Lesson 7.2, the Benguela Current flows north along the coast of southwest Africa, toward the equator. Is it warm or cold? Predict the climate of the coast beside it.

1. A current flowing from high latitudes toward the equator carries cooler water from colder seas, so it is a cold current.
2. A cold current chills the air above it; cool air near the surface does not rise to make rain clouds.
3. So the coast beside it should be very dry and often foggy.

**Answer:** It is a cold current, and the coast beside it is a dry, foggy desert: the Namib Desert.

## PRACTICE

1. **EASY** Name the warm current that carries Gulf Stream water toward Britain and Norway.
2. **EASY** Name the cold current along the coast of Labrador, and two things it carries south.
3. **EASY** Which prevailing winds blow onto Western Europe from the Atlantic?
4. **MEDIUM** Give two reasons London has milder winters than Labrador at nearly the same latitude.
5. **MEDIUM** Murmansk, Russia, is at about 69° N. Why is its harbor free of ice in winter when Baltic ports much farther south freeze?
6. **MEDIUM** In July London averages about 19°C and Cartwright about 13°C. Convert both to °F ( $^{\circ}\text{F} = ^{\circ}\text{C} \times 9 \div 5 + 32$ ).
7. **MEDIUM** Use Figure g6-london-labrador. A ship sails from London to Labrador. Through which current does it sail first, and which current does it meet near the end?  
(Use the map or drawing “Follow the ship’s route west.” shown earlier in this lesson.)
8. **HARD** Explain why the Atacama Desert, right beside the Pacific Ocean, is one of the driest places on earth.
9. **HARD** In your convection pan, which end is like the tropics and which is like the Arctic? Which way does the water flow along the top, and which way along the bottom?
10. **CHALLENGE** Write a paragraph (4–5 sentences) for a travel guide explaining to a visitor why the Isles of Scilly, at about 50° N, can grow palm trees while the coast of Labrador, a little farther north, is icebound in winter. Use the words latitude, current and westerlies.

## COMMON MISTAKES

- Thinking latitude alone decides climate. Currents, winds, altitude and distance from the sea all matter.
- Thinking every coast is mild. A coast where the winds blow from the land, or that faces a cold current, can be very cold or very dry.



- Mixing up warm and cold currents. A current flowing from the tropics toward the poles is warm; one flowing from the poles toward the equator is cold.

**Make it a game · Warm Coast, Cold Coast.** One player names a coast and the current beside it (for example, Norway and the North Atlantic Drift, or Peru and the Humboldt Current). The other player says “warm!” or “cold!” and names one thing you would expect there: mild winters, fog, desert, sea ice, rich fishing. Two points for both parts right. Play to ten.

**Scripture.** “The wind goeth toward the south, and turneth about unto the north; it whirlleth about continually, and the wind returneth again according to his circuits.” (Ecclesiastes 1:6, KJV)

The Preacher noticed that the winds travel in great circuits. We now know the winds and currents together carry the warmth of the tropics around the world, so that palms can grow on an English island at nearly the latitude of icebound Labrador.

#### Practice answers

1. The North Atlantic Drift.
2. The Labrador Current. It carries sea ice and icebergs (and cold Arctic water).
3. The westerlies.
4. (1) The warm North Atlantic Drift keeps the sea near Britain warm, while the cold Labrador Current chills Labrador’s coast. (2) The westerlies blow onto Britain from the warm ocean, but onto Labrador from the frozen interior of the continent.
5. The warm water of the North Atlantic Drift reaches the sea off northern Norway and Murmansk and keeps the harbor from freezing. The Baltic is an almost enclosed sea that this warm water does not reach.
6. London:  $19 \times 9 \div 5 + 32 = 34.2 + 32 \approx 66^\circ\text{F}$ . Cartwright:  $13 \times 9 \div 5 + 32 = 23.4 + 32 \approx 55^\circ\text{F}$ .
7. First it crosses the warm North Atlantic Drift; near Labrador it meets the cold Labrador Current, with its sea ice and icebergs.
8. The cold Humboldt Current flows offshore. It cools the air above it, and cool air near the surface does not rise to form rain clouds. Instead the coast gets fog, but almost no rain. (A strong answer may add that the Andes block moist air from the east.)
9. The end over the hot mug is like the tropics; the end with the ice is like the Arctic. Warm water flows along the top from the warm end toward the cold end; cold water flows along the bottom from the cold end back toward the warm end.
10. Answers will vary. A strong answer explains that latitude alone would make both places cool, but that the warm North Atlantic Drift keeps the sea around Scilly mild, the westerlies carry that mild sea air ashore, and frost is rare; meanwhile Labrador has the cold Labrador Current offshore and westerlies blowing from the frozen interior of North America.



## UNIT 7 REVIEW

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Answer each question. Show your work for calculations, give both metric and U.S. units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (5 pts) Why did the British mail packets take about two weeks longer to cross from England to New York than Rhode Island merchant ships? Who explained it to Franklin?
2. (6 pts) A ship sails 9 km/h (about 5.5 mph) through the water. The current flows at 4 km/h (about 2.5 mph). Find its speed over the ground against the current and with it, and how far it goes in 24 hours with the current.
3. (5 pts) How could a ship's captain in Franklin's day tell, even at night, that the ship had entered the Gulf Stream?
4. (6 pts) Explain how the trade winds, the westerlies and the Coriolis effect make the North Atlantic gyre. Which way does it turn?
5. (6 pts) Map reading: On a world currents map, sort these currents into warm and cold, and name the ocean each is in: Gulf Stream, Canary, Kuroshio, Humboldt, East Australian, Benguela.
6. (5 pts) A drifting buoy moves at 0.4 km/h (0.25 mph). How far does it drift in 50 days?
7. (6 pts) Why are there usually two high tides a day? Why does each day's high tide come about 50 minutes later than the day before?
8. (6 pts) High tide at a harbor is at 4:15 a.m. with a height of 7.2 m; low tide follows with a height of 0.4 m. (a) What is the tidal range in meters and feet? (b) About when is the next high tide? (c) Is this more likely a spring or a neap tide if the moon is full?
9. (5 pts) Give two reasons the Bay of Fundy has the highest tides in the world, and one way engineers make harbors work where tides are large.
10. (5 pts) London (about 51.5° N) averages about 5°C (41°F) in January; Cartwright, Labrador (about 53.7° N) averages about -14°C (7°F). Find the difference in °C and °F, and the north-south distance between them (1° ≈ 111 km or 69 miles).
11. (5 pts) Explain why London is mild and Labrador is cold at nearly the same latitude. Name both currents and the prevailing winds.

## UNIT PROJECT: MY MAP OF THE WORLD'S OCEAN CURRENTS

Draw a large world map of the major ocean currents. Show the five great gyres with arrows turning the right way, color the warm currents red and the cold currents blue, and label at least ten currents, including the Gulf Stream, North Atlantic Drift, Labrador, Canary, Kuroshio, California, Humboldt, Benguela, Brazil and the Antarctic Circumpolar Current. Mark London, Labrador, the Bay of Fundy and one coastal desert beside a cold current.

Beside the map, include your Gulf Stream chart from Lesson 7.1, your tide graph from Lesson 7.3 and a labeled drawing of your convection pan from Lesson 7.4, with a paragraph explaining how the ocean carries heat from the tropics toward the poles.

- **Accuracy:** Currents are placed correctly, gyres turn the right way, and warm and cold currents are colored correctly.
- **Labels and places:** At least ten currents and the required places are labeled clearly and spelled correctly.
- **Explanation:** The paragraph correctly explains how winds, the earth's turning and convection move the water, and how currents shape the climate of coasts.
- **Care:** The map and attached work are neat, colorful and easy to read, with a title, compass rose and key.

#### Answer key

1. The packet captains sailed west against the Gulf Stream, which slowed them and in light winds carried them backward. The Rhode Island captains knew the stream and avoided it. Captain Timothy Folger, a Nantucket whaler and Franklin's cousin, explained it.
2. Against:  $9 - 4 = 5$  km/h ( $5.5 - 2.5 = 3$  mph). With:  $9 + 4 = 13$  km/h ( $5.5 + 2.5 = 8$  mph). In 24 hours with the current:  $13 \times 24 = 312$  km ( $8 \times 24 = 192$  miles).
3. By measuring the sea temperature with a thermometer. The water of the Gulf Stream is clearly warmer than the sea around it. (The stream's water color and floating gulfweed are other clues by day.)
4. The trade winds push surface water west near the tropics; the westerlies push it east in the middle latitudes. The continents turn the water along their coasts, and the Coriolis effect turns moving water to the right in the Northern Hemisphere. The result is a loop that turns clockwise.
5. Warm: Gulf Stream (North Atlantic), Kuroshio (North Pacific), East Australian (South Pacific). Cold: Canary (North Atlantic), Humboldt (South Pacific), Benguela (South Atlantic).
6.  $50 \times 24 = 1,200$  hours.  $0.4 \times 1,200 = 480$  km.  $0.25 \times 1,200 = 300$  miles.
7. The moon's pull makes two bulges of water, one facing the moon and one on the far side, and the earth turns through both each day. Because the moon moves along its orbit, a place needs about 24 hours 50 minutes to come back under the moon, so the tides come about 50 minutes later each day.
8. (a)  $7.2 - 0.4 = 6.8$  m;  $6.8 \times 3.28 \approx 22.3$  ft. (b) 4:15 a.m. + 12 h 25 min = 4:40 p.m. (c) A spring tide, because at full moon the sun, earth and moon are in a line.
9. Reasons: the bay is long and narrows and shallows toward its head, squeezing the tide; and the water in the bay sloshes in a natural rhythm of about 13 hours, close to the tide's 12 hours 25 minutes, so the tide builds up like a pushed swing. Engineering: any one of tall wharves, floating docks, dredged channels, wet docks or floating harbors with lock gates, or tide tables.
10. Temperature:  $5 - (-14) = 19^\circ\text{C}$ ;  $41 - 7 = 34^\circ\text{F}$ . Distance:  $53.7 - 51.5 = 2.2^\circ$ ;  $2.2 \times 111 \approx 244$  km;  $2.2 \times 69 \approx 152$  miles.
11. The warm North Atlantic Drift keeps the sea near Britain warm, and the westerlies blow that mild ocean air onto Britain. Labrador lies beside the cold Labrador Current, which carries sea ice and icebergs south, and its westerlies blow from the frozen interior of North America.

## LIVING WITH NATURAL HAZARDS

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All through this course you have watched the earth at work: plates moving, rivers carrying sand to the sea, winds and currents carrying heat around the globe. The same processes that build deltas and water the plains can also flood a valley, drive the sea over an island or send a tornado across a town. The psalmist praises the God “who laid the foundations of the earth, that it should not be removed for ever” (Psalm 104:5), and in Job 38 the Lord Himself speaks of shutting up the sea with doors. People cannot command the wind and the waves, but God has given us minds to study them, hands to build and neighbors to warn.

In this unit you will see how people have learned to live safely where nature is dangerous. You will stand on a Dutch dike after the North Sea flood of 1953 and watch the Delta Works rise; follow the Mississippi in the great flood of 1927 and see how the Corps of Engineers gave the river safe places to go; walk the Galveston seawall built after the hurricane of 1900; and sit with the forecasters who first predicted a tornado in 1948. In every lesson you will ask the same questions: **What is the hazard, how does it work, and how have people prepared and built against it?**

Your hands-on work includes a model dike and polder in a pan, a levee test in a sand tray, a seawall wave tank, and a real shelter plan for your own home. At the end you will put it all together on a hazard map of the United States.

### BEFORE YOU BEGIN

- Can read heights above and below sea level and find the difference between them
- Knows how rivers carry and drop sediment to build floodplains and deltas (Unit 4)
- Understands prevailing winds, ocean currents and the earth’s spin bending moving air and water (Units 5 and 7)
- Can convert between miles and kilometers and between feet and meters

### MASTERY CHECKLIST

- I can explain how dikes, windmills, pumps and storm surge barriers keep the Netherlands dry, and tell the story of the 1953 flood and the Delta Works.
- I can explain how a river builds natural levees, why “levees only” failed in 1927, and how spillways and floodways now protect the lower Mississippi.
- I can explain how a hurricane forms, why storm surge is its deadliest part, and how Galveston answered the storm of 1900 with a seawall and a raised city.
- I can explain why Tornado Alley has so many tornadoes, use the EF scale, and tell the difference between a watch and a warning.
- I can compute water depths, flood distances and warning times in both customary and metric units.
- I can draw a hazard map of the United States and name a way people prepare in each region.

## OPTIONAL BOOKS AND RESOURCES

- **NOAA SciJinks** (<https://scijinks.gov/>): Free. Short, clear articles and pictures from NOAA on hurricanes, tornadoes, radar and weather satellites, written for students. Parents should preview, as with any site.
- **National Hurricane Center** (<https://www.nhc.noaa.gov/>): Free. During hurricane season (June 1 to November 30), follow a real storm's forecast track and cone, and practice reading watches and warnings (Lesson 8.3).
- **Ready.gov** (<https://www.ready.gov/>): Free. The federal government's guide to family emergency plans and kits for floods, hurricanes and tornadoes. Use it with the shelter plan in Lesson 8.4.

## 8.1 THE NETHERLANDS AND THE SEA ★ ⚙️

### OBJECTIVES

- Explain how dikes, windmills and pumps let the Dutch live and farm on land that lies below the level of the sea.
- Tell the story of the North Sea flood of 1953 and describe how the Delta Works were built so it would not happen again.
- Read heights above and below sea level on a dike cross-section and work out water depths in meters and feet.

**Warm-up.** Stand an empty plastic cup in the middle of a mixing bowl and hold it down with one finger. Slowly pour water into the bowl until it reaches halfway up the outside of the cup. The inside of the cup is now dry “land” that lies lower than the “sea” around it. Talk it over: Where would water try to get in? If a little leaked in, how could you get it out again with only a spoon? That is the whole problem of the Netherlands in one bowl.

**Watch.** *Why are the Dutch So Good at Waterworks?* (Practical Engineering, 22:20).

<https://www.youtube.com/watch?v=qQCB3N8Vaxk>

After the story: watch how the Dutch answered the 1953 flood with the Delta Works, and look for the Oosterschelde barrier and the Maeslantkering.

**Note:** Captions were not available to check; preview it first. This is a long video (about 22 minutes), and Practical Engineering videos usually include a sponsor message you can skip. It may also mention sea-level rise.

**Backup video.** *De Afsluitdijk: Why The Dutch Built A Motorway In The Sea* (The Tim Traveller, 5:40). <https://www.youtube.com/watch?v=6r6zcMl2Xmw>

As review: ride along across the Afsluitdijk and see how a long dike can hold back the sea and turn salt water into a freshwater lake. Note: Captions were not available to check; preview it first. The host is British and gives distances in kilometres. The Afsluitdijk (1932) belongs to the earlier Zuiderzee Works, not the Delta Works built after the 1953 flood.

### KEY TERMS

#### dike

A long bank of earth, clay and stone built to hold back the sea or a river. The Dutch spelling is *dijk*.

#### polder

A piece of low land surrounded by dikes and kept dry by pumping. Many Dutch polders were once lakes, marshes or seabed.

#### storm surge

A rise of the sea far above the normal tide, caused mostly by strong winds pushing water toward the shore.

**spring tide**

The extra-high (and extra-low) tides that come near new moon and full moon, when the sun and moon pull in line.

**storm surge barrier**

A dam with huge movable gates that stay open in calm weather and close when a storm surge threatens.

**Delta Works**

The great set of dams, sluices and storm surge barriers the Netherlands built after 1953 across the river mouths of the southwest.

**CORE IDEAS**

**The story.** On the night of January 31 to February 1, 1953, a fierce northwesterly gale blew for hours down the length of the North Sea. The sea there grows narrow and shallow toward the south, like a funnel, and the wind piled the water up against the coast of the Netherlands. Worse, it was the time of a **spring tide**, when the sun and moon pull together and the tides run highest. Long before dawn the water stood higher than anyone living had seen. In the province of Zeeland and the islands around it, old dikes were overtopped, softened and then broken in many places. Families woke in the dark to water pouring into their houses and climbed into attics and onto roofs. When the storm passed, 1,836 people had died in the Netherlands, and hundreds more in England and Belgium. The Dutch still call it the *Watersnoodramp*, “the flood disaster.”

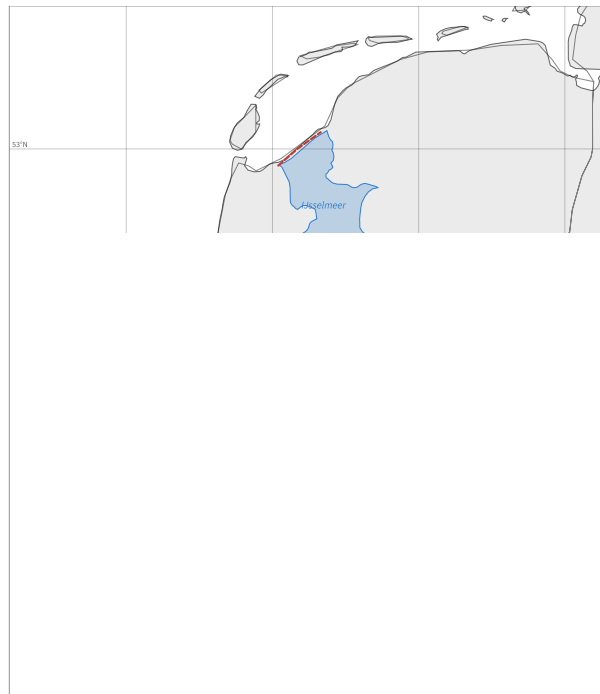
**How they live below the sea.** About a quarter of the Netherlands lies below sea level, and the lowest polder, near Rotterdam, is nearly 7 meters (about 22 feet) below it. The country sits where three rivers, the Rhine, the Meuse and the Scheldt, reach the sea and spread out into a delta of clay, sand and peat. Long ago farmers here lived on mounds of earth. Then they learned to build **dikes**: wide banks of clay with a gentle slope on the sea side, so that waves run up the slope and lose their force instead of smashing against a wall. Land closed in by dikes is a **polder**. But a polder fills like a bathtub, because rain falls on it and water seeps up from below, so the water must be lifted out every day. From the 1400s on, the Dutch used **windmills** for this. Between 1607 and 1612 the engineer Jan Leeghwater used dozens of windmills to pump dry the Beemster, a lake north of Amsterdam, and turn it into farmland. At Kinderdijk, near Rotterdam, nineteen mills built around 1740 still stand in rows, lifting water step by step into higher channels until it can flow out to the river. Later, steam engines (the Cruquius pumping station, 1849), then diesel and electric pumps, took over the work.

**The big idea.** A storm is a natural event. It becomes a disaster when it meets people and places that are not ready for it. Engineers cannot stop a North Sea gale, but they can study how high the water has risen before, build dikes higher and stronger than that, shorten the line of coast they must guard, and warn people in time. In 1953 many of Zeeland’s dikes

were too low, and their steep inner slopes washed away once water began spilling over the top. A dike usually fails from the back side first.

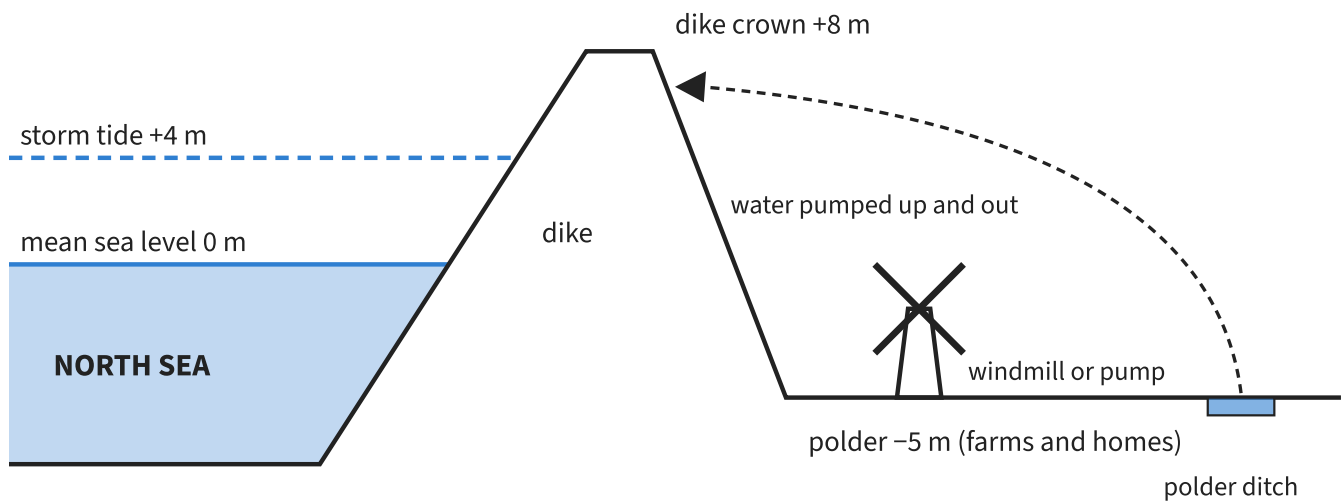
**Technology overcoming geography.** Within weeks of the flood the government formed the Delta Committee, and in 1958 the Delta Act became law. The plan was bold: instead of raising hundreds of kilometers of old dikes along every winding inlet, close off the sea arms themselves with great dams, shortening the coastline that had to be defended. In the Eastern Scheldt, fishermen and oyster and mussel growers asked that the water stay salty and tidal, so the engineers built a **storm surge barrier** instead of a solid dam: about 9 kilometers (5.6 miles) long, with 62 enormous sliding steel gates that stand open in calm weather and close only when a storm surge threatens. It was finished in 1986. The last great work, the Maeslantkering, was finished in 1997 near Hook of Holland. Its two curved arms, each about 210 meters (690 feet) long, float out from the banks and swing shut across the New Waterway, the shipping channel to Rotterdam, one of the largest moving structures ever built. The Dutch now design the dikes that guard their most crowded provinces to withstand a storm expected only once in 10,000 years.

**On the map.** Look at the map of the Netherlands below. Find the North Sea to the west and north, and the river mouths in the southwest where the Delta Works stand. Farther north, the Afsluitdijk, finished in 1932, runs 32 kilometers (20 miles) across the mouth of the old Zuiderzee and turned that salty bay into a freshwater lake, the IJsselmeer. Notice something else: when peat soil is drained, it dries, shrinks and slowly sinks, so many polders lie lower today than when they were first drained. The pumping can never stop. Living in the Netherlands means keeping watch over the water every day, and the Dutch have done it, generation after generation, with clay, wind, steam and steel.



*The Netherlands: the Afsluitdijk (1932), Kinderdijk's windmills and the Delta Works in the southwest.*





*A dike and polder in cross-section. Heights are measured from mean sea level (0 m).*

## PICTURE STUDY



*The Windmill at Wijk bij Duurstede, Jacob van Ruisdael, about 1668-1670 · Oil on canvas · Rijksmuseum, Amsterdam*

Jacob van Ruisdael was born in Haarlem and became perhaps the greatest landscape painter of the Dutch Golden Age. Here he painted a stone tower mill on the bank of the river Lek at Wijk bij Duurstede, a small town southeast of Utrecht. He set our eye very low, almost at the water, so the mill rises like a tower against the sky.

Windmills like this one ground grain, sawed timber and, all over Holland, pumped water out of the polders. To Ruisdael's countrymen a mill beside a river was a picture of their whole life: wind, water and the work of hands, held in balance under a great sky.

**Look closely**

- Find where the land meets the water. How much of the painting is sky, and how much is land and river?
- Follow the four sails of the mill. Are they turning, or still? What does the sky tell you about the wind?
- Find the small figures of people and the sailboat. How do they help you feel how big the mill is?
- Look for where the light falls brightest. Why might the painter have put it there?

### Talk about it

1. Why would a Dutch painter make a windmill the hero of a painting instead of a king or a battle?
2. What would happen to the polders of Holland if the wind stopped blowing for a month and there were no other pumps?
3. How does this calm river scene look different from the night of the 1953 flood?

**Safety first.** Work over a towel or outdoors. Wipe up spilled water at once so no one slips, and ask an adult before using the kitchen pan.

## PROJECT: A MODEL DIKE AND POLDER IN A PAN

You will build a polder that lies lower than the “sea” beside it, protect it with a clay dike, test the dike with waves and a storm surge, and pump out the leaks. You will also test whether a gentle slope or a steep wall holds up better against waves.

### You will need

- A 9 x 13 inch baking pan or a shallow plastic storage box
- About 2 pounds (1 kg) of modeling clay or play dough
- Play sand or garden soil, and a handful of small pebbles
- A turkey baster, large syringe or spoon (your “pump”)
- A pitcher of water with a few drops of blue food coloring
- A ruler, a pencil, masking tape and your map notebook
- Small toy houses, blocks or Lego bricks

### Steps

1. Spread sand across the right two-thirds of the pan about 1 inch (2.5 cm) deep. This is your polder. Set the little houses on it.
2. Stick a strip of masking tape on the left inside wall of the pan and mark it in centimeters from the bottom. This is your sea gauge.
3. Build a clay dike across the pan between the sea (left) and the polder (right). Make it about 2 inches (5 cm) tall, with a long gentle slope facing the sea and a shorter slope facing the polder. Press it firmly against the bottom and the sides of the pan.
4. Pour colored water into the sea side until it stands about 1 inch (2.5 cm) deep, higher than your polder. Watch the polder side for 3 minutes and record any leaks.

5. Make waves by rocking a ruler in the water at the far left end, about one wave a second for one minute. Record what happens to the sea slope of the dike.
6. Make a storm surge: slowly add water until the sea stands 1.5 inches (about 4 cm) deep, and keep making waves. Note the gauge reading when water first spills over or seeps through.
7. Pump the polder dry with your baster, counting the squeezes. Write the number in your notebook.
8. Rebuild one half of the dike with a steep, straight face toward the sea and leave the other half gentle. Repeat the wave test. Which half wears away first?
9. Draw a cross-section of your best dike in your notebook, labeled like the diagram in this lesson, with heights in centimeters.

### Tips

- Seal the clay to the pan bottom by pressing hard with your thumbs; most leaks start along the bottom, just as seepage does under real dikes.
- Pebbles pressed into the sea slope act like the stone armor on real Dutch dikes. Try it and compare.
- Keep the polder sand a little damp so it does not float away when the first leak comes.

### Check your work

- My polder lies lower than my sea, and my dike kept it dry in calm water.
- I recorded the gauge reading where my dike began to fail.
- I can explain from my test why Dutch dikes have gentle slopes toward the sea.
- I pumped out my polder and counted the work it took.

### MAP NOTEBOOK

1. Trace or draw the outline of the Netherlands. Mark the North Sea, the Rhine, Meuse and Scheldt, Amsterdam, Rotterdam, the Afsluitdijk and the Eastern Scheldt barrier.
2. Draw a cross-section of a dike and polder. Label mean sea level, the storm tide, the dike crown and the polder, each with its height in meters.
3. Sketch a Kinderdijk windmill and add arrows showing how water moves from the polder ditch, up through the mill, and out toward the river.

**From history.** Many Americans know the tale of a little Dutch boy who saved Haarlem by holding his finger in a leaking dike all night. That story was never Dutch history. It appears as a story read in a classroom in *Hans Brinker, or the Silver Skates* (1865), a novel by the American writer Mary Mapes Dodge, who had never visited Holland when she wrote it. The tale became so famous that Dutch towns later put up statues of the boy for visitors, including one at Spaarndam in 1950. The real heroes of Dutch water history are less famous: dike workers, millers, pump keepers and engineers.

## WORKED EXAMPLES

**Example 1.** Use the dike-and-polder diagram. If the dike failed during the storm tide shown, and the sea flowed in until the polder water stood level with the storm tide, how deep would the water be over the polder? Give meters and feet.

*(Use the map or drawing “Measure from the polder up to the storm tide line.” shown earlier in this lesson.)*

1. Read the storm tide: +4 m (4 meters above mean sea level).
2. Read the polder: −5 m (5 meters below mean sea level).
3. The depth is the distance between them:  $4\text{ m} + 5\text{ m} = 9\text{ m}$ . (From −5 up to 0 is 5 m, and from 0 up to +4 is 4 m more.)
4. Convert to feet:  $9\text{ m} \times 3.28\text{ ft per meter} \approx 29.5\text{ ft}$ .

**Answer:** About 9 m, or about 29.5 feet (30 ft) of water, deep enough to cover a two-story house.

**Example 2.** The Afsluitdijk is 32 km long. How long is it in miles? A cyclist crosses it on the bike path at 16 km per hour. How long does the ride take?

1.  $1\text{ km} \approx 0.621\text{ miles}$ , so  $32\text{ km} \times 0.621 \approx 19.9\text{ miles}$ , about 20 miles.
2. Time = distance ÷ speed =  $32\text{ km} \div 16\text{ km per hour} = 2\text{ hours}$ .

**Answer:** About 20 miles; the ride takes about 2 hours.

**Example 3.** A polder covers 10 square kilometers. A rainy night drops 20 millimeters of rain on it. How many cubic meters of water must be pumped out? If the pumping station lifts 100 cubic meters a minute, how long will it take?

1. Change the area to square meters:  $1\text{ km}^2 = 1,000\text{ m} \times 1,000\text{ m} = 1,000,000\text{ m}^2$ , so  $10\text{ km}^2 = 10,000,000\text{ m}^2$ .
2. Change the rain to meters:  $20\text{ mm} = 0.02\text{ m}$ .
3. Volume = area  $\times$  depth =  $10,000,000\text{ m}^2 \times 0.02\text{ m} = 200,000\text{ m}^3$ .
4. Time =  $200,000\text{ m}^3 \div 100\text{ m}^3\text{ per minute} = 2,000\text{ minutes}$ .
5.  $2,000\text{ minutes} \div 60 \approx 33.3\text{ hours}$ , about 33 hours 20 minutes.

**Answer:** 200,000 cubic meters of water, taking about 33 hours to pump. One rainy night means more than a day of pumping.

## PRACTICE

1. **EASY** What is a polder, and why must it be pumped even when there is no storm?

2. **EASY** Name the two things that came together on the night of January 31 to February 1, 1953, to raise the North Sea so high.
3. **EASY** About what fraction of the Netherlands lies below sea level? Which three rivers built the delta the country stands on?
4. **MEDIUM** The Eastern Scheldt storm surge barrier is about 9 km long. How many miles is that?
5. **MEDIUM** The lowest point in the Netherlands is about 6.7 m below sea level. How many feet is that?
6. **MEDIUM** Why do Dutch dikes have a long, gentle slope on the side facing the sea instead of a straight wall?
7. **MEDIUM** Use the map of the Netherlands. Which large port city stands closest to the Maeslantkering? Which body of water did the Afsluitdijk turn into a freshwater lake? *(Use the map or drawing "Find Hook of Holland, Rotterdam and the Afsluitdijk." shown earlier in this lesson.)*
8. **HARD** Why did the engineers build a barrier with gates across the Eastern Scheldt instead of a solid dam?
9. **HARD** A polder lies at  $-5$  m. A farmhouse on it is 3 m tall. A dike breaks, and the water inside the polder rises to  $+1$  m. How deep is the water over the polder, and how far is the water surface above the roof? Give the last answer in feet too.
10. **CHALLENGE** Write three or four sentences: Why do many Dutch polders lie lower today than when they were first drained, and what does that mean for the people who live there?

## COMMON MISTAKES

- Thinking the sea is the only danger. Rain and seepage fill a polder every day, and the great rivers can flood the land from behind too.
- Adding heights below sea level wrongly. From  $-5$  m up to  $+4$  m is 9 m, not 1 m: count down to zero and up again.
- Thinking the Delta Works are one dam. They are a whole system of dams, sluices and storm surge barriers built over about forty years.

**Make it a game · Dike Watch.** One player is the North Sea and rolls a die each turn: 1–2 calm, 3–4 high tide, 5 storm, 6 storm plus spring tide. The other players are dike keepers who start with 10 sandbag tokens (beans or coins) and a dike strength of 3. A calm turn lets keepers add 1 to dike strength by spending 1 token. High tide needs strength 2, a storm needs 4, and a storm with spring tide needs 6. If the dike is too weak, keepers must spend tokens equal to the difference or the polder floods. Play ten turns. Talk about it afterward: was it wiser to build in calm weather or to rush in the storm?

**Scripture.** “And said, Hitherto shalt thou come, but no further: and here shall thy proud waves be stayed?” (Job 38:11, KJV)

In Job 38 God speaks of setting bars and doors for the sea. The Dutch built their dikes in the same spirit: the sea has its place, and with skill and steady work people may keep it there.

The Creator alone commands the sea; we are given wisdom to build wisely beside it.

#### Practice answers

1. A polder is low land surrounded by dikes and kept dry by pumping. Rain falls on it and groundwater seeps into it every day, and since it lies below the water around it, the water cannot drain away by itself.
2. A strong northwesterly storm (gale) that piled water against the coast, and a spring tide, when the tides were already at their highest.
3. About a quarter. The Rhine, the Meuse (Maas) and the Scheldt.
4.  $9 \times 0.621 \approx 5.6$  miles.
5.  $6.7 \times 3.28 \approx 22$  feet below sea level.
6. Waves run up a gentle slope and spend their energy, so they do less damage. A steep wall takes the full blow of each wave and is more easily undercut or broken.
7. Rotterdam. The old Zuiderzee, now the IJsselmeer.
8. Fishermen and shellfish growers, and people who valued the estuary's life, wanted the water to stay salty and tidal. A barrier with gates lets the tide flow in and out in normal weather and still closes to stop a storm surge.
9. Depth: from  $-5$  m to  $+1$  m is 6 m. The roof top is at  $-5 + 3 = -2$  m, so the water stands 3 m above the roof, about  $3 \times 3.28 \approx 10$  feet.
10. Much polder land is peat. When it is drained, the peat dries out, shrinks and slowly sinks, so the land drops lower over the years. That makes the gap between the land and the sea or rivers larger, so the dikes must be kept strong and the pumping can never stop. Each generation has to keep up the work of watching the water.

## 8.2 LEVEES ON THE MISSISSIPPI

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### OBJECTIVES

- Explain how a river builds natural levees and why people raised artificial levees on top of them.
- Tell the story of the Great Mississippi Flood of 1927 and explain how the Flood Control Act of 1928 changed the plan from levees alone to levees plus spillways and floodways.
- Use river miles, gauge heights and area conversions to reason about a flood in miles and kilometers.

**Warm-up.** Over a sink, fill a balloon partly with water and tie it. Gently squeeze the middle with your hand. Where does the water go? Now imagine a river in flood squeezed between two tall walls of earth. If it cannot spread out sideways, which way must it go? Write your guess in one sentence and keep it until the end of the lesson.

**Watch.** *How Do Flood Control Structures Work?* (Practical Engineering, 11:18).

<https://www.youtube.com/watch?v=5mCJh5SJEis>

As review: watch how levees, floodwalls, spillways and reservoirs each hold back or send away floodwater, and connect them to the levees and the Bonnet Carré Spillway in the lesson.

**Note:** Captions were not available to check; preview it first. The description says the video is sponsored by Nebula, so skip that message. It covers flood control in general, not the Mississippi in particular.

### KEY TERMS

#### levee

A raised bank along a river that keeps floodwater in the channel. Rivers build low natural levees; people build taller artificial ones.

#### floodplain

The flat land beside a river that the river covers when it floods, built of the mud and sand the river leaves behind.

#### crevasse

On the Mississippi, a break in a levee through which the river pours out onto the land.

#### spillway

A gated channel or structure that lets engineers send part of a flood out of the river on purpose, to lower the water downstream.

#### river stage

The height of the water surface read on a river gauge. The highest stage of a flood is its crest.

#### U.S. Army Corps of Engineers



The army's engineering branch, which builds and keeps the nation's large flood-control works, locks and navigation channels.

## CORE IDEAS

**The story.** Heavy rains fell across the middle of the United States in the late summer and fall of 1926 and kept falling into the spring of 1927. The Mississippi drains about 40 percent of the lower 48 states, and that spring the Missouri, the Ohio, the Arkansas and their many branches rose at the same time and poured into it together. On April 21, 1927, at Mounds Landing, a little north of Greenville, Mississippi, the levee gave way. The crevasse grew to well over half a mile (about 1 km) wide, and a wall of brown water spread across the flat cotton country of the Mississippi Delta. Greenville stood under water for weeks, and thousands of people camped on top of the levee itself, the only dry ground for miles. Up and down the valley, levees failed in about 145 places. Roughly 27,000 square miles (70,000 km<sup>2</sup>) went under water, about 700,000 people were driven from their homes, and hundreds died.

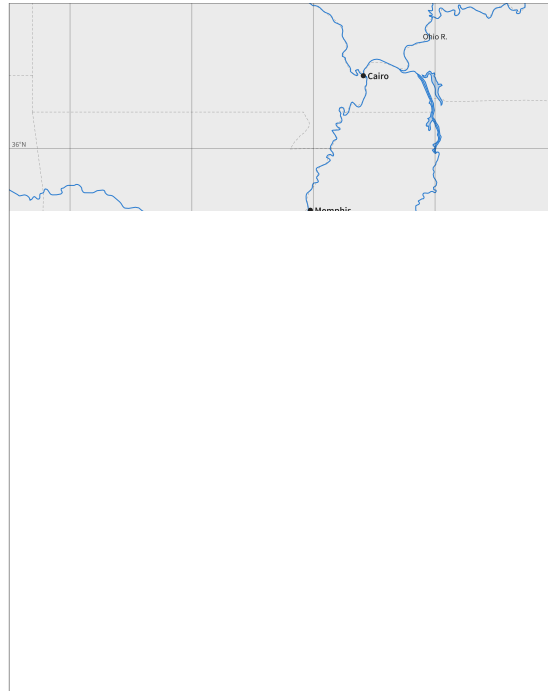
**What people did.** Herbert Hoover, the Secretary of Commerce, took charge of rescue and relief with the Red Cross. Boats, trains and tent camps carried and sheltered the homeless. There were real wrongs too. At Greenville many Black farm workers were kept in the levee camp under guard and made to unload relief supplies, while most white women and children were sent away by boat, an injustice the people there long remembered. Downstream, to make sure New Orleans would not flood, officials blasted open the levee at Caernarvon below the city on April 29, sending the river over the homes and trap lines of St. Bernard and Plaquemines Parishes. Those families were promised payment for their losses, and many felt they never received what they were owed.

**The big idea.** A river in flood spills over its banks, slows down and drops its heaviest sand right at the edge of the channel. Flood after flood, this builds a low ridge along each bank, a **natural levee**. Behind it the floodplain slopes down to low, swampy ground. People settled on the natural levees because they were the highest and driest land, and then built **artificial levees** on top of them. For decades the official plan was "levees only": wall the river in, and its faster current would scour a deeper bed. But a river that cannot spread out must rise. The taller the levees, the higher the floodwater stood between them, and when a levee did break, the water fell on the land behind it with terrible force. 1927 proved that levees alone could not hold the greatest floods.

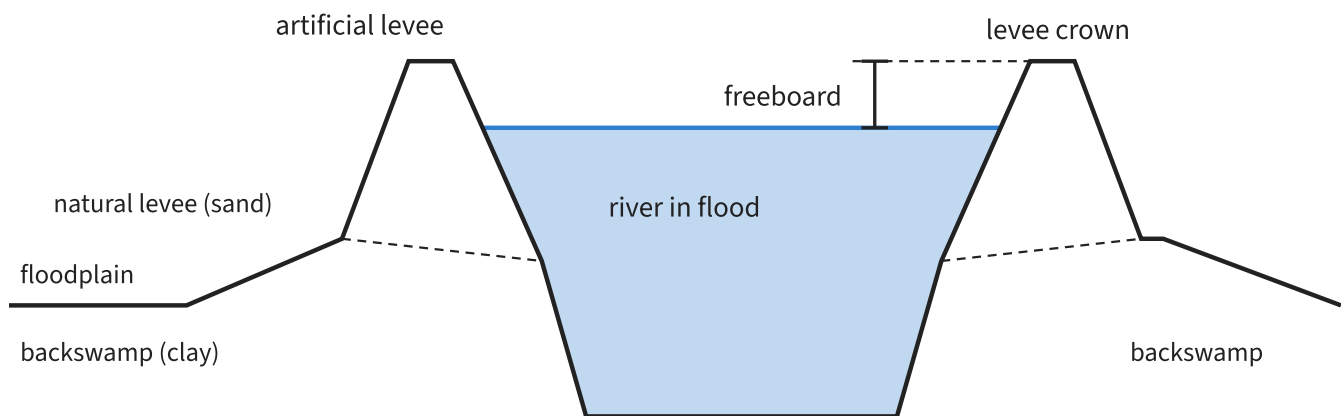
**Technology overcoming geography.** The Flood Control Act of 1928 made flood control on the lower Mississippi a national task and gave the job to the U.S. Army Corps of Engineers. Their new plan kept the levees, made them higher and stronger, and added safety valves: places where part of a great flood can be let out of the river on purpose. The Bonnet Carré Spillway above New Orleans, finished in 1931, is a concrete structure about 7,000 feet (2.1 km) long with 350 bays closed by heavy timbers. In a big flood, cranes lift out the timbers and part of the river flows into Lake Pontchartrain instead of past the city. It was first opened in 1937. Floodways such as Birds Point-New Madrid in Missouri, the Morganza structure (1954) and the Old River Control Structure (1963), which keeps the Mississippi from

changing its course into the shorter, steeper Atchafalaya River, complete the system. Concrete mats now armor the banks so the river cannot easily cut new paths.

**On the map.** Distances on the lower Mississippi are measured in **river miles**, counted upstream from the Head of Passes near the river's mouth. Cairo, Illinois, where the Ohio joins the Mississippi, is at about mile 954; Memphis about 735; Vicksburg about 437; Baton Rouge about 230; and New Orleans about 95. Forecasters read the river stage at gauges in these towns and track the crest as it moves downstream, giving people days of warning that a high river is coming. Find these places on the map, and notice how the river winds: the river distance is much longer than a straight line between the towns.



*The lower Mississippi, scene of the 1927 flood.*



*A river in flood between levees. Freeboard is the safety margin between the water and the top of the levee.*

## PICTURE STUDY



*"High Water" in the Mississippi*, Frances F. (Fanny) Palmer, published by Currier & Ives, 1868 · Lithograph, colored by hand · Missouri Historical Society, St. Louis (this copy); other copies at the Metropolitan Museum of Art and Harvard Art Museums

Currier & Ives of New York sold inexpensive colored prints that hung in thousands of American homes. Fanny Palmer, an English-born artist, drew many of their best river and country scenes. This print shows the Mississippi after it has broken out of its banks. The water has spread over a plantation, rising nearly to the second floor of the big house. The owners have climbed onto their roof, and in front of them families who worked on the plantation huddle on the roof of a smaller building, waiting for the water to go down.

Behind them a steamboat named the *Stonewall Jackson* keeps steaming along the river as if nothing were wrong. In 1868 the levees along the river were mostly built by planters and local districts, each guarding its own stretch, and when one gave way the land behind it flooded. The big national flood-control system you read about in this lesson was still sixty years in the future. Currier & Ives sold this print as a pair with another called *Low Water in the Mississippi*.

### Look closely

- Find the big house. How high has the water risen on its walls?
- Find all the people waiting on rooftops. What do you think they are watching and hoping for?
- Find the uprooted trees in the water. What does that tell you about how strong the flood is?
- Find the steamboat. Why can a boat travel easily when the people on land are in danger?

### **Talk about it**

1. Why did people live and farm right beside the river, even though it could flood?
2. If a levee had held at this place, where would the high water have gone instead?
3. Why would one landowner's levee not be enough to protect a whole river valley?

### **PROJECT: LEVEES IN A TRAY**

You will build a river in sand and test three plans: no levees, tall levees, and levees with a spillway. You will measure how high the water rises in each case and where it breaks out.

#### **You will need**

- A long plastic storage bin, a boot tray or a paint-roller tray
- Play sand, slightly damp, enough to fill the tray 2 inches (5 cm) deep
- A pitcher of water with blue food coloring, and a paper cup with a small hole punched in the bottom
- Modeling clay, a ruler, toothpicks and small paper flags
- A book or block to tilt one end of the tray

#### **Steps**

1. Fill the tray with damp sand and tilt it about 1 inch (2.5 cm) at one end. Scoop a winding river channel about 1 inch (2.5 cm) wide and deep from the high end to the low end.
2. Stand toothpick "towns" with paper flags on the flat land beside the river near the middle.
3. Test 1, no levees: hold the leaking cup at the top and pour water into it steadily. Watch where the water spreads. Measure how far from the channel it reaches.
4. Smooth the sand and rebuild the channel. Test 2, tall levees: build sand ridges about 1 inch (2.5 cm) high along both banks. This time pour straight from the pitcher in a slow, steady stream, the same amount you will use in Test 3. Mark the highest water level on a toothpick stuck in the channel, and note where the levee breaks first.
5. Rebuild. Test 3, levees with a spillway: cut a low notch in one levee upstream of your towns and line it with a little clay so it does not wash out. Pour the same amount as in Test 2. Mark the high water at the towns again.
6. Record all three tests in a table: highest water level, where the water escaped, and whether the towns stayed dry.
7. Look at the sand left behind in Test 1. Can you find a low ridge of sand along the banks? That is a natural levee.

#### **Tips**

- Pour the same amount of water in each test so your comparison is fair. Count cups.
- Levee breaks often start at the outside of a bend, where the current pushes hardest. Watch for it.

### Check your work

- I can show where my river built a natural levee.
- I measured that the water stood higher between tall levees than with no levees.
- I can explain how my spillway kept the towns downstream drier.

### MAP NOTEBOOK

1. Draw a map of the Mississippi from Cairo to the Gulf. Mark Cairo, Memphis, Greenville, Vicksburg, Baton Rouge and New Orleans with their river miles, and draw a star at Mounds Landing.
2. Draw a cross-section of a river between levees. Label the natural levee, the artificial levee, the backswamp, the flood water and the freeboard.
3. Draw the Bonnet Carré Spillway as a long row of bays, with arrows showing water going from the river to Lake Pontchartrain.

**From history.** Mark Twain, who had been a Mississippi steamboat pilot before the Civil War, wrote in *Life on the Mississippi* (1883) that no number of river commissions, however rich, could ever tame that lawless stream or make it go where they told it. The Mississippi River Commission had been formed in 1879, and Twain doubted that engineers could command such a river. The 1927 flood seemed to prove him partly right; the Corps of Engineers' answer after 1928 was not to command the river but to give it safe places to go.

### WORKED EXAMPLES

**Example 1.** A flood crest passes Vicksburg (river mile 437). Suppose it travels downstream at about 40 river miles a day. About how long until it reaches Baton Rouge (river mile 230)? How far is that in kilometers?

*(Use the map or drawing "Find Vicksburg and Baton Rouge on the river." shown earlier in this lesson.)*

1. River distance =  $437 - 230 = 207$  river miles.
2. Time =  $207 \div 40 \approx 5.2$  days.
3. In kilometers:  $207 \times 1.609 \approx 333$  km.

**Answer:** About 5 days for 207 river miles (about 333 km). Those days give towns downstream time to strengthen levees and move people out.

**Example 2.** In 1927 about 27,000 square miles were flooded. How many square kilometers is that? West Virginia covers about 24,000 square miles. Was the flooded area larger or smaller than West Virginia?

- 1 square mile  $\approx$  2.59 square kilometers.
- $27,000 \times 2.59 = 69,930 \text{ km}^2$ , about 70,000  $\text{km}^2$ .
- 27,000 square miles is more than 24,000 square miles.

**Answer:** About 70,000  $\text{km}^2$ , an area larger than the whole state of West Virginia.

**Example 3.** At a river town the top (crown) of the levee stands at 58 feet on the river gauge. The river is at 54 feet and rising 0.5 foot a day. What is the freeboard in feet and meters? If the river kept rising at that rate, how many days until it reached the crown?

*(Use the map or drawing “Freeboard is the gap between the water and the levee crown.” shown earlier in this lesson.)*

- Freeboard = crown – river stage =  $58 - 54 = 4$  feet.
- In meters:  $4 \times 0.305 \approx 1.2$  m.
- Days to the crown =  $4 \text{ feet} \div 0.5 \text{ foot per day} = 8$  days.

**Answer:** 4 feet (about 1.2 m) of freeboard; about 8 days. Engineers would watch this levee closely and might open a spillway upstream to stop the rise.

## PRACTICE

- EASY** What is a crevasse on the Mississippi? Where did the largest crevasse of 1927 open?
- EASY** How does a river build a natural levee?
- EASY** What did the Flood Control Act of 1928 do, and which agency was put in charge?
- MEDIUM** How many river miles is it from Cairo (mile 954) to New Orleans (mile 95)? Give the answer in kilometers too.
- MEDIUM** The Bonnet Carré Spillway is about 7,000 feet long. How long is that in miles and in kilometers? ( $5,280 \text{ ft} = 1 \text{ mile}$ ;  $1 \text{ ft} = 0.305 \text{ m}$ )
- MEDIUM** Suppose flood stage at a river gauge is 43 feet and the river crests at 50.5 feet. How far above flood stage is the crest, in feet and meters?
- MEDIUM** Use the map of the lower Mississippi. Which great river joins the Mississippi at Cairo? Which city lies farthest downstream on the map?  
*(Use the map or drawing “Follow the river from Cairo to the Gulf.” shown earlier in this lesson.)*
- HARD** Explain why the “levees only” plan made great floods more dangerous rather than less.
- HARD** The Bonnet Carré Spillway has 350 bays. If crane crews can open 20 bays an hour, how long does it take to open them all?

10. **CHALLENGE** Write three or four sentences: What is the Old River Control Structure for, and what might happen to Baton Rouge and New Orleans without it?

## COMMON MISTAKES

- Thinking levees make floods smaller. Levees keep water off the land behind them, but they make the water rise higher in the channel.
- Measuring river distance with a straight ruler. The Mississippi winds, so river miles are much longer than straight-line miles between towns.
- Thinking a spillway is a failure of the plan. A spillway is part of the plan: it lets the river out safely in a chosen place instead of breaking out wherever it likes.

**Make it a game · Crest Coming Down.** Write the river towns and their river miles on cards: Cairo 954, Memphis 735, Greenville 537, Vicksburg 437, Baton Rouge 230, New Orleans 95. Shuffle and lay them out. Racing a timer, put them in order from upstream to downstream. Then a caller says “The crest is at Memphis and moves 50 miles a day. Which town is next, and in how many days?” The first player with the right town and the right answer (rounded to the nearest day) wins the card. Most cards wins.

**Scripture.** “When thou passest through the waters, I will be with thee; and through the rivers, they shall not overflow thee: when thou walkest through the fire, thou shalt not be burned; neither shall the flame kindle upon thee.” (Isaiah 43:2, KJV)

God does not promise that floods will never come, but He promises His presence in them. Engineers, relief workers and neighbors who carry people to safety in a flood are doing the work of love that the Lord asks of His people.

### Practice answers

1. A break in a levee through which the river pours onto the land. The largest opened at Mounds Landing, a little north of Greenville, Mississippi, on April 21, 1927.
2. When the river overflows, the water slows as it leaves the channel and drops its heaviest sand right beside the bank. Flood after flood, this builds a low ridge along the bank.
3. It made flood control on the lower Mississippi a national responsibility and gave the job to the U.S. Army Corps of Engineers, who added spillways and floodways to the levees.
4.  $954 - 95 = 859$  river miles;  $859 \times 1.609 \approx 1,382$  km.
5.  $7,000 \div 5,280 \approx 1.3$  miles;  $7,000 \times 0.305 = 2,135$  m  $\approx 2.1$  km.
6.  $50.5 - 43 = 7.5$  feet;  $7.5 \times 0.305 \approx 2.3$  m.
7. The Ohio River. New Orleans.
8. Walled in by levees, the floodwater could not spread across the floodplain, so it rose higher between the levees. Higher water pressed harder on the levees, and when one broke, the water poured onto the land behind with great force and depth. There was no safe place to let the extra water go.
9.  $350 \div 20 = 17.5$  hours, about 17 hours 30 minutes. (In practice engineers open only as many bays as they need.)



10. The Atchafalaya River offers the Mississippi a shorter, steeper path to the Gulf, and a river tends to switch to the steeper route. The Old River Control Structure (1963) keeps most of the flow in the Mississippi and lets only a set share, about 30 percent, go down the Atchafalaya. Without it, the main river could shift its course, leaving the ports and water supplies of Baton Rouge and New Orleans on a weak, salty channel and flooding the Atchafalaya basin.

## 8.3 HURRICANES

### OBJECTIVES

- Explain how a hurricane forms over warm tropical water and name its parts: the eye, the eyewall, the rain bands and the storm surge.
- Tell how the 1900 hurricane struck Galveston, Texas, and how the city answered with a seawall and by raising the ground of the whole city.
- Use the Saffir-Simpson scale and compare storm surge heights with ground elevations in feet and meters.

**Warm-up.** Pour water about half an inch (1 cm) deep into a baking pan. Lay a drinking straw almost flat near one end and blow steadily across the water toward the far end for 20 seconds. Watch the far end closely, and lay a ruler against the side if you can. What happens to the water there? You have just made a tiny storm surge with nothing but wind.

**Watch.** *The 1900 "Great Storm" and Raising Galveston* (The History Guy: History Deserves to Be Remembered, 13:22). [https://www.youtube.com/watch?v=BEIQES\\_Dh0Q](https://www.youtube.com/watch?v=BEIQES_Dh0Q). After the story: watch how Galveston rebuilt after the 1900 storm, and look for the seawall and the way the whole city was raised.

**Note:** Captions were not available to check; preview it first. The video tells of the storm's many deaths, the deadliest natural disaster in U.S. history, and may show historical photos of the destruction.

**Backup video.** *How Do Hurricanes Form?* (NOAA SciJinks, 2:23).

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

With the big idea: watch how warm ocean water feeds a hurricane and why its winds spin. Note: Captions were not available to check; preview it first.

### KEY TERMS

#### hurricane

A great spinning storm that forms over warm tropical ocean water, with sustained winds of at least 74 miles per hour (119 km/h).

#### eye and eyewall

The eye is the calm, often clear center of a hurricane. The eyewall is the ring of towering clouds around it, where the winds are strongest.

#### storm surge

The rise of the sea pushed ashore by a hurricane's winds, far above the normal tide. Historically it has been the deadliest part of a hurricane.

#### Saffir-Simpson scale

A scale that ranks hurricanes from Category 1 to Category 5 by their sustained wind speed.

**barrier island**

A long, narrow, low island of sand lying parallel to a coast, with open sea on one side and a bay on the other.

**seawall**

A strong wall built along the shore to stop waves and storm surge from washing over the land behind it.

**CORE IDEAS**

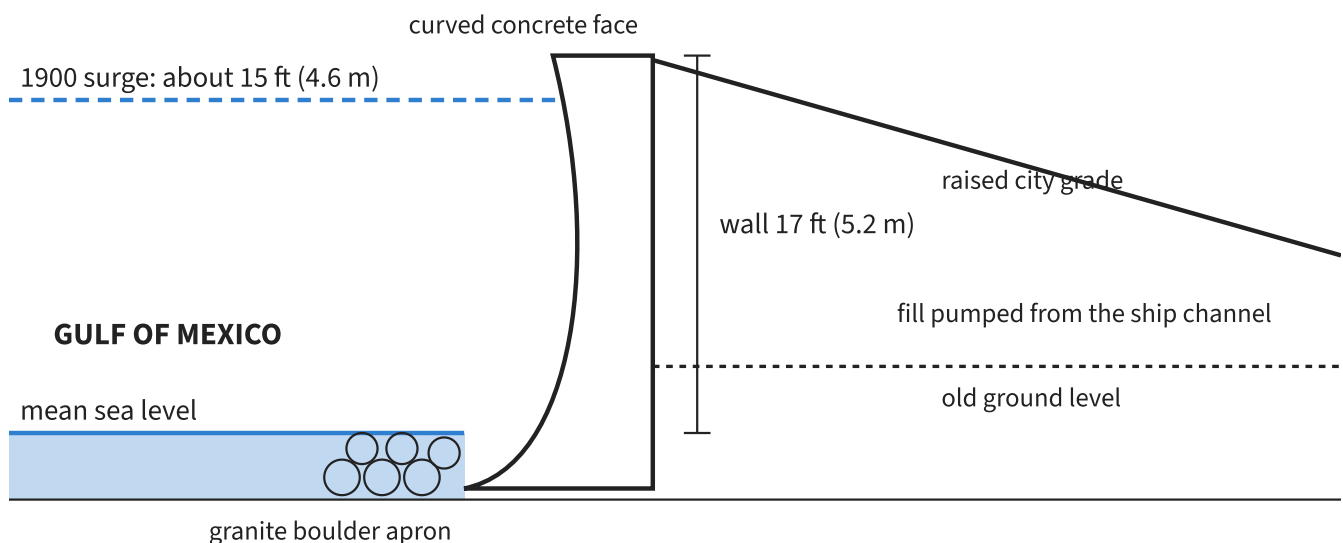
**The story.** In 1900 Galveston, Texas, was a proud, busy port of about 37,000 people, with cotton ships at its wharves and fine houses along its streets. It stood on a **barrier island**, a long ribbon of sand between the Gulf of Mexico and Galveston Bay, and its highest ground was less than 9 feet (under 3 m) above sea level. In the first days of September a hurricane crossed Cuba and moved out over the warm Gulf. Forecasters of the Weather Bureau had no satellites and no radar, only reports sent by telegraph from places the storm had already passed, and no one could see its strength or its path out at sea. On Saturday, September 8, the water began creeping into the streets. By evening the wind was screaming and a storm surge of more than 15 feet (4.6 m) rolled across the entire island. Houses broke apart, and their wreckage formed a moving wall that smashed the houses behind them. Isaac Cline, the local Weather Bureau chief, survived with his daughters, but his wife was lost. At least 6,000 people died in the city, perhaps 8,000. It is still the deadliest natural disaster in the history of the United States.

**How a hurricane works.** Hurricanes are born over tropical oceans where the surface water is warmer than about 80°F (27°C). Warm water evaporates into the air; the moist air rises, cools and forms towering clouds, and as the water vapor condenses into rain, it releases heat that makes the air rise even faster. Air rushes in along the sea surface to take its place, and because the earth is turning, that inflowing air is bent into a great spiral, counterclockwise in the Northern Hemisphere. At the center is the calm **eye**, ringed by the violent **eyewall**, with spiral **rain bands** reaching out hundreds of miles. When a hurricane moves over land or cold water, it loses its supply of warm moisture and weakens. Forecasters rank hurricanes on the **Saffir-Simpson scale**: Category 1, 74–95 mph (119–153 km/h); Category 2, 96–110 mph (154–177 km/h); Category 3, 111–129 mph (178–208 km/h); Category 4, 130–156 mph (209–251 km/h); Category 5, 157 mph (252 km/h) or more. The Galveston storm is thought to have been a Category 4.

**The big idea.** The wind is frightening, but the water is the greater killer. A hurricane's winds drive the sea toward the shore, and where the sea floor is shallow and slopes gently for many miles, as it does along the Texas coast, the water has nowhere to go but up. Add the waves riding on top of the surge, and a low island like Galveston in 1900 can be swept from end to end. The danger depends on geography: how low the land lies, how shallow the water offshore is, and which side of the storm a town is on. The front right side of a hurricane, where its own spin adds to its forward motion, usually brings the strongest winds and the highest surge.

**Technology overcoming geography.** Galveston chose to rebuild, and to rebuild wisely. A board of three engineers, Henry M. Robert (a retired Army general, best known for *Robert's Rules of Order*), Alfred Noble and H. C. Ripley, designed a concrete **seawall** 17 feet (5.2 m) high, with a curved face to turn the waves back on themselves and a broad apron of granite boulders at its foot to stop the waves from digging under it. The first section, about 3 miles (5 km) long, was built from 1902 to 1904; later extensions brought it to about 10 miles (16 km). Then the people did something astonishing: they raised their city. Dredges pumped sand and water from the ship channel into the city behind the seawall, building up the ground as much as 17 feet at the wall and sloping down toward the bay. More than 2,000 buildings, including churches, were jacked up so fill could be pumped beneath them, while people walked to work on wooden catwalks above the muddy fill. In 1915 another powerful hurricane struck. The seawall held, and far fewer people died in the city than in 1900.

**On the map and today.** Atlantic hurricane season runs from June 1 to November 30, and storms threaten the whole Gulf and Atlantic coast from Texas to New England. Today the National Hurricane Center in Miami watches every storm with satellites, radar and “hurricane hunter” aircraft that fly right into the eye, and it issues watches and warnings days ahead so people can board up and leave on marked evacuation routes. Engineering still has limits. In 2008 Hurricane Ike pushed its surge into Galveston Bay and flooded much of the city from the bay side, behind the seawall. Living on a coast means knowing your elevation, knowing your route out, and heeding the warning when it comes.



*The Galveston seawall and the raised city grade. Heights are above mean sea level.*

## PICTURE STUDY



*After the Hurricane, Bahamas*, Winslow Homer, 1899 · Watercolor over graphite on paper · Art Institute of Chicago

Winslow Homer, the great American painter of the sea, spent two winters in the Bahamas and painted the islanders who lived by fishing and sponging in small boats. In this watercolor a storm has passed. A sailor lies on the beach beside the wreck of his boat, while the sea still heaves and the sky begins to clear.

Homer does not tell us whether the man is alive. He leaves us to stand on the beach and wonder, and to feel how small a person and his boat are beside a hurricane sea.

### Look closely

- Find the broken boat. What parts of it can you recognize?
- Look at the sky. Which part is still stormy, and where is it clearing?
- Find the waves. How has Homer used white paper and quick brushstrokes to show foam?
- Look at the man's position on the sand. What does it suggest happened to him?

### Talk about it

1. Why do you think Homer chose to paint the moment after the storm instead of the storm itself?
2. What would this fisherman have needed to know, before he set out, to stay safe? How do people get that warning today?

## **PROJECT: SEAWALL WAVE TANK**

You will build a beach and a “town” in a pan, then test three kinds of seawall against waves and a storm surge: no wall, a straight wall and a curved wall with stones at its foot. You will see why Galveston’s engineers chose a curved face and a boulder apron.

### **You will need**

- A long baking pan or clear plastic storage box
- Play sand and a handful of pebbles
- Modeling clay or a strip of stiff cardboard covered with plastic tape
- A plastic lid or ruler to make waves
- Water, a measuring cup, a ruler and masking tape
- Small blocks or Lego bricks for houses

### **Steps**

1. Build a sand island across the pan, a little past the middle, with a beach sloping gently up from the open “Gulf” end to a flat top about 1 inch (2.5 cm) above the water you will add. Leave a narrow strip of empty pan behind it for the “bay.” Put three or four block houses on the island.
2. Mark a sea gauge in centimeters on masking tape on the far wall of the pan.
3. Add water at the open end until it stands about 1.5 cm below the island top.
4. Test 1, no wall: make 30 steady waves with the lid. Then add water to raise the sea 1 cm (your storm surge) and make 30 more. Record what happens to the beach and the houses.
5. Rebuild. Test 2, straight wall: press a straight clay wall about 1 inch (2.5 cm) tall along the edge of the island. Repeat the waves and surge. Watch the foot of the wall closely.
6. Rebuild. Test 3, curved wall with an apron: shape the sea face of the clay wall so it curves outward at the top, and press a row of pebbles into the sand in front of it. Repeat the test.
7. Make a table for the three tests: Did water reach the houses? Was sand dug out at the foot of the wall? Did the waves splash over?
8. Finally, add water behind the island (on the “bay” side) and raise it. What does this show about Hurricane Ike in 2008?

### **Tips**

- Make every wave the same size by moving the lid the same distance each time.
- Watch for scour, the digging away of sand at the foot of a wall. It is how many real seawalls fail.

### **Check your work**

- I tested three designs fairly with the same waves and surge.
- I can explain why a curved face and a stone apron protect a seawall.



- I can show why a seawall on the Gulf side cannot stop water rising from the bay side.

## MAP NOTEBOOK

1. Draw a map of Galveston Island between the Gulf of Mexico and Galveston Bay. Mark the seawall along the Gulf side and the city behind it.
2. Draw a hurricane from above, with the eye, eyewall and rain bands labeled, and arrows showing its counterclockwise spin.
3. Draw the seawall cross-section from this lesson with the 1900 surge line, the wall height, the raised grade and the old ground level.

**From history.** Isaac Cline, the Weather Bureau official at Galveston, lived through the storm and served for many more years as a forecaster, later in New Orleans. In 1891 he had written in a Galveston newspaper that fears of a hurricane seriously harming the city were unfounded, an opinion he had to unlearn in the cruelest way. The storm taught the whole country to take hurricanes on the Gulf seriously, and over the following decades the Weather Bureau built a much better network for tracking storms at sea.

## WORKED EXAMPLES

**Example 1.** The highest ground in Galveston in 1900 was about 8.7 feet above sea level. The storm surge rose to about 15 feet. How deep was the water over the very highest ground? Give feet and meters.

1. Depth = surge height – ground height =  $15 - 8.7 = 6.3$  feet.
2. In meters:  $6.3 \times 0.305 \approx 1.9$  m.
3. Remember that most of the city was lower than its highest point, so the water was deeper almost everywhere, and waves rode on top of it.

**Answer:** About 6.3 feet (1.9 m) of water even over the highest ground. No part of the island stayed dry.

**Example 2.** The 1900 storm's winds are estimated at about 140 miles per hour. What Saffir-Simpson category is that? What is 140 mph in kilometers per hour?

1. Category 4 covers 130–156 mph. 140 falls in that range.
2. 1 mile  $\approx 1.609$  km, so  $140 \times 1.609 \approx 225$  km/h.

**Answer:** Category 4; about 225 km/h.



**Example 3.** A hurricane is 360 miles southeast of Galveston and moving northwest toward it at 12 miles per hour. About how many hours until it arrives? How far away is it in kilometers?

1. Time = distance  $\div$  speed =  $360 \div 12 = 30$  hours.
2. Distance in km:  $360 \times 1.609 \approx 579$  km.

**Answer:** About 30 hours (a day and a quarter), from about 580 km away. Today forecasters would have watched this storm for days, giving families time to leave; in 1900 no one knew it was coming so directly.

## PRACTICE

1. **EASY** Name the calm center of a hurricane and the ring of clouds around it. Where are the strongest winds?
2. **EASY** When does the Atlantic hurricane season begin and end?
3. **EASY** Why does a hurricane weaken after it moves over land?
4. **MEDIUM** Give the Saffir-Simpson category for a hurricane with sustained winds of (a) 100 mph, (b) 160 mph, (c) 115 mph.
5. **MEDIUM** The finished Galveston seawall is about 10 miles long. How many kilometers is that?
6. **MEDIUM** The seawall stands 17 feet high. How many meters is that? Is it taller or shorter than the 15-foot surge of 1900, and by how much?  
(Use the map or drawing “Compare the wall top with the surge line.” shown earlier in this lesson.)
7. **MEDIUM** In the Northern Hemisphere, which way do a hurricane’s winds spin around the eye? What makes them turn?
8. **HARD** Give three geographic reasons Galveston was in such danger in 1900.
9. **HARD** In 2008 Hurricane Ike flooded much of Galveston even though the seawall stood. Explain how.
10. **CHALLENGE** A city block measures 300 feet by 400 feet. Workers raise its ground by an average of 8 feet with sand pumped from the ship channel. How many cubic feet of fill is that? How many cubic yards? (1 cubic yard = 27 cubic feet)

## COMMON MISTAKES

- Thinking wind is the main danger. In most great hurricanes, the storm surge has killed far more people than the wind.
- Thinking the calm eye means the storm is over. The other side of the eyewall comes next, with winds from the opposite direction.
- Thinking a seawall makes a city completely safe. It guards one side against waves and surge; people still need warnings and evacuation plans.

**Make it a game • Category Call.** Write wind speeds on twenty cards, some in miles per hour and some in kilometers per hour (for example 80 mph, 120 mph, 145 mph, 170 mph, 200 km/h, 260 km/h, 100 km/h). Include a few below 74 mph (119 km/h) as “not a hurricane.” Flip a card; the first player to call the right Saffir–Simpson category, and one thing families should do at that strength, keeps the card. Most cards wins.

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

Jesus speaks of the storms of life, and every builder on a coast knows the picture is true. Galveston rebuilt on a stronger footing. Hearing Christ’s words and doing them is the firm foundation that no storm can wash away.

#### Practice answers

1. The eye is the calm center; the eyewall is the ring around it. The strongest winds are in the eyewall.
2. June 1 to November 30.
3. It loses its supply of warm, moist air from the ocean, which is the fuel that keeps it going, and friction with the land slows the winds.
4. (a) Category 2. (b) Category 5. (c) Category 3.
5.  $10 \times 1.609 \approx 16$  km.
6.  $17 \times 0.305 \approx 5.2$  m. It is 2 feet (about 0.6 m) taller than the 1900 surge.
7. Counterclockwise. The turning of the earth bends the air flowing in toward the low-pressure center.
8. It stood on a low, narrow barrier island, with its highest ground under 9 feet; it faced the open Gulf of Mexico, where warm water feeds hurricanes; and the sea floor offshore is shallow and gently sloping, which lets a surge pile up high. (Also accepted: there was no high ground to flee to and no quick way off the island.)
9. The seawall guards only the Gulf side of the island. Ike’s surge filled Galveston Bay and the water rose into the city from the bay side, behind the wall, where the ground is lower.
10.  $300 \times 400 \times 8 = 960,000$  cubic feet.  $960,000 \div 27 \approx 35,600$  cubic yards, for just one block.

## 8.4 TORNADO ALLEY AND WARNING SYSTEMS ⚙️

### OBJECTIVES

- Explain why the Great Plains, where warm moist air from the Gulf of Mexico meets dry and cold air, have more strong tornadoes than anywhere else on earth.
- Tell how Ernest Fawbush and Robert Miller made the first tornado forecast in 1948 and how radar learned to find tornadoes inside storms.
- Use the Enhanced Fujita scale, compute warning times from a storm's distance and speed, and make a family shelter plan.

**Warm-up.** Fill a clear jar or bottle with water almost to the top, add a drop of dish soap and a pinch of glitter or pepper, and close the lid tightly. Swirl it hard in a circle for ten seconds, then stop and hold it still. Watch the funnel that forms in the middle. Where does the water spin fastest, near the center or near the outside? Write down what you see.

**Watch.** *Tornado Intercept: The Union City Twister and the Birth of Doppler Radar* (NOAA Weather Partners, 4:50). [https://www.youtube.com/watch?v=\\_u3qolstr50](https://www.youtube.com/watch?v=_u3qolstr50)

After the story: watch how scientists chased the 1973 Union City tornado while an experimental Doppler radar saw its spinning winds, and listen for the 'tornadic vortex signature' that later made earlier warnings possible.

**Note:** Captions were not available to check; preview it first. The Union City tornado caused deaths, and the video may mention this. The video uses the old F-scale ('F-4'); today's warnings use the Enhanced Fujita (EF) scale.

### KEY TERMS

#### tornado

A violently spinning column of air reaching from a thunderstorm down to the ground.

#### supercell

A large, long-lasting thunderstorm with a deep, rotating updraft. Most strong tornadoes come from supercells.

#### wind shear

A change in wind speed or direction with height. Strong shear helps a thunderstorm begin to rotate.

#### Enhanced Fujita (EF) scale

A scale from EF0 to EF5 that rates a tornado by the wind speeds estimated from the damage it causes.

#### tornado watch / tornado warning

A watch means conditions are right for tornadoes in the next several hours: be ready. A warning means a tornado has been seen or detected by radar: take shelter now.

#### Doppler radar

Radar that measures not only where rain is but whether it is moving toward or away from the radar, so it can detect spinning winds.

## CORE IDEAS

**The story.** On the evening of March 20, 1948, a tornado tore across Tinker Air Force Base near Oklahoma City with no warning at all, wrecking buildings and damaging many aircraft. The base commander ordered his weather officers to find out whether such storms could be foreseen. Two of them, Major Ernest Fawbush and Captain Robert Miller, studied the weather maps of that day. Five days later, on March 25, they were astonished to see the maps forming nearly the same pattern again. With the commander's urging, they issued a forecast that a tornado was possible at the base that evening. Crews tied down and moved aircraft and prepared for the storm. That evening a second tornado struck Tinker. Damage was still heavy, but no one had been caught by surprise. It was the first successful tornado forecast, and the start of the modern warning system.

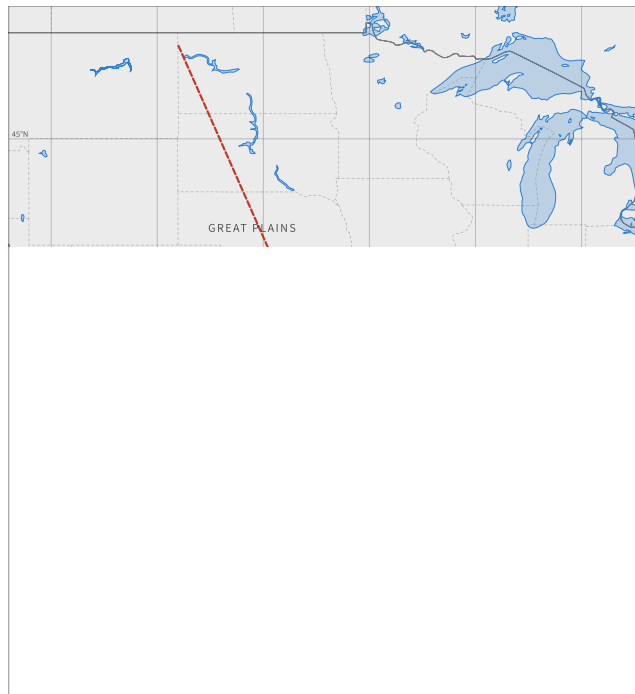
**The big idea.** Tornadoes happen on every continent except Antarctica, but the United States has more than any other country, about 1,200 in an average year. The reason is geography. In spring, warm, moist air flows north from the Gulf of Mexico close to the ground. Above it, hot, dry air drifts east off the high deserts of the Southwest and Mexico, and cold, dry air pushes south from Canada. There is no east-west mountain range to keep these air masses apart, so they meet over the flat Great Plains. Strong winds high above, blowing faster and from a different direction than the winds near the ground, set the air rolling; when a powerful updraft tilts that rolling air upright, the whole storm begins to turn. Such a rotating storm is a **supercell**, and from its base a tornado may reach down. The belt from Texas through Oklahoma, Kansas and Nebraska is called Tornado Alley, and the lower Mississippi valley and the Southeast see many tornadoes too.

**Measuring a tornado.** Few instruments survive a direct hit, so tornadoes are rated by what they do. In 1971 Ted Fujita of the University of Chicago created a scale that matched damage to wind speed. In 2007 the National Weather Service began using an improved version, the **Enhanced Fujita scale**: EF0, 65–85 mph (105–137 km/h), broken branches and shingles; EF1, 86–110 mph (138–177 km/h); EF2, 111–135 mph (178–217 km/h), roofs torn off; EF3, 136–165 mph (218–266 km/h); EF4, 166–200 mph (267–322 km/h), well-built houses leveled; EF5, over 200 mph (over 322 km/h). Most tornadoes are weak, but the rare EF4 and EF5 tornadoes cause most of the deaths.

**Technology overcoming geography.** Radar was perfected for war in the 1940s, and afterward weathermen turned it on storms. On April 9, 1953, a research radar at Champaign, Illinois, run by the Illinois State Water Survey, recorded a hook-shaped echo curling from the edge of a storm at the same time a tornado was on the ground. Forecasters learned to watch for that **hook echo**. **Doppler radar** went further: by measuring whether raindrops are moving toward or away from it, it can show winds spinning inside a storm, often before a tornado touches down. In the 1990s the National Weather Service installed a network of about 160 Doppler radars across the country. Today the Storm Prediction Center in Norman, Oklahoma, issues **tornado watches** hours ahead, and local weather offices issue

**warnings** that reach people through sirens, NOAA Weather Radio, television and phone alerts, often about ten minutes before a tornado arrives and sometimes much more.

**Ready to act.** Ten minutes is enough only for people who already know what to do. The safest place is a basement or a storm shelter; without one, go to a small room in the middle of the lowest floor, away from windows, and cover your head. On May 3, 1999, a violent tornado struck Moore and south Oklahoma City, and a mobile Doppler radar measured winds of about 300 mph (480 km/h), among the fastest ever recorded. Many Oklahoma families have since built steel or concrete safe rooms. Compare 1925, when the Tri-State Tornado crossed Missouri, Illinois and Indiana with no warning at all and killed 695 people. Forecasts, radar and drills cannot stop the wind, but they give people the minutes that save their lives.



*Three kinds of air meet over the Great Plains. Tinker Air Force Base, Norman, Garnett and Champaign are marked.*



*A hazard map of the United States. Each region has its own danger and its own way of preparing.*

## PICTURE STUDY



*The First Known Photograph of a Tornado, A. A. Adams (photographer), April 26, 1884 · Photograph · Taken near Garnett, Anderson County, Kansas; copies in the NOAA Photo Library*

In 1884 photography was slow: a camera stood on a tripod, and the picture was made on a glass plate that had to be held still. On April 26 of that year, a Kansas photographer named A. A. Adams saw a tornado crossing the prairie near Garnett, set up his camera and made this picture. It is the earliest known photograph of a tornado.

Look at it as a record and as a warning. There was no radar and no siren in 1884. People on the prairie watched the sky, and a funnel like this one might be their only warning.

### Look closely

- Find the funnel. Where does it meet the cloud, and where does it meet the ground?
- Look at the land. How does the flat prairie help you see the storm from far away?
- Look at the shape of the cloud above the funnel. What does it tell you about the storm it came from?

### Talk about it

1. How would a Kansas farm family in 1884 have known a tornado was coming? How would they know today?
2. Why do you think this photograph was copied and kept for so many years?

**Safety first.** Never go outside to watch or photograph a storm. If a tornado warning is issued while you are working on this lesson, stop and go to your shelter.

## PROJECT: VORTEX BOTTLE AND FAMILY TORNADO PLAN

First you will make a lasting vortex in a pair of bottles to see how a spinning column of fluid behaves. Then you will do the real work: make a shelter plan for your home and practice it with a timer.

### You will need

- Two empty 2-liter plastic bottles with labels removed
- A plastic “tornado tube” connector, or a metal washer and strong duct tape
- Water and a drop of food coloring
- Graph paper, a pencil, a stopwatch or phone timer
- A shoebox or bag for a shelter kit: flashlight, spare batteries, whistle, shoes, water bottles, a small first-aid kit

### Steps

1. Fill one bottle about two-thirds full of water with a drop of coloring.
2. Join the bottles mouth to mouth with the connector, or with a washer between them, wrapped tightly with duct tape so it does not leak.
3. Flip the bottles so the full one is on top. Swirl them in a quick circle a few times, then hold still. Watch the funnel form and the water drain. Time it.
4. Flip again and let the water drain without swirling. Time it. Which way drained faster? Why might a spinning funnel let water and air pass each other more easily?
5. Now draw a floor plan of your home on graph paper. With a parent, mark the safest shelter spot: a basement, or a small room in the middle of the lowest floor, away from windows.



6. Draw the path from each bedroom to the shelter. Mark where the shelter kit will be kept.
7. Pack the shelter kit and put it in place.
8. Hold a drill: a parent calls “Tornado warning!” and starts the timer. Everyone goes to the shelter, crouches low and covers their head. Record the time. Practice until everyone is there in under one minute.
9. Find out how your family will receive warnings: outdoor sirens, NOAA Weather Radio, phone alerts. Write them on your plan.

### Tips

- Sirens are meant for people outdoors. Indoors, you may not hear them, so have a second way to get warnings.
- If you have no basement, a bathroom or closet in the middle of the house is better than any room with an outside wall.

### Check your work

- I made a vortex and compared draining with and without a spin.
- My family has a shelter spot, a floor plan with routes, and a kit.
- We practiced a drill and timed it.
- I can explain the difference between a watch and a warning.

### MAP NOTEBOOK

1. Draw the three arrows of air that meet over the Great Plains on an outline map of the United States, and shade Tornado Alley.
2. Draw a supercell thunderstorm from the side: the tall anvil cloud, the rotating updraft and a tornado beneath it. Then draw a hook echo as it might look on a radar screen.
3. Begin your hazard map of the United States: color the regions most at risk from hurricanes, tornadoes, river floods, earthquakes and volcanoes, and make a key.

**From history.** Ted Fujita, who gave his name to the tornado scale, was born in Japan and studied the damage at Nagasaki after the atomic bomb, learning to read the force of a blast from the way trees and buildings fell. He later brought that skill to tornado damage surveys in the United States, flying over storm paths and mapping how debris was scattered. From the patterns he discovered that some powerful storms contain smaller whirls inside them, and he also identified downbursts, sudden plunges of air from thunderstorms that endangered airplanes landing and taking off.

## WORKED EXAMPLES

**Example 1.** Doppler radar detects strong rotation in a storm 18 miles southwest of a town. The storm is moving northeast, straight toward the town, at 36 miles per hour. How many minutes do people have? Give the distance in kilometers too.

1. Time = distance  $\div$  speed =  $18 \div 36 = 0.5$  hour.
2.  $0.5 \text{ hour} \times 60 = 30$  minutes.
3. Distance:  $18 \times 1.609 \approx 29$  km.

**Answer:** About 30 minutes of warning, with the storm about 29 km away. That is far more than the average lead time and plenty for every family to reach shelter.

**Example 2.** After a tornado, a survey team estimates winds of 175 mph from the damage. What is its EF rating? What is 175 mph in kilometers per hour?

1. EF4 covers 166–200 mph. 175 falls in that range.
2.  $175 \times 1.609 \approx 282$  km/h.

**Answer:** EF4; about 282 km/h.

**Example 3.** Radar works by sending out a radio pulse and timing its echo. Radio waves travel about 300,000 km per second. A storm is 150 km from the radar. How long does it take the pulse to go out to the storm and come back? How far is the storm in miles?

1. The pulse must travel there and back:  $150 \text{ km} \times 2 = 300 \text{ km}$ .
2. Time = distance  $\div$  speed =  $300 \text{ km} \div 300,000 \text{ km per second} = 0.001$  second.
3. That is one thousandth of a second (one millisecond).
4. In miles:  $150 \times 0.621 \approx 93$  miles.

**Answer:** About 0.001 second for the round trip; the storm is about 93 miles away. The radar can send and hear back from hundreds of pulses every second.

## PRACTICE

1. **EASY** What is the difference between a tornado watch and a tornado warning? What should you do for each?
2. **EASY** Your home has no basement. Where is the safest place to go in a tornado warning?
3. **EASY** Who made the first successful tornado forecast, and where and when?
4. **MEDIUM** Give the EF rating for estimated winds of (a) 120 mph, (b) 80 mph, (c) 210 mph.
5. **MEDIUM** A rotating storm is 24 km from a town and moving toward it at 48 km/h. How many minutes until it arrives? Give the distance and speed in miles too.

6. **MEDIUM** What is a hook echo, and where and when was one first recorded with a tornado?
7. **MEDIUM** Use the air-mass map. Name the three kinds of air that meet over the Great Plains and where each comes from.  
*(Use the map or drawing "Follow each arrow back to where it starts." shown earlier in this lesson.)*
8. **HARD** Why is Doppler radar better at finding tornadoes than the older radars of the 1950s?
9. **HARD** No one can stop a tornado. In three or four sentences, explain how warning systems still save lives. Compare 1925 with today.
10. **CHALLENGE** Use the hazard map. For each place, name the main natural hazard and one way people there prepare or build against it: (a) Galveston, (b) Moore, (c) Greenville, Mississippi, (d) San Francisco, (e) Mount St. Helens.  
*(Use the map or drawing "Each marked place has its own main hazard." shown earlier in this lesson.)*

## COMMON MISTAKES

- Mixing up a watch and a warning. Watch: be ready. Warning: take shelter now.
- Thinking a highway overpass is a good shelter. Wind speeds up under an overpass and flying debris is deadly there; get to a sturdy building or a low ditch instead.
- Thinking tornadoes happen only in Tornado Alley. They have struck every one of the fifty states, and the Southeast has many deadly ones.

**Make it a game · Watch or Warning?** A caller reads short weather messages: "Storms possible this evening across Kansas," "Rotation seen on radar five miles west of town," "Funnel cloud reported near the school," and so on. Players hold up a W card for watch (be ready) or a second card marked SHELTER for warning (act now). For each warning, the first player to name the right shelter spot in your own home scores a point. Finish the game with a real timed drill to your shelter.

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

A tornado warning is a gift of foresight. Wisdom is not only knowing danger is coming, but acting on it: having a plan, practicing it and taking shelter when the call comes.

### Practice answers

1. A watch means conditions are right for tornadoes in the next several hours: stay alert, check your plan and keep a way to get warnings. A warning means a tornado has been seen or detected on radar: go to your shelter at once.
2. A small room in the middle of the lowest floor, such as a bathroom, closet or hallway, away from windows. Crouch low and cover your head.
3. Air Force weather officers Major Ernest Fawbush and Captain Robert Miller, at Tinker Air Force Base near Oklahoma City, on March 25, 1948.
4. (a) EF2. (b) EF0. (c) EF5.
5.  $24 \div 48 = 0.5$  hour = 30 minutes.  $24 \text{ km} \approx 15$  miles;  $48 \text{ km/h} \approx 30$  mph.

6. A hook-shaped curl of rain at the edge of a storm on a radar screen, a sign of rotation that may hold a tornado. It was first recorded by a research radar at Champaign, Illinois, on April 9, 1953.
7. Warm, moist air from the Gulf of Mexico (from the south); hot, dry air from the deserts of the Southwest and Mexico (from the southwest); and cold, dry air from Canada (from the north).
8. Older radar showed only where rain was, so forecasters had to guess from shapes like the hook echo. Doppler radar also measures whether the rain is moving toward or away from the radar. Winds rushing toward it right beside winds rushing away from it reveal rotation inside the storm, often before a tornado forms.
9. In 1925 the Tri-State Tornado struck towns with no warning, and 695 people died because no one knew to take cover. Today forecasters issue watches hours ahead and radar lets them issue warnings minutes before a tornado arrives. Those minutes, used by families who already have a plan and a shelter, let people get below ground or into a strong inner room. The tornado still destroys buildings, but far fewer people are in harm's way.
10. (a) Hurricanes and storm surge: the seawall, raised ground, evacuation routes. (b) Tornadoes: radar warnings, sirens, safe rooms. (c) River floods: levees, spillways and floodways upstream and downstream. (d) Earthquakes: building codes, flexible frames and base isolation. (e) Volcanic eruptions: monitoring the mountain with instruments, hazard zones and evacuation plans.

## UNIT 8 REVIEW

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Answer each question. Show your work for calculations, give both customary and metric units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (6 pts) What is a polder? Name two machines the Dutch have used, in different centuries, to keep polders dry, and explain why the pumping can never stop.
2. (6 pts) What two things caused the North Sea flood of 1953? Why did the engineers build a barrier with gates, rather than a solid dam, across the Eastern Scheldt?
3. (6 pts) A polder lies 6 m below sea level. A storm tide rises to 4 m above sea level. If the dike failed, how deep could the water over the polder become? Give meters and feet.
4. (6 pts) Explain how a river builds a natural levee, and why the “levees only” plan made the 1927 flood so destructive.
5. (6 pts) About 27,000 square miles flooded in 1927. Convert this to square kilometers. Then find the river distance from Memphis (river mile 735) to Vicksburg (river mile 437) in miles and kilometers.
6. (6 pts) What did the Flood Control Act of 1928 change? Name one spillway or control structure and tell what it does.
7. (6 pts) Explain how a hurricane forms and why it weakens over land. In which direction do its winds turn in the Northern Hemisphere?
8. (6 pts) A town’s ground stands 5 feet above sea level and a 15-foot storm surge is forecast. How deep would the water be, in feet and meters? Then name two things Galveston did after 1900 to protect itself.
9. (6 pts) Why does the Great Plains have so many strong tornadoes? What is the difference between a tornado watch and a tornado warning?
10. (6 pts) Radar finds rotation 20 miles from a town, moving toward it at 40 mph. How many minutes of warning are there, and how far away is the storm in kilometers? Then, on a hazard map of the U.S., name the main hazard at Moore, Oklahoma, and at Galveston, Texas.

### UNIT PROJECT: LIVING WITH HAZARDS: MY DIKE MODEL AND HAZARD MAP

Rebuild your best model dike and polder in a pan and photograph or sketch it before and after a storm-surge test, with your gauge readings. Then make a large hazard map of the United States: color the regions most at risk from hurricanes, tornadoes, river floods, earthquakes and volcanoes, make a key, and mark Galveston, Moore, Greenville, San Francisco, Mount St. Helens and your own town.

Beside the map, write a short paragraph for each of the four lessons telling how people prepared or built against that hazard (dikes and the Delta Works, levees and spillways, the seawall and raised city, radar and warnings). Finish with your family’s own shelter plan and one sentence on the main hazard where you live.

- **Model and test:** The dike and polder are built carefully, tested with waves and a surge, and the results are recorded with measurements.
- **Map accuracy:** Hazard regions and the named places are located correctly, the map has a clear key, and both miles and kilometers appear on the scale bar.
- **Explanation:** The paragraphs explain each hazard as a physical process and name the engineering or warning system that answers it, using correct facts and numbers.
- **Care and preparedness:** The work is neat and labeled, and the family shelter plan is complete, practiced and dated.

#### Answer key

1. A polder is low land enclosed by dikes and kept dry by pumping. Windmills (from the 1400s on; Kinderdijk, the Beemster) and later steam pumps (Cruquius, 1849), then diesel and electric pumps. Rain and seepage fill the polder every day, and drained peat keeps sinking, so the land stays below the water around it.
2. A strong northwesterly gale piling water into the narrow southern North Sea, together with a spring tide. The gates let the salty tide flow in and out in normal weather, keeping the fishing, shellfish and life of the estuary, and close only when a storm surge threatens.
3.  $6 + 4 = 10$  m;  $10 \times 3.28 \approx 33$  feet.
4. Floodwater leaving the channel slows and drops its heaviest sand right beside the bank, building a low ridge over many floods. Walling the river in with tall levees kept floodwater from spreading, so it rose higher in the channel; when levees broke (about 145 crevasses, the largest at Mounds Landing), the water fell on the land behind with great depth and force.
5.  $27,000 \times 2.59 \approx 70,000$  km<sup>2</sup>.  $735 - 437 = 298$  river miles;  $298 \times 1.609 \approx 479$  km.
6. It made Mississippi flood control a national task under the U.S. Army Corps of Engineers and added spillways and floodways to the levees. Examples: the Bonnet Carré Spillway (1931) lets part of a flood flow into Lake Pontchartrain above New Orleans; the Old River Control Structure (1963) keeps the Mississippi from shifting into the Atchafalaya; the Birds Point-New Madrid Floodway or Morganza structure divert floodwater.
7. Over tropical ocean water warmer than about 80°F (27°C), warm moist air rises and its water vapor condenses into clouds and rain, releasing heat that drives the air up faster; air flows in along the sea surface and the earth's turning bends it into a spiral. Over land it loses its warm, moist fuel and is slowed by friction. Counterclockwise.
8.  $15 - 5 = 10$  feet;  $10 \times 0.305 \approx 3$  m. Galveston built a 17-foot (5.2 m) concrete seawall with a curved face and a granite apron, about 10 miles (16 km) long when finished, and raised the ground of the city with fill pumped from the ship channel, jacking up more than 2,000 buildings.
9. Warm, moist air from the Gulf of Mexico meets hot, dry air from the Southwest and cold, dry air from Canada over flat land with no east-west mountains to separate them, and winds that change with height set storms rotating into supercells. A watch means conditions are right for tornadoes in the next several hours (be ready); a warning means a tornado has been seen or detected on radar (take shelter now).
10.  $20 \div 40 = 0.5$  hour = 30 minutes;  $20 \times 1.609 \approx 32$  km. Moore: tornadoes. Galveston: hurricanes and storm surge.

## BONUS: MAP LAB

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This bonus unit turns the year’s physical geography into four map puzzles and games. Each lesson is lighter than a regular lesson, with a short story, one worked example and five practice problems, but each one asks you to **use** a skill you have learned: reading contour lines, plotting earthquakes, reading climate charts and mapping a river as it works.

You will read a contour puzzle the way Bradford Washburn’s mapmakers read Mount Everest, follow George Plafker along the Alaska coast after the 1964 earthquake as he used barnacles to find a plate edge, meet Alexander von Humboldt and his “equal heat” lines, and visit the giant Mississippi River Basin Model, where engineers ran floods across a model of the great river system that drains much of the United States. In every lesson the same truth shows through: the earth God made follows patterns that a careful observer can read, map and use to keep people safe.

### BEFORE YOU BEGIN

- Can read contour lines and find a contour interval (Unit 1)
- Knows the three kinds of plate edges (Unit 2)
- Can explain how latitude, altitude, ocean currents and winds shape climate (Units 5 and 7)
- Has seen how rivers carve, carry and drop sediment (Unit 4)

### MASTERY CHECKLIST

- I can find summits, saddles, steep slopes and stream directions on a contour map and draw a profile.
- I can plot an earthquake by latitude and longitude and name the plate edge that caused it.
- I can read a climate chart and use hemisphere, range, altitude and rainfall clues to name a mystery city.
- I can build a stream table, map its river at several times on a grid, and convert model measurements with a scale.
- I can explain how maps of hazards and models of rivers help people prepare for earthquakes and floods.

### OPTIONAL BOOKS AND RESOURCES

- **USGS Latest Earthquakes map** (<https://earthquake.usgs.gov/earthquakes/map/>): Free. A live world map of recent earthquakes with magnitude, depth and location. Use it with a parent in Lesson 9.2 to plot and solve this week’s real earthquakes.
- **USGS topoView** (<https://ngmdb.usgs.gov/topoview/>): Free. Browse and download historical and current USGS topographic maps of any place in the United States. Find a hill and a saddle near your home for Lesson 9.1.



## 9.1 CONTOUR MAP PUZZLE

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### OBJECTIVES

- Read a contour puzzle map to find summits, a saddle, steep and gentle slopes, and the direction a stream flows.
- Turn a line across a contour map into a side-view profile, measuring distances with a scale bar in meters and feet.
- Make and play a set of contour match-up cards that pair map views with side views.

**Warm-up.** Turn a cereal bowl upside down on the table and set a paper cup upside down beside it. Look straight down from above and, with a finger in the air, trace the rings you would draw for each one at the heights of 2 cm, 4 cm and 6 cm. Which shape would give rings far apart? Which would give rings stacked almost on top of each other? Now guess: what would a ring look like that wraps around both the bowl and the cup at once?

**Video.** Coming soon. Reading contour lines, saddles and V-shaped valleys on topographic maps: search NASA Earth Observatory, Homeschool Pop (Alternate), and the USGS and National Park Service channels (candidates, need vetting).

### KEY TERMS

#### **summit**

The highest point of a hill or mountain, shown inside the smallest closed contour loop and often marked with a spot height.

#### **saddle**

A low dip in a ridge between two higher summits. On a map it sits between two sets of closed loops, like the low seat of a horse's saddle.

#### **spot height**

A single measured elevation printed on a map beside a dot or triangle.

#### **profile**

A side view of the land along a line drawn across a map, showing where the ground rises and falls.

#### **contour V**

The bend a contour line makes where it crosses a stream. The point of the V always aims upstream, toward higher ground.

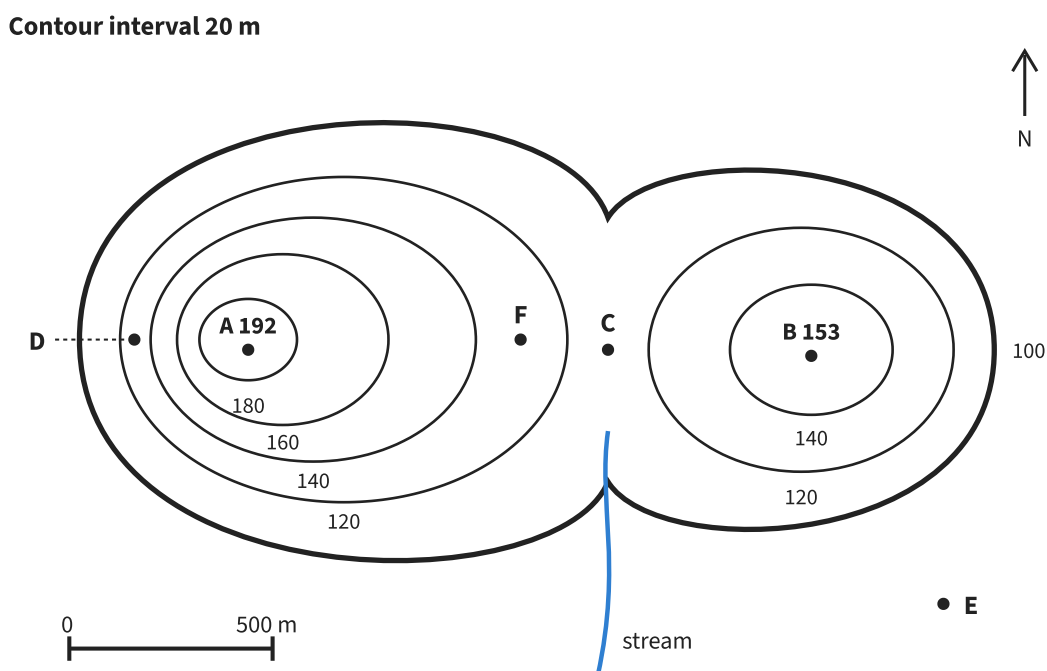
### CORE IDEAS

**The story.** In 1988 the National Geographic Society published a new map of Mount Everest, the highest mountain on earth. The man behind it was Bradford Washburn, a mountaineer and mapmaker from Boston who had already mapped Alaska's great peaks. No surveyor could walk all over the icy faces of Everest, so Washburn arranged for photographs to be

taken from an airplane flying high above the mountain. Cartographers in Switzerland then studied overlapping pairs of those photos, which show the land in depth the way your two eyes do, and traced the contour lines one by one. When the map was printed, climbers could see on paper what had taken earlier expeditions years to learn on foot: where the ridges ran, where the faces were steepest, and where the low passes lay between the peaks.

**How to solve a contour puzzle.** Every contour map is a puzzle with a few sure clues. Closed loops one inside another mark a summit, and the smallest loop is the top. Lines crowded together mean steep ground; lines spread apart mean gentle ground. Where one loop wraps around *two* sets of smaller loops, the land between the two summits is a **saddle**: higher than the outer loop but lower than the loops around either peak. And where a contour line crosses a stream, it bends into a V whose point aims *upstream*, because the valley floor is lower than the slopes on either side, so the line has to travel up the valley to find ground of the same height. Count the lines from a labeled index contour, and you can name the elevation of any spot on the map, or at least the two heights it lies between.

**On the map.** Look at the puzzle map in the figure. The contour interval is 20 m (about 66 feet), and the bold line is the 100 m index contour. Point A, the west summit, has a spot height of 192 m; point B, the east summit, is 153 m. Point C sits in the saddle between them, and a small stream runs south from the saddle, with the 100 m line making a V where it crosses. Points D and F lie on opposite sides of the west hill, and point E lies outside every loop. Before you read on, try to answer: which side of the west hill would you rather climb, and why? Washburn and his Swiss partners answered the same kind of question on Everest, only with lines rising for thousands of meters. Mapmakers have learned to read the shape of the land God made from a few honest rules, and a careful student can learn the same rules in an afternoon.



*The contour puzzle map. Contour interval 20 m; the bold line is the 100 m index contour.*

## PICTURE STUDY



*Mont Sainte-Victoire Seen from Les Lauves*, Paul Cézanne, about 1902–1906 · Oil on canvas · Nelson-Atkins Museum of Art, Kansas City, Missouri

Paul Cézanne lived in Aix-en-Provence in southern France, and from his hillside studio he could see the long limestone ridge of Mont Sainte-Victoire. He painted the mountain again and again, dozens of times in oil and watercolor, trying to show not just how it looked but how it was built: its solid mass, its planes of light and shadow, and the way it rose from the plain.

In this late view the fields, houses and trees below are made of blocks of color, and the mountain rises at the top like a great tilted wedge. Cézanne was not making a map, but he was studying shape the way a mapmaker does. Try to read his mountain as if you had to draw its contour lines.

### Look closely

- Find the highest point of the mountain. Is it in the middle of the ridge or toward one end?
- Find a side of the mountain that looks steep and a side that looks gentle. How did Cézanne show the difference?
- Look at the plain in front of the mountain. Is it flat, or does it rise and fall in gentle hills?
- Find the line where the mountain meets the sky. If you walked that skyline, where would you climb and where would you go down?

### Talk about it

1. If you drew contour lines on this mountain, where would they be crowded together and where would they spread apart?
2. Why might an artist paint the same mountain many times? What might he notice the tenth time that he missed the first?

## **PROJECT: CONTOUR MATCH-UP CARDS**

You will make a deck of puzzle cards: on some, a contour map seen from above; on others, the same landform seen from the side. Then you will build a cardboard model of the lesson's puzzle map to check your thinking. When you finish, you will be able to look at any set of contour lines and picture the land rising off the page.

### **You will need**

- 12 index cards and a pencil, fine marker and colored pencils
- A ruler
- Corrugated cardboard (a cereal box or shipping box), scissors and glue
- Tracing paper or baking parchment

### **Steps**

1. Choose six landforms: a round hill, a long ridge, a hill with one cliff side, two hills joined by a saddle, a valley with a stream, and a hollow (depression).
2. On six cards, draw each landform as a contour map from above, using a 20 m interval and labeling one line with its height. On the other six cards, draw the side view of each landform. Write a small matching code on the back, such as 1A and 1B.
3. Shuffle the cards and ask someone to match each map with its side view. Time them, then switch and let them make two new cards for you.
4. Now trace the lesson's puzzle map onto tracing paper, one loop at a time.
5. Cut the 100 m loop from cardboard as the base. Cut each higher loop from another layer of cardboard and glue it on top in its place, so the 120, 140, 160 and 180 m layers stack up into the two hills.
6. Lay a pencil across the model from A to B and look at it from the side. Does the profile match the one you worked out in the worked example?
7. Drip a few drops of water onto the saddle with a dropper and watch which way it wants to run.

### **Tips**

- Make the cards tricky: two hills that look alike from above but have different steep sides are the best puzzles.
- Each layer of cardboard stands for one contour interval, so all layers must be the same thickness.

### **Check your work**

- I made six matching pairs of map and side-view cards.

- My cardboard model shows the steep west side of the west hill and the saddle between the hills.
- I can point to the summit, the saddle and the stream valley on both the map and the model.

## MAP NOTEBOOK

1. Copy the puzzle map into your notebook and color it in bands: green below 100 m, yellow from 100 to 140 m, tan from 140 to 180 m and brown above 180 m.
2. Draw a stream crossing three contour lines and show the V in each line pointing upstream. Add an arrow showing which way the water flows.
3. Draw two summits and a saddle as a side view, and label the saddle with a little picture of a horse's saddle above it.

**From history.** Washburn did not stop with the 1988 map. In 1999 he helped organize a team that carried a GPS receiver to the summit of Everest to measure its height by satellite, one of the first times the world's highest point was measured that way. Every few decades surveyors measure Everest again with better tools, and the numbers they publish differ by only a few meters, a sign of how carefully the work is done.

## WORKED EXAMPLES

**Example 1.** Draw the profile (side view) along a straight line from summit A to summit B on the puzzle map. Use the scale bar, which stands for 500 m. List the distance from A where the line crosses each contour, then describe the profile.

*(Use the map or drawing “Lay a ruler from A to B and mark where it crosses each contour line.” shown earlier in this lesson.)*

1. Start at A (192 m). Walking east, the line leaves the 180 m loop, then crosses 160 m, 140 m and 120 m. Measuring from A with the scale bar, these crossings come at about 120 m, 345 m, 560 m and 785 m from A.
2. Next comes the saddle C at about 885 m from A. It is outside both 120 m loops but inside the 100 m line, so it is between 100 and 120 m high (call it about 110 m).
3. Climbing again, the line crosses the east hill’s 120 m loop at about 985 m from A and its 140 m loop at about 1,185 m from A.
4. B (153 m) is about 1,385 m from A. On graph paper, plot distance across the bottom and height up the side, mark each crossing, and join the points with a smooth curve.
5. The curve drops quickly at first (the crossings near A are close together) and then more gently toward the saddle, dips to about 110 m at C, and rises to a lower second peak at B.

**Answer:** The profile runs from 192 m at A, down to about 110 m at the saddle C about 885 m (0.55 mile) from A, and up to 153 m at B, about 1.4 km (0.86 mile) from A. A is the higher summit by 39 m (about 128 feet).

## PRACTICE

1. **EASY** On the puzzle map, which summit is higher, A or B? By how many meters, and about how many feet?  
*(Use the map or drawing “Read the spot heights beside A and B.” shown earlier in this lesson.)*
2. **EASY** Points D and F both lie between the 120 m and 140 m contours of the west hill. Which point is on steeper ground? How can you tell?
3. **MEDIUM** What landform is at point C? Between what two elevations does it lie, and why would a hiker crossing from one valley to another choose to go through it?
4. **HARD** Which way does the stream flow, north or south? Explain how the bold 100 m contour line shows you, even without the stream drawn.
5. **CHALLENGE** A hiker starts at E and climbs straight to summit A. What can you say about E’s elevation? How many contour lines will the hiker cross, and at least how many meters will the hiker climb?

## COMMON MISTAKES

- Thinking the saddle is a low valley below everything around it. A saddle is low only compared with the two summits; it is still higher than the land outside the loop that

wraps around both hills.

- Reading the contour V backward. The point of the V aims upstream, toward the source, not downstream.
- Guessing an exact elevation for a point between two lines. Without a spot height, give the range: “between 120 and 140 m.”

**Make it a game • Contour Charades.** Shuffle your match-up cards and lay them face down. A player draws a map card and, without showing it, shapes the landform with their hands or with a blanket over pillows. The others race to name the landform (hill, ridge, cliff, saddle, valley or hollow) and to say where the lines would be crowded. Score one point for the landform and one for the steep side. First to ten points wins.

**Scripture.** “In his hand are the deep places of the earth: the strength of the hills is his also.” (Psalm 95:4, KJV)

A contour map shows the deep places and the hills on one sheet of paper. The psalmist reminds us that every valley and summit we trace belongs to the God who made it.

#### Practice answers

1. A is higher:  $192\text{ m} - 153\text{ m} = 39\text{ m}$ , which is about 128 feet ( $39 \div 0.3048$ ).
2. D is on steeper ground. On the west side of the west hill the contour lines are crowded close together; on the east side, where F is, they are spread far apart.
3. C is a saddle. It lies between 100 m and 120 m: inside the 100 m line that wraps around both hills, but outside each hill’s 120 m loop. A hiker would cross there because it is the lowest way over the ridge between the two summits.
4. It flows south, away from the saddle and downhill. Where the 100 m line crosses the stream it bends into a V whose point aims north. The point of a contour V always aims upstream, toward higher ground, so the water runs the other way, to the south.
5. E is outside the 100 m line, so it is below 100 m. The hiker crosses five lines: 100, 120, 140, 160 and 180 m. A is 192 m, so the climb is more than  $192 - 100 = 92\text{ m}$  (more than about 300 feet).



## 9.2 PLATE BOUNDARY DETECTIVE

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### OBJECTIVES

- Plot real earthquakes by latitude and longitude on a world map.
- Match each earthquake to the kind of plate edge that caused it, using clues such as trenches, mountains, volcanoes, depth and fault lines.
- Tell how George Plafker read the rocks of the Alaska coast after the 1964 earthquake to find the plate edge beneath it.

**Warm-up.** Lay two paperback books flat on the table, edges touching. Push them together until one edge rides up. Pull them apart. Slide them past each other with their edges pressed together. Each time, notice where the books catch, jump or grind. Those three motions are the three kinds of plate edges. Which motion felt the most jerky?

**Watch.** *27th March 1964: Most powerful earthquake ever recorded in North America struck Alaska* (HistoryPod, 2:30). <https://www.youtube.com/watch?v=jgaY4qj2aco>  
After the story: watch this short retelling of the Good Friday 1964 Alaska earthquake and look for how long the shaking lasted, where the epicenter was and how far the fault stretched.

**Note:** Captions were not available to check; preview it first. It describes destruction, tsunamis and loss of life, and compares the quake's energy to the atomic bomb dropped on Hiroshima. The video tells about the earthquake itself and probably says little about plate boundaries, so use the lesson to explain the subduction zone.

### KEY TERMS

#### **epicenter**

The point on the earth's surface directly above the place where an earthquake starts.

#### **focus depth**

How far below the surface an earthquake starts, measured in kilometers or miles.

#### **subduction zone**

A converging plate edge where one plate dives beneath another, marked by an ocean trench, a line of volcanoes, and earthquakes both shallow and deep.

#### **transform fault**

A plate edge where two plates slide past each other sideways, such as the San Andreas Fault.

#### **intraplate earthquake**

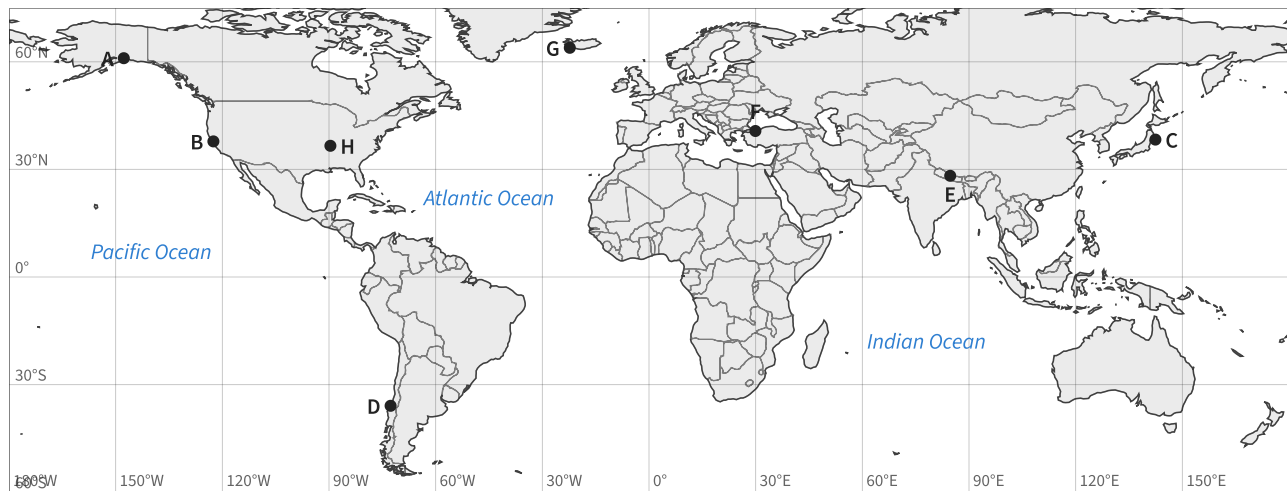
An earthquake far from any plate edge, inside a plate.

## CORE IDEAS

**The story.** On Good Friday, March 27, 1964, at about 5:36 in the evening, the ground in southern Alaska began to shake and did not stop for about four minutes. It was a magnitude 9.2 earthquake, the strongest ever measured in North America. In Anchorage, a whole street front dropped as the ground beneath it slid; along the coast, sea waves swept into harbors. That summer a young geologist from the U.S. Geological Survey, George Plafker, set out by boat and plane along the shores of Prince William Sound to find out what the earthquake had done to the land. He found a strange clue clinging to the rocks: barnacles and seaweed. These creatures live only in a narrow band at the edge of the tide. In some places their band now stood high and dry above the reach of the sea, and the barnacles had died; on Montague Island the shore had risen more than 10 m (more than 30 feet). In other places, farther inland, the land had dropped, and trees stood dying in salt water. Measuring the old barnacle line at place after place, Plafker drew a map of where the land rose and where it sank. The pattern could be explained only one way: the floor of the Pacific Ocean was sliding *under* Alaska along a great, gently sloping fault, and on Good Friday the two plates had lurched.

**How a detective reads the clues.** When seismograph stations around the world began recording earthquakes in large numbers in the 1960s, scientists plotted them on maps and found they were not scattered at random. They lie in narrow belts that trace the edges of the plates. Each kind of edge leaves its own clues. A **converging edge where an ocean plate dives under another plate** (a subduction zone) has a deep ocean trench offshore, a line of volcanoes inland, and earthquakes that get deeper the farther inland you go, some more than 600 km (about 370 miles) down. A **collision of two continents** builds high mountains like the Himalaya, with many shallow earthquakes but few volcanoes. A **sliding (transform) edge** shows a long, straight fault where fences, roads and streams are offset sideways, with shallow earthquakes. A **spreading edge** shows a ridge or rift valley with small, shallow earthquakes and lava flows. A few earthquakes break the rule and strike in the middle of a plate; a good detective notes these too and asks what weakness in the crust lies hidden there.

**On the map.** The figure shows eight real earthquakes. A is the 1964 Alaska earthquake. B is the 1906 San Francisco earthquake. C is the 2011 Tōhoku earthquake off northeastern Japan, magnitude 9.0. D is the 2010 earthquake off central Chile, magnitude 8.8. E is the 2015 Gorkha earthquake in Nepal, magnitude 7.8. F is the 1999 İzmit earthquake in northwestern Turkey, magnitude 7.6. G is the swarm of many thousands of small earthquakes on Iceland's Reykjanes Peninsula in early 2021, just before lava broke out at Fagradalsfjall that March. H is the series of strong earthquakes at New Madrid, Missouri, in the winter of 1811–1812. Your job is to be the detective: find each one on a plate map from Unit 2 and name the edge, if any, that it sits on. Because people know where these belts lie, they can write stronger building codes, plan tsunami warnings and choose safer places for hospitals and schools.



*Eight real earthquakes for the detective to solve. Compare with a map of the world's plates.*

## PICTURE STUDY



*Fourth Avenue, Anchorage, after the Good Friday Earthquake, U.S. Army photographer (name not recorded), 1964 · Black-and-white photograph · U.S. government photograph collections (public domain); widely reproduced by the U.S. Geological Survey*

Photographers working for the U.S. government recorded the damage in Anchorage in the days after the earthquake of March 27, 1964. One of the best-known pictures shows Fourth Avenue downtown. During the shaking, a layer of soft clay beneath part of the city gave way, and a long block of land slid and dropped, carrying the street, parked cars and shop fronts down with it.

Pictures like this one taught engineers and city planners a lasting lesson. After 1964, studies of the ground beneath Anchorage helped decide where it was safe to rebuild and where land should be left as open space.

### Look closely

- Find the line where the ground broke. How far did one side drop compared with the other?
- Look at the buildings and cars on the low side. Are they smashed, tilted, or carried down mostly in one piece?
- Look for people in the photograph. What are they doing?

### Talk about it

1. Plafker studied the land along the coast, and engineers studied the ground under the city. Why would both kinds of study matter for rebuilding?
2. What would you want to know about the ground before building a school in an earthquake region?

## PROJECT: EARTHQUAKE DETECTIVE BOARD

You will plot real earthquakes on a world map, mark the plate edges, and label each earthquake with the kind of edge it belongs to. Then you will add new earthquakes from this week's real reports and solve them too.

### You will need

- A printed or hand-drawn world map with latitude and longitude lines, taped to cardboard
- A world plate map (from Unit 2, an atlas, or the USGS website)
- Four colors of map pins or round stickers, plus a pencil and fine marker
- Index cards for case files

### Steps

1. Lightly draw the main plate edges on your map in pencil, copying from the plate map. Mark spreading ridges with double lines, subduction zones with a line with small triangles, and transform faults with a single line.
2. Make a color key: red for converging (subduction), orange for collision, blue for spreading, green for transform, and an open circle for earthquakes in the middle of a plate.
3. Plot the eight earthquakes from the figure using these positions: A 61.0° N, 147.7° W; B 37.8° N, 122.5° W; C 38.3° N, 142.4° E; D 35.9° S, 72.7° W; E 28.2° N, 84.7° E; F 40.7° N, 29.9° E; G 63.9° N, 22.3° W; H 36.6° N, 89.6° W.
4. For each one, write a case file on an index card: place, date, the clues you see nearby (trench, volcanoes, mountains, straight fault, ridge), and your verdict. Pin the right color on the map.
5. With a parent, open the U.S. Geological Survey's latest-earthquakes map and choose five earthquakes from the past week. Plot them and solve them the same way.
6. Count how many of your earthquakes lie on or near a plate edge and how many do not.

## Tips

- Longitudes west of Greenwich are on the left half of the map; longitudes east are on the right half.
- Depth is a strong clue: earthquakes deeper than about 70 km (about 45 miles) almost always come from a plate sinking beneath another.

## Check your work

- I plotted all eight earthquakes within about 2° of their true positions.
- Each case file names a clue and a verdict.
- I can explain why most earthquakes line up along narrow belts.

## MAP NOTEBOOK

1. Draw the three plate motions as pairs of arrows (toward, apart, sliding past) and beside each, draw the landform it makes: trench and volcano, ridge, straight fault.
2. Draw a barnacle line on a rock before and after the 1964 earthquake, showing how Plafker could tell the land had risen.
3. Make a side view of a subduction zone and mark three earthquakes at shallow, middle and deep levels along the sinking plate.

**From history.** The 1964 earthquake also sent sea waves across the Pacific, reaching as far as the coasts of Oregon and California. That disaster helped lead to the founding of a tsunami warning center in Alaska in 1967. Today warning centers use seismographs and ocean sensors to send alerts to coastal towns within minutes of a large undersea earthquake, giving people time to climb to high ground.

## WORKED EXAMPLES

**Example 1.** Case D: On February 27, 2010, a magnitude 8.8 earthquake struck off the coast of central Chile, at about  $35.9^{\circ}$  S,  $72.7^{\circ}$  W, with a focus about 23 km (about 14 miles) deep. Find it on the map and decide what kind of plate edge caused it.

*(Use the map or drawing “Find D and look for the trench and the line of volcanoes nearby.” shown earlier in this lesson.)*

1. Locate it:  $35.9^{\circ}$  S is in the Southern Hemisphere, a little more than a third of the way from the equator to the South Pole.  $72.7^{\circ}$  W is in the Western Hemisphere. The point lies just off the Pacific coast of South America.
2. Look offshore: a plate map shows a deep ocean trench (the Peru–Chile Trench) running along the whole west coast of South America.
3. Look inland: the Andes mountains run parallel to the coast and carry a long line of volcanoes.
4. Check the depth: a shallow earthquake near the trench fits the place where the two plates first meet. Farther inland under the Andes, earthquakes are deeper, tracing the sinking plate.
5. Trench offshore plus volcanoes inland plus deepening earthquakes is the signature of a subduction zone. The Nazca Plate is diving beneath the South American Plate.

**Answer:** Case D is a converging edge, a subduction zone: the Nazca Plate sliding under the South American Plate.

## PRACTICE

1. **EASY** Two of the eight earthquakes happened on sliding (transform) edges, where one plate grinds sideways past another. Which two letters are they, and what are the faults called?
2. **MEDIUM** Earthquake E struck Nepal in 2015. There is no ocean trench nearby and few volcanoes, but the highest mountains on earth rise there. What kind of edge is it?
3. **MEDIUM** Earthquake H, at New Madrid in 1811–1812, is the odd one out. Explain why, and what a good detective should conclude.
4. **HARD** On June 9, 1994, a strong earthquake struck beneath Bolivia, in the middle of South America, at a depth of about 631 km. Convert the depth to miles ( $1 \text{ km} \approx 0.62 \text{ mile}$ ). What kind of plate edge explains an earthquake so deep?
5. **CHALLENGE** Earthquake G was a swarm of small, shallow earthquakes in Iceland before lava erupted in 2021. What kind of edge is this? GPS stations show the two sides of Iceland moving apart about 2 cm (about 0.8 inch) a year. How far apart would they move in 50 years, in meters and feet?

## COMMON MISTAKES

- Thinking every earthquake must be on a plate edge. Most are, but intraplate earthquakes like New Madrid do happen.
- Mixing up the two kinds of converging edges. An ocean plate diving under another plate makes a trench and volcanoes; two continents colliding make high mountains with few volcanoes.
- Reading east and west longitude backward when plotting. Places in the Americas have west longitudes; Japan and Nepal have east longitudes.

**Make it a game · Name That Edge.** A caller reads one clue at a time: “a deep trench offshore,” “a line of volcanoes,” “a fence offset sideways,” “a rift valley with lava,” “high mountains with few volcanoes,” or “an earthquake 500 km deep.” Players hold up one of four cards: Subduction, Collision, Spreading or Sliding. A correct card scores a point; a player who can also name a real place with that clue scores a bonus point. Play to ten.

**Scripture.** “God is our refuge and strength, a very present help in trouble. Therefore will not we fear, though the earth be removed, and though the mountains be carried into the midst of the sea;” (Psalm 46:1–2, KJV)

The people of Alaska in 1964 saw the earth moved and the shore lifted out of the sea. Knowing where earthquakes strike helps us prepare wisely, and knowing God helps us face what we cannot control without fear.

### Practice answers

1. B (San Francisco, 1906) on the San Andreas Fault, and F (İzmit, Turkey, 1999) on the North Anatolian Fault.
2. A collision of two continental plates: the Indian Plate pushing into the Eurasian Plate. Continental crust is too light to sink deep into the mantle, so instead of a trench and volcanoes the crust crumples and thickens upward into the Himalaya.
3. New Madrid is in the middle of the North American Plate, far from any plate edge, so it is an intraplate earthquake. A good detective concludes that most earthquakes follow plate edges but not all; old weak zones deep in the crust inside a plate can also break.
4.  $631 \times 0.62 \approx 391$ , so about 390 miles deep. Only a subduction zone explains it: the Nazca Plate dives under South America at the Peru–Chile Trench and keeps sinking inland, so earthquakes far inland happen deep inside the sinking plate.
5. A spreading (diverging) edge: the Mid-Atlantic Ridge, where the North American and Eurasian Plates pull apart and rise above the sea in Iceland.  $2 \text{ cm} \times 50 = 100 \text{ cm} = 1 \text{ m}$ , which is about 3.3 feet.



## 9.3 CLIMATE MYSTERY CITIES

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### OBJECTIVES

- Read a climate chart: monthly average temperature as a line and monthly rainfall as bars.
- Use clues of latitude, altitude, hemisphere, ocean distance, winds and rainy seasons to name a mystery city from its chart.
- Make a set of climate chart cards for real cities and play a guessing game with them.

**Warm-up.** Without looking anything up, write down the warmest month and the wettest month where you live. Then guess: in which month is it warmest in Sydney, Australia? Keep your guesses; you will check them before the lesson ends.

**Watch.** *What are the Biggest and Smallest Climate Zones?* (Geodiode, 9:37).

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

Before the game: watch this tour of the world's climate zones so you know what clues to look for in each mystery city.

**Note:** Captions were not available to check; preview it first. The channel's climate videos describe physical geography; skip any part that turns to future change.

### KEY TERMS

#### climate chart

A graph of a place's average weather month by month, usually with temperature as a line and precipitation as bars.

#### annual temperature range

The warmest month's average temperature minus the coldest month's average temperature.

#### continentality

The way places far from the ocean have hotter summers and colder winters than coastal places at the same latitude.

#### monsoon

A seasonal reversal of winds that brings a long wet season and a long dry season, as in India.

#### isotherm

A line on a map joining places with the same average temperature.

### CORE IDEAS

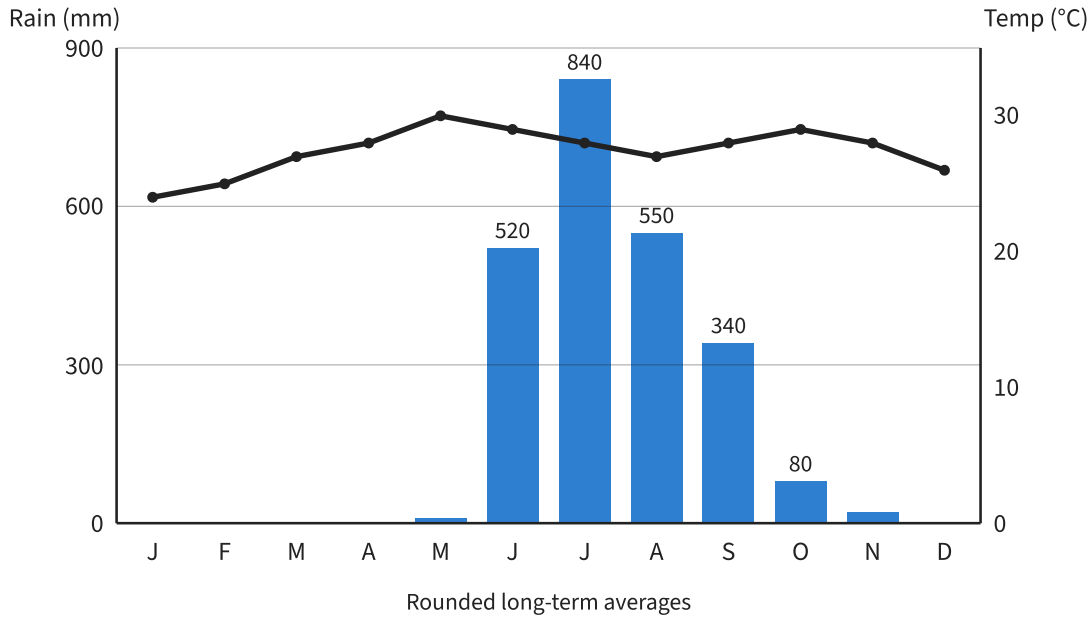
**The story.** In 1817 the German naturalist Alexander von Humboldt, who had climbed the volcanoes of the Andes and measured the temperature at every height he reached, published a short paper with a new kind of map. He gathered average temperatures from weather

records kept in cities across Europe, North America and Asia and drew lines joining places with the same yearly average. He called them **isotherms**, “equal heat” lines. If temperature depended on latitude alone, the lines would run straight across the map along the parallels. They did not. They bent north over the western coasts of Europe and dipped south across the middle of the continents. Humboldt had shown with numbers what travelers had long felt: latitude matters most, but oceans, winds, mountains and height above the sea bend the pattern.

**How to read the clues.** A climate chart is a fingerprint of a place. Read it like a detective. *Which month is warmest?* If it is July, the city is in the Northern Hemisphere; if it is January, the Southern. *How big is the temperature range?* A city near the equator barely changes all year. A coastal city in the middle latitudes changes moderately, because the sea warms and cools slowly. A city deep inside a continent swings wildly; that is continentality. *Is it warm all year but cool?* A city near the equator that is cool every month must be high in the mountains. *When does the rain fall?* Rain every month suggests rising air near the equator or steady ocean storms. Almost no rain suggests the dry, sinking air of the desert belts near 30° latitude or a rain shadow. A long wet season and a long dry season suggest a monsoon.

**On the map.** Look at the chart in the figure for Mystery City X. The temperature line stays between about 24 and 30°C (75 and 86°F) all year, so the city is in the tropics and not high up. The warmest month is May, just before the rains. Then come the bars: almost nothing from December to April, and then a flood of rain from June through September, with about 840 mm (33 inches) in July alone. This is the fingerprint of the Indian monsoon, when moist winds from the Indian Ocean blow onto the land each summer. Mystery City X is Mumbai, on the west coast of India. In this lesson you will meet more mystery cities. Each one’s climate comes from the same handful of physical causes, set in order by the Creator who promised that “cold and heat, and summer and winter” would not cease.

## Mystery City X



*Mystery City X. Bars: rainfall in mm (left scale). Line: average temperature in °C (right scale). Rounded long-term averages; exact numbers vary by station and years.*

## PICTURE STUDY



*Heart of the Andes*, Frederic Edwin Church, 1859 · Oil on canvas · The Metropolitan Museum of Art, New York

Frederic Church was an American painter who read Humboldt's books and followed his path to South America, traveling in Colombia and Ecuador in 1853 and again in 1857. Back in his New York studio he painted this enormous canvas, about 10 feet (3 m) wide, combining many

sketches into one view. When it was shown in 1859, crowds lined up and paid to see it, some bringing opera glasses to study the details.

Church painted the idea Humboldt taught: near the equator, you can travel from steamy tropical forest to permanent snow without changing latitude at all, just by climbing. Every belt of plants in the picture is a climate zone set by altitude.

### **Look closely**

- Find the snow-covered peak in the distance. Why can snow last there so close to the equator?
- Look at the plants in the foreground. What kind of climate do they need?
- Find the village and the small figures in the painting. At what height do the people seem to live?
- Follow the land from front to back. Where do the plants change?

### **Talk about it**

1. If you made a climate chart for the foreground forest and another for the snowy peak, how would the temperature lines differ? How would they be alike?
2. Why do you think Church filled the picture with so many small, exact details?

## **PROJECT: MYSTERY CITY CLIMATE CARDS**

You will draw climate charts for six real cities on cards, without the names showing, and challenge your family to name each city. Drawing the charts yourself fixes the patterns in your memory.

### **You will need**

- Six index cards or half-sheets of graph paper
- A ruler, pencil, blue colored pencil and red colored pencil
- A world map or globe
- Sticky notes for the city names

### **Steps**

1. On each card, draw a box with twelve month columns (J F M A M J J A S O N D), a rainfall scale on the left and a temperature scale on the right.
2. Draw these six cities, using the rounded yearly figures as your guide (January and July temperatures; yearly rainfall): Singapore 27°C and 28°C, about 2,300 mm with rain every month; Cairo 14°C and 28°C, about 25 mm; Sydney 23°C and 13°C, about 1,200 mm spread through the year; Quito 14°C and 14°C, about 1,000 mm, drier from June to August; Yakutsk (Siberia) –39°C and 19°C, about 240 mm, mostly in summer; Vancouver 4°C and 18°C, about 1,200 mm, mostly in winter.
3. Sketch the temperature line in red through the January and July points, curving smoothly through the months between. Draw blue rain bars that fit each description.

4. Write the city name on a sticky note on the back of each card.
5. Shuffle the cards and challenge a family member to name each city from a list of the six names. Ask them to say which clue gave it away.
6. Find all six cities on the map and write one physical cause for each climate (latitude, altitude, ocean, continent, desert belt or winds).

### Tips

- Keep the same scales on every card so the charts can be compared fairly.
- The real monthly numbers for any city can be found in an atlas or a national weather service's climate tables; ask a parent to help you check one.

### Check your work

- All six cards use the same scales and show the right warmest month.
- My family could name at least four cities from my charts.
- I can give a physical cause for each city's climate.

## MAP NOTEBOOK

1. Draw a tiny thumbnail chart for each of three climates (equatorial rain, desert, monsoon) and label the clue that gives each one away.
2. On a sketch map of the world, mark Quito and Singapore near the equator and write their elevations: Quito about 2,850 m (9,350 feet), Singapore near sea level.
3. Draw Humboldt's idea: two straight latitude lines and one wavy isotherm that bends north over a western ocean coast.

**From history.** Humboldt spent five years, from 1799 to 1804, traveling in Spanish America with the French botanist Aimé Bonpland. In 1802 they climbed high on Chimborazo in Ecuador, then thought to be the highest mountain in the world, carrying thermometers and a barometer, and recorded how plants changed with height. Humboldt later drew a famous cross-section of the mountain showing which plants grew at each level, an early picture of climate changing with altitude.

## WORKED EXAMPLES

**Example 1.** Mystery City Q: Every month averages about 14°C (57°F). Yearly rainfall is about 1,000 mm (39 inches), with a drier season from June to August. The city lies almost exactly on the equator. Which is it: Singapore, Quito or Cairo? Explain the clues.

1. The temperature hardly changes all year: a range of about 0°C. A tiny range points to a place near the equator, where the sun is high in every month.
2. But 14°C is cool, far cooler than a lowland equatorial city like Singapore, which averages about 27°C (81°F).
3. A city near the equator that is cool all year must be high above sea level. Air cools as it rises, by roughly 6.5°C for every 1,000 m (about 3.6°F per 1,000 feet).
4. Cairo is ruled out: it is near 30° N, has a range of about 14°C between January and July, and gets only about 25 mm (1 inch) of rain.
5. Check Quito: it stands about 2,850 m high in the Andes of Ecuador. It is about  $27 - 14 = 13^\circ\text{C}$  cooler than Singapore. At 6.5°C per 1,000 m, a drop of 13°C needs a climb of about  $13 \div 6.5 \times 1,000 = 2,000$  m, and Quito is higher than that, so altitude easily explains the cool air.

**Answer:** Mystery City Q is Quito, Ecuador. The equator gives it the same temperature all year; its altitude of about 2,850 m (9,350 feet) makes that temperature cool, giving it its name as the city of eternal spring.

## PRACTICE

1. **EASY** A mystery city averages 23°C (73°F) in January and 13°C (55°F) in July, with rain spread through the year. Which is it: Moscow, Cairo or Sydney? What is the key clue?
2. **MEDIUM** Yakutsk, in eastern Siberia, averages about -39°C (-38°F) in January and 19°C (66°F) in July. Find its annual temperature range in °C and °F. What does this tell you?
3. **MEDIUM** Vancouver and Winnipeg, Canada, lie at about the same latitude (about 49-50° N). Vancouver averages 4°C in January and 18°C in July; Winnipeg averages -16°C in January and 20°C in July. Find each range and explain the difference.
4. **HARD** Use the chart for Mystery City X. Add the rainfall for June, July, August and September. The yearly total is about 2,360 mm. What percent of the year's rain falls in those four months? Give the yearly total in inches (1 inch = 25.4 mm).  
*(Use the map or drawing "Read the June through September bars." shown earlier in this lesson.)*
5. **CHALLENGE** Cairo lies near 30° N and gets only about 25 mm (1 inch) of rain a year, while Singapore, near the equator, gets about 2,300 mm (about 90 inches). In three or four sentences, explain the physical causes of the difference.

## COMMON MISTAKES

- Assuming the warmest month is always July. In the Southern Hemisphere the warmest months are December to February.



- Thinking every city near the equator is hot. Altitude can make an equatorial city cool all year.
- Reading the rain bars against the temperature scale. Check which side of the chart each scale is on.

**Make it a game · Twenty Climate Questions.** One player secretly chooses a city from the six climate cards or from a world map. The others may ask up to twenty yes-or-no questions, but only about climate and physical geography: “Is the warmest month January?” “Is it near the sea?” “Is it high in the mountains?” “Does it get more than 1,000 mm of rain?” The player who names the city wins and chooses the next one.

**Scripture.** “While the earth remaineth, seedtime and harvest, and cold and heat, and summer and winter, and day and night shall not cease.” (Genesis 8:22, KJV)

A climate chart is possible only because the seasons return in faithful order year after year. God promised Noah that this order would continue, and every farmer who plants by the seasons trusts that promise.

#### Practice answers

1. Sydney, Australia. January is the warmest month, so the city is in the Southern Hemisphere, and only Sydney is south of the equator.
2.  $19 - (-39) = 58^{\circ}\text{C}$ ;  $66 - (-38) = 104^{\circ}\text{F}$ . Such a huge range shows extreme continentality: Yakutsk lies deep inside the largest continent, far from any ocean to soften its winter and summer.
3. Vancouver:  $18 - 4 = 14^{\circ}\text{C}$ . Winnipeg:  $20 - (-16) = 36^{\circ}\text{C}$ . Vancouver is on the Pacific coast, where westerly winds blow in from an ocean that warms and cools slowly. Winnipeg is in the middle of the continent, so its winters are much colder and its summers a little warmer.
4.  $520 + 840 + 550 + 340 = 2,250$  mm.  $2,250 \div 2,360 \approx 0.95$ , so about 95 percent.  $2,360 \div 25.4 \approx 93$  inches a year.
5. Near the equator the sun heats the ground strongly all year, so warm, moist air rises, cools and drops its water as heavy rain almost every day. That air spreads toward the poles high in the sky and sinks again near  $30^{\circ}$  latitude. Sinking air warms and dries, so clouds rarely form, and a belt of deserts, including the Sahara where Cairo lies, stretches around the world near  $30^{\circ}$ . Singapore is also surrounded by warm sea, which supplies plenty of moisture.



## 9.4 MAKE A STREAM-TABLE MAP

### OBJECTIVES

- Build a stream table and map the river it carves at timed intervals on a grid.
- Identify cut banks, point bars and a delta on a stream-table map and give their grid squares.
- Use horizontal and vertical model scales, as the engineers of the Mississippi River Basin Model did, to turn model measurements into real distances.

**Warm-up.** Tilt a baking sheet slightly and pour a spoonful of water at the high end. Watch the path it takes. Pour another spoonful in exactly the same place. Does the second trickle follow the first one's path? Sprinkle a pinch of sugar or salt in the way and pour again. What does the water do when something blocks it?

**Watch.** *Flood vs Steady Side by Side* (Emriver, Inc., 5:35).

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

During the project: compare the two stream tables side by side to see how a sudden flood reshapes the land differently from a steady flow, and try both on your own model.

**Note:** Captions were not available to check, but this looks like wordless stream-table footage from the model's maker; preview it first. The model's size is given in meters.

### KEY TERMS

#### stream table

A tilted tray of sand or soil with water running across it, used to watch rivers carve, carry and drop sediment.

#### cut bank

The steep outer bank of a river bend, where the fastest water wears the bank away.

#### point bar

The low sandbar on the inside of a bend, where slower water drops sediment.

#### vertical exaggeration

Making heights on a model or profile larger in scale than horizontal distances so that slopes can be seen and measured.

#### sinuosity

How much a river winds: the channel length divided by the straight-line distance between its ends.

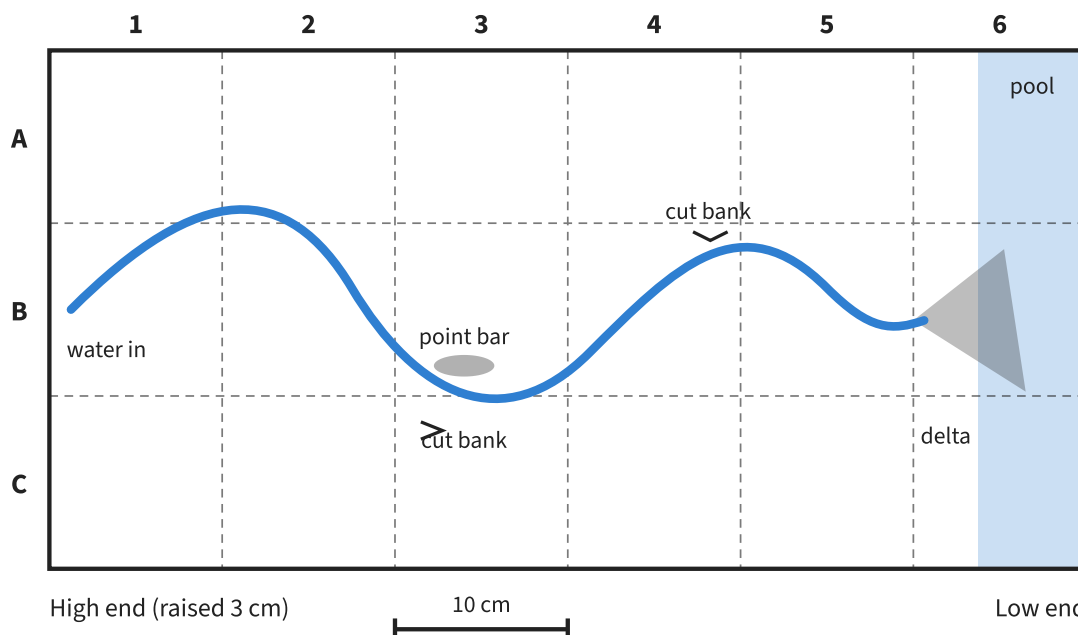
### CORE IDEAS

**The story.** After the great Mississippi flood of 1927, engineers of the U.S. Army Corps of Engineers wanted a way to test flood plans before trying them on a real river. In 1943 they began building one of the largest models ever made, the Mississippi River Basin Model, on

about 200 acres of rolling land near Clinton, Mississippi. Workers, including German prisoners of war held at a nearby camp, cleared the ground, and over the following years crews shaped in concrete the valleys of the Mississippi and its great branches, the Missouri, Ohio, Arkansas, Tennessee and more. The model shrank horizontal distances by 2,000 times but heights by only 100 times, so the gentle slopes of the real valleys would show up and water would flow realistically. Engineers poured in measured floods and watched where water rose against levees and towns. During the Missouri River flood of 1952 they used it to help forecast how high the water would rise downstream, giving cities time to prepare.

**How it works.** A stream table is the same idea on your kitchen table. Water running down a tilted tray of sand behaves like a small river: it picks up sand where it flows fast and drops it where it slows. On a bend, the fastest water swings to the outside, cutting a steep **cut bank**, while on the inside slower water drops a low **point bar**. Over minutes, the bends grow, wander and sometimes cut through to make a shortcut. Where the stream reaches the still water of a pool, it slows suddenly and drops its load in a fan-shaped **delta**. Mapping these changes is the real lesson. A river map is only true for one moment; a series of maps shows the river at work.

**On the map.** Look at the figure. It is a map of a stream table 60 cm long and 30 cm wide (about 24 by 12 inches), with a grid of 10 cm squares. Columns are numbered 1 to 6 from the high end, and rows are lettered A to C from top to bottom. Water enters at the left in square B1, winds through bends with cut banks and point bars, and builds a delta in square B6 where it meets the pool. You will build your own table, run water through it, and draw the river at 0, 5 and 10 minutes on the same grid. Then you will measure your river with a string and turn your model numbers into real ones, just as the Corps engineers did on their model of the whole Mississippi river system.



*A stream-table map, 60 cm × 30 cm, with a 10 cm grid. The high end, raised 3 cm, is at the left.*

## PICTURE STUDY



Mississippi Basin Model  
Vertical scale - 1:100; horizontal scale - 1:2000. Looking upstream on the Ohio River from Evansville. Indiana, Tennessee, and Cumberland Rivers are in the foreground showing the site of the Kentucky and Barkley Dams. Tradewater and Green Rivers are shown center. File No. 1270-4

*The Mississippi River Basin Model, Clinton, Mississippi, U.S. Army Corps of Engineers photographers, about 1950s · Photograph · U.S. Army Corps of Engineers collections (U.S. government works, public domain)*

The Corps of Engineers photographed the Mississippi River Basin Model many times while it was in use. The pictures show narrow concrete channels winding across the open countryside, small model towns and levees beside them, and engineers in shirtsleeves watching gauges. From the ground it looks like a strange, empty landscape; from the air it looks like a map come to life.

Today the site is a park, and much of the concrete model can still be seen, overgrown with grass and trees. The photographs remain the best way to imagine it full of water.

### Look closely

- Find something in the photograph that shows scale, such as a building, a road, a tree or a person. How big are the channels compared with it?
- Look for bends in the channels. Do they look like the meanders of a real river on a map?
- Look for gauges, pipes or small buildings. What do you think engineers measured?

### Talk about it

1. Why would engineers build a model this large instead of a small one on a table?
2. What can a physical model show that a map alone cannot?

**Safety first.** Work outdoors or on a covered table, wipe up spills at once so no one slips, and wash your hands after handling wet sand or soil.

## PROJECT: MY STREAM-TABLE MAP

You will build a stream table, run a river through it, and make three maps on graph paper showing how the river changes over 10 minutes. Then you will measure your river and test a small levee.

### You will need

- A long plastic tray, paint-roller tray or storage-bin lid about 60 cm (24 inches) long
- Fine sand or a mix of sand and a little soil, enough to fill the tray about 3 cm (just over 1 inch) deep
- A paper cup with a pinhole in the bottom, or a plastic bottle with a small hole in the cap
- A pitcher of water and a bucket to catch the overflow
- Books or blocks to raise one end 3 cm
- Masking tape or string to make a 10 cm grid over the tray; graph paper ruled to match
- A ruler, a piece of string and colored pencils (three colors)
- Modeling clay for the levee test

### Steps

1. Fill the tray with damp sand and smooth it flat. Scoop out a shallow pool, about 8 cm long, at the low end.
2. Run tape or string across the top of the tray every 10 cm to make a grid. Number the columns from the high end (1, 2, 3 ...) and letter the rows (A, B, C). Draw the same grid on graph paper.
3. Raise the high end 3 cm. Hold the cup at the middle of the high end (square B1) and keep it filled from the pitcher so water drips steadily.
4. At 0 minutes, as the first water runs, draw its path on your map in the first color.
5. At 5 minutes and at 10 minutes, stop the water and draw the channel again in the second and third colors on the same map. Mark each cut bank with a short zigzag, each point bar with dots, and the delta with a fan.
6. Lay a string along the channel from inlet to pool, then straighten it and measure it. Measure the straight distance between the same two points. Divide to find the sinuosity.
7. Press a thin ridge of clay along one side of the channel as a levee and run the water again. Map where the water goes and whether the river cuts deeper or spills elsewhere.
8. Raise the high end to 6 cm, smooth a fresh table and repeat for 5 minutes. Compare the two rivers.

### Tips

- A slow, steady drip makes better meanders than a gush; a gush cuts a straight ditch.
- Take a photo from straight above each time you map. A photo and a hand-drawn map together make a strong record.

- Damp sand holds banks better than dry sand.

### Check your work

- My map shows the river at 0, 5 and 10 minutes in three colors on a labeled grid.
- I marked at least one cut bank, one point bar and the delta, with their grid squares.
- I measured my river's length and found its sinuosity.

### MAP NOTEBOOK

1. Draw one river bend from above. Mark the fast water on the outside with long arrows and the slow water on the inside with short arrows, and label the cut bank and point bar.
2. Draw a side view across a river bend: a steep cut bank on one side and a gently sloping point bar on the other.
3. Write three sentences comparing your 3 cm river with your 6 cm river. Which one wandered more?

**From history.** Physical models of rivers and harbors were common engineering tools for much of the twentieth century. The Corps of Engineers built many of them at its Waterways Experiment Station in Vicksburg, Mississippi, founded a few years after the 1927 flood. Later, computers could do much of the same work with numbers, and the great Clinton model fell out of use. But engineers still build scale models in laboratories today to test dams, spillways and harbor walls, because water sometimes surprises even the best calculations.

### WORKED EXAMPLES

**Example 1.** A student's stream table is 60 cm long. The string laid along the river from inlet to pool measures 84 cm. The tray stands for a valley at a scale of 1:5,000. Find the river's sinuosity and its real length in kilometers and miles.

*(Use the map or drawing "The string follows every bend; the straight line runs the length of the tray." shown earlier in this lesson.)*

1. Sinuosity = channel length  $\div$  straight distance =  $84 \text{ cm} \div 60 \text{ cm} = 1.4$ . The river is 40 percent longer than a straight line.
2. At 1:5,000, every 1 cm on the model stands for 5,000 cm on the ground.  $84 \text{ cm} \times 5,000 = 420,000 \text{ cm}$ .
3.  $420,000 \text{ cm} \div 100 = 4,200 \text{ m} = 4.2 \text{ km}$ .
4.  $4.2 \text{ km} \times 0.62 \approx 2.6 \text{ miles}$ .

**Answer:** The sinuosity is 1.4, and the river stands for a real river about 4.2 km (about 2.6 miles) long.

## PRACTICE

1. **EASY** On the stream-table map, in which grid square does the water enter, and in which square is the delta?  
*(Use the map or drawing “Read the column number across the top and the row letter down the side.” shown earlier in this lesson.)*
2. **EASY** The Mississippi River Basin Model used a horizontal scale of 1:2,000. How much real distance did 1 m of model stand for? How much did 50 m of model stand for, in kilometers and miles?
3. **MEDIUM** The model’s vertical scale was 1:100 and its horizontal scale 1:2,000. What was the vertical exaggeration? If water rose 5 cm on the model, how much would that be on the real river, in meters and feet?
4. **MEDIUM** Your stream table is 60 cm long and raised 3 cm at the high end. What is its slope as a percent? If you raise it to 6 cm, what happens to the slope, and how do you expect the river to change?
5. **HARD** Explain why sand is worn away on the outside of a bend but piles up on the inside. Then explain why a delta forms where the stream meets the pool.

## COMMON MISTAKES

- Drawing only one map. A river changes; mapping it at several times is what shows the process.
- Using a big gush of water. Too much flow cuts a straight ditch and hides the meanders.
- Forgetting that a model can have two scales. On a vertically exaggerated model, heights and lengths must be converted with different numbers.

**Make it a game • River Engineer Challenge.** Smooth a fresh stream table. One player places a small toy house or block near the river as a “town.” The other player has one lump of clay and three tries to build a levee, a channel or a pond that keeps the town dry when a full cup of water is poured at the high end. Score 3 points for a dry town on the first try, 2 on the second and 1 on the third. Switch roles and move the town each round.

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

Your stream table runs from the high end to the pool, just as every river runs to the sea. The Preacher saw the great water cycle God set in motion, and you can watch a small piece of it in a tray of sand.

### Practice answers

1. The water enters in square B1. The delta is in square B6, beside the pool.
2.  $1 \text{ m} \times 2,000 = 2,000 \text{ m} = 2 \text{ km}$  (about 1.2 miles).  $50 \text{ m} \times 2,000 = 100,000 \text{ m} = 100 \text{ km}$  (about 62 miles).
3. Vertical exaggeration =  $2,000 \div 100 = 20$  times.  $5 \text{ cm} \times 100 = 500 \text{ cm} = 5 \text{ m}$ , about 16 feet.

4.  $3 \div 60 = 0.05 = 5$  percent. At 6 cm the slope doubles to 10 percent. The water flows faster, cuts a straighter and deeper channel, carries more sand, and builds a bigger delta; it meanders less.
5. On a bend the fastest water swings to the outside, and fast water has the energy to pick up sand, so it wears away the outer bank (the cut bank). On the inside the water moves slowly and cannot carry as much, so it drops sand as a point bar. At the pool the moving stream suddenly meets still water, slows almost to a stop, and drops nearly all the sand it was carrying, building a fan-shaped delta.



## UNIT 9 REVIEW

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Answer each question. Show your work for calculations, give both metric and U.S. units where asked, and use complete sentences for explanations. The review is worth 60 points.

1. (10 pts) On a contour map, two index contours are labeled 300 m and 400 m, with four thin lines between them. (a) What is the contour interval? (b) A point lies on the third thin line above 300 m. What is its elevation in meters and about how many feet? (c) A summit on the same map has a spot height of 467 m. What is the elevation of the smallest contour loop around it?
2. (10 pts) A stream crosses three contour lines, and each line bends into a V whose point aims northeast. Which way does the stream flow? Then describe how a saddle looks on a contour map and why travelers often cross a ridge there.
3. (10 pts) Match each earthquake to its plate edge and give one clue for each: (a) Alaska, 1964; (b) San Francisco, 1906; (c) Reykjanes Peninsula, Iceland, 2021; (d) New Madrid, Missouri, 1811–1812.
4. (10 pts) A mystery city averages 25°C (77°F) in January and 15°C (59°F) in July, with rain in every month. (a) In which hemisphere is it, and how do you know? (b) What is its annual range in °C and °F? (c) Is it more likely on a coast or deep inside a continent? Explain.
5. (10 pts) Quito and Singapore are both near the equator, but Quito averages about 14°C (57°F) and Singapore about 27°C (81°F). Vancouver and Winnipeg are at about the same latitude, but Vancouver's annual range is about 14°C and Winnipeg's about 36°C. Name the physical cause of each difference and explain it in two or three sentences.
6. (10 pts) The Mississippi River Basin Model used a horizontal scale of 1:2,000 and a vertical scale of 1:100. (a) A model channel 3 m long stands for how long a real river, in kilometers and miles? (b) Water rises 4 cm on the model. How much is that on the real river, in meters and feet? (c) What is the vertical exaggeration? (d) On a stream table, where on a river bend does sand pile up, and what is that feature called?

## UNIT PROJECT: MY MAP LAB FIELD BOOK

Gather your four Map Lab projects into one field book: your contour match-up cards and a photo of your cardboard contour model, your earthquake detective board with its case files, your six mystery-city climate cards, and your three-color stream-table map with your measurements. Add a title page with a hand-drawn world map marking every real place you studied in this unit (Mount Everest, Alaska, Chile, Nepal, Iceland, New Madrid, Mumbai, Quito, Sydney, Yakutsk and the Mississippi), and finish with a paragraph explaining which map skill you found most useful and how it could help people prepare for a natural hazard.

- **Accuracy:** Contours, earthquake positions, climate charts and grid squares are correct, and every calculation shows its units in both metric and U.S. measures where asked.

- **Reasoning:** Each earthquake case file and mystery city names the clues used and the physical cause behind the answer.
- **Records:** The stream-table map shows three timed stages with cut banks, point bars and the delta labeled, and the river length and sinuosity are measured.
- **Care:** The field book is neat, labeled and organized, with a clear world map on the title page and a thoughtful closing paragraph.

#### Answer key

1. (a)  $100 \text{ m} \div 5 = 20 \text{ m}$ . (b)  $300 + 3 \times 20 = 360 \text{ m}$ , about 1,181 feet ( $360 \div 0.3048$ ). (c) Contours run every 20 m (420, 440, 460, 480 ...). The highest one below 467 m is 460 m, so the smallest loop around the summit is the 460 m line.
2. The point of a contour V aims upstream, so the stream flows southwest. A saddle lies between two sets of closed loops (two summits), inside a larger line that wraps around both. It is the lowest point on the ridge between the summits, so it is the easiest place to cross.
3. (a) Converging edge, subduction zone: the Pacific Plate sliding under Alaska (clues: a trench offshore, volcanoes inland, coastal land raised and lowered as Plafker found with barnacles). (b) Sliding (transform) edge: the San Andreas Fault (a long straight fault; fences and roads offset sideways). (c) Spreading edge: the Mid-Atlantic Ridge on land (rift, small shallow earthquakes, lava eruption). (d) No plate edge: an intraplate earthquake in the middle of the North American Plate.
4. (a) The Southern Hemisphere, because January is the warmest month. (b)  $25 - 15 = 10^\circ\text{C}$ ;  $77 - 59 = 18^\circ\text{F}$ . (c) On a coast: a small range for a city outside the tropics shows that a nearby ocean, which warms and cools slowly, keeps its summers and winters mild.
5. Quito is cooler because of altitude: it stands about 2,850 m (9,350 feet) high, and air cools as it rises, roughly  $6.5^\circ\text{C}$  per 1,000 m. Winnipeg has the larger range because of continentality: it lies deep inside North America, far from the ocean, while Vancouver sits on the Pacific coast where ocean air keeps winters mild and summers cool.
6. (a)  $3 \text{ m} \times 2,000 = 6,000 \text{ m} = 6 \text{ km}$ , about 3.7 miles. (b)  $4 \text{ cm} \times 100 = 400 \text{ cm} = 4 \text{ m}$ , about 13 feet. (c)  $2,000 \div 100 = 20$  times. (d) On the inside of the bend, where the water is slowest; it is a point bar.