SCHOOL LAUNCH · EARTH SCIENCE K–8

Grade 8 Earth Science: Earth Resources and Careers

A year of true stories about the ground under our feet and the people who work it, from the black blizzards of the Dust Bowl and the woman at Jacob’s well to the gold at Sutter’s Mill, Drake’s first oil well, the gusher at Spindletop, William Smith’s map that changed the world and the forecasters of the National Weather Service, each one taken apart to see how it works, measured at the kitchen table or in the back yard, and gathered at the end into a real report on the earth resources of the student’s own county.

First edition

> *“In the beginning God created the heaven and the earth.” (Genesis 1:1, KJV)*

Course guide

This course follows the earth's resources through one school year: soil, groundwater, minerals and mines, oil, gas and coal, the maps that show where they lie, and the weather that governs the people who dig, drill, plant and fly. Each unit is built around real moments from history: the dust storms that darkened Cimarron County in 1935, Jacob's well at Sychar, James Marshall's flake of gold in the tailrace at Sutter's Mill in 1848, Edwin Drake's sixty-nine-foot well at Titusville in 1859, the Lucas gusher at Spindletop in 1901, William Smith's 1815 geological map of England and Wales, and the founding of a national weather service in 1870. The year ends with a capstone: the student gathers maps and samples, interviews a working geologist, driller, miner or forecaster, and writes and presents an earth-resources report on his or her own county.

Every lesson follows the same path. First comes **the story**. Then **how they figured it out**: what people saw, what they measured, what failed and what they changed. Then **the big idea** underneath, explained for an eighth grader and building toward high-school Earth Science: soil horizons and erosion rates, porosity and permeability, ore grade and the cost of a ton, source rock, trap and reservoir, contour lines and map scale, pressure, fronts and forecasts. Then **at work today**: how a soil scientist, well driller, mine engineer, petroleum geologist, GIS technician or meteorologist uses the idea now, what the job pays and asks, and what a careful and honest person does with it. Last, the student does it in miniature: a soil column in a jar, a model aquifer in a clear box, a cardboard open-pit mine, a candle-wax oil trap, a potato topographic map, a week of forecasts checked against the sky.

Measurement runs through everything. Students read data tables and graphs the way a working scientist does, work three quantitative examples in every lesson, and finish ten practice problems with answers, including two data-reading items in the style of the SAT and ACT science-reasoning sections and one experiment-design item. Metric units are used throughout, because they are the units of every laboratory, drilling rig and weather station in the world.

The course is written from a Christian view of the world. "In the beginning God created the heaven and the earth." (Genesis 1:1) The iron in the hills, the water in the aquifer and the oil in the trap are gifts to be found, used wisely and handed on, as Moses told Israel of "a land whose stones are iron, and out of whose hills thou mayest dig brass" (Deuteronomy 8:9). Job 28 is the course's poem: man cuts channels through the rock and brings hidden things to light, yet wisdom is found only in the fear of the Lord. Unit 7 lays out the young-earth, old-earth and secular accounts of the earth's history fairly, each in its own strongest form, and teaches the student to summarize a view he or she does not hold without caricature.

WHO IT IS FOR

Written for students in grade 8 (about ages 13–14) who read independently, can work with ratios, rates, percents and simple linear equations, and can plot and read a graph. No prior earth science is needed, though the Grade 6 and Grade 7 courses in this series are good

preparation. A parent or teacher reads the core ideas when wanted, supervises experiments, checks practice answers and helps arrange the career interview and the county capstone. Nothing needs to be bought beyond ordinary household items and a free computer program for the map unit.

HOW TO USE THIS COURSE

The weekly rhythm. The year has 32 lessons, one a week, plus an optional four-lesson Field Lab. Each lesson takes two sessions of 45 minutes. Session 1 is the warm-up, the story, the core ideas, the key terms and the picture study, with the three worked examples done together. Session 2 is the experiment, the field notebook entry and the ten practice problems. In the last week of each unit add a third session for the unit test and the unit project.

The ★ quarter path. Ten lessons are marked with a star: 1.1, 2.1, 3.1, 3.2, 4.1, 5.1, 5.2, 6.1, 7.1 and 8.4. A family with one quarter to give to earth science can do those ten in order and still meet soil, groundwater, mines, oil, maps, weather and the origins question, and finish with the county report. Lessons marked ⏳ carry a Thinking About Time box, explained below.

The field notebook. Use one graph-paper composition book for the whole year. Every experiment ends with something measured and written down: a soil-column drawing with layer thicknesses in centimeters, a table of drainage times, a mine's ore grade and cost per ton, a contour sketch, a week of pressure and temperature readings. Date every page, label every column with its unit, and write one sentence on what the numbers mean and one on what you would change. Honest records matter more than tidy ones; a result that surprised you, written down plainly, is worth more than a result you expected.

Experiments and safety. Every experiment works with household things: jars, sand, gravel, clay, a kitchen scale, a measuring cup, vinegar, candle wax, cardboard, string and a potato. A parent supervises anything with heat, a knife or a drill, and safety glasses go on for any rock-breaking or chemical test. Field Lab days are done only with an adult, on land you have permission to walk, and never near an open well, a quarry edge or a mine opening. Rock and soil samples are washed off the hands before eating.

Worked examples, practice, unit tests and unit projects. Each lesson's three worked examples are quantitative: an erosion rate in tonnes per hectare, a porosity ratio, an ore-grade calculation, a decline curve read from a graph, a map scale, a half-life worked step by step. The ten practice problems follow the same pattern and have answers, so the student can check his or her own work and the parent can see at a glance where help is needed. Each unit ends with a 60-point test of 10–12 problems (multiple choice, short answer and one diagram to label or draw) and a unit project such as a soil-testing report, a model well log, a mine reclamation plan, a barrel-of-oil chart, a county geology map, a forecast log, a respectful summary of three origins views and, in Unit 8, the county earth-resources report.

A word about time. This course is written from a Christian view of creation (Genesis 1:1) and of the Flood (Genesis 6–9). Students will meet deep-time names such as "Jurassic,"

“Carboniferous” or “Ice Age” on museum signs, on the USGS map of their county and in every textbook, and they are taught here as museum words: the labels by which rock layers are named and ordered, so the student can read any sign, map or book with understanding. Wherever a deep-time claim comes up, a ⏳ Thinking About Time box sets out three things plainly: what the sign says, what we actually observe in the rock, and how Christians have read it. The box reports the textbook number with its source, for example “the museum sign says about 66 million years,” and leaves the student able to explain both the observation and the interpretations with honesty and respect.

SCOPE AND SEQUENCE

Unit 1: Soil (1–4)

The Dust Bowl and what it taught; the O, A, B and C horizons; contour plowing and the Soil Conservation Service; testing texture, drainage and pH in a jar.

Unit 2: Water Wells (5–8)

Jacob’s well and the water under the ground; aquifers, porosity and permeability; drilling and logging a model well; who owns the water in the dry West.

Unit 3: Minerals and Mining (9–12)

Gold at Sutter’s Mill; open-pit and underground mines and the arithmetic of ore grade; mine safety and the Act of 1977; putting the land back.

Unit 4: Oil, Gas and Coal (13–16)

Drake’s well at Titusville; the Lucas gusher at Spindletop; source rock, reservoir, seal and trap; refining a barrel into the things we use.

Unit 5: Maps and GIS (17–20)

William Smith’s map of 1815; reading contour lines and scale on a topographic map; a first look at free GIS software; mapping the student’s own county from the USGS.

Unit 6: Weather Careers (21–24)

The National Weather Service from 1870 to today; how storm chasers and forecasters gather and read data; weather for pilots; interviewing someone whose work depends on the sky.

Unit 7: Origins Debate Fairly Told ⏳ (25–28)

The young-earth creation view; old-earth Christian views (day-age and gap) summarized fairly; what secular geology claims and why; writing a respectful summary of each.

Unit 8: Capstone: My County’s Earth Resources (29–32)

Choosing the county and gathering its maps; collecting and labeling soil, rock and water samples; interviewing a working geologist, driller, miner or forecaster; writing and

presenting the report.

Unit 9: Field Lab (optional bonus unit) (Optional)

Four field days with an adult: a soil survey across the yard or a park, a visit to a working well, a walk across the county rock map, and a day of interviews.

MATERIALS

- **Field notebook (a graph-paper composition book)**: One for the whole year: soil columns, drainage tables, well logs, ore-grade calculations, contour sketches, weather logs and the county report drafts.
- **Clear jars, a clear plastic box or cut-down bottle, and a bag each of sand, gravel and potting soil or clay**: For the soil column, the drainage test and the model aquifer and well in Units 1 and 2.
- **Kitchen scale (grams), measuring cup (milliliters), metric ruler or tape, and a stopwatch or phone timer**: Nearly every experiment measures mass, volume, length or time in metric units.
- **White vinegar, a drinking straw, a steel nail, a penny and a hand lens**: For mineral hardness and acid tests in Unit 3 and sample identification in Unit 8.
- **Candle wax or cooking oil, food coloring, a cardboard box and string**: For the oil-trap model in Unit 4 and the cardboard open-pit mine in Unit 3.
- **A potato or modeling clay, toothpicks and a sharp knife (parent handles the knife)**: For the topographic map model in Unit 5.
- **A computer with internet access**: For the free QGIS program in Unit 5, the free USGS geologic and topographic maps of your county, and National Weather Service forecasts and data in Unit 6.
- **Safety glasses, work gloves and a bucket with zip bags and labels**: For rock-breaking, acid tests and sample collecting in Unit 8 and the Field Lab.
- **A simple barometer or a free weather app that reports pressure, and an outdoor thermometer**: For the week of forecasts and readings in Unit 6.
- **Optional: a field guide to rocks and minerals or a small labeled rock kit**: Never required. See the list in each unit.

GRADING

Grades come from the unit tests, the field notebook, the experiments and the unit projects, with the county capstone standing in for a final exam. Earth science is learned by measuring and recording, so an experiment whose numbers did not turn out as expected but are honestly recorded and explained earns full credit.

- Unit tests (eight tests, 60 points each): 35%
- Field notebook (dated pages, labeled units, honest records, one sentence of meaning): 20%
- Experiments and weekly practice (predict, measure, record, check the answers): 20%

- Unit projects (Units 1–7): 15%
- Capstone county earth-resources report and presentation: 10%

A 90–100, B 80–89, C 70–79, D 60–69. Below 60: redo the test or the notebook pages with help and retake.

- Each unit test is 60 points and has 10–12 problems: multiple choice, short answer and one diagram to label or draw. Answers and a point breakdown are given with each test.
- Grade the process as well as the result. Did the student predict, measure in metric units, record honestly, explain the numbers and suggest an improvement?
- A field notebook page earns full marks when it has a date, a title, labeled columns with units, correct arithmetic and one sentence about what the numbers mean.
- The Unit 7 project is graded on fairness and accuracy: can the student state each view in a form its own holders would recognize? It is not graded on which view the student holds.
- Unit tests may be done orally for a student who writes slowly; the parent records the answers. The Field Lab is ungraded.
- Keep each unit’s project in one folder. Together with the capstone report they make a fine record of the year and a strong start on a high-school science portfolio.

A NOTE TO PARENTS

You do not need to be a geologist to teach this course. Read the story together, do the experiment at the kitchen table, and ask three questions: “What did you measure?”, “What does the number mean?” and “How would you check it?” The worked examples are written out step by step, and every practice problem has an answer, so you can mark the work and see at a glance where a second look is needed. The career interview and the county capstone are the two places where your help matters most: a phone call to a county extension office, a well driller, a quarry, a surveyor or the local National Weather Service office will usually find someone glad to talk to a serious thirteen-year-old.

The course is written from a Christian view of creation and of the Flood, and it is honest about the fact that Christians have read the earth’s history in more than one way. Unit 7 presents the young-earth view, the old-earth views and the secular account each in its strongest form, and the project asks the student to summarize all three so fairly that a holder of each would say “yes, that is what I think.” The deep-time names on museum signs and government maps are taught as the working vocabulary of the field, so that your student can read any map or textbook and still think clearly about what was observed and what was inferred. Nothing in the course asks you or your child to take a side in present-day public debates about energy or land use; mining, drilling and farming are shown with their real benefits, their real costs and the rules that grew up around them.

Experiments and field days need an adult nearby: for the knife and the heat, for the acid test, and for any walk near water, rock cuts or working ground. Above all, the course hopes to raise a young person who looks closely at the ground God made, measures it honestly, respects the people who work it, and can say with Job that man “cutteth out rivers among

the rocks; and his eye seeth every precious thing” (Job 28:10), and still knows where wisdom is found.

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★ quarter path · ⏳ Thinking About Time box

UNIT 1

Soil

Everything we eat comes, one way or another, out of a layer of ground that is often thinner than the height of a kitchen table. God “formed man of the dust of the ground” (Genesis 2:7) and set him in a garden “to dress it and to keep it” (Genesis 2:15). This unit is about that ground: what it is made of, how it is layered, how it is lost and how it is kept. You will begin on Black Sunday, April 14, 1935, when the sky over the southern Plains turned black with blowing topsoil, and you will follow Hugh Hammond Bennett to Washington, where the Soil Conservation Service was created less than two weeks later.

Then you will dig. With Vasily Dokuchaev on the Russian steppe you will learn to read a soil profile, horizon by horizon, and to sort a soil into sand, silt and clay with nothing but a jar of water. At Coon Valley, Wisconsin, you will see the first watershed where farmers plowed with the shape of the land instead of against it, and you will measure in a tray how much soil that saves. With George Washington Carver at Tuskegee you will learn to ask the soil what it needs, test its pH, and work out lime and fertilizer for a garden bed from a laboratory report.

Along the way you will practice the skills every Earth scientist and every working farmer uses: measuring slopes and rates, reading data tables, converting tonnes per hectare into millimeters of soil, and designing a fair test. The unit ends with your own soil report on a plot you have dug, tested and measured yourself.

BEFORE YOU BEGIN

- Can convert between millimeters, centimeters and meters and between grams, kilograms and tonnes
- Can calculate a percent and a ratio and read a bar graph or data table
- Knows that rock weathers into smaller pieces and that plants need water, air and nutrients from the soil
- Can follow a multi-step experiment, keep variables constant and record measurements in a notebook

MASTERY CHECKLIST

- I can explain the three causes of the Dust Bowl and how wind moves soil by creep, saltation and suspension.
- I can name and describe the soil horizons O, A, E, B, C and R and identify them in a diagram or a dug pit.
- I can classify a soil’s texture with the jar test using the USDA size limits for sand, silt and clay.
- I can calculate a slope percent and estimate soil loss in tonnes per hectare and millimeters per year, with and without contouring.
- I can explain what a soil test measures, compare pH values as powers of ten, and scale a per-hectare recommendation to a garden bed.

- I can tell the stories of Hugh Hammond Bennett, Vasily Dokuchaev, the Coon Valley farmers and George Washington Carver, and say what each taught about keeping the soil.

OPTIONAL BOOKS AND RESOURCES

- **USDA Web Soil Survey** (https://websoilsurvey.nrcs.usda.gov/): Free. Draw a box around your home or a nearby farm and the Natural Resources Conservation Service will show the mapped soil series, texture, drainage and slope for that spot. Use it to compare the official description with the pit you dig in Lesson 1.2.
- **Farm Security Administration photographs, Library of Congress** (https://www.loc.gov/pictures/collection/fsa/): Free. Search for “dust storm” or “Cimarron County” to see Arthur Rothstein’s 1936 photographs and thousands of others from the 1930s, all public domain and downloadable for your notebook.
- **Soils 4 Teachers (Soil Science Society of America)** (https://www.soils4teachers.org/): Free. Lesson plans, the soil texture triangle, soil profile posters and a state-soil map, written by soil scientists for students and teachers.

1.1 The Dust Bowl (1930s) ★

OBJECTIVES

- Tell what happened on Black Sunday, April 14, 1935, and explain the three causes of the Dust Bowl: plowed-up grassland, drought and wind.
- Describe how wind moves soil by creep, saltation and suspension, and calculate the mass of topsoil lost from a field in tonnes per hectare.
- Explain how Hugh Hammond Bennett and the Soil Conservation Service of 1935 helped farmers keep their soil, and read a rainfall data table to compare drought years with normal years.

Warm-up. Put a handful of dry flour on a plate and a handful of damp potting soil with a tuft of grass (roots and all) on another plate. Take both outside, hold them at arm's length, and blow across each one as hard as you can. Which one scatters? Which one stays? Write one sentence about why the roots matter.

Video. Coming soon. Dust Bowl 1930s Black Sunday documentary footage and Soil Conservation Service history; look for Library of Congress and National Archives newsreel clips, USDA NRCS history videos, PBS American Experience excerpts, Smithsonian and Ken Burns Dust Bowl trailers, and homeschool history channels such as Homeschool Pop (Alternate).

KEY TERMS

topsoil
The dark upper layer of soil, rich in humus and roots, where most plant food is held. It is the layer a farm cannot afford to lose.

erosion
The carrying away of soil or rock by wind, water or ice. Wind erosion is the kind that made the Dust Bowl.

sod
The top layer of a grassland, where living and dead grass roots knit the soil into a tough mat that wind and rain cannot easily break.

drought
A long stretch of much less rain than normal. The southern Plains drought ran, with few breaks, from about 1931 to 1939.

saltation
The bouncing motion of sand-sized grains in wind. Bouncing grains knock loose finer silt and clay, which rise as dust.

Soil Conservation Service
The United States agency created by the Soil Conservation Act of April 27, 1935, to help farmers stop erosion. Since 1994 it has been called the Natural Resources Conservation

Service (NRCS).

CORE IDEAS

The story. Sunday, April 14, 1935, began as a clear, warm spring day in the Oklahoma panhandle. Families went to church, hung laundry, and sat on porches. In the middle of the afternoon the temperature dropped, birds flew past in a panic, and a wall of black dust hundreds of meters high rolled in from the north. Within minutes, day became night. People could not see their own hands. Drivers stopped on the roads. Children were caught in the open and found their way home by following fences. Dust sifted through every crack and settled in drifts against barns like dirty snow. People remembered it as *Black Sunday*. The next day an Associated Press reporter named Robert Geiger, writing from Guymon, Oklahoma, used two words that stuck: the *Dust Bowl*. The worst-hit region covered the panhandles of Oklahoma and Texas, southwestern Kansas, southeastern Colorado and northeastern New Mexico, an area of roughly 400,000 square kilometers. A year after Black Sunday, in April 1936, a government photographer named Arthur Rothstein stood in Cimarron County, Oklahoma, and photographed a farmer and his two small sons leaning into the stinging wind beside a half-buried shed. His picture became the face of the disaster.

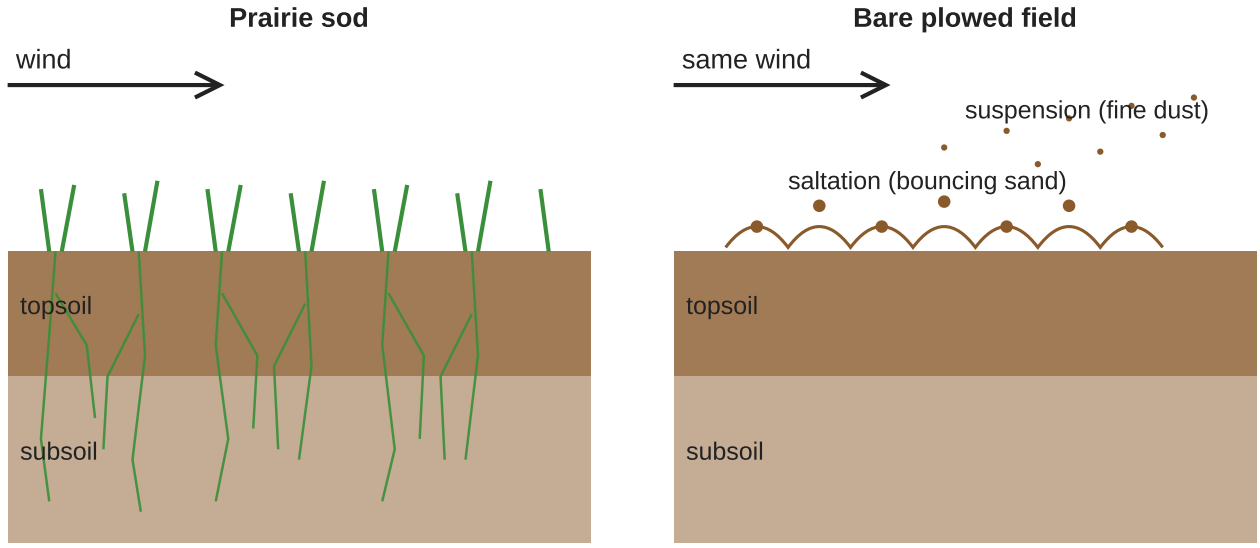
How they figured it out. Why did the sky fall in the 1930s and not before? For as long as anyone remembered, the southern Plains had been short-grass prairie. Buffalo grass and grama grass sent roots a meter or more into the ground and knit the soil into a tough mat called **sod**. The prairie had survived droughts before, because even when the grass turned brown, its roots held the soil. Then came the First World War. Wheat prices soared, new gasoline tractors and one-way disk plows made it possible for one farmer to break far more land than a team of horses could, and in the 1920s farmers turned millions of hectares of grass into wheat fields. Historians call it the Great Plow-Up. Wheat prices collapsed in 1929, and in 1931 the rains failed and kept failing for most of a decade. Now the soil lay bare, dry and powdery, with nothing to hold it, under a Plains wind that blew hard every spring. One soil scientist in the Department of Agriculture had been warning about this for years. His name was Hugh Hammond Bennett, and in 1928 he had written a government bulletin called *Soil Erosion: A National Menace*. In the spring of 1935 Bennett was explaining erosion to a Senate committee when dust that had blown all the way from the Plains dimmed the sky over Washington itself. Congress passed the Soil Conservation Act, and President Roosevelt signed it on April 27, 1935. It created the **Soil Conservation Service**, with Bennett as its first chief.

The big idea. Soil is a resource, like iron ore or clean water, and **erosion** is how it is lost. Wind erosion works in three ways. Large grains too heavy to lift roll along the surface, which is called *creep*. Sand-sized grains, about 0.1 to 0.5 mm across, hop along in short bounces, which is called **saltation**. Each bouncing grain strikes the ground like a tiny hammer and knocks loose silt and clay particles far smaller than itself. Those fine particles rise into *suspension* and can travel hundreds or thousands of kilometers; dust from the Plains fell on ships in the Atlantic. Dry, bare, fine-grained soil begins to move in winds of roughly 20 kilometers per hour. The loss adds up fast. Topsoil has a density of about 1.3 grams per cubic centimeter, so stripping just 1 millimeter from one hectare removes about 13 tonnes of soil.

A single storm in May 1934 was estimated at the time to carry roughly 300 million tonnes of soil eastward. The richest part of a soil is its **topsoil**, so a farm loses its best layer first.

In the world today. The Dust Bowl ended because the rains returned around 1939 and 1940, but it also ended because people changed how they farmed. Soil Conservation Service agents worked with farmers county by county to plow along the contour of the land, to plant strips of grass between strips of crops, and to leave stubble on the fields through the winter. The Prairie States Forestry Project of 1935 to 1942 planted more than 200 million trees in shelterbelts from North Dakota to Texas to slow the wind. The government bought the worst land and seeded it back to grass; today you can walk on it in the Cimarron National Grassland in Kansas and the Comanche National Grassland in Colorado. Modern farmers go further with no-till planting, which leaves the old crop residue on the surface, and with cover crops that keep living roots in the ground all year. The Natural Resources Conservation Service still has an office in nearly every farming county, and every one of those offices traces back to Bennett and the spring of 1935.

God's handiwork. God "formed man of the dust of the ground" (Genesis 2:7) and set him in a garden "to dress it and to keep it" (Genesis 2:15). Soil is where the dust of the ground becomes bread, and it is His gift. The Dust Bowl was not a judgment anyone could read from the sky; it was the plain result of taking a good gift for granted, breaking the sod that God had grown over the Plains and leaving the ground naked to the wind. The farmers who stayed, learned, and planted trees and grass were not fighting nature. They were doing what Adam was told to do: dressing the land and keeping it. That is what this unit is about.



Same wind, two fields. Grass roots knit the topsoil into sod; a bare, dry plowed field gives the wind loose grains to bounce and lift.

PICTURE STUDY



Farmer and Sons Walking in the Face of a Dust Storm, Cimarron County, Oklahoma, Arthur Rothstein, April 1936 · Photograph (Farm Security Administration) · Library of Congress, Prints and Photographs Division, Washington, D.C.

Arthur Rothstein was twenty years old when the Resettlement Administration (later the Farm Security Administration) sent him west to photograph the Dust Bowl. In April 1936 he met a farmer named Arthur Coble and his sons Milton and Darrel on their farm in Cimarron County, in the far western tip of the Oklahoma panhandle, and photographed them walking into the wind beside a shed half-buried in drifted soil.

The picture was printed in newspapers across the country and became the single most famous image of the Dust Bowl. Notice that it is not a picture of a storm from far away. It is a picture of a family on their own land, trying to keep going.

Look closely

- Find the shed. How high has the soil drifted against its wall? What does that tell you about how many storms have passed?
- Look at the boys. One trails behind with a hand over his face. What is the wind doing to the smaller boy?
- Look at the ground. Can you see any plants at all? What should be growing on a farm in April?
- Look at the sky and the horizon. Where does the land end and the sky begin? Why is it hard to tell?

Talk about it

1. This picture shows a family walking across their own farm, not the storm cloud itself. Why would such an ordinary moment say more than a photo of the storm cloud itself?
2. What three things had to happen together to make a day like this: one thing people did, and two things people did not control?
3. If you were the Soil Conservation Service agent visiting this farm the next week, what would you suggest first?

> **Safety first.** The wind-erosion tray makes fine dust. Work outdoors or over a large tray, point the fan or hair dryer away from faces, and wear safety glasses. Do not breathe the dust; a simple dust mask is a good idea for the person holding the fan.

EXPERIMENT: WIND TUNNEL ON A TRAY: DOES COVER STOP WIND EROSION?

You will build three miniature fields in baking pans and blow the same wind across each one to measure how much soil each loses. **Question:** how much does plant cover or a surface crust reduce wind erosion? **Prediction:** write down which pan you think will lose the most soil and the least, and by roughly how much.

You will need

- Three identical shallow baking pans or foil trays
- Dry, sifted garden soil or sandy potting mix, enough to fill each pan 2 cm deep
- A square of living turf (grass with roots) or a tray of grass you sprouted two weeks ahead
- A spray bottle of water
- A small fan or a hair dryer on the cool setting
- A large sheet of white paper or an old sheet to catch blown soil, a kitchen scale, a ruler, a stopwatch and your lab notebook

Steps

1. Fill all three pans with the same mass of dry soil (weigh them). Pan A: bare, dry soil, raked smooth. Pan B: dry soil with the turf pressed into it so grass covers the surface. Pan C: bare soil lightly misted with water the day before so it dries into a thin crust.
2. Record what you change (the surface cover) and what you keep the same: soil mass, pan size, fan distance, fan speed and blowing time.
3. Set the fan 30 cm from the first pan at the same height as the soil surface. Spread the white sheet downwind. Blow for exactly 60 seconds.
4. Weigh the pan again. Soil lost = starting mass minus ending mass. Also measure the farthest distance any grain traveled on the sheet. Record both.
5. Repeat for the other two pans with the same fan setting, distance and time. Then run all three a second time to check your results.
6. Make a bar graph of soil lost (grams) for A, B and C. Convert each to tonnes per hectare using the worked example method: divide the mass lost by the pan area in

square meters, then multiply by 10,000 for a hectare and divide by 1,000,000 to turn grams into tonnes.
7. Write a conclusion that answers the question with your numbers and says whether your prediction was right.

Tips

- If the dry soil will not move, sift it finer or add a handful of dry sand. The Plains soils that blew worst were fine, silty loams.
- Watch for saltation: grains hopping along the surface before fine dust rises. That is exactly what Bennett's scientists saw on the Plains.
- A second trial matters. One run can be a fluke; two runs that agree are evidence.

Check your work

- I kept every variable the same except the surface cover.
- I recorded mass before and after and calculated soil lost for each pan.
- I made a labeled bar graph and wrote a conclusion that uses my numbers.

FIELD NOTEBOOK

1. Draw a map of the Great Plains from Texas to North Dakota and shade the Dust Bowl core: the Oklahoma and Texas panhandles, southwestern Kansas, southeastern Colorado and northeastern New Mexico. Mark Boise City, Oklahoma, and Guymon, Oklahoma.
2. Draw a cross-section of prairie sod showing grass roots a meter deep beside a cross-section of a plowed wheat field after harvest. Label topsoil, roots and bare surface.
3. Make a timeline from 1914 to 1940 with at least six events: wartime wheat prices, the Great Plow-Up, the 1929 crash, the 1931 drought begins, Black Sunday (April 14, 1935), the Soil Conservation Act (April 27, 1935), the shelterbelt project, and rains return.

> **From history.** Hugh Hammond Bennett grew up on a cotton farm in Anson County, North Carolina, where his father terraced the fields and told him it was to keep the land from washing away. Bennett joined the Bureau of Soils in 1903 and spent decades mapping soils across the South, where he saw gullied, abandoned farms that convinced him erosion was a national problem. He led the Soil Conservation Service from 1935 until he retired in 1951, and farmers across the country still call him the father of soil conservation.

WORKED EXAMPLES

Example 1. A wind storm strips 1 millimeter of topsoil from a wheat field. The topsoil has a density of 1.3 g/cm³. How many tonnes of soil did one hectare lose?

1. One hectare is 100 m × 100 m = 10,000 m². In centimeters that is 10,000 cm × 10,000 cm = 100,000,000 cm², or 10^8 cm².
2. The layer is 1 mm = 0.1 cm thick, so the volume removed is 10^8 cm² × 0.1 cm = 10^7 cm³.
3. Mass = density × volume = 1.3 g/cm³ × 10^7 cm³ = 1.3 × 10^7 g.
4. Convert to tonnes: 1 tonne = 1,000,000 g, so 1.3 × 10^7 g ÷ 10^6 g/t = 13 tonnes.

Answer: About 13 tonnes of soil per hectare for every millimeter lost. A truckload of soil can vanish from a field in an afternoon without the loss even being visible.

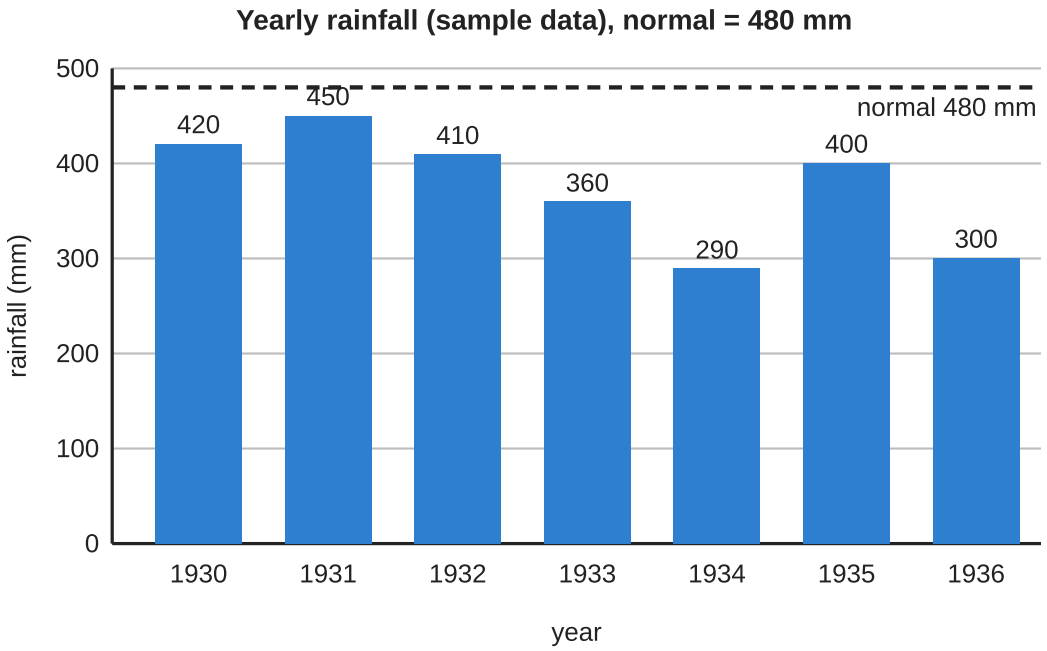
Example 2. A Plains farm has 20 cm of topsoil. In the drought years it loses about 4 mm per year to wind. A textbook figure often quoted says that under good conditions soil forms at roughly 2.5 cm per 500 years. (a) At the drought rate, how long until the topsoil is gone? (b) How much faster is this loss than the quoted formation rate?

1. (a) Convert to the same unit: 20 cm = 200 mm. Time = 200 mm ÷ 4 mm/yr = 50 years.
2. (b) Quoted formation rate: 2.5 cm per 500 years = 25 mm ÷ 500 yr = 0.05 mm/yr.
3. Ratio: 4 mm/yr ÷ 0.05 mm/yr = 80.

Answer: (a) About 50 years. (b) The drought-year loss is about 80 times faster than the textbook formation rate. Whatever one thinks about the formation estimate, the farm clearly cannot wait for new topsoil.

Example 3. The table shows yearly rainfall for a town on the southern Plains (simplified sample data). The long-term normal is 480 mm. Find the percent of normal for 1934, and tell which years were drought years if a drought year is any year at or below 75% of normal.

Year: 1930, 1931, 1932, 1933, 1934, 1935, 1936
Rainfall (mm): 420, 450, 410, 360, 290, 400, 300



Sample rainfall data for a southern Plains town, 1930 to 1936. Every bar is below the normal line.

1. Percent of normal for 1934 = (290 ÷ 480) × 100 = 60.4%, about 60%.
2. The drought cutoff is 75% of 480 mm = 0.75 × 480 = 360 mm.
3. Years at or below 360 mm: 1933 (360), 1934 (290), 1936 (300). The others are above the cutoff.

Answer: 1934 received about 60% of normal rain. By the 75% rule, 1933, 1934 and 1936 were drought years. Notice that even the ‘good’ years of the decade were below normal, which is why the soil never had a chance to recover.

PRACTICE

1. EASY What date was Black Sunday, and in what part of the country was the dust storm worst?
2. EASY Name the three causes of the Dust Bowl, and say which one people controlled.
3. EASY Put these in order of particle size, largest first, and match each with its wind motion: silt and clay, sand grains, pebbles. Motions: creep, saltation, suspension.

4. MEDIUM Using a soil density of 1.3 g/cm³, how many tonnes does a hectare lose if 3 mm of topsoil blows away?
5. MEDIUM A county had 60,000 hectares of wheat in 1920 and 150,000 hectares in 1930. By what percent did the plowed area increase?
6. MEDIUM Data reading. A scientist measured soil moved past a fence in one hour at different wind speeds on a bare field:
   Wind speed (km/h): 15, 20, 25, 30, 35
   Soil caught (g): 0, 2, 9, 24, 50
   (a) At about what wind speed does soil begin to move? (b) When the wind speed doubles from 15 to 30 km/h, by how much does the soil caught change? (c) Does soil loss grow at a steady rate, or faster and faster, as wind speed rises? Use the numbers.
7. MEDIUM Data reading. Sample data: two neighboring fields were compared during a 1936 storm. Field 1 was bare, plowed wheat stubble; Field 2 had been left in grass. Field 1 lost 2.6 mm of soil; Field 2 lost 0.1 mm. (a) How many times more soil did Field 1 lose? (b) What single variable differed between the fields? (c) What else would you want to know before concluding that grass cover made the whole difference?
8. HARD Experiment design. You want to test whether leaving wheat stubble on a field reduces wind erosion compared with plowing it under. Describe your experiment: the independent variable, the dependent variable, two controls (things kept the same), and how you would measure the result.
9. HARD The shelterbelt project planted more than 200 million trees between 1935 and 1942. If a shelterbelt row holds one tree every 2 m, how many kilometers of tree row is 200 million trees?
10. CHALLENGE Write a paragraph of five or six sentences explaining why the prairie survived earlier droughts but the plowed Plains of the 1930s did not. Use the words sod, roots, saltation and topsoil.

COMMON MISTAKES

- Thinking the drought alone caused the Dust Bowl. The Plains had survived droughts before; what changed was that the protective sod had been plowed away, leaving the soil bare.
- Picturing dust storms as fine dust simply blowing off the ground. Most of the work is done by sand-sized grains bouncing (saltation) and knocking the fine particles loose; the dust cloud is the result, not the start.
- Assuming erosion is only a problem for farmers of the past. Erosion happens every windy, rainy season on bare soil anywhere, including a garden bed or a construction site, and the same fixes apply: cover, roots and residue.

Make it a game · Hold the Topsoil. Each player starts with a card marked 20 cm of topsoil. Each round, roll a die for the weather: 1 or 2 is a wet year (no loss), 3 or 4 is a dry year (lose 2 mm if your field is bare, 0 if it is covered), 5 or 6 is a dust storm (lose 6 mm if bare, 1 mm if covered). Before each roll you choose: plant wheat for 3 points but leave the field bare after harvest, or plant a cover crop or grass strips for 1 point and keep it

covered. Play ten rounds. Add up your points, but anyone whose topsoil falls below 15 cm loses half their points. Discuss: did the wheat gamble pay off?

Scripture. “He causeth the grass to grow for the cattle, and herb for the service of man: that he may bring forth food out of the earth;” (Psalm 104:14, KJV)

The psalm puts grass first. God grows the grass for the cattle and the herb for man, and the grass that covers the ground is also what keeps the earth able to bring forth food at all. The farmers of the Plains learned, at great cost, to leave some of that grass in place.

Practice answers

1. April 14, 1935; the southern Great Plains, especially the Oklahoma and Texas panhandles, southwestern Kansas, southeastern Colorado and northeastern New Mexico.
2. Plowing up the native grassland (people controlled this), a decade of drought, and strong Plains winds (the last two were not controlled by people).
3. Pebbles (creep, rolling along the ground), sand grains (saltation, bouncing), silt and clay (suspension, carried high in the air).
4. 1 mm per hectare is 13 t, so 3 mm is 3 × 13 = 39 tonnes.
5. Increase = 90,000 ha. 90,000 ÷ 60,000 = 1.5, so the plowed area increased 150%.
6. (a) Between 15 and 20 km/h, about 20 km/h. (b) From 0 g to 24 g. (c) Faster and faster: each 5 km/h step adds more than the last (2, 7, 15, 26 g), so the relationship is not a straight line.
7. (a) 2.6 ÷ 0.1 = 26 times more. (b) Surface cover (bare versus grass). (c) Whether the fields had the same soil texture, slope, moisture and exposure to the wind; otherwise another difference could explain part of the result.
8. Independent variable: surface treatment (stubble left standing versus plowed bare). Dependent variable: mass of soil lost or caught in a trap per unit time. Keep the same: soil type, plot size and shape, slope, moisture, wind exposure and the time period measured; run the plots side by side in the same storms. Measure by weighing soil caught in identical traps downwind of each plot, or by measuring the surface level against fixed pins before and after. Repeat on several plots so one unusual plot does not decide the result.
9. 200,000,000 trees × 2 m = 400,000,000 m = 400,000 km. That is long enough to circle the earth about ten times (the equator is about 40,000 km).
10. A good answer explains that prairie sod is a mat of living and dead grass roots that holds soil even when the grass is brown and dormant, so earlier droughts dried the land without moving it. In the 1920s the sod was plowed up for wheat, so when drought came in 1931 the soil lay bare, dry and loose. Wind set sand grains bouncing (saltation), and those grains knocked fine silt and clay into the air as dust. Because the topsoil is the finest, richest layer, it was the first to go, and nothing was left to hold what remained. The land did not fail; the cover that protected it had been removed.

1.2 Soil Horizons: Reading a Soil Profile

OBJECTIVES

- Name and describe the soil horizons O, A, E, B, C and R and identify them in a diagram, a roadcut or a dug pit.
- Classify a soil by texture (sand, silt and clay) using the jar test and the USDA size limits, and name the five soil-forming factors.
- Explain how Vasily Dokuchaev's study of the Russian black earth in the 1870s and 1880s led to the idea of soil as a natural body with a profile.

Warm-up. Take a clear jar and pour in a handful of garden soil, then fill it two-thirds with water, cap it and shake it hard for one minute. Set it down and watch for two minutes. What settles first? What is still cloudy? Sketch what you see and leave the jar to settle overnight for the project.

Video. Coming soon. Soil horizons and soil profile explained, soil texture jar test and the USDA soil texture triangle; search USDA NRCS soil education videos, Soil Science Society of America, Smithsonian soils exhibit clips, SciShow, Crash Course Kids soil, and university extension (land-grant) channels.

KEY TERMS

soil profile
A vertical slice of soil from the surface down to bedrock, showing its layers.

horizon
One layer of a soil profile, roughly parallel to the surface, that differs in color, texture or makeup from the layers above and below. Named with the letters O, A, E, B, C and R.

humus
Dark, decayed plant and animal matter in soil. It holds water and nutrients and gives topsoil its dark color.

parent material
The rock or loose sediment from which a soil formed, such as weathered granite, river silt, glacial till or volcanic ash.

texture
The mix of sand (0.05 to 2 mm), silt (0.002 to 0.05 mm) and clay (less than 0.002 mm) particles in a soil. Loam is a balanced mix of all three.

chernozem
Russian for "black earth": the deep, dark, humus-rich grassland soil of the steppe that Dokuchaev studied. The American prairie soils are its cousins.

CORE IDEAS

The story. In the summer of 1877 a thirty-one-year-old geologist named Vasily Dokuchaev left St. Petersburg for the open steppe of southern Russia. The Imperial Free Economic Society had hired him to study the **chernozem**, the famous black earth that fed the Russian Empire, because a run of bad harvests had farmers and landowners worried. Dokuchaev did something that geologists of his day rarely did: he dug pits. Hundreds of them, across several summers and thousands of kilometers of grassland. In pit after pit he saw the same thing. At the top lay a black layer, sometimes a meter thick, full of grass roots. Below it the black faded through brown to a pale, lime-flecked layer, and below that lay the loose yellowish loess, the wind-blown silt from which the whole soil had formed. In 1883 he published his findings in a book called *Russian Chernozem*. Its great claim was that soil is not just crushed rock or dirt lying on the ground. Soil is a natural body with its own structure, built in place by climate, living things and time working on the parent rock. Dokuchaev is remembered today as the founder of soil science.

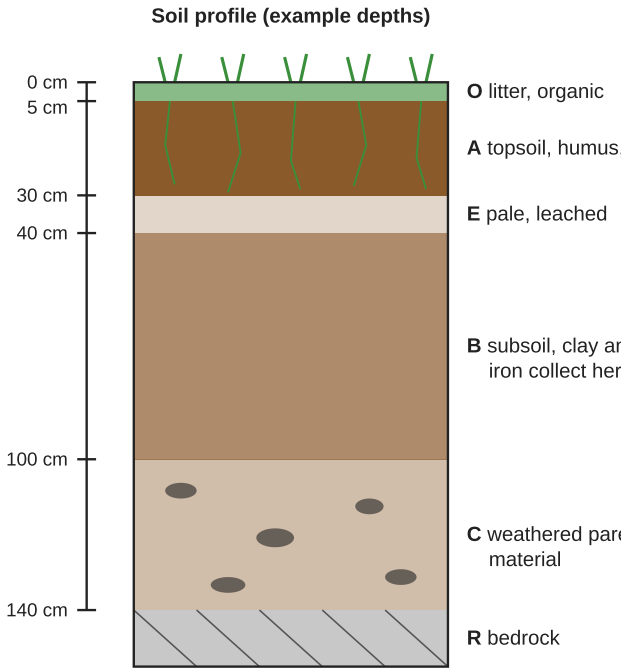
How they figured it out. Dokuchaev's layers are now called **horizons**, and a vertical slice showing them is a **soil profile**. Soil scientists label the horizons with letters, top to bottom. The **O horizon** is organic: leaf litter, dead grass and partly rotted plant matter. The **A horizon** is the topsoil, dark with **humus**, where most roots, worms, fungi and bacteria live. In many forest soils an **E horizon** lies next, pale and washed out because water has leached (*eluviated*) clay, iron and humus downward out of it. The **B horizon**, or subsoil, is where those washed-down materials collect, so it is often reddish or yellowish from iron oxides and denser with clay. The **C horizon** is weathered **parent material**, broken rock or loose sediment only slightly changed. Below everything is the **R horizon**, solid bedrock. Not every soil has every horizon: a prairie chernozem may have a very thick A and no E at all, while a sandy pine-forest soil may have a thin A and a bright white E. Soil scientists read a profile by digging a pit, cleaning one face with a knife, and marking where color, feel and structure change.

The big idea. Why do soils differ from place to place? Dokuchaev listed the causes, and in 1941 the American soil scientist Hans Jenny arranged them into five soil-forming factors that students still memorize with the letters *CLORPT*: **Cl**imate (rain and temperature), **O**rganisms (plants, animals, microbes and people), **R**elief (the shape and slope of the land), **P**arent material and **T**ime. The feel of a soil comes mostly from its **texture**, the mix of particle sizes. The United States Department of Agriculture sets the limits: **sand** grains are 0.05 to 2 millimeters across and feel gritty; **silt** is 0.002 to 0.05 millimeters and feels smooth and floury; **clay** is smaller than 0.002 millimeters and feels sticky when wet. A soil with roughly 40% sand, 40% silt and 20% clay is called a **loam**, and loams are the farmer's favorite because they drain well yet hold water and nutrients. A typical loam by volume is about 45% minerals, 5% organic matter, 25% water and 25% air. Half of good soil is pore space, which is why trampled or compacted soil grows so poorly.

Try it and see. You can read a soil without a laboratory. Color tells a story: black and dark brown mean humus; red and yellow mean iron oxides in a well-drained soil; gray, blue-gray or mottled patches mean the soil is waterlogged for part of the year and the iron has lost its

oxygen. The jar test from the warm-up sorts texture by settling speed. Sand drops in seconds, silt in minutes, and clay stays cloudy for hours or days, so after a night of settling you can measure each layer with a ruler and work out the percentages. The ribbon test is faster: wet a lump of soil, roll it, and squeeze it out between thumb and finger. Sandy soil will not ribbon at all, loam makes a short ribbon that breaks, and clay makes a long shiny ribbon. A roadcut, a creek bank or a construction trench is a free soil profile; take a photo, a tape measure and your notebook.

God's handiwork. Genesis says that "the LORD God formed man of the dust of the ground" (Genesis 2:7). In Hebrew the words are close kin: the man is *adam* and the ground is *adamah*. We are made from soil and fed from it, and when Dokuchaev looked closely he found that soil is not dead dust but a living, ordered body, layered and working, full of roots and creatures, built in exactly the way that turns rock into food. A teaspoon of healthy topsoil holds more living things than there are people on earth. That is a made thing, and it rewards a careful reader.



A soil profile with all six horizons. Depths are for one example soil; real profiles vary, and many soils lack an O or E horizon.

⏳ Thinking About Time

What the sign says. Soil textbooks and park signs commonly say that it takes about 500 years to form 2.5 cm of topsoil, and that deep, well-developed profiles record tens of thousands of years or more.

What we observe. What can be measured today is the present rate under present conditions, and it varies enormously. On Surtsey, the volcanic island that rose from the sea off Iceland in 1963, and on the 1980 deposits around Mount St. Helens in Washington, plants, humus and the beginnings of horizons appeared within a few

decades. Fine ash, silt and soft sediment weather and build soil far faster than hard granite, and warm, wet, plant-covered ground far faster than cold bare rock.

How Christians read it. Young-earth creationists read today's soils as having formed since the Flood, on soft fresh sediments under vigorous plant growth, over a few thousand years, and point out that 500 years per 2.5 cm is an average under present conditions on hard material, not a stopwatch that ran from the beginning. Some Christians hold old-earth views and accept the longer figures. Both agree that the soil is God's gift and that the rates we measure now are the ones that matter for keeping it.

Try it. Drop a pinch of fine volcanic ash or silt and a granite pebble into two cups of vinegar and compare how much each changes in a week.

Genesis 8:22

PICTURE STUDY



The Gleaners, Jean-François Millet, 1857 · Oil on canvas · Musée d'Orsay, Paris

Jean-François Millet grew up on a farm in Normandy and painted the people who worked the land near Barbizon, south of Paris. Here three women glean, gathering the stray stalks left after the harvest, a right the poor had held since Bible times (Leviticus 19:9–10; Ruth 2). The painting shocked some critics in 1857 for making poor laborers the heroes of a large, serious canvas.

For a soil scientist the picture is also a portrait of a soil. The pale gold stubble, the dark earth beneath it, and the fat haystacks on the horizon tell you this is deep, fertile loam under a well-watered sky.

Look closely

- Look at the ground under the women’s hands. What color is it? Is it bare, or covered with stubble?
- Count the haystacks and wagons in the distance. What does the size of the harvest tell you about the soil?
- Look at the women’s backs and hands. What does the painter want you to feel about their work?
- Where is the light coming from, and what does it make glow?

Talk about it

1. Millet shows a harvest field, not a plowed one. Which horizon are the women touching, and what covers it?
2. Why did God command Israel to leave the corners and gleanings of the field for the poor (Leviticus 19:9–10)? How does that connect to the idea that soil is a gift?
3. If you dug a pit at the women’s feet, what would you expect the A horizon to look like, and how thick might it be compared with a sandy pine-forest soil?

> **Safety first.** Dig soil pits only where you have permission and never near buried utility lines. Wear gloves, wash hands after handling soil, and keep a parent nearby when working on a creek bank or roadcut. Do not dig deeper than about 60 cm without an adult.

EXPERIMENT: DIG A SOIL PIT AND RUN THE JAR TEST

You will open a real soil profile in your own yard or a nearby field, describe its horizons like Dokuchaev did, and measure its texture with the jar test. **Question:** how many horizons does your soil have, and what is its texture? **Prediction:** before digging, guess how thick the topsoil will be and whether the soil will be sandy, loamy or clayey.

You will need

- Spade or trowel, and a kitchen knife for cleaning the pit face
- Tape measure or meter stick, a camera and your lab notebook
- Two or three tall clear jars with lids (one per horizon you want to test)
- Water and one teaspoon of powdered dishwasher detergent or liquid dish soap per jar to help the particles separate
- Ruler, calculator and colored pencils

Steps

1. Choose a spot with permission and dig a pit about 30 cm wide and as deep as you safely can, at least 40 to 60 cm. Keep one wall straight and vertical.
2. Clean the vertical wall with the knife so the natural colors show. Hang the tape measure from the surface down the wall and photograph it.
3. Look and feel for changes in color, grittiness, stickiness and root density. Mark each boundary with a twig. Label the horizons you can see (O, A, E, B, C) and record the

depth of each boundary in centimeters.

4. Take a fist-sized sample from the A horizon and another from the deepest horizon you reached. Remove roots and stones.
5. Fill each jar one-third with its sample, add water to two-thirds, add the soap, cap and shake for two minutes. Set it where it will not be bumped.
6. After 1 minute, mark the top of the sand layer with a marker. After 2 hours, mark the top of the silt layer. After 24 to 48 hours, when the water is clear, mark the top of the clay layer.
7. Measure each layer in millimeters and calculate the percentage of each (layer ÷ total × 100). Use the worked example to name the texture. Record it beside the horizon in your notebook.
8. Fill the pit back in, replacing the topsoil on top. Draw a scaled profile with colored pencils, labeled with horizon letters, depths, colors and textures.

Tips

- Clay may take two days or more to settle, which is itself a clue: the longer the water stays cloudy, the more clay the soil holds.
- If you cannot dig, a creek bank, a roadcut or a trench at a construction site (viewed from outside the fence) shows the same horizons.
- Compare the A and B horizons in your two jars. Usually the B holds more clay.

Check your work

- I measured and recorded the depth of each horizon boundary in centimeters.
- I ran the jar test and calculated sand, silt and clay percentages for at least one horizon.
- I drew a labeled, scaled soil profile and named the texture of the topsoil.

FIELD NOTEBOOK

1. Draw your own soil profile to scale (for example 1 cm on paper = 5 cm of soil) with horizon letters, depths and colors matched as closely as you can with colored pencils.
2. Make a chart of the three particle classes with their USDA size limits, how each feels wet (gritty, smooth, sticky), and how fast each settles in water.
3. Write CLORPT down the margin and beside each letter describe that factor as it works in your own yard: your climate, the plants and animals, the slope, the parent material and what you can see of time.

> **From history.** Charles Darwin spent his last years watching earthworms. In 1881 he published *The Formation of Vegetable Mould through the Action of Worms*, in which he reported weighing worm castings on English pastures and estimated that worms bring up roughly 20 tonnes of soil per hectare each year, slowly burying stones and old Roman floors. He showed that the dark topsoil of a meadow is to a large degree the work of worms, which is one reason soil scientists count worms as a sign of healthy soil.

WORKED EXAMPLES

Example 1. In the soil profile figure the horizon boundaries are at 5 cm (bottom of O), 30 cm (bottom of A), 40 cm (bottom of E), 100 cm (bottom of B) and 140 cm (bottom of C, top of bedrock). How thick is each horizon, and what percent of the whole soil above bedrock is the A horizon?

(Use the map or drawing "Read horizon thickness from the depth scale on the left." shown earlier in this lesson.)

1. Thickness of each horizon is the difference between its boundaries: O = 5 − 0 = 5 cm; A = 30 − 5 = 25 cm; E = 40 − 30 = 10 cm; B = 100 − 40 = 60 cm; C = 140 − 100 = 40 cm.
2. Total soil above bedrock = 140 cm.
3. Percent A = 25 ÷ 140 × 100 = 17.9%, about 18%.

Answer: O 5 cm, A 25 cm, E 10 cm, B 60 cm, C 40 cm. The topsoil (A) is only about 18% of the profile, which shows how thin the layer that feeds us really is.

Example 2. After a jar test settles, the layers measure: sand 30 mm, silt 20 mm, clay 10 mm. What are the percentages, and what is the texture class?

1. Total = 30 + 20 + 10 = 60 mm.
2. Sand = 30 ÷ 60 × 100 = 50%; silt = 20 ÷ 60 × 100 = 33%; clay = 10 ÷ 60 × 100 = 17%.
3. On the USDA texture triangle, a soil with 50% sand, 33% silt and 17% clay falls in the loam class (loam runs from about 23% to 52% sand, 28% to 50% silt and 7% to 27% clay).

Answer: 50% sand, 33% silt, 17% clay: a loam. Check: the three percentages always add to 100%.

Example 3. Why does sand settle first in the jar? Compare a sand grain 0.5 mm across with a clay particle 0.002 mm across. How many times wider is the sand grain, and how many clay particles would fit side by side across it?

1. Ratio of diameters = 0.5 mm ÷ 0.002 mm = 250.
2. So 250 clay particles lined up would span one sand grain of that size.
3. Larger, heavier particles fall faster through water; the tiny clay particles are so light that they stay suspended for hours, which is why the water stays muddy.

Answer: The sand grain is 250 times wider than the clay particle, and 250 clay particles would fit across it. That size difference is why sand settles in seconds and clay takes a day or more.

PRACTICE

1. EASY List the six horizon letters from the surface down and give a two- or three-word description of each.
2. EASY Who was Vasily Dokuchaev, and what was his main claim in *Russian Chernozem* (1883)?
3. EASY Give the USDA size limits for sand, silt and clay in millimeters.
4. MEDIUM A jar test gives sand 12 mm, silt 36 mm, clay 12 mm. Find the percentages. Is this soil mostly sand, silt or clay?
5. MEDIUM A soil profile has an A horizon from 0 to 18 cm and a B horizon from 18 to 75 cm. How thick is the B horizon, and how many times thicker is it than the A?
6. MEDIUM Data reading. Four soil pits were dug along a hillside from the top (Pit 1) to the valley floor (Pit 4). The A horizon thickness was: Pit 1, 8 cm; Pit 2, 12 cm; Pit 3, 20 cm; Pit 4, 45 cm. (a) Describe the trend. (b) Which soil-forming factor from CLORPT best explains it? (c) Suggest the physical reason.
7. MEDIUM Data reading. A student timed how long each jar stayed cloudy for three soils: Soil X, 3 minutes; Soil Y, 2 hours; Soil Z, 36 hours. (a) Rank the soils from most clay to least. (b) Which soil would feel stickiest when wet? (c) Which would drain fastest after rain, and why?
8. HARD Experiment design. You want to find out whether the B horizon in your yard holds more water than the A horizon. Describe an experiment: what you would change, what you would keep the same, what you would measure, and one way to make the result trustworthy.
9. HARD Explain why a forest soil often has a pale E horizon but a prairie chernozem usually does not. Use the words leaching, humus and roots.
10. CHALLENGE A textbook says topsoil forms at about 2.5 cm per 500 years. A farmer measures that his field is losing 1 mm of topsoil per year to erosion. Compare the two rates in the same units, and write two sentences about what the farmer should conclude regardless of how one views the textbook’s formation estimate.

COMMON MISTAKES

- Thinking soil is just finely ground rock. Soil also contains humus, living organisms, water and air, and about half of a good soil's volume is pore space.
- Assuming every soil has all six horizons in neat bands. Many soils lack an O or E horizon, boundaries are often gradual, and thickness varies from a few centimeters to meters.
- Confusing texture with structure. Texture is the mix of particle sizes (sand, silt, clay); structure is how those particles clump into crumbs, blocks or plates. Adding sand to a clay soil does not make loam; it often makes something like concrete.

Make it a game · Horizon Stack. Cut six strips of paper and label them O, A, E, B, C and R with a one-line description on the back. Shuffle them. On "go," race a sibling or parent to stack them in the right order from the surface down, then flip them to check. Second round: the caller names a soil (prairie, pine forest, desert, river floodplain) and you must remove the horizons that soil probably lacks and explain why. Third round: the caller describes a layer ("pale, sandy, washed out") and you slap the right letter.

Scripture. "And the LORD God formed man of the dust of the ground, and breathed into his nostrils the breath of life; and man became a living soul." (Genesis 2:7, KJV)

The Bible ties us to the soil from the first chapters. The ground that Dokuchaev found to be a living, layered body is the same ground we are made from and fed by, and the care we give it is care for a gift.

Practice answers

1. O: organic litter. A: dark topsoil with humus. E: pale leached layer. B: subsoil where clay and iron collect. C: weathered parent material. R: solid bedrock.
2. A Russian geologist who studied the black earth of the steppe by digging pits; he claimed that soil is a natural body with its own profile, formed in place by climate, organisms, relief, parent material and time, not just crushed rock.
3. Sand 0.05 to 2 mm; silt 0.002 to 0.05 mm; clay smaller than 0.002 mm.
4. Total 60 mm. Sand 20%, silt 60%, clay 20%. It is mostly silt (a silt loam).
5. B = 75 − 18 = 57 cm. 57 ÷ 18 ≈ 3.2, so the B is a little more than three times as thick as the A.
6. (a) The topsoil gets thicker downhill. (b) Relief (slope position). (c) Rain washes soil off the steep upper slopes and deposits it at the foot of the hill, so the valley floor collects topsoil while the hilltop loses it.
7. (a) Z (most clay), Y, X (least). (b) Soil Z. (c) Soil X; it is mostly sand and silt with large pores, so water passes through quickly, while clay's tiny particles and pores hold water.
8. Independent variable: which horizon the sample comes from (A or B). Keep the same: the mass of dry soil in each test (say 200 g), the container, the amount of water poured in, the time allowed to drain, the temperature. Measure: the mass of water held (wet mass minus dry mass) or the volume that drains out of a filter in 10 minutes. Make it trustworthy by drying both samples fully first, running each test three times and averaging.

9. Under forest, rain soaks down through acidic leaf litter and leaches clay, iron and humus out of the upper layer, leaving a pale E horizon above the B where they collect. Under prairie grass, dense roots a meter deep add humus all through the upper soil every year, and the drier climate leaches less, so the dark humus-rich A horizon extends deep without a washed-out layer.
10. Formation: 25 mm ÷ 500 yr = 0.05 mm/yr. Loss: 1 mm/yr, which is 20 times faster. The farmer should conclude that at present rates his topsoil is leaving far faster than any estimate of its forming, so he must cut erosion now with cover, residue or contouring. The exact formation figure does not change the decision; the loss rate does.

1.3 Contour Plowing: Farming With the Shape of the Land

OBJECTIVES

- Explain how water erosion works on a slope and why furrows plowed along the contour, strip cropping and terraces slow it down.
- Calculate slope as a percent and estimate soil loss in tonnes per hectare and millimeters per year, using a contouring factor of about one half.
- Tell the story of the Coon Creek watershed project in Wisconsin (1933), the first soil conservation demonstration in the United States.

Warm-up. Make a hill out of a towel folded over a stack of books and lay a sheet of paper on it. Draw deep pencil lines down the slope on one half and across the slope on the other half. Dribble a teaspoon of water at the top of each half. Which lines carry the water fastest to the bottom? Which lines hold it? Write one sentence.

Video. Coming soon. Contour plowing, strip cropping and terracing explained; Coon Valley Wisconsin soil conservation history 1933; look for USDA NRCS soil conservation videos, historic Soil Conservation Service films at the National Archives, Wisconsin Public Television and university extension channels, aerial drone footage of contour strip farms, and SciShow or Crash Course erosion videos.

KEY TERMS

contour
A line that follows one elevation around a hill, staying level. Contour plowing runs the furrows along these lines, across the slope rather than up and down it.

runoff
Rainwater that does not soak into the ground but flows over the surface downhill, carrying soil with it.

infiltration
Water soaking into the soil. Every drop that infiltrates is a drop that cannot run off and carry soil away.

strip cropping
Planting alternating bands of row crops and close-growing crops such as grass, clover or alfalfa along the contour, so each grass strip catches soil washing off the strip above.

terrace
A broad step or ridge built across a slope to shorten the distance water can run and to hold it where it falls.

shelterbelt

A row or several rows of trees planted across the wind to slow it and protect fields, farmsteads and livestock. Also called a windbreak.

CORE IDEAS

The story. In October 1933 a team of soil scientists and foresters drove into Coon Valley, a dairy-farming town in Vernon County, in the steep hill country of southwestern Wisconsin. They had come to try something no government had tried before: to work with every willing farmer in a single watershed, the whole area drained by Coon Creek, and show that erosion could be stopped. The problem was plain from any ridge road. Farmers had plowed their cornfields straight up and down the slopes, because that was easiest with a team of horses. Every heavy rain cut the furrows into gullies, washed the topsoil off the ridges and dumped it on the valley floor, where the creek bed had risen several meters on a bed of lost farmland. The new Soil Erosion Service, led by Hugh Hammond Bennett, chose Coon Creek as the nation's first demonstration project. Young men from the Civilian Conservation Corps supplied the labor, the University of Wisconsin supplied the science, and a wildlife professor named Aldo Leopold helped plan the woodlots and stream banks. Hundreds of farmers signed five-year agreements. Within three years the hills of Coon Valley were striped with curving bands of corn and hay following the shape of the land, and visitors came from across the country to see them. Later surveys found that far less soil reached the valley floor than had in the 1930s, and the pattern spread to the whole Midwest.

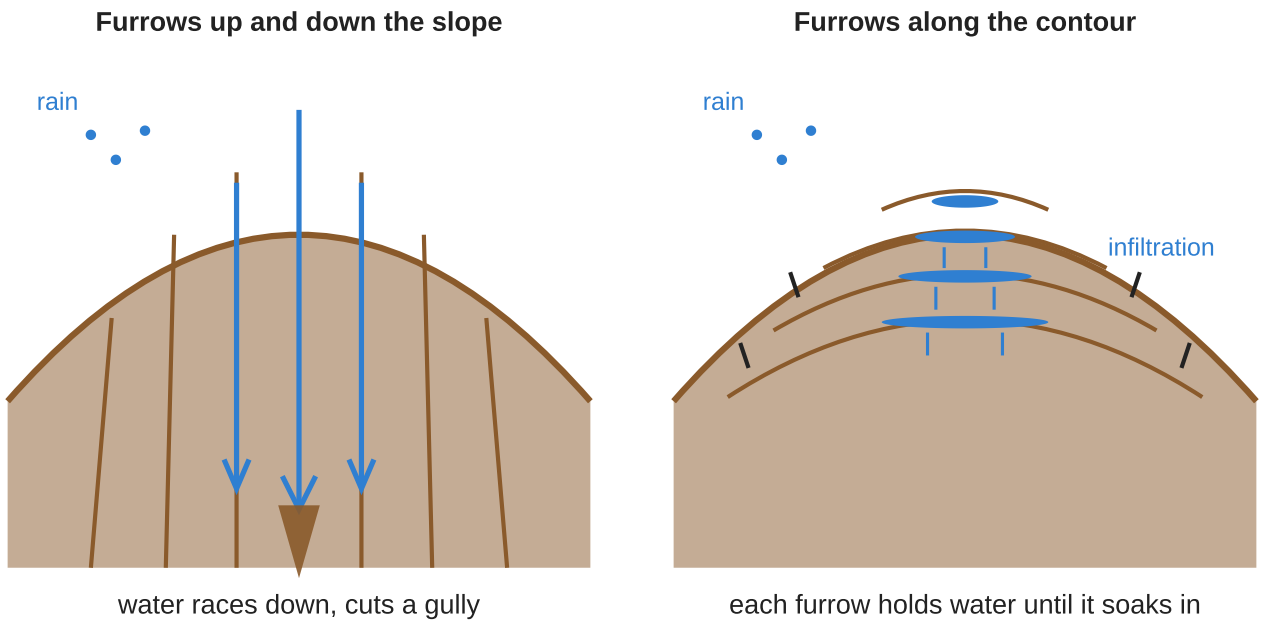
How they figured it out. Water erosion begins with the raindrop. A large drop hits bare soil at about 9 meters per second, blasting particles loose and sealing the surface so water cannot soak in. The water that does not **infiltrate** becomes **runoff**, and runoff gathers speed as it flows downhill. Speed is the enemy: the energy of moving water grows with the square of its speed, so water moving twice as fast carries four times the energy and can move much larger grains. A furrow plowed down a slope is a ready-made channel that lets water run fast and far. A furrow plowed along the **contour** is a tiny dam. Each one holds a little water until it soaks in, and the field becomes a staircase of small ponds instead of a slide. Scientists at experiment stations across the country measured soil washing off test plots for decades, and in 1965 Walter Wischmeier and Dwight Smith of the Department of Agriculture boiled the results into the Universal Soil Loss Equation. In their tables, plowing on the contour on a gentle slope of 3 to 8 percent cuts soil loss to about half of what up-and-down plowing allows, and **strip cropping** on the contour cuts it to about a quarter.

The big idea. Slope is measured as a percent: rise divided by horizontal run, times 100. A field that climbs 5 meters over 100 meters has a 5% slope. Steeper and longer slopes shed water faster and lose more soil, so conservation attacks both: contouring and **terraces** break a long slope into short ones, and cover crops and crop residue shield the surface from the raindrop in the first place. The Natural Resources Conservation Service sets a tolerable soil loss for most deep soils of about 11 tonnes per hectare per year, which is roughly 1 millimeter of soil (recall that 1 millimeter over a hectare weighs about 13 tonnes). A bare corn field on a 6% slope can lose two or three times that in a wet year. For wind, the matching tool is the **shelterbelt**. A row of trees slows the wind noticeably for a distance downwind of about ten times the trees' height, so a belt of 15-meter trees protects about 150

meters of field. Between 1935 and 1942 the Prairie States Forestry Project planted more than 200 million such trees across the Plains.

In the world today. Fly over Iowa, Wisconsin or Pennsylvania in summer and you will see what Coon Valley started: hills striped with curving bands of green and gold. The tools have grown. Most Midwestern farmers now plant with no-till drills that leave last year's stalks on the surface, cutting erosion by more than half by themselves. Cover crops such as rye and radish keep living roots in the soil through winter. Grassed waterways carry the runoff that does gather, and buffer strips of grass along streams catch soil and fertilizer before they reach the water. In each county the local NRCS office writes a conservation plan with any farmer who asks, free of charge, and the farmer decides what to adopt. The same ideas work in a garden: run your rows across the slope, mulch the bare ground, and never leave a bed naked through a rainy season.

God's handiwork. The prophet Isaiah asks whether the plowman plows all day without sowing, and answers that "his God doth instruct him to discretion, and doth teach him" (Isaiah 28:24–26). Farming well is a kind of listening. The land has a shape, water has laws, and a farmer who plows with the contour instead of against it is reading those laws and obeying them. The farmers of Coon Valley did not invent new physics in 1933; they learned to see what God had built into every hill and raindrop, and the land answered. That is dominion as Genesis means it: not forcing the earth, but keeping it.



Up-and-down furrows are channels; contour furrows are small dams. The water and soil behave differently on the same hill.

PICTURE STUDY



The Harvesters, Pieter Bruegel the Elder, 1565 · Oil on wood · Metropolitan Museum of Art, New York

Pieter Bruegel the Elder painted a set of six pictures of the months for a wealthy merchant in Antwerp, and this one, for late summer, is one of the five that survive. A wheat field on a hillside is half cut; men swing scythes, women bind sheaves and carry them, and a tired crew eats bread and porridge under a tree.

Bruegel's farmers worked long before Coon Valley, but look at the shape of the land. The field drops away toward the valley, and the standing wheat runs in a band across the slope with a path cut through it. Bruegel painted what farmers have always known: the land has a shape, and work follows it.

Look closely

- Find where the field slopes downhill. Does the standing wheat run up and down the hill or across it?
- Look at the cut stubble in the foreground. What does stubble do for a soil through the autumn rains?
- Find the tree. Why would farmers leave a tree standing in a grain field?
- Follow the land into the distance. What covers the slopes there: bare ground, grass, trees or crops?

Talk about it

1. If a heavy thunderstorm hit this hillside the week after harvest, where would the water run and what would protect the soil?
2. This field is cut by hand with scythes. How did the arrival of tractors in the 1920s change how fields were plowed, and why did that matter for erosion?

3. Bruegel shows harvesters resting and eating. What does Scripture say about rest for the land itself (Leviticus 25:4), and why might a rested field hold its soil better?

> **Safety first.** The erosion trays use water and soil; work outdoors or over a tarp. Lift wet trays with two hands and wipe spills so no one slips. Wash hands after handling soil.

EXPERIMENT: RAIN ON TWO HILLSIDES: DOES CONTOUR PLOWING CUT SOIL LOSS?

You will build two identical sloping fields in trays, plow one up and down and one on the contour, and pour the same rain on both. **Question:** how much less soil washes off a contour-plowed slope? **Prediction:** write down your guess as a percent reduction before you begin.

You will need

- Two identical rectangular trays or shallow boxes about 40 cm long (foil roasting pans work), each with a 2 cm notch cut in the middle of one short end
- Enough moist, sifted garden soil to fill both trays 4 cm deep
- A pencil or dowel for drawing furrows
- Two books or blocks of the same thickness to prop the trays
- A watering can with a sprinkler head, or a plastic bottle with holes punched in the cap, and a measuring jug
- Two clear catch cups or jars, coffee filters, a kitchen scale, a ruler and your lab notebook

Steps

1. Fill both trays with the same mass of moist soil, pat them to the same firmness, and smooth the surface. Prop each tray on a block so the notched end is lowest. Measure the rise and run and calculate the slope percent (keep it the same for both, about 10%).
2. In Tray A draw furrows 1 cm deep straight down the slope, 3 cm apart. In Tray B draw furrows 1 cm deep across the slope (level, on the contour), 3 cm apart.
3. Record what you change (furrow direction) and what you keep the same: slope, soil mass, soil moisture, furrow depth and spacing, water volume, pouring height and pouring time.
4. Place a catch cup under each notch. Pour exactly 1 liter of water onto the top third of Tray A from 30 cm above, steadily over 60 seconds, like a hard rain. Repeat exactly for Tray B.
5. Let the catch cups settle for 30 minutes. Pour each through a labeled coffee filter, dry the filters overnight, and weigh the soil caught. Also record how much water ran off (volume) and how long the water took to start running out of each notch.
6. Calculate the percent reduction: (soil from A − soil from B) ÷ soil from A × 100. Compare with the Universal Soil Loss Equation's contouring factor of about 0.5 (a 50% reduction).
7. Run a second trial on fresh smoothed soil to check your result. Then try a third tray with strips of moss, grass clippings or paper towel across the slope every 10 cm to

imitate strip cropping.

Tips

- Keep the furrows truly level in Tray B. Even a slight tilt lets water drain sideways along the furrow and out the end.
- Pour from the same height and at the same speed each time; a raindrop’s energy depends on how far it falls.
- Watch where the first channel forms in Tray A. Real gullies start the same way.

Check your work

- I measured the slope percent and kept it the same for both trays.
- I weighed the soil lost from each tray and calculated the percent reduction.
- I compared my result with the textbook contouring factor and explained any difference.

FIELD NOTEBOOK

1. Draw a hill in two views, from the side and from above, and add contour lines every 2 meters of elevation. Then draw furrows along those lines.
2. Sketch an aerial view of a strip-cropped farm with alternating bands of corn and alfalfa curving around a hill, and add a grassed waterway down the main hollow.
3. Draw a shelterbelt of 15-meter trees in cross-section and shade the protected zone of about 150 meters downwind, with wind arrows slowing as they pass.

> **From history.** Contour farming in America is older than the Soil Conservation Service. In the early 1800s Thomas Jefferson’s son-in-law, Thomas Mann Randolph, worked out a method of plowing the red hills of Albemarle County, Virginia, in level furrows that he called horizontal plowing, and designed a hillside plow to do it. Jefferson wrote with delight to friends that his fields at Monticello now followed the curves of the hills, so that rain was caught and held where it fell instead of washing the soil into the rivers.

WORKED EXAMPLES

Example 1. A field rises 3 meters over a horizontal distance of 60 meters. What is its slope as a percent, and does it fall in the gentle range (3 to 8 percent) where contouring works best?

1. Slope % = rise ÷ run × 100 = 3 m ÷ 60 m × 100.
2. 3 ÷ 60 = 0.05, and 0.05 × 100 = 5%.
3. 5% is between 3% and 8%, so it is in the gentle range.

Answer: A 5% slope, which is in the range where contour plowing cuts soil loss by about half. (For reference, a 5% slope is a little under 3 degrees, gentle to walk but steep enough to lose soil.)

Example 2. A corn field plowed up and down the slope loses 24 tonnes of soil per hectare per year. The tolerable loss for its soil is 11 t/ha/yr. Using the Universal Soil Loss Equation factors of 0.5 for contour plowing and 0.25 for contour strip cropping, what would the loss be with each practice, and which brings the field under the tolerable limit?

(Use the map or drawing "The same hill under the same rain: furrow direction changes how far and how fast" shown earlier in this lesson.)

1. Contour plowing: 24 t/ha/yr × 0.5 = 12 t/ha/yr. This is still just above 11.
2. Contour strip cropping: 24 t/ha/yr × 0.25 = 6 t/ha/yr. This is below 11.
3. Convert to depth to picture it: 1 mm of soil over a hectare is about 13 t, so 24 t is about 1.8 mm/yr, 12 t is about 0.9 mm/yr and 6 t is about 0.5 mm/yr.

Answer: Contour plowing drops the loss to about 12 t/ha/yr (about 0.9 mm/yr), still slightly over the limit; contour strip cropping drops it to about 6 t/ha/yr (about 0.5 mm/yr), well under. The farmer should add strips, or combine contouring with residue cover.

Example 3. In the tray experiment, Tray A (furrows down the slope) yielded 180 g of soil in the catch cup and Tray B (contour furrows) yielded 45 g. What was the percent reduction, and how does it compare with the textbook contouring factor?

1. Reduction = 180 g − 45 g = 135 g.
2. Percent reduction = 135 ÷ 180 × 100 = 75%.
3. The textbook factor for contouring alone is 0.5, a 50% reduction. The tray gave a larger reduction, probably because the tray slope was short and the furrows held all the water until it soaked in, with no long slope above to overflow them.

Answer: A 75% reduction, larger than the 50% the equation predicts for real fields. A short model slope flatters contouring; on a long real hillside, water eventually overtops the furrows, which is why farmers add terraces and strips.

PRACTICE

1. EASY Where and when was the first soil conservation demonstration project in the United States, and what made it different from earlier advice to farmers?
2. EASY A field rises 4 m over 80 m of horizontal distance. What is the slope percent?
3. EASY Explain in two sentences why a furrow plowed down a slope increases erosion while a furrow along the contour reduces it.
4. MEDIUM If water flowing at 0.5 m/s has a certain energy, how many times more energy does water at 1.5 m/s have? (Energy of motion grows with the square of the speed.)
5. MEDIUM A field loses 1.5 mm of soil per year. Using 13 tonnes per millimeter per hectare, how many tonnes per hectare is that, and is it above or below the 11 t/ha/yr tolerable

limit?

6. MEDIUM Data reading. Soil loss was measured on test plots with the same soil and rainfall but different slope lengths, all at 5% slope, all plowed up and down:
   Slope length (m): 20, 40, 80, 160
   Soil loss (t/ha/yr): 8, 11, 16, 22
   (a) What happens to soil loss as slope length doubles? (b) Does loss double each time length doubles? (c) Which conservation practice directly attacks slope length?
7. MEDIUM Data reading. Four plots on a 6% slope were measured for one year:
   Plot 1, bare, plowed up and down: 30 t/ha
   Plot 2, corn, plowed up and down: 20 t/ha
   Plot 3, corn, contour plowed: 10 t/ha
   Plot 4, corn and alfalfa strips on the contour: 5 t/ha
   (a) What fraction of Plot 2's loss did contouring (Plot 3) allow? (b) Which single comparison isolates the effect of plant cover alone? (c) Which plots meet the 11 t/ha tolerable limit?
8. HARD Experiment design. A farmer wants to know whether rye planted as a winter cover crop reduces soil loss from a sloping field compared with leaving it bare after harvest. Design a fair field test: independent and dependent variables, at least three things held constant, how to measure, and why using several strips of each treatment matters.
9. HARD A shelterbelt of trees 12 m tall protects a field for roughly ten times its height downwind. A square field is 600 m on a side with the wind usually from the west. How many north–south shelterbelts, including one on the west edge, would be needed to protect the whole field?
10. CHALLENGE Write a paragraph of five or six sentences that a Coon Valley farmer in 1933 might have written to a neighbor explaining why he signed the conservation agreement and what he expects to change on his farm. Use at least four of these words: contour, runoff, infiltration, strip cropping, terrace, gully.

COMMON MISTAKES

- Thinking contour plowing stops erosion completely. It roughly halves soil loss on gentle slopes; on long or steep slopes water overtops the furrows, so farmers add strips, terraces, residue and cover crops.
- Believing that bigger raindrops or more rain are the whole story. Bare soil and the speed of runoff matter as much; the same storm on a covered field with contour rows may move almost no soil.
- Confusing contour lines with straight horizontal rows. Contours curve around the hill at one elevation, so contour furrows curve too; a straight row on a curving hill ends up running partly downhill.

> **Make it a game · Watershed Planner.** Draw a hill on a large sheet with five fields on it, each labeled with a slope percent (2, 4, 6, 10 and 15). Players take turns drawing one conservation practice on a field: contour rows (halves loss), contour strips (quarters loss), a terrace (allowed only above 8%, halves loss again), a cover crop (halves loss) or a shelterbelt (protects the field downwind from wind only). Each field starts with a soil loss

of 4 times its slope percent in tonnes per hectare. The round ends when every field is under 11 t/ha. Score one point per practice used; the lowest score wins, because the best planner reaches the goal with the fewest changes.

Scripture. “For his God doth instruct him to discretion, and doth teach him.” (Isaiah 28:26, KJV)

Isaiah has just described a plowman who breaks the clods, levels the ground and sows each seed in its place (verses 24 and 25). The prophet says the farmer’s skill comes from God, who teaches him through the land itself. Contour plowing is one of those lessons: the hill shows the farmer where to run his furrows, if he will look.

Practice answers

1. Coon Valley (the Coon Creek watershed), Vernon County, Wisconsin, beginning October 1933. It treated a whole watershed at once, working with hundreds of farmers together rather than advising one farm at a time.
2. 4 ÷ 80 × 100 = 5%.
3. A furrow down the slope is a channel that gathers runoff and lets it speed up, and faster water carries more soil. A furrow along the contour is level, so it holds water like a small dam until it soaks in, slowing runoff and keeping soil in place.
4. Speed is 3 times greater, so energy is $3^2 = 9$ times greater.
5. 1.5 × 13 = 19.5 t/ha/yr, above the limit.
6. (a) It increases. (b) No; it rises by a factor of about 1.4 each time (8 to 11 to 16 to 22), less than doubling. (c) Terraces (and contour strips), which break a long slope into several short ones.
7. (a) 10 ÷ 20 = one half, matching the 0.5 factor. (b) Plot 1 versus Plot 2 (same plowing, cover differs). (c) Plots 3 and 4.
8. Independent variable: winter cover (rye versus bare). Dependent variable: soil lost over winter and spring, measured by weighing sediment in identical collection troughs at the bottom of each strip or by erosion pins. Hold constant: slope, soil type, strip width and length, previous crop, tillage, planting dates and the same rainfall (strips side by side). Use several alternating strips of each treatment so that one unusual patch of soil or one gully does not decide the result, and average the strips.
9. Each belt protects about 10 × 12 = 120 m. 600 ÷ 120 = 5 belts, spaced 120 m apart starting at the west edge (at 0, 120, 240, 360 and 480 m).
10. A good answer explains that plowing up and down the hill has let runoff cut gullies and carry the topsoil to the valley floor; that plowing on the contour and strip cropping with alfalfa will slow the water so it has time for infiltration; that terraces may be needed on the steepest fields; and that the farmer expects less soil loss, fewer gullies to fill, and in time better yields, while admitting the curved rows take more skill to lay out.

1.4 Soil Testing: Asking the Ground What It Needs

OBJECTIVES

- Explain what a soil test measures (pH, nitrogen, phosphorus, potassium and organic matter) and why each matters for plant growth.
- Use the pH scale to compare acidity, and calculate lime and fertilizer amounts for a garden plot from a per-hectare recommendation.
- Tell how George Washington Carver at Tuskegee Institute taught poor farmers to test and rebuild worn-out soil with legumes, compost and careful records.

Warm-up. Put a spoonful of dry soil in each of two cups. Pour a little vinegar on the first; if it fizzes, the soil contains carbonate and is alkaline. Wet the second with distilled water, then sprinkle baking soda on it; if it fizzes, the soil is acidic. If neither fizzes, the soil is probably near neutral. Write down what you saw and what you think your soil's pH might be.

Video. Coming soon. How to take a soil sample and read a soil test report, soil pH and NPK explained, George Washington Carver Tuskegee experiment station history; look for university extension (land-grant) channels, USDA NRCS soil health videos, Smithsonian and National Park Service Carver videos, SciShow, and Moody Science classics on plants and soil.

KEY TERMS

pH
: A number from 0 to 14 that tells how acidic or alkaline a soil is. 7 is neutral; each step down is ten times more acidic. Most crops grow best between about 6.0 and 7.0.

macronutrient
: A nutrient plants need in large amounts. The big three are nitrogen (N), phosphorus (P) and potassium (K); calcium, magnesium and sulfur are also macronutrients.

lime
: Ground limestone (calcium carbonate) spread on soil to raise its pH and supply calcium. Sulfur does the opposite, lowering pH.

legume
: A plant of the pea and bean family, such as peanut, cowpea, clover or alfalfa, whose roots carry nodules of bacteria that turn nitrogen gas from the air into nitrogen the plant can use.

fertilizer grade
: The three numbers on a fertilizer bag, such as 10-10-10, giving the percent by mass of nitrogen, phosphate (P_2O_5) and potash (K_2O).

soil sample

Soil collected for testing: usually 10 to 15 small cores taken 15 cm deep across a field, mixed together, dried and sent to a laboratory.

CORE IDEAS

The story. In the autumn of 1896 a young botanist stepped off the train at Tuskegee, Alabama, to take charge of the agriculture department at Booker T. Washington's school for Black students. His name was George Washington Carver. He had been born into slavery in Missouri near the end of the Civil War, had worked his way through Iowa State as its first Black student, and had just finished a master's degree there. What he found around Tuskegee was ruined land: red clay hills gullied by rain, worn out by decades of cotton grown year after year, with sand hills and swamps the farmers thought were worthless. The farmers themselves were mostly poor tenants who could not read a chemistry book, let alone buy fertilizer. Carver asked the state for an agricultural experiment station, got it in 1897 on a piece of poor campus land, and began to test. He measured the soil, hauled muck from the swamps and leaves from the woods to make compost, planted cowpeas and peanuts to feed the soil, and recorded every yield. In 1905 he published a bulletin for farmers called *How to Build Up Worn Out Soils*. In 1906 he put a laboratory on a wagon, the Jesup Agricultural Wagon, and drove it from farm to farm so that farmers who could not come to the school could learn to read their own land.

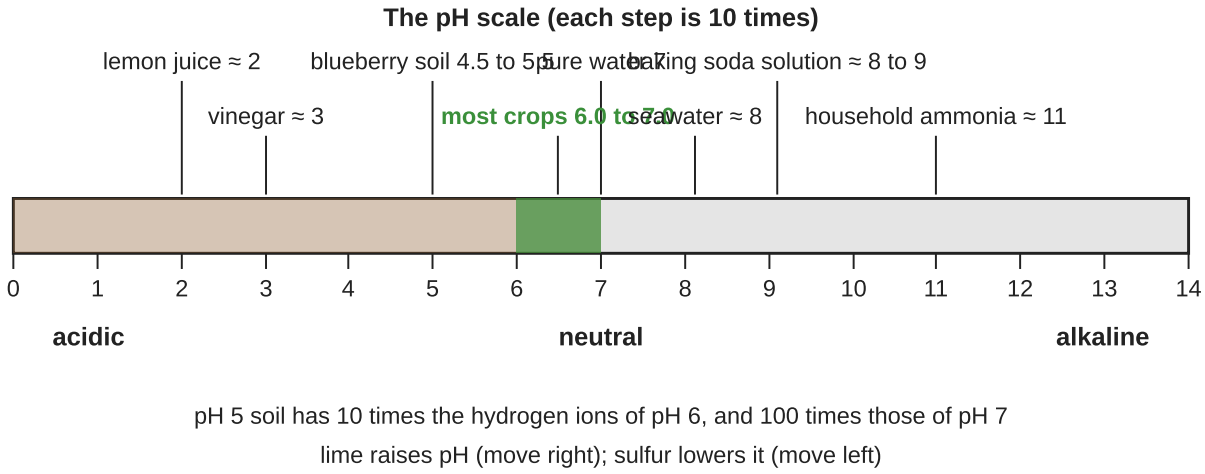
How they figured it out. Carver was building on a century of discovery. In 1840 the German chemist Justus von Liebig showed that plants are fed not by humus directly but by mineral elements, especially nitrogen, phosphorus and potassium, dissolved in soil water. In 1843 John Lawes and Joseph Gilbert began the Broadbalk wheat experiment at Rothamsted in England, applying different fertilizers to the same strips of field year after year; the experiment is still running, the oldest continuous field experiment in the world. In 1886 Hermann Hellriegel and Hermann Wilfarth proved that peas and other **legumes** grow without nitrogen fertilizer because bacteria in the nodules on their roots capture nitrogen gas from the air. Carver put all of this to work for farmers with no money: peanuts and cowpeas to add nitrogen, compost and swamp muck to add humus and the other nutrients, and rotation so the same field did not grow cotton every year. He also tested the soil itself, because a cure must match the disease.

The big idea. A soil test is a set of measurements. The first is **pH**, which runs from 0 (very acidic) to 14 (very alkaline), with 7 neutral. The scale is logarithmic: a soil at pH 5 has ten times as many hydrogen ions as a soil at pH 6, and a hundred times as many as one at pH 7. Most vegetables and grains do best between about 6.0 and 7.0, where the **macronutrients** are most available; blueberries want pH 4.5 to 5.5, and in very acidic soils aluminum dissolves and poisons roots. **Lime**, ground calcium carbonate, raises pH; elemental sulfur lowers it. The second set of measurements is nutrients: nitrogen for leaves and protein, phosphorus for roots, flowers and seeds, potassium for strong stems and disease resistance, plus calcium, magnesium and sulfur. The third is organic matter, which holds water and feeds the soil's living things. A laboratory report gives each result and a recommendation per hectare, and the gardener scales it down to the plot. **Fertilizer grade** makes the

arithmetic possible: a 20 kg bag of 10-10-10 holds 2 kg of nitrogen, 2 kg of phosphate and 2 kg of potash.

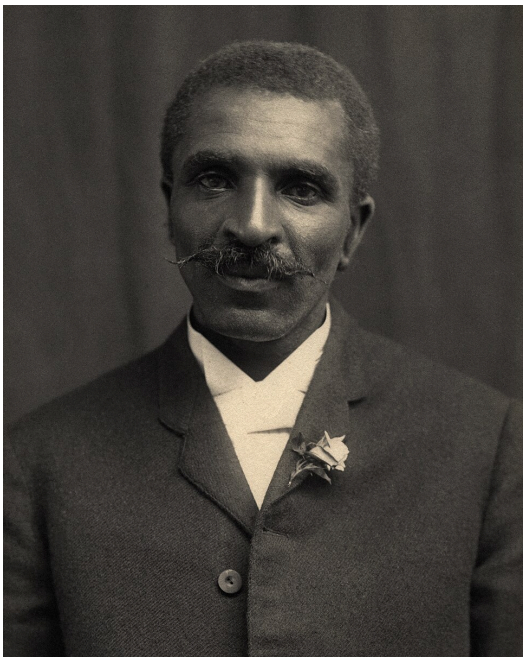
Try it and see. You can test soil at home in three grades of exactness. The quickest tests are the vinegar and baking soda fizz tests from the warm-up, which tell you only whether the soil is strongly alkaline or acidic. A cheap probe or a paper-strip kit gives pH to about half a unit; juice from boiled red cabbage, which turns pink in acid and blue-green in base, is a homemade version. The most exact test is to send a proper **soil sample** to your state university's extension soil laboratory, which most states run for a few dollars. The sampling itself is the science: ten to fifteen cores, 15 cm deep, spread across the whole plot in a zigzag, mixed in a clean bucket, air-dried and sent in a labeled bag. One scoop from one corner tells you about that corner, not the garden. Carver's farmers learned the same lesson: look at the whole field before you decide what it needs.

God's handiwork. Carver rose before dawn to walk in the woods and said that he went there to hear what God had to say to him about the plants; he called the Creator his teacher and his laboratory "God's little workshop." He was not being sentimental. He believed that the ground would answer plainly if it were asked carefully, and he spent fifty years teaching farmers how to ask. Job says the same: "speak to the earth, and it shall teach thee" (Job 12:8). A soil test is a way of speaking to the earth and recording its answer, and the farmer who reads that answer and feeds the soil what it lacks is keeping the garden the way Adam was told to keep it.



The pH scale. Each step is a factor of ten in hydrogen ion concentration. Most crops grow best between 6.0 and 7.0.

PICTURE STUDY



George Washington Carver, Unknown photographer (Tuskegee Institute), about 1910 · Photograph · Tuskegee University Archives, Tuskegee, Alabama

This portrait, kept in the Tuskegee University archives, was made by a photographer whose name was not recorded. It shows Carver in his forties, some years after he arrived in Alabama, when his experiment station bulletins were already reaching farmers across the South.

Carver kept a flower in his lapel most days and mended his own clothes. He turned down high-paying offers from industry to stay at Tuskegee, where his salary never rose much above what Booker T. Washington first offered him.

Look closely

- Look at the face and eyes. What does the expression tell you about the man’s habit of looking closely at things?
- Notice the plain suit and tie. What does the way he presented himself say about how he wanted farmers and students to see a scientist?
- A portrait like this shows no laboratory or field. If you could add one object from his work to the picture, what would it be, and why?

Talk about it

1. Carver brought his laboratory to farmers on a wagon. Why was it important that the farmers test their own soil instead of simply being told what to do?
2. Carver said he learned from God’s creation by looking closely and asking questions. How is that like the way a soil test works?

3. What would Carver have told a farmer whose cotton field had grown nothing but cotton for twenty years?

> **Safety first.** Vinegar and baking soda are safe, but keep them out of eyes. If you use a purchased soil test kit, follow its instructions and keep the chemicals away from younger children. Boiling red cabbage needs adult help at the stove. Wash hands after handling soil.

EXPERIMENT: TEST YOUR GARDEN LIKE CARVER: PH, FIZZ AND A NITROGEN TRIAL

You will sample a garden bed properly, measure its pH two ways, and set up a small pot trial to see whether a legume cover crop changes how well a second crop grows. **Question:** what is my soil's pH, and does growing a legume first improve the growth of the plant that follows? **Prediction:** write down the pH you expect and whether you think the legume pots will grow taller radishes.

You will need

- Trowel, clean bucket, paper bags and a marker for samples
- Distilled water, white vinegar, baking soda and clear cups
- A red cabbage, a pot and strainer (adult help), or a purchased pH test kit or strips
- Six identical pots, potting soil from one bag, pea or bean seeds and radish seeds
- Ruler, kitchen scale, calculator and your lab notebook

Steps

1. Walk your garden bed in a zigzag and take 10 small cores of soil 15 cm deep. Mix them in the bucket, spread the mix on newspaper to air-dry overnight, and remove roots and stones. This is your sample.
2. Fizz tests: put a spoonful of dry sample in a cup and add vinegar; put a second spoonful in another cup, wet it with distilled water and sprinkle baking soda on it. Record which fizzed, if either.
3. Cabbage indicator: with an adult, boil chopped red cabbage in water for 10 minutes, strain and cool the purple juice. Make a reference set by adding juice to small cups of vinegar (acid), distilled water (neutral) and baking soda solution (alkaline) and noting the colors. Then stir a spoonful of soil into distilled water, let it settle, pour off the clear water and add juice. Match the color to your reference set and estimate the pH. If you have a kit or strips, test the same water and compare.
4. Nitrogen trial: fill six pots with the same mass of potting soil. In three pots plant pea or bean seeds; leave three pots bare. Water all six the same. After three weeks, cut the pea plants off at the soil line and chop the tops into the soil of those pots (farmers call this green manure). Leave them one week.
5. Plant three radish seeds in every pot, thin to one seedling each, and grow them for three to four weeks with equal water and light. Record what you change (legume first or not) and what you keep the same.

6. Measure the height of each radish plant every week and the mass of the whole plant at harvest. Average the three legume pots and the three bare pots and make a bar graph.
7. Write a conclusion: report your pH estimate, say whether the fizz tests agreed with the indicator, and tell whether the legume pots grew larger radishes and by how much. Say what you would do next to test the result more strongly.

Tips

- A small pot trial over a month will show a modest effect at best, because nodule bacteria need time to build up; real farmers see the benefit over a season. A small or no difference is an honest result.
- Use distilled water for the pH test; tap water has its own pH and can shift the color.
- If your extension service tests soil cheaply, send a second portion of your sample and compare the lab pH with your estimate.

Check your work

- I took a mixed sample from at least ten spots and dried it before testing.
- I estimated the pH with an indicator or kit and checked it against the fizz tests.
- I ran a fair trial with three pots per treatment, averaged the results and graphed them.

FIELD NOTEBOOK

1. Draw the pH scale from 0 to 14 and mark lemon juice, vinegar, blueberry soil, the best crop range, pure water, seawater and baking soda solution; shade the band where most vegetables grow.
2. Draw a legume root with nodules and label what the bacteria inside do; beside it, write out the nitrogen path from air to nodule to plant to soil.
3. Copy a sample soil test report (pH, N, P, K, organic matter, and a per-hectare recommendation) and beneath it work out the amounts for a 25 m^2 bed.

> **From history.** Carver published more than forty bulletins from the Tuskegee experiment station, written in plain language for farmers who had little schooling, with titles such as *How to Build Up Worn Out Soils* (1905) and *How to Grow the Peanut and 105 Ways of Preparing It for Human Consumption* (1916). He never patented most of his discoveries, saying God had given them to him freely. He died at Tuskegee on January 5, 1943, and in the same year Congress made his Missouri birthplace a national monument, the first for a Black American.

WORKED EXAMPLES

Example 1. A garden soil tests at pH 5.0. A neighbor's soil tests at pH 7.0. How many times more hydrogen ions does the first soil hold than the second, and which common fruit would be happy in the first soil?

(Use the map or drawing "Two pH units apart means a factor of one hundred in acidity." shown earlier in this lesson.)

1. Each pH unit is a factor of 10 in hydrogen ion concentration. The difference is 7.0 − 5.0 = 2 units.
2. Factor = 10 × 10 = 10^2 = 100.
3. Blueberries prefer pH 4.5 to 5.5, so pH 5.0 suits them well. Most vegetables (best at 6.0 to 7.0) would need lime first.

Answer: The pH 5.0 soil holds 100 times more hydrogen ions than the pH 7.0 soil. It is good blueberry soil but would need lime for most vegetables.

Example 2. A soil test report recommends 2 tonnes of lime per hectare to raise a garden's pH from 5.5 to 6.5. The garden bed is 5 m by 10 m. How many kilograms of lime should be spread on the bed?

1. Area of the bed = 5 m × 10 m = 50 m^2.
2. One hectare = 10,000 m^2, so the bed is 50 ÷ 10,000 = 0.005 hectare.
3. Lime needed = 2 t/ha × 0.005 ha = 0.01 t = 10 kg.

Answer: 10 kilograms of ground limestone for the 50 m^2 bed. A 20 kg bag would treat two such beds.

Example 3. The report also recommends 50 kg of nitrogen per hectare for a 0.2 hectare vegetable plot. The gardener has 10-10-10 fertilizer. How much nitrogen is needed, how many kilograms of 10-10-10 supply it, and how much phosphate and potash come along with it?

1. Nitrogen needed = 50 kg/ha × 0.2 ha = 10 kg of N.
2. 10-10-10 is 10% nitrogen by mass, so each kilogram of fertilizer holds 0.1 kg of N. Fertilizer needed = 10 kg ÷ 0.10 = 100 kg.
3. The same 100 kg also carries 10% phosphate (P_2O_5) and 10% potash (K_2O): 0.10 × 100 kg = 10 kg of each.

Answer: 10 kg of nitrogen, supplied by 100 kg of 10-10-10, which also adds 10 kg of phosphate and 10 kg of potash. If the test showed phosphorus was already high, a grade such as 20-0-10 would fit better, which is why the test comes first.

PRACTICE

1. EASY Name the three main things a soil test measures and give one reason each matters.
2. EASY What do the numbers 5-10-10 on a fertilizer bag mean?
3. EASY Why did Carver tell farmers to plant peanuts and cowpeas on worn-out cotton land?
4. MEDIUM Soil A has pH 6.0 and Soil B has pH 8.0. Which is more acidic, and by what factor in hydrogen ion concentration?
5. MEDIUM A recommendation calls for 3 t/ha of lime. How many kilograms are needed for a 4 m × 6 m bed?
6. MEDIUM Data reading. A student grew bean plants in pots of the same soil adjusted to different pH values and measured average height after four weeks:
   pH: 4.0, 5.0, 6.0, 7.0, 8.0
   Height (cm): 9, 17, 26, 25, 15
   (a) In which pH range did the beans grow best? (b) Describe the pattern as pH moves away from that range in either direction. (c) What might explain the poor growth at pH 4.0?
7. MEDIUM Data reading. A soil test lab reports for a field: pH 5.4; phosphorus, low; potassium, high; organic matter 1.8%. The farmer wants to grow corn (best pH 6.0 to 6.8). (a) Which two problems does the report show? (b) Would a 10-10-10 fertilizer be a good match? Explain using the potassium result. (c) Name one practice from Carver's bulletins that would raise organic matter.
8. HARD Experiment design. You want to test whether adding lime to an acidic garden soil (pH 5.0) increases lettuce growth. Design the experiment with at least three lime levels, state the variables and controls, say how you would measure the outcome, and explain why you should measure pH as well as plant growth.
9. HARD A farmer takes one soil sample from the gateway corner of a 2-hectare field, where the cattle gather, and sends it to the lab. The report says nitrogen is very high. Why might this report mislead him about the whole field, and how should the sample have been taken?
10. CHALLENGE Write a paragraph of five or six sentences that Carver might have put in a farmers' bulletin explaining how to rebuild a worn-out cotton field over two years without buying fertilizer. Use the words legume, nitrogen, compost, rotation and pH (or lime).

COMMON MISTAKES

- Thinking more fertilizer is always better. Extra nutrients the soil already holds are wasted money and can wash into streams; the test tells you what is lacking and what is not.
- Treating pH as a simple count. The scale is logarithmic, so pH 5 is ten times more acidic than pH 6 and a hundred times more than pH 7, which is why small-looking pH changes need real amounts of lime.

- Sampling one spot and calling it the field. Soil varies within a few meters; a proper sample mixes many cores so the result describes the whole plot.

Make it a game · Soil Doctor. One player is the farmer and draws a card describing a field: its pH, whether N, P and K are low, medium or high, its organic matter and the crop wanted (make a dozen cards ahead of time). The other player is the soil doctor and has sixty seconds to prescribe: lime or sulfur or neither, which fertilizer grade (choose from 10-10-10, 20-0-10, 0-20-0, 5-10-10) and how much for a 100 m^2 plot, and one organic practice. The farmer checks the prescription against the card. Score a point for each correct part; switch roles. Bonus point for catching a field that needs no fertilizer at all.

Scripture. “But ask now the beasts, and they shall teach thee; and the fowls of the air, and they shall tell thee: Or speak to the earth, and it shall teach thee: and the fishes of the sea shall declare unto thee.” (Job 12:7–8, KJV)

Job says the created world can be asked and will answer. A soil test is a careful question put to the ground, and Carver spent his life teaching farmers to ask it. The answer always points back to the One who made the soil able to give bread.

Practice answers

1. pH (controls whether nutrients are available and whether aluminum becomes toxic); nutrients, especially nitrogen, phosphorus and potassium (plants need them in large amounts for leaves, roots and seeds, stems and disease resistance); organic matter (holds water and nutrients and feeds soil life).
2. 5% nitrogen, 10% phosphate (P_2O_5) and 10% potash (K_2O) by mass.
3. They are legumes; bacteria in their root nodules take nitrogen from the air and add it to the soil, so the land is rebuilt without costly fertilizer, and the crops themselves can be eaten or sold.
4. Soil A is more acidic (lower pH). The difference is 2 units, so Soil A has $10^2 = 100$ times the hydrogen ion concentration of Soil B.
5. Area 24 m^2 = 0.0024 ha. 3,000 kg/ha × 0.0024 ha = 7.2 kg.
6. (a) pH 6.0 to 7.0. (b) Height falls off on both sides; growth is worst at the extremes (9 cm at pH 4.0, 15 cm at pH 8.0). (c) In very acidic soil aluminum dissolves and harms roots, and several nutrients become less available.
7. (a) The pH is too low (acidic) for corn, and phosphorus is low. (b) No; potassium is already high, so paying for potash is waste, and a grade with nitrogen and phosphate but little or no potash would fit better. (c) Composting leaves and manure, or growing a legume cover crop and turning it in.
8. Independent variable: lime added (for example 0, 5, 10 and 20 g per pot of the same soil, giving several pH levels). Dependent variable: lettuce growth, measured as leaf mass at harvest and height each week. Controls: same soil and mass per pot, same seeds, water, light and temperature, several pots per level. Measure pH in each pot after two weeks so you know what pH each lime level actually produced; otherwise you would be guessing at the cause, and too much lime could push the pH past the best range and reduce growth.
9. The gateway corner is enriched by manure and is not typical of the field, so the lab is correctly describing one unusual spot. He should take 10 to 15 cores 15 cm deep in a zigzag

across the whole field, avoiding obvious odd spots or sampling them separately, mix the cores and send the mixed sample.

10. A good answer: plant cowpeas or peanuts (a legume) the first year so the nodule bacteria add nitrogen; gather leaves, swamp muck and barnyard manure into compost and spread it to add humus and nutrients; follow with a rotation so cotton does not return every year; check whether the soil is too acidic and, if so, add lime or wood ashes to raise the pH; keep records of yields each year to see what works. The land will give back what is put into it.

Unit 1 review

Answer each question. Show your work for calculations and use complete sentences for explanations. Use metric units. The test is worth 60 points.

1. (5 pts) Multiple choice. Which of the following was NOT a cause of the Dust Bowl of the 1930s? (a) A decade of drought on the southern Plains. (b) Plowing up the native grassland for wheat in the 1920s. (c) Strong spring winds. (d) Farmers planting too many shelterbelts.
2. (5 pts) Describe the three ways wind moves soil (creep, saltation, suspension), and explain why saltation is the key step in starting a dust storm.
3. (5 pts) A field loses 2 mm of topsoil in a dust storm. Using a soil density of 1.3 g/cm³, calculate the mass lost from one hectare in tonnes. Show your steps.
4. (5 pts) Diagram item. Draw a soil profile about 10 cm tall and label the O, A, E, B, C and R horizons in the correct order. Beside each letter write a two- or three-word description, and mark which horizon is the topsoil.
5. (5 pts) A jar test settles into layers of sand 24 mm, silt 30 mm and clay 6 mm. Calculate the percent of each. Is the soil mostly sand, silt or clay?
6. (5 pts) Multiple choice. The five soil-forming factors (CLORPT) are: (a) color, light, oxygen, rain, pressure, temperature; (b) climate, organisms, relief, parent material, time; (c) clay, loam, organic matter, rock, pH, texture; (d) carbon, lime, ore, roots, phosphorus, tillage.
7. (5 pts) A hillside field rises 6 m over a horizontal distance of 75 m. Calculate its slope as a percent. Then explain in one or two sentences why a furrow plowed along the contour reduces soil loss on this slope.
8. (5 pts) A field plowed up and down the slope loses 20 t/ha/yr. Using the Universal Soil Loss Equation factors of 0.5 for contouring and 0.25 for contour strip cropping, find the loss under each practice and state which practices bring it below the tolerable 11 t/ha/yr. Then convert the strip-cropping result to millimeters of soil per year (1 mm per hectare is about 13 t).
9. (5 pts) Data reading. Soil loss was measured on four plots with the same soil, slope and rainfall for one year: Plot 1, bare and plowed up and down, 32 t/ha; Plot 2, corn plowed up and down, 24 t/ha; Plot 3, corn on the contour, 12 t/ha; Plot 4, corn with grass strips on the contour, 6 t/ha. (a) Which comparison shows the effect of contouring alone? (b) By what fraction did strip cropping reduce the loss compared with Plot 2? (c) Why must the plots share the same slope and rainfall?
10. (5 pts) Soil X has pH 5.0 and Soil Y has pH 7.0. (a) Which is more acidic? (b) How many times more hydrogen ions does it have? (c) Name a crop suited to each soil.
11. (5 pts) A soil test recommends 2.5 tonnes of lime per hectare and 40 kg of nitrogen per hectare. For a 4 m × 5 m garden bed, how many kilograms of lime are needed, and how many kilograms of 10-10-10 fertilizer would supply the nitrogen?
12. (5 pts) Short essay. In five or six sentences, explain how George Washington Carver helped poor farmers rebuild worn-out soil at Tuskegee, and name two things from his

method that a soil scientist today would still recommend.

UNIT PROJECT: MY SOIL REPORT

Produce a soil report for one plot of ground you choose, in the style of a county soil survey. Include a scaled drawing of the soil profile from your pit with horizons labeled and measured; jar-test results with sand, silt and clay percentages and the texture class; the slope percent of the plot and an estimate of its erosion risk with a recommended practice (contour rows, mulch, cover crop or strips); your pH estimate and fizz-test results with a lime or sulfur recommendation scaled to the plot's area; and the data table and bar graph from either your wind-tray or rain-tray erosion experiment.

Finish with a one-page written summary that tells what your soil is, what it needs and how you would keep it, and connects your plot to one of the unit's stories (the Dust Bowl, Dokuchaev, Coon Valley or Carver). Compare your findings with the Web Soil Survey description for your location if it is available.

- **Observation and measurement**: The profile drawing is to scale with horizons correctly labeled and depths in centimeters; the jar test, slope and pH results are recorded with units.
- **Calculation**: Texture percentages add to 100%, slope percent is computed correctly, and the lime or fertilizer recommendation is correctly scaled from per-hectare to the plot's area.
- **Experiment**: The erosion experiment states the question, variables and controls, includes a data table and labeled bar graph, and draws a conclusion from the numbers.
- **Explanation and care**: The summary explains what the soil needs and how to keep it, connects to a unit story accurately, and the whole report is neat, labeled and easy to read.

Answer key

1. (d). Shelterbelts were planted after 1935 as part of the cure, not a cause.
2. Creep: large grains roll along the surface. Saltation: sand-sized grains bounce in short hops. Suspension: fine silt and clay are lifted high and carried far. Saltation is the key because the bouncing grains strike the surface and knock loose the fine particles that rise as dust; without it, little dust leaves the ground.
3. 1 ha = 10^8 cm^2. 2 mm = 0.2 cm. Volume = $10^8 \times 0.2 = 2 \times 10^7$ cm^3. Mass = $1.3 \times 2 \times 10^7 = 2.6 \times 10^7$ g = 26 tonnes.
4. A vertical column with, from top to bottom: O (organic litter), A (dark topsoil with humus and roots; this is the topsoil), E (pale, leached), B (subsoil where clay and iron collect), C (weathered parent material), R (bedrock). Full credit for correct order, labels and descriptions.
5. Total 60 mm. Sand 40%, silt 50%, clay 10%. Mostly silt; the three percentages add to 100%.
6. (b).
7. $6 \div 75 \times 100 = 8\%$. A contour furrow is level, so it holds rainwater like a small dam until it soaks in, instead of channeling it downhill where it would speed up and carry soil.

8. Contouring: 20 × 0.5 = 10 t/ha/yr (below 11). Strip cropping: 20 × 0.25 = 5 t/ha/yr (below 11). Both work. 5 ÷ 13 ≈ 0.4 mm/yr.
9. (a) Plot 2 versus Plot 3 (same crop, only plowing direction differs). (b) 6 ÷ 24 = one quarter, a 75% reduction. (c) So that the only difference between plots is the practice being tested; otherwise slope or rain could explain the result instead.
10. (a) Soil X. (b) $10^2 = 100$ times. (c) Soil X: blueberries (pH 4.5 to 5.5). Soil Y: most vegetables and grains (best at 6.0 to 7.0; 7.0 is at the top of the range).
11. Area 20 m^2 = 0.002 ha. Lime: 2,500 kg × 0.002 = 5 kg. Nitrogen: 40 × 0.002 = 0.08 kg; 10-10-10 is 10% N, so 0.08 ÷ 0.10 = 0.8 kg of fertilizer.
12. A good answer: Carver started an experiment station in 1897 on poor land, tested the soil, made compost from leaves, swamp muck and manure, planted legumes such as cowpeas and peanuts to add nitrogen through their root nodules, rotated crops, kept records of yields, and published plain-language bulletins such as How to Build Up Worn Out Soils (1905); in 1906 he took his laboratory to farms on the Jesup Wagon. Still recommended today: legume cover crops or rotation, adding organic matter and compost, testing the soil before adding anything, and keeping records.

UNIT 2

Water Wells

Under almost every field and town lies water that no one can see: rain that soaked into sand, gravel and cracked rock and stayed there, cool and clean, in the pores between the grains. People have reached down for it since Abraham and Isaac dug wells in the Negev, and Jesus sat on the rim of one such well at Sychar and called its water “living.” In this unit you will learn what the Samaritan woman meant when she said “the well is deep,” how groundwater is stored and moves through **aquifers**, how a modern driller finds water, finishes a well and tests it, and how the people of the American West learned, often the hard way, to divide a river that is not big enough for everyone.

You will measure like a hydrogeologist: the porosity of gravel and sand, the drawdown of a model well under a pump, the time it takes water to recover, the cubic meters in an acre-foot and the share each farm gets from a dry-year stream. You will meet Henry Darcy with his iron pipe of sand in Dijon, the drillers of Zigong who pounded a well past 1,000 m in 1835, and John Wesley Powell, who warned Los Angeles in 1893 that there was not enough water for the land. Several careers run through these lessons: licensed well driller, hydrogeologist, state hydrographer, ditch rider and water commissioner.

The unit stands on two Scriptures. Moses promised Israel “a land of brooks of water, of fountains and depths that spring out of valleys and hills” (Deuteronomy 8:7), and Isaac, driven off two wells by quarrels, dug a third and named it Rehoboth, “for now the LORD hath made room for us” (Genesis 26:22). Groundwater is God’s ordered storehouse, and the rules by which neighbors share it are a matter of justice and peace.

BEFORE YOU BEGIN

- Can compute the volume of a cylinder and a rectangular solid and convert between m^3, liters and milliliters
- Can work with percents, ratios and rates (liters per minute, meters per day)
- Can read a data table and a bar graph and identify independent and dependent variables
- Knows the soil horizons and infiltration ideas from Unit 1

MASTERY CHECKLIST

- I can retell the meeting at Jacob’s well and explain the difference between a dug well, a spring and a cistern.
- I can define porosity and permeability, measure the porosity of a sample, and explain why clay is porous but not permeable.
- I can draw and label unconfined and confined aquifers, the water table, a recharge area and an artesian well.
- I can describe how a well is drilled, cased, screened, gravel packed and grouted, and compute specific capacity from a pump test.

- I can explain prior appropriation, apply it to a dry-year stream, and convert acre-feet to cubic meters.
- I can tell what John Wesley Powell warned about in 1893 and what the Colorado River Compact of 1922 did.

OPTIONAL BOOKS AND RESOURCES

- **USGS Water Science School** (https://www.usgs.gov/special-topics/water-science-school): Free. Clear pages and diagrams on groundwater, aquifers, the water table, wells and how much water the earth holds. Good for checking the numbers in Lessons 2.1 and 2.2 and for finding the groundwater pages on artesian wells and land subsidence.
- **Bureau of Reclamation, Law of the River (Colorado River Compact and related documents)** (https://www.usbr.gov/lc/region/pao/lawofrvr.html): Free. The text of the 1922 compact and the agreements that followed. A parent can read aloud the short Article III that divides the river into basins for Lesson 2.4.

2.1 Jacob's Well: Living Water at Sychar (John 4) ★

OBJECTIVES

- Retell the meeting at Jacob's well in John 4 and locate the well in the valley between Mount Ebal and Mount Gerizim near ancient Shechem.
- Explain the difference between a dug well, a spring and a cistern, and why a well that reaches the water table gives "living water."
- Calculate how much water a hand-drawn well can supply per hour and estimate how much rainfall soaks in to recharge groundwater under a plot of land.

Warm-up. Fill a clear glass two-thirds full of clean gravel or dry rice. Slowly pour in water from a measuring cup and stop the moment water shows at the surface. How much water disappeared into the spaces? That hidden water is a tiny model of groundwater, and the surface you just reached is a model water table. Write the number down; you will use the idea all unit.

Video. Coming soon. Jacob's Well at Nablus today, how a hand-dug well works, groundwater and the water table for middle school; look for USGS Water Science School, Smithsonian, Bible Land tour footage of the Greek Orthodox church at Jacob's Well, Moody Science classics on water, and Homeschool Pop (Alternate).

KEY TERMS

groundwater
Water that fills the cracks and pore spaces in soil and rock beneath the surface.

water table
The top of the zone where every pore in the ground is full of water. Below it the ground is saturated; above it the pores hold air and some moisture.

dug well
A hole dug by hand down past the water table, usually lined with stone, so groundwater seeps in and can be lifted out with a bucket.

cistern
A lined, waterproof pit or tank that stores rainwater collected from roofs or courtyards. It holds only what is poured in.

spring
A place where the water table meets the land surface and groundwater flows out on its own.

recharge
Rain or snowmelt that soaks down through the soil and refills the groundwater.

CORE IDEAS

The story. Around the year AD 30, Jesus was walking north from Judea to Galilee through the hill country of Samaria. At midday, "about the sixth hour," he stopped at a well outside the town of Sychar and sat down on its stone rim while his disciples went to buy food (John 4:5–8). The Gospel tells us whose well it was: "Now Jacob's well was there." Centuries before, Jacob had bought a piece of ground near Shechem (Genesis 33:18–19), and Joseph's bones were later buried in that same field (Joshua 24:32). A Samaritan woman came to draw water, and when Jesus offered her "living water," she answered with a very practical objection: "Sir, thou hast nothing to draw with, and the well is deep" (John 4:11). She was right about the well. The traditional site, inside a Greek Orthodox church near Balata on the edge of Nablus, is a shaft cut straight down through solid limestone, a little over 2 m across and, by modern measurements, about 40 m deep. Mount Gerizim rises just to the south, which is why the woman could point and say, "Our fathers worshipped in this mountain" (John 4:20).

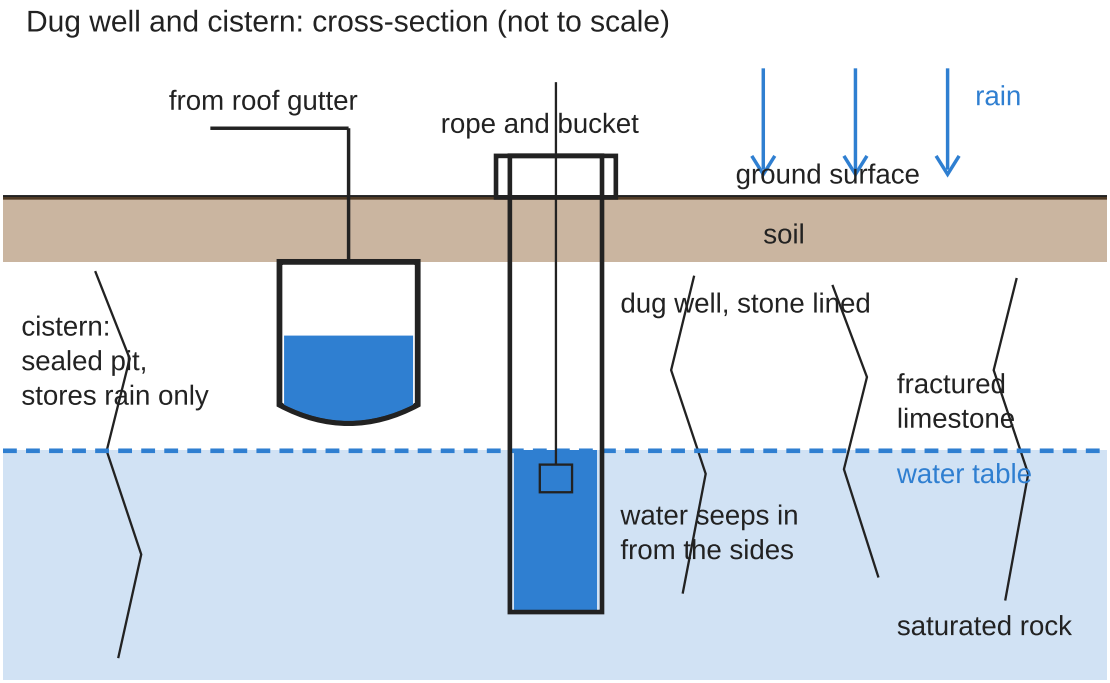
How they figured it out. Why dig a well there, and why so deep? Shechem sits in a narrow valley between two limestone mountains, Mount Ebal to the north (about 940 m) and Mount Gerizim to the south (about 880 m). The region gets roughly 600 mm of rain a year, almost all of it between November and March. Limestone is full of cracks and small openings, so much of that winter rain does not run off; it soaks in, trickles down through the rock, and collects where the openings are already full. The top of that saturated zone is the **water table**. Ancient well diggers did not know the word, but they knew the fact: dig far enough down and the hole begins to seep. In a valley floor the water table is closer to the surface than it is under the mountains, so the valley is the right place to dig, but at Sychar it still lay dozens of meters down. A crew with iron picks, baskets and rope cut through the rock a few centimeters at a time until water seeped in from the sides and bottom.

The big idea. There are three ways to get water in a dry land, and the Bible names all three. A **spring** flows out by itself where the water table meets the surface. A **dug well** reaches down to the water table so the same groundwater can be lifted up. A **cistern** is different in kind: it is a sealed, plastered pit that stores rainwater poured into it from a roof or courtyard, and when it is empty it stays empty until the next rain. Jewish speech called spring water and well water "living water" because it moved and renewed itself, while cistern water sat still. That is why Jeremiah's picture of "broken cisterns, that can hold no water" (Jeremiah 2:13) was such a sharp one, and why Jesus chose the words "a well of water springing up" for the gift he offered (John 4:14). Groundwater is not a rare thing. Of all the fresh water on earth, about 30 percent is groundwater, more than all the rivers and lakes combined (most of the rest is locked in glaciers and ice caps). It lies beneath almost every place people live, cool, filtered by meters of sand and rock, and protected from evaporation.

In the world today. Wells are still how a great part of the world drinks. In the United States more than 40 million people get their household water from private wells, most of them drilled, some of them still hand dug and stone lined like the wells of Abraham and Isaac. A dug well has real limits that this unit will measure: it yields only as fast as water seeps in

from the surrounding rock, and the water table it reaches rises after wet winters and falls after dry summers or heavy pumping. Hydrogeologists, the scientists who study groundwater, and licensed well drillers spend their careers answering the Samaritan woman's question in reverse: how deep is the water here, how fast will it come, and how long will it last?

God's handiwork. The psalmist praises God who "sendeth the springs into the valleys, which run among the hills" (Psalm 104:10), and Moses promised Israel "a land of brooks of water, of fountains and depths that spring out of valleys and hills" (Deuteronomy 8:7). Those "depths" are the aquifers you will study next lesson. The same ordered design that lets rain soak into cracked limestone and reappear as a cool, clean well at Sychar lets a farm family in Nebraska or Idaho pump clean water from under their own yard. The well at Sychar was a gift of geology and hard work together, and Jesus used it to point to a greater gift that no drought can empty.



A dug well reaches below the water table so groundwater seeps in; a cistern only stores the rain that is poured into it.

PICTURE STUDY



Christ and the Samaritan Woman, Annibale Carracci, about 1595–1597 · Oil on canvas · Museum of Fine Arts (Szépművészeti Múzeum), Budapest

Annibale Carracci was a painter from Bologna who helped bring natural light and real human gestures back into Italian painting at the end of the 1500s. Here he paints the moment from John 4 when the woman has just set down her water jar and Jesus, resting on the stone rim of Jacob’s well, speaks to her about living water. Carracci dresses the scene in the clothes and landscape of his own Italy, but the well-head, the vessel and the conversation are the heart of the picture.

Look closely

- Find the well. What tells you this is a deep dug well and not a stream or a spring?
- Look at the woman’s water vessel and the rope or cord, if you can see one. How would water have been lifted from 40 m down?
- Study the two faces and the hands. Who is speaking, and who is listening hard?
- Look at the background. What has Carracci placed behind the two figures, and how is it like or unlike the hills around Sychar?

Talk about it

1. The woman said, “the well is deep.” Why was that a sensible thing to say to a traveler with no bucket?
2. Why do you think Jesus used a well instead of a cistern for his picture of the gift he offers?
3. If you had to carry every liter your family used today up from a well, how would your family’s habits change?

> **Safety first.** Work over a tray or outdoors; spilled water makes floors slippery. Use clean aquarium gravel or washed sand, and wash hands after handling it.

EXPERIMENT: WELL OR CISTERN? A SEEP-WELL MODEL

You will build a small landscape in a clear tub, make it rain, and watch a water table rise and a dug well fill from below. Then you will compare the well with a cistern and measure how fast your well refills after you draw from it.

Question: Does a well in gravel refill faster or slower than a well in sand? Prediction: write yours first. What we change: the material around the well. What we keep the same: the tub, the well cup, the amount of water poured in, and how much we draw out. What we measure: the seconds it takes the well to refill after we draw 50 mL.

You will need

- A clear plastic tub or large clear food container (about 2 to 4 L)
- Clean aquarium gravel and washed play sand, enough to fill the tub about 10 cm deep
- A tall plastic cup or a 10 cm piece of pipe with several small holes punched around the bottom 3 cm (the well), and a second cup with no holes (the cistern)
- A kitchen baster or large syringe (the bucket), a measuring cup, a watering can or cup for rain
- Stopwatch, ruler, permanent marker, lab notebook

Steps

1. Set the holed cup upright in the empty tub and fill the tub around it with gravel to about 10 cm, keeping gravel out of the cup. This is your dug well. Set the solid cup beside it on top of the gravel; this is your cistern.
2. Make it rain with the watering can over the whole surface (not into the cups) until water appears at the gravel surface. Record how much water you poured. Watch the well fill from below and mark the water level in the well and the level in the tub with the marker.
3. Pour a little “rain” into the cistern directly. Notice: the cistern has only what you poured in, while the well filled by itself from the saturated gravel.
4. Draw 50 mL out of the well with the baster. Start the stopwatch and time how long the well takes to refill to the mark. Repeat three times and average.
5. Empty the tub, rinse the cup, and rebuild the landscape with sand instead of gravel. Pour the same amount of rain, draw 50 mL, and time the refill three times.
6. Record both averages in a table: material, trial 1, 2, 3, average seconds. Which refilled faster? Was your prediction right?
7. Finally, let the tub sit uncovered for a day and measure how far the water table (the wet line in the tub) dropped. Where did the water go? Compare with the covered cistern.

Tips

- If the well refills almost instantly in gravel, draw 100 mL instead so you can time it.
- Rinse sand before use so the water is not cloudy; cloudy water hides the water table line.
- A dug well in real life is like your holed cup: water enters through the sides and bottom, not the top.

Check your work

- I can point to the water table in my model and explain why the well filled from below.
- I can explain in one sentence how a cistern differs from a well.
- I recorded three trials for each material and computed averages.

FIELD NOTEBOOK

1. Draw a labeled cross-section of the valley at Shechem: Mount Ebal, Mount Gerizim, the valley floor, the water table, and Jacob's well reaching about 40 m down. Use a scale bar.
2. Draw your tub model twice, before and after the rain, and shade the saturated zone blue. Label the water table and the well.
3. Copy John 4:13–14 neatly and beside it make a two-column chart: "Cistern water" and "Living water," listing three physical differences.

> **From history.** In 1697 an English chaplain named Henry Maundrell traveled from Aleppo to Jerusalem and stopped at Jacob's well. He wrote that it was cut in firm rock, about three yards across and thirty-five yards deep, and that the bottom five yards held water. That is roughly 32 m deep with about 4.5 m of water, a measurement that still fits the shaft pilgrims see today, allowing for rubble that has been cleared since.

WORKED EXAMPLES

Example 1. A family draws water from a 40 m dug well with a rope and a goatskin bucket that holds 8 L. One round trip (lower, fill, raise, pour) takes 3 minutes. How many liters can one person draw in an hour, and how long will it take to draw the 120 L a family of six needs for a day at 20 L per person?

1. Round trips per hour: 60 min ÷ 3 min = 20 trips.
2. Water per hour: 20 trips × 8 L = 160 L per hour.
3. Daily need: 6 people × 20 L = 120 L.
4. Time needed: 120 L ÷ 160 L per hour = 0.75 hour = 45 minutes.

Answer: About 160 L per hour; the family's 120 L takes about 45 minutes of steady drawing.

Example 2. Jacob’s well is about 40 m deep. A two-story house is about 8 m tall. How many houses deep is the well? If you draw the well to scale at 1 cm = 4 m, how long is the shaft on your page, and how tall is the house?

1. Ratio: 40 m ÷ 8 m = 5. The well is as deep as five two-story houses stacked up.
2. Shaft on paper: 40 m ÷ 4 m per cm = 10 cm.
3. House on paper: 8 m ÷ 4 m per cm = 2 cm.

Answer: Five houses deep; on the page the shaft is 10 cm long and the house is 2 cm tall.

Example 3. Nablus receives about 600 mm of rain a year. Suppose 20 percent of the rain falling on a 1 hectare (10,000 m²) hillside soaks in to become groundwater. How many cubic meters and liters recharge the ground each year, and how many people could that supply for a year at 50 L per person per day?

1. Convert rainfall to meters: 600 mm = 0.6 m.
2. Total rain on the hectare: 0.6 m × 10,000 m² = 6,000 m³.
3. Recharge: 20% × 6,000 m³ = 1,200 m³. Since 1 m³ = 1,000 L, that is 1,200,000 L.
4. One person for a year: 50 L × 365 days = 18,250 L.
5. People supplied: 1,200,000 L ÷ 18,250 L ≈ 66 people.

Answer: About 1,200 m³ (1.2 million liters) a year, enough for roughly 66 people at 50 L a day.

PRACTICE

1. EASY Near which ancient city did Jacob buy the field where his well stands, and which two mountains stand on either side of that valley?
2. EASY Define the water table in your own words.
3. EASY State one physical difference between a dug well and a cistern.
4. MEDIUM A bucket holds 10 L and a round trip from a well takes 2.5 minutes. How many liters can be drawn in one hour?
5. MEDIUM You draw a 40 m well to scale at 1 cm = 5 m. How long is the shaft on paper? How wide is a 2 m shaft at that scale?
6. MEDIUM A hydrogeologist measured the depth from the ground surface down to the water in a dug well every two months: January 9.5 m; March 8.2 m; May 9.0 m; July 10.8 m; September 11.9 m; November 11.1 m. (a) In which month was the water table highest? (b) How far did the water table fall between March and September? (c) In which season does recharge happen in this climate?
7. MEDIUM Four years of records for one well: Year 1, rainfall 420 mm, water table change −1.2 m; Year 2, 650 mm, +0.8 m; Year 3, 580 mm, +0.3 m; Year 4, 390 mm, −1.5 m. (a) Describe the relationship between rainfall and water table change. (b) Roughly how

much rain is needed in a year for the water table to hold steady? (c) Predict the change in a year with 700 mm of rain.

8. HARD A 2 hectare field gets 600 mm of rain a year and 15 percent of the rain soaks in. How many cubic meters of recharge is that?
9. HARD Design an experiment to test the claim that water drawn from a dug well at midday is cooler than water in an open cistern. Name the independent variable, dependent variable, two things you would keep the same, and how many measurements you would take.
10. CHALLENGE In two or three sentences, explain why the Samaritan woman's words "the well is deep" fit the geology of Shechem, and why Jesus' picture of "a well of water springing up" fits a well or spring better than a cistern.

COMMON MISTAKES

- Thinking groundwater sits in underground lakes or rivers. Almost all of it fills tiny pores and cracks in sand, gravel and rock, like water in a sponge.
- Thinking a well "makes" water. A well only reaches water that is already there; its supply depends on recharge from rain and on how fast water can seep through the surrounding rock.
- Mixing up a cistern with a well. A cistern is a sealed tank for stored rainwater; a well reaches the water table.

> **Make it a game · Deep Well Relay.** Set a bucket of water (the aquifer) at one end of the yard and an empty jug (the house) at the other. Each player carries water with a small cup, one cup per trip, for two minutes. Measure the jug with a measuring cup afterward and compute each team's liters per hour. Then play a second round where the "well" is twice as far away (a deeper well). How much did the rate drop? Fastest honest rate wins; spills count as "lost to evaporation."

> **Scripture.** "Jesus answered and said unto her, Whosoever drinketh of this water shall thirst again: But whosoever drinketh of the water that I shall give him shall never thirst; but the water that I shall give him shall be in him a well of water springing up into everlasting life." (John 4:13–14, KJV)

Jesus used the physical truth of a real well, water that keeps seeping in from below, to picture a gift that renews itself and never runs dry.

Practice answers

1. Shechem (the town is called Sychar in John 4); Mount Ebal to the north and Mount Gerizim to the south.
2. The top of the zone underground where all the pores and cracks are completely filled with water.
3. A well reaches groundwater and refills itself by seepage; a cistern is sealed and holds only the rainwater poured into it (or: well water is "living," cistern water is still).

4. 60 ÷ 2.5 = 24 trips; 24 × 10 L = 240 L per hour.
5. 40 ÷ 5 = 8 cm long; 2 ÷ 5 = 0.4 cm (4 mm) wide.
6. (a) March (the smallest depth to water, 8.2 m, means the highest water table). (b) 11.9 − 8.2 = 3.7 m. (c) Winter: the water table rises from November through March, when the rains fall.
7. (a) More rainfall produces a rise; less produces a fall. (b) Between 420 and 580 mm, probably about 500 to 550 mm. (c) A rise somewhat larger than +0.8 m, perhaps about +1.0 m, since 700 mm exceeds the 650 mm that gave +0.8 m.
8. 2 ha = 20,000 m^2; 0.6 m × 20,000 m^2 = 12,000 m^3 of rain; 15% × 12,000 = 1,800 m^3.
9. Independent variable: the source (well vs cistern). Dependent variable: water temperature in °C, read with the same thermometer. Keep the same: time of day, the depth at which the sample is taken, the time the sample sits before reading, the container. Take at least three readings from each source on each of several days and compare averages.
10. The valley at Shechem is floored by fractured limestone, so the water table lies dozens of meters down and the shaft had to be cut about 40 m to reach it. A well or spring is fed by groundwater that keeps seeping in, so it renews itself and was called “living water”; a cistern only holds what is poured in and goes dry. Jesus promised something that keeps springing up, not a store that runs out.

2.2 Aquifers: Where Groundwater Lives

OBJECTIVES

- Define aquifer, porosity and permeability, and explain why gravel, sand, sandstone and fractured limestone make good aquifers while clay and shale do not.
- Distinguish an unconfined aquifer, a confined aquifer and an artesian well, and sketch each in cross-section with the water table or confining layer labeled.
- Measure the porosity of a sample and calculate how much water an aquifer of known size and porosity can hold.

Warm-up. Take a dry kitchen sponge and a dry bar of soap. Set each in a saucer and pour 50 mL of water over each. Which one soaked up water, and which let it run off? Now squeeze the sponge over a cup and measure what comes out. The sponge is a model aquifer: it has empty spaces (porosity) and the spaces connect (permeability). Write one sentence about what the soap is a model of.

Video. Coming soon. What is an aquifer, porosity and permeability demonstration, unconfined vs confined aquifers and artesian wells, the High Plains (Ogallala) aquifer; look for USGS Water Science School, state geological survey channels, Smithsonian, SciShow, and Science Max style classroom demos.

KEY TERMS

aquifer
A body of saturated rock or sediment that holds water in its pores and lets enough of it flow to supply a well or spring.

porosity
The fraction of a material’s volume that is empty space (pores), usually given as a percent. Water can be stored only in the pores.

permeability
How easily water can move through a material, which depends on whether the pores are large and connected.

unconfined aquifer
An aquifer open to the surface above, so its top is the water table and it is recharged directly by rain soaking down.

confined aquifer
An aquifer sandwiched beneath a confining layer of clay or shale, so its water is under pressure and is recharged only where the layer reaches the surface.

artesian well
A well drilled into a confined aquifer in which pressure pushes water up above the top of the aquifer, sometimes all the way to the surface.

CORE IDEAS

The story. In 1856 a French engineer named Henry Darcy published a report on the new public water supply he had built for the city of Dijon. Tucked into it was a set of experiments that founded the science of groundwater. Darcy packed a vertical iron pipe with sand, let water flow down through it, and measured two things with care: how much water came out per second, and the difference in water pressure between the top and bottom of the sand. He changed the length of the sand column and the pressure difference and ran the test again and again. The result was simple and exact: the flow through sand is proportional to the pressure difference and inversely proportional to the length of the sand, and every kind of sand has its own constant that tells how easily water passes through it. We now call that constant hydraulic conductivity, and we call the rule Darcy's law. With one iron pipe and a notebook, Darcy showed that water underground obeys a measurable law, just as the planets obey Kepler's.

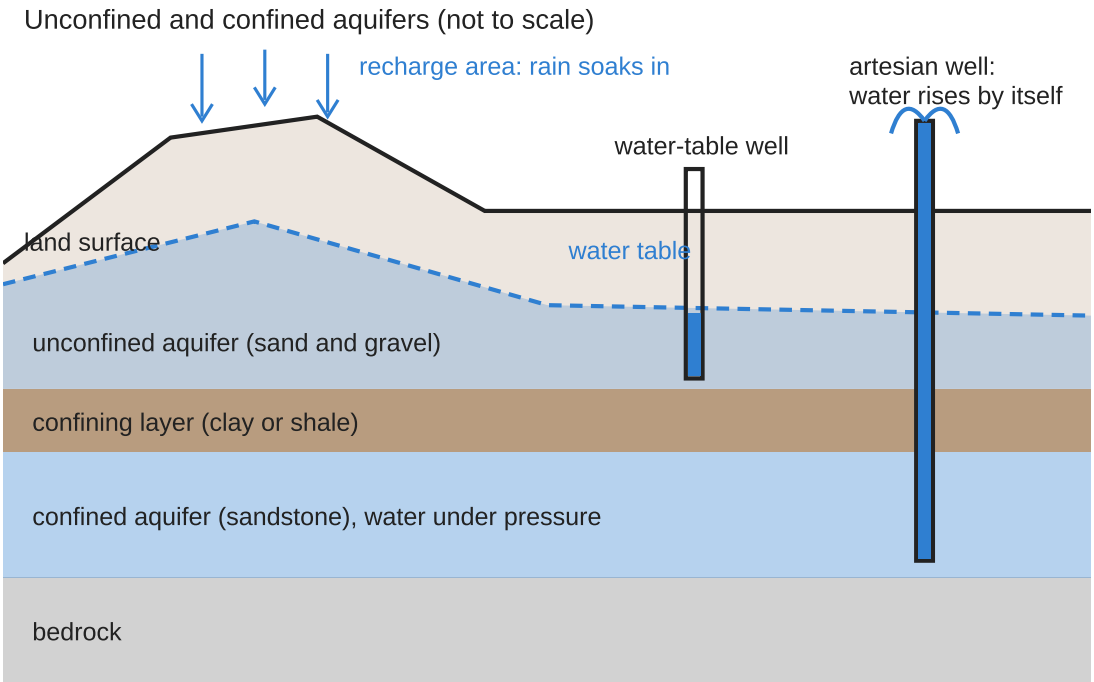
How they figured it out. Darcy's sand column teaches the two properties that make an **aquifer**. The first is **porosity**: how much of the material is empty space. Loose sand and gravel are typically about 25 to 40 percent pore space; sandstone 5 to 30 percent; clay is surprisingly porous, often 40 percent or more, because its flat flakes stack loosely. The second is **permeability**: whether the pores are big enough and connected enough for water to move. Here clay fails. Its pores are so tiny that water clings to the flakes and barely moves, which is why wet clay stays wet and why a clay layer acts as a lid. Gravel and coarse sand have large connected pores, so water moves through them at centimeters to meters per day. Fractured limestone and basalt carry water along cracks and can move it even faster. A good aquifer needs both: room to store water and open paths for it to travel. You can measure porosity in a kitchen: fill a measuring cup with dry gravel to the 500 mL mark, then pour in water until it just reaches the surface. If 170 mL went in, the porosity is 170 ÷ 500 = 34 percent.

The big idea. Aquifers come in two arrangements. An **unconfined aquifer** is open to the sky: rain soaks straight down through soil into sand or gravel, and the top of the saturated zone is the **water table**, which rises in wet seasons and falls in dry ones. Most shallow wells, including the hand-dug well at Sychar, tap unconfined aquifers. A **confined aquifer** lies beneath a **confining layer** of clay or shale. It is recharged only where its layers tilt up to meet the surface, perhaps many kilometers away in the hills. Because the recharge area is higher than the aquifer, the water inside is squeezed under pressure. Drill a hole through the clay lid and the water rises in the pipe by itself; if the pressure is great enough it flows out at the surface without a pump. Such a well is called **artesian**, after the province of Artois in northern France, where, by tradition, flowing wells were bored as early as the 1100s. Artesian water is not automatically purer; it is simply pressurized. Groundwater also moves, slowly, from recharge areas toward rivers, springs and the sea, so an aquifer is not a still tank but a very slow river in a sponge.

In the world today. Under the Great Plains lies the High Plains aquifer, often called the Ogallala. It is a blanket of sand, gravel and silt washed off the Rocky Mountains, underlying about 450,000 km² in parts of eight states from South Dakota to Texas. The United States

Geological Survey reports that it supplies roughly 30 percent of all the groundwater used for irrigation in the country. It is an unconfined aquifer recharged by the sparse rain of the plains, only a few millimeters to a few centimeters a year, while in places farmers pump far more than that. The USGS has measured the water table in thousands of wells since the 1950s; across the whole aquifer the average decline is about 5 m, and in parts of Texas and western Kansas the water table has dropped more than 30 m. In Nebraska, where the aquifer is thickest and rainfall is higher, levels have held nearly steady. These are real measurements, not guesses, and they let farmers, well drillers and state engineers plan: how deep to drill, how big a pump, and how much to pump so the aquifer lasts.

God’s handiwork. Moses described the Promised Land as “a land of brooks of water, of fountains and depths that spring out of valleys and hills” (Deuteronomy 8:7). The “depths that spring out” are aquifers feeding springs, and a spring is simply the place where the water table meets the ground. The design is remarkable: rain falls unevenly and briefly, yet the earth stores it in porous rock, filters it through meters of sand, keeps it cool and dark, and lets it out slowly all year. Darcy’s law describes the order of that storehouse; the Psalmist names its maker, who “sendeth the springs into the valleys, which run among the hills.”



Unconfined and confined aquifers. The artesian well taps the confined aquifer, where water is under pressure.

PICTURE STUDY



Rebecca and Eliezer, Bartolomé Esteban Murillo, about 1660 · Oil on canvas · Museo del Prado, Madrid

Murillo, the great painter of Seville, shows the scene from Genesis 24 where Abraham's servant Eliezer arrives at a well outside the city of Nahor and asks a young woman for a drink. Rebekah draws water for him and for all his camels, and Eliezer knows that God has answered his prayer. Murillo paints the well as a plain stone basin that the women of the town visit every evening, with heavy earthen jars balanced on the rim.

Look closely

- Find the well and the water. Is this water being lifted from deep below, or does it come from a basin near the surface?
- Count the jars. How much water do you think each one holds, and how many trips would ten camels require?
- Look at the camels and the dry hills behind. What does the landscape tell you about how precious this well was?
- Notice how Murillo lights Rebekah and the traveler. Who is the painter asking you to watch?

Talk about it

1. A well in Mesopotamia was dug down to an aquifer. Which kind of aquifer, unconfined or confined, do you think a hand-dug town well most likely reached? Why?
2. Rebekah offered to water the camels, a very large task. What does that tell you about her character, and about how the Bible treats hard work at a well?

> **Safety first.** Use washed sand and gravel and work over a tray. Wipe up spills so the floor

> is not slippery.

EXPERIMENT: POROSITY AND PERMEABILITY LAB

You will measure the porosity of three materials and then time how fast water drains through each one. The two numbers together tell you which material would make the best aquifer and which would make a confining layer.

Question: Which material has the highest porosity, and is it also the most permeable? Prediction: rank gravel, sand and soil (or modeling clay crumbs) for both before you start. What we change: the material. What we keep the same: the volume of material (500 mL), the volume of water poured, and the funnel. What we measure: milliliters of water absorbed (porosity) and seconds for 100 mL to drain through (permeability).

You will need

- Clean aquarium gravel, washed play sand, and garden soil or crumbled modeling clay
- A 500 mL or larger clear measuring cup, a second measuring cup for water
- A funnel or a plastic bottle with the bottom cut off, a coffee filter or piece of cloth, a jar to catch water
- Stopwatch, lab notebook, pencil

Steps

1. Porosity: fill the measuring cup with dry gravel exactly to 500 mL. Slowly pour measured water in until it just reaches the gravel surface. Record the milliliters poured. Porosity = water added ÷ 500 × 100 percent.
2. Repeat the porosity test with sand, then with soil or clay crumbs. Record each in a table.
3. Permeability: line the funnel with the filter, add 500 mL of gravel, hold it over the jar, pour 100 mL of water in at once and start the stopwatch. Stop when dripping slows to one drop every few seconds. Record the time.
4. Repeat the drain test with sand and with soil or clay. If clay has not drained after 5 minutes, record “more than 300 s.”
5. Make a two-column bar graph: porosity (percent) and drain time (seconds) for each material.
6. Write a conclusion: Which would you choose as an aquifer? Which would make a confining layer? Did the most porous material turn out to be the most permeable? Explain using the size of the pores.
7. Extension: build a confined aquifer. Put 3 cm of gravel in a clear tub, press a 1 cm sheet of modeling clay over it leaving one edge open, add sand on top, and pour water only onto the open edge. Push a straw through the clay. Does water rise in the straw?

Tips

- Tap the cup to settle the material before you read the 500 mL mark, or your porosity will be too high.
- Pour slowly for porosity. If you pour fast, air gets trapped and the water surface appears before the pores are full.
- Dry soil may float and swell; press it gently and give it time.

Check your work

- I measured porosity for three materials and showed the calculation.
- I timed drainage for three materials and recorded them in a table and graph.
- I can explain why clay can be porous yet not permeable.

FIELD NOTEBOOK

1. Draw a cross-section with an unconfined aquifer, a confining layer and a confined aquifer. Label the water table, the recharge area, a water-table well and an artesian well.
2. Draw a close-up of three magnified “pore” pictures: gravel, sand and clay. Shade the pore space blue and write the typical porosity under each.
3. Record your porosity and drain-time table and bar graph from the lab, with the date and your conclusion.

> **From history.** The word artesian comes from Artois, a province of northern France. Writers since the Middle Ages have described flowing wells bored there, traditionally dated to the 1100s near the town of Lillers, in which water rose and spilled out of the hole without any pump. When nineteenth-century engineers drilled deep flowing wells for Paris and London, they borrowed the old name, and “artesian” came to mean any well in which confined groundwater rises on its own.

WORKED EXAMPLES

Example 1. A student fills a cup with 1,000 mL of dry gravel, then pours in water until it just reaches the surface of the gravel. It takes 350 mL. What is the porosity of the gravel?

1. Porosity is the pore volume divided by the total volume.
2. The water filled the pores: pore volume = 350 mL.
3. Porosity = 350 ÷ 1,000 = 0.35 = 35 percent.

Answer: 35 percent.

Example 2. Groundwater in a sand aquifer moves about 0.5 m per day. A farm well is 300 m downhill from a leaking fuel tank. How long until the contaminated water could reach the well? Compare with a stream flowing 1 m per second over the same distance.

1. Groundwater: time = distance ÷ speed = 300 m ÷ 0.5 m per day = 600 days.
2. 600 days ÷ 365 days per year ≈ 1.6 years.
3. Stream: 300 m ÷ 1 m/s = 300 s = 5 minutes.
4. Groundwater is slow, which gives time to act, but it also means pollution lingers underground for years.

Answer: About 600 days (1.6 years) through the aquifer, compared with 5 minutes in the stream.

Example 3. A town's unconfined aquifer covers 10 km², its saturated sand is 20 m thick, and the porosity is 25 percent. How much water does it hold? If the town pumps 5,000 m³ per day and no rain recharged the aquifer, how many years would the water last?

1. Area in square meters: 10 km² = 10 × 1,000,000 m² = 10,000,000 m².
2. Saturated volume: 10,000,000 m² × 20 m = 200,000,000 m³ of sand.
3. Water volume: 25% × 200,000,000 m³ = 50,000,000 m³.
4. Days of supply: 50,000,000 ÷ 5,000 = 10,000 days.
5. Years: 10,000 ÷ 365 ≈ 27 years. In reality not all pore water drains out, and rain recharge adds water back, so the real answer depends on the yearly recharge.

Answer: About 50 million m³ of water; with no recharge it would last about 27 years at that pumping rate.

PRACTICE

1. EASY What two properties must a material have to be a good aquifer?
2. EASY Why does a layer of clay act as a confining layer even though clay is porous?
3. EASY What is an artesian well, and where does the pressure come from?
4. MEDIUM A 500 mL cup of dry sand absorbs 160 mL of water before the surface is reached. What is the porosity?
5. MEDIUM Groundwater moves 2 m per day through gravel. How long does it take to travel 1 km?
6. MEDIUM A lab tested four materials. Porosity and the time for 100 mL to drain: Material A, porosity 38%, drain time 12 s; Material B, 30%, 45 s; Material C, 45%, more than 600 s; Material D, 12%, 90 s. (a) Which material has the highest porosity? (b) Which is the most permeable? (c) Which would make the best confining layer, and why? (d) Is porosity alone a good predictor of permeability in this data?

7. MEDIUM Water-table measurements from four monitoring wells in an unconfined aquifer, as depth below the land surface, in 1960 and 2020: Well 1, 15 m and 48 m; Well 2, 22 m and 24 m; Well 3, 30 m and 61 m; Well 4, 10 m and 10 m. (a) Which well shows the greatest decline in the water table, and by how much? (b) Which wells show little or no change? (c) Suggest two possible reasons Well 4 stayed steady while Well 1 fell.
8. HARD An aquifer under a county covers 50 km², its saturated thickness is 30 m, and porosity is 20 percent. How many cubic meters of water does it hold?
9. HARD Design an experiment to find out whether grain size affects permeability. State your hypothesis, the independent variable, the dependent variable, three things you would control, and how you would present the results.
10. CHALLENGE A friend says, “Our farm’s well is artesian, so it will never run out and the water must be pure.” In three or four sentences, correct both claims using what you know about confined aquifers.

COMMON MISTAKES

- Thinking groundwater fills caves and underground rivers. Except in some limestone regions, it fills tiny pores between grains, like water in a sponge.
- Thinking porosity and permeability are the same. Clay is very porous but nearly impermeable; a material needs connected pores for water to flow.
- Thinking the water table is flat like a lake surface. It rises under hills and recharge areas and slopes down toward streams and pumped wells, so groundwater flows downhill underground.

> **Make it a game · Aquifer or Not?.** Make twelve cards: gravel, coarse sand, fine sand, silt, clay, shale, sandstone, fractured limestone, solid granite, basalt with cracks, loose soil, hard-packed clay. Shuffle and deal. On your turn, flip a card and say “aquifer” or “confining layer” and give the reason in terms of porosity and permeability in ten seconds. A correct call with a correct reason scores 2; a correct call with no reason scores 1. For a bonus point, name whether a hand-dug well or a deep drilled well would more likely reach it.

> **Scripture.** “He sendeth the springs into the valleys, which run among the hills.” (Psalm 104:10, KJV)

A spring is where the water table meets the surface. The Psalm names the One who ordered rock and rain so that stored water flows out to the valleys all year.

Practice answers

1. High porosity (room to store water) and high permeability (connected pores so water can flow).
2. Its pores are extremely small, so water clings to the clay particles and moves through it very slowly. It has porosity but almost no permeability.

3. A well drilled into a confined aquifer in which water rises above the aquifer by itself. The pressure comes from the recharge area being higher than the well, with the confining layer keeping the water from escaping upward.
4. 160 ÷ 500 = 0.32 = 32 percent.
5. 1,000 m ÷ 2 m per day = 500 days, about 1.4 years.
6. (a) C (45%). (b) A (fastest drain, 12 s). (c) C: it stores water but barely lets it drain, like clay. (d) No. The most porous material (C) is the least permeable, so pore size and connection matter as much as total pore space.
7. (a) Well 1: 48 − 15 = 33 m (Well 3 fell 31 m, slightly less). (b) Wells 2 (2 m) and 4 (0 m). (c) Less pumping nearby, more rainfall or recharge, a thicker or more permeable aquifer that refills faster, or being close to a river that feeds the aquifer.
8. 50 km^2 = 50,000,000 m^2; 50,000,000 × 30 = 1,500,000,000 m^3 of sediment; 20% of that is 300,000,000 m^3 (300 million cubic meters) of water.
9. Hypothesis: larger grains drain faster. Independent variable: grain size (fine sand, coarse sand, pea gravel). Dependent variable: time for 100 mL to drain through 500 mL of material. Controls: same volume of material, same volume of water, same funnel and filter, material tapped down the same way, same temperature water. Repeat three times each, average, and plot a bar graph of drain time against grain size.
10. Artesian means the well taps a confined aquifer whose water is under pressure, so it rises on its own; it says nothing about how much water the aquifer holds or how pure it is. If many wells pump the confined aquifer faster than it is recharged at its distant outcrop, pressure drops and the well can stop flowing. The water is often clean because it has been filtered through rock and sealed from the surface, but it can still carry dissolved minerals or contaminants, so it must be tested like any other well.

2.3 Drilling a Model Well

OBJECTIVES

- Describe the steps of drilling and finishing a modern water well: drilling, logging the layers, setting casing and screen, gravel packing, grouting, developing and pump testing.
- Define yield, static water level, drawdown and cone of depression, and compute a well's specific capacity from a pump test.
- Build a model well with casing, screen and gravel pack in a layered tub, pump it, and measure drawdown and recovery.

Warm-up. Push a plain drinking straw straight down into a cup of wet sand and suck gently. What happens? Now wrap the bottom 2 cm of a second straw in a scrap of cloth held on by a rubber band, push it in and try again. The cloth is a well screen. Write one sentence on why every real well needs one.

Video. Coming soon. How a water well is drilled, rotary and cable-tool drilling rigs, well casing screen and gravel pack, pump test and drawdown explained, ancient Chinese percussion drilling at Zigong; look for USGS Water Science School, state well-driller association channels, Smithsonian, Science Max style demos and Moody Science classics.

KEY TERMS

casing
The steel or plastic pipe set in a drilled hole to keep it from collapsing and to seal out surface water and dirt.

well screen
A slotted or mesh section at the bottom of the casing that lets water in while keeping sand and gravel out.

driller's log
The written record a driller keeps of every layer passed through, with its depth, color and material, and where water was found.

yield
How much water a well can supply over time, usually measured in liters per minute.

drawdown
The distance the water level in a well drops below its resting (static) level while the well is being pumped.

cone of depression
The funnel-shaped dip in the water table around a pumping well, deepest at the well and fading out with distance.

CORE IDEAS

The story. Long before anyone drilled for water in America, the well drillers of Sichuan in China were pounding holes a thousand meters into the earth. Around the salt town of Zigong, crews raised a wooden tower, hung a heavy iron bit from a cable of woven bamboo, and let it fall again and again, chipping rock a few millimeters at a stroke. Men walked a treadle to lift the bit; every so often they hauled it up and lowered a long bamboo tube with a leather flap valve to scoop out the crushed rock and water. The holes were lined with hollowed bamboo or wooden casing to keep them open. In 1835 the Shenhai well at Zigong passed 1,000 m, the first well anywhere to reach that depth, and it produced brine for salt and natural gas to boil it. Their method, percussion drilling, is still used today under the name cable-tool drilling, and every modern water-well rig keeps the same three jobs those crews solved: break the rock, lift out the cuttings, and keep the hole from caving in.

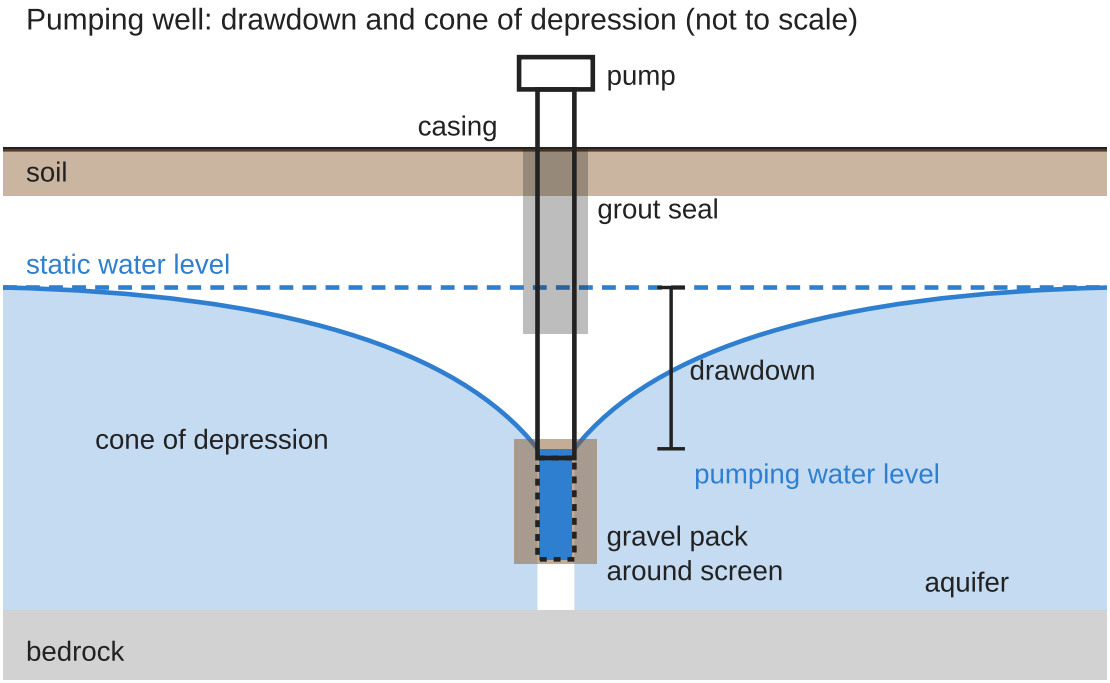
How they figured it out. A modern water well begins with a licensed driller reading the land. Neighboring well records, the state geological survey's maps and the lay of the valley tell roughly how deep the water table or the confined aquifer lies. Most wells today are drilled with a rotary rig: a rotating bit on a string of steel pipe grinds downward while a stream of water, mud or compressed air flushes the cuttings up and out of the hole. The driller watches those cuttings the way a doctor watches an X-ray and writes a **driller's log**: 0 to 3 m brown soil; 3 to 12 m yellow clay; 12 to 30 m gray sand, water at 18 m; 30 m dense shale. That log is a column of the local geology, and thousands of them filed with state agencies are how we know the shape of aquifers. When the bit reaches enough water-bearing sand, the driller lowers **casing**, with a slotted **well screen** at the bottom sized so that water passes but sand does not. Clean gravel is poured around the screen as a **gravel pack** filter, and the top several meters outside the casing are sealed with cement **grout** so that surface water, fertilizer or animal waste cannot trickle down the outside of the pipe into the drinking water.

The big idea. Finishing a well is a measuring job. First the driller "develops" the well, surging and pumping until the water runs clear. Then comes the pump test. The water level before pumping is the **static water level**, say 12.0 m below the ground. A pump runs at a steady rate, perhaps 40 liters per minute, and the water level falls and then steadies, say at 17.0 m. The difference, 5.0 m, is the **drawdown**. The well's **yield** is the pumping rate it can sustain, and the ratio of yield to drawdown, here 40 ÷ 5 = 8 L per minute per meter, is the **specific capacity**, the single best number for comparing wells. A well in coarse gravel has a high specific capacity: it gives much water for little drawdown. A well in silty sand gives little water for a large drawdown. Around every pumping well the water table dips into a **cone of depression**, deepest at the well and spreading outward, sometimes hundreds of meters in a heavily pumped aquifer. When two cones overlap, each well lowers the other, which is why your neighbor's new irrigation well can drop the level in yours. Stop the pump and the cone fills back in; the time it takes to recover is another clue to how permeable the aquifer is.

Try it and see. Your model well in a clear tub will show all of this in miniature. Layer gravel, sand and a clay lid; drive in a slotted straw wrapped in mesh; pack gravel around it; seal the top with clay; then pump with a syringe and watch the water table funnel down toward the

straw. You will measure static level, pumping level, drawdown and recovery time just as a driller does, and you will keep a driller's log of your own layers. Try pumping twice as fast and see whether drawdown doubles. Pull the mesh off and watch what sand does to your pump. The model is small, but every quantity you record has the same name and meaning on a real job.

In the world today. Well drilling is a skilled trade and a career. Drillers are licensed by their states, keep logs that become public geological records, and must follow rules on casing, grouting and distance from septic systems. A household well in the United States is commonly 30 to 150 m deep, takes a rotary rig a day or two to drill, and is finished with a submersible pump that pushes water up to a pressure tank in the house. Hydrogeologists design larger city and irrigation wells and run longer pump tests to predict how a whole aquifer will respond. The Scriptures remember well digging as honest, hopeful labor: Isaac's servants "digged in the valley, and found there a well of springing water" (Genesis 26:19). The rig is new; the joy of finding water is very old.



A finished well during a pump test. Drawdown is the drop from static level to pumping level; the dip in the water table around the well is the cone of depression.

PICTURE STUDY



The Waterseller of Seville, Diego Velázquez, about 1620 · Oil on canvas · Apsley House (Wellington Collection), London

Velázquez painted this when he was about twenty, still in his home city of Seville. In the heat of southern Spain men made a living carrying water through the streets in great earthenware jars and selling it by the glass. The painter gives the old waterseller the dignity of a prophet, and he paints the beads of water sweating through the porous clay jar so truly that you can almost feel the cool.

Clay jars like this were themselves a kind of well science: the clay was porous enough to let a little water seep out and evaporate, which kept the water inside cool. The same porosity you measured in the last lesson is at work on the jar's surface.

Look closely

- Find the drops of water on the big jar. Why would a potter choose a porous clay for a water jar in a hot city?
- Look at the glass. What is in the bottom of it? (A fig, which was said to freshen the taste.)
- Compare the three faces, old, young and the shadowy one between. What is each one doing?
- Where does the light come from, and what does it fall on first?

Talk about it

1. This water had to come from a well or spring, be carried in jars and sold by the glass. How does a drilled well with a pump change the value of a liter of water?

2. Velázquez made a poor waterseller look noble. What does that say about the worth of ordinary work?

> **Safety first.** Keep syringes without needles. Wash sand and gravel before use and wash hands afterward. Work over a tray and wipe spills. If you use scissors or a nail to slot the straw, have an adult help.

EXPERIMENT: DRILL, CASE AND PUMP-TEST A MODEL WELL

You will build a layered aquifer in a clear tub, finish a model well with casing, screen, gravel pack and grout, and run a pump test like a real driller. Then you will test one variable.

Question: If you pump twice as fast, does the drawdown double? Prediction: write yours. What we change: the pumping rate (how many milliliters per 10 seconds). What we keep the same: the tub, the aquifer, the well, the starting water level. What we measure: the drawdown in millimeters and the recovery time in seconds.

You will need

- A clear plastic tub or large clear jar (3 L or more)
- Washed aquarium gravel, washed play sand, modeling clay
- A wide drinking straw or 1 cm clear tubing (casing), a scrap of nylon stocking or fine mesh and a rubber band (screen), scissors or a nail to cut slots
- A 20 to 60 mL syringe without a needle or a kitchen baster (the pump)
- Ruler, permanent marker, stopwatch, lab notebook

Steps

1. Build the aquifer: 3 cm gravel on the bottom, then 4 cm sand, then a thin layer of clay pressed to the tub walls as a confining layer, then 2 cm sand on top as soil. Write a driller’s log of your layers with depths measured from the top.
2. Make the well: cut several short slots in the bottom 2 cm of the straw and wrap that part in mesh held by a rubber band. Push the straw straight down through the layers until the screen sits in the bottom gravel. Spoon a little gravel in around the screen (the gravel pack) and press a ring of clay around the straw at the surface (the grout seal).
3. Add water slowly at one edge until the water table (the wet line in the tub) stands about 2 cm above the screen. Wait until the level in the straw stops changing. Mark it: this is the static water level.
4. Pump test 1: draw 20 mL out through the straw in 10 seconds, then at once mark the lowest level in the straw. Measure the drop in millimeters: this is the drawdown. Start the stopwatch and record how long the level takes to return to the static mark (recovery time).
5. Pump test 2: let the well fully recover, then draw 40 mL in 10 seconds. Measure drawdown and recovery time. Repeat each test twice more and average.

6. Compute specific capacity for each test: milliliters per 10 seconds divided by drawdown in millimeters. Are the two values similar? Did drawdown double?
7. Watch the tub wall while pumping: can you see the water table funnel down toward the well? Sketch the cone of depression.
8. Extension: remove the mesh and pump again. What comes up with the water? Write two sentences on why a screen and gravel pack matter.

Tips

- If the straw clogs with sand, your slots are too large or your mesh is torn. Real drillers choose slot size from the sand's grain size.
- Pump smoothly; a jerky pull gives a false low reading.
- Pumping tests are easier to read if you color the water with a drop of food coloring.

Check your work

- My driller's log lists every layer with depths.
- I recorded static level, drawdown and recovery time for two pumping rates, three trials each.
- I computed specific capacity and can explain what a cone of depression is.

FIELD NOTEBOOK

1. Draw a labeled cross-section of a finished well: casing, grout seal, gravel pack, screen, static water level, pumping water level, drawdown and cone of depression.
2. Copy your driller's log in a neat column with a scale, coloring each layer (brown soil, yellow sand, gray clay, blue for the water-bearing zone).
3. Make a two-bar graph of drawdown at the slow and fast pumping rates, and write one sentence on what it shows.

> **From history.** In 1854 Daniel Halladay, a mechanic in Ellington, Connecticut, patented a windmill that turned itself into the wind and feathered its blades in a gale, so it could run unattended for weeks. Bolted over a drilled well, the self-governing windmill lifted water on the treeless Great Plains where there was no stream for miles, and it watered railroad locomotives, cattle and homesteads. The tall steel windmill beside a stock tank became the signature of the American West, and tens of thousands still pump wells today.

WORKED EXAMPLES

Example 1. Before pumping, the water in a well stands 12.0 m below the ground. A pump runs at 40 L per minute, and after an hour the level has steadied at 17.0 m below ground. Find the drawdown and the specific capacity.

1. Drawdown = pumping level − static level = 17.0 m − 12.0 m = 5.0 m.
2. Specific capacity = yield ÷ drawdown = 40 L/min ÷ 5.0 m = 8 L per minute per meter of drawdown.
3. Meaning: each meter the level is pulled down buys about 8 L/min of water. A well in coarser gravel might give 30 L/min per meter; one in silty sand perhaps 2.

Answer: Drawdown 5.0 m; specific capacity 8 L/min per meter.

Example 2. A rotary rig drills through sandstone at about 6 m per hour. The driller must reach 90 m. How many hours of drilling is that, and if the contractor charges $60 per meter drilled plus $1,500 for casing and screen, what is the total cost?

1. Drilling time: 90 m ÷ 6 m per hour = 15 hours, about two working days.
2. Drilling charge: 90 m × $60 per m = $5,400.
3. Total: $5,400 + $1,500 = $6,900 (before the pump and electrical work).

Answer: About 15 hours of drilling; $6,900.

Example 3. A well’s casing is 15 cm in diameter and holds a standing water column 30 m tall. How many liters of water stand in the casing? (Volume of a cylinder = π r^2 h; use π ≈ 3.14; 1 m^3 = 1,000 L.)

1. Radius: 15 cm ÷ 2 = 7.5 cm = 0.075 m.
2. r^2 = 0.075 × 0.075 = 0.005625 m^2.
3. Volume = 3.14 × 0.005625 m^2 × 30 m ≈ 0.53 m^3.
4. Convert: 0.53 m^3 × 1,000 = 530 L.
5. That is less than one bathtub. A well’s real supply is not the water in the pipe but the water that flows in from the aquifer through the screen.

Answer: About 530 L.

PRACTICE

1. EASY Name the three jobs every drilling method, ancient or modern, must do.
2. EASY What does the grout seal at the top of a well protect against?
3. EASY Define drawdown.

4. MEDIUM A well pumps 60 L/min with a drawdown of 4 m. What is its specific capacity?
5. MEDIUM A cable-tool rig advances 1.5 m per hour in hard limestone. How many 8-hour days will it take to drill a 72 m well?
6. MEDIUM A driller's log reads: 0–2 m topsoil; 2–9 m brown clay; 9–24 m coarse sand and gravel, water first seen at 11 m; 24–40 m gray clay; 40–55 m fine sand with water; 55 m granite. (a) How thick is the first water-bearing layer? (b) Which layer would act as a confining layer between the two aquifers? (c) In which layer would you set the screen for a high-yield well, and why?
7. MEDIUM A pump test recorded the water level in a well over time while pumping at a constant 30 L/min: 0 min, 10.0 m; 5 min, 12.1 m; 15 min, 13.0 m; 30 min, 13.4 m; 60 min, 13.5 m; 120 min, 13.5 m. (a) What is the static water level? (b) What is the final drawdown? (c) Describe how the rate of water-level change varies with time. (d) What is the specific capacity?
8. HARD A casing 20 cm in diameter holds a 25 m water column. About how many liters stand in the casing? ($\pi \approx 3.14$.)
9. HARD Design an experiment with the tub model to test whether a gravel pack increases a model well's specific capacity. Give the hypothesis, the independent and dependent variables, three controls and the number of trials.
10. CHALLENGE Your neighbor drills a large irrigation well 200 m from your house well, and your well's water level drops 3 m whenever the irrigation pump runs. In three or four sentences, explain what is happening using the idea of a cone of depression, and suggest one measurement a hydrogeologist would make.

COMMON MISTAKES

- Thinking a well is a pipe full of water. The casing holds only a few hundred liters; the supply is the water flowing in from the aquifer through the screen.
- Thinking pumping affects only the well being pumped. The cone of depression spreads outward and lowers water levels in nearby wells tapping the same aquifer.
- Thinking deeper is always better. A well must be screened in a permeable water-bearing layer; drilling past the aquifer into dense shale or granite adds cost and no water.

Make it a game · Driller's Log Challenge. One player secretly layers four materials (gravel, sand, clay, soil) in a tall clear jar and covers the sides with paper. The driller pushes a clear straw down the middle, pulls it out with a thumb over the top, and must read the core and write a driller's log with depths measured by ruler. Remove the paper and score one point for each layer named correctly and one for each boundary within 1 cm. Switch roles. Bonus point for correctly naming which layer would hold the most water.

Scripture. "And Isaac's servants digged in the valley, and found there a well of springing water." (Genesis 26:19, KJV)

Finding water is still the driller’s joy. Isaac’s men dug in the valley, where the water table lies nearest the surface, and found water that flowed in on its own.

Practice answers

1. Break the rock, lift out the cuttings, and keep the hole from collapsing (casing).
2. Surface water, fertilizer, septic or animal waste trickling down the outside of the casing into the aquifer and the well water.
3. The drop in water level in a well from its static (resting) level to its level while pumping.
4. 60 ÷ 4 = 15 L/min per meter.
5. 72 ÷ 1.5 = 48 hours; 48 ÷ 8 = 6 days.
6. (a) 24 − 9 = 15 m. (b) The gray clay from 24 to 40 m. (c) The coarse sand and gravel from 9 to 24 m: it is the thickest water-bearing layer and coarse material has the highest permeability, so it would give the most water for the least drawdown.
7. (a) 10.0 m. (b) 13.5 − 10.0 = 3.5 m. (c) The level falls quickly at first (2.1 m in the first 5 minutes) and then more and more slowly until it steadies, because inflow from the aquifer catches up with the pumping. (d) 30 ÷ 3.5 ≈ 8.6 L/min per meter.
8. r = 0.10 m; r^2 = 0.01 m^2; volume = 3.14 × 0.01 × 25 = 0.785 m^3 ≈ 785 L.
9. Hypothesis: a gravel pack around the screen raises specific capacity (less drawdown for the same pumping). Independent variable: gravel pack present or absent. Dependent variable: drawdown in mm for a fixed draw of 30 mL in 10 s (specific capacity = 30 ÷ drawdown). Controls: same tub and layers, same straw and screen, same static water level, same pumping speed, same person pumping. At least three trials each condition, averaged.
10. The irrigation well pulls water from the aquifer faster than it flows in, so the water table dips into a cone of depression around it that reaches out hundreds of meters. Your well sits inside that cone, so its static level is lowered by about 3 m while the pump runs and recovers when it stops. The two wells share one aquifer, so each affects the other. A hydrogeologist would measure water levels in both wells over time during pumping and recovery, which shows the size of the cone and the aquifer’s permeability.

2.4 Water Rights in the West: First in Time, First in Right

OBJECTIVES

- Contrast the riparian water law of the humid eastern states with prior appropriation in the arid West, and explain why the roughly 50 cm rainfall line made the difference.
- Tell how John Wesley Powell described the arid region and how the Colorado River Compact of 1922 divided the river, and convert acre-feet to cubic meters.
- Apply the priority rule to a stream in a dry year and read a precipitation bar graph to decide which places need irrigation.

Warm-up. Pour 300 mL of water into a pitcher: this is a small river in a dry summer. Set out three cups labeled 1880, 1895 and 1910, each with a line marked at 150 mL, the amount each farm “needs.” First fill the cups in order of their dates until the pitcher is empty. Who goes short? Pour it all back and try again, sharing equally. Write one sentence on which rule seems fairer and one on which rule would make it easier to plan a farm you had to borrow money to start.

Video. Coming soon. Prior appropriation and western water rights explained, John Wesley Powell and the arid region, the Colorado River Compact of 1922, acre-feet and streamflow gauges; look for USGS, Bureau of Reclamation, state engineer and water-court explainers, Smithsonian, and PBS or C-SPAN history segments on Powell.

KEY TERMS

riparian rights
The water law of England and the eastern United States: people who own land along a stream may make reasonable use of its water and share shortages, and the right stays with the land.

prior appropriation
The water law of most western states: the first person to divert water and put it to beneficial use has the senior right, and later users are served only after earlier ones. “First in time, first in right.”

beneficial use
A recognized useful purpose for water, such as irrigation, drinking, livestock, industry or mining. A western water right is for a measured amount for a stated use, and a right not used can be lost.

senior and junior rights
Rights ranked by their priority date. In a shortage the senior (older) right receives its full amount first; junior (newer) rights are cut off in order until the stream runs out.

acre-foot

The volume of water that covers one acre to a depth of one foot, about 1,233 cubic meters (1.23 million liters). Western water agencies still state yearly amounts in acre-feet.

interstate compact
A formal agreement between states, approved by Congress, that divides the water of a river that crosses state lines.

CORE IDEAS

The story. John Wesley Powell lost his right arm at the Battle of Shiloh in 1862, yet in 1869 he led nine men in four wooden boats down the Green and Colorado Rivers through the unmapped Grand Canyon. The trip convinced him that the West was a different kind of country. In 1878 he handed Congress his *Report on the Lands of the Arid Region of the United States*: west of about the 100th meridian, he wrote, there is too little rain to farm without irrigation, and the rivers could water only a small fraction of the land. Few listened. In October 1893, as director of the United States Geological Survey, he told the International Irrigation Congress in Los Angeles, a room full of boosters, that they were piling up a heritage of conflict and litigation over water rights, because there was not enough water to supply the land. He was booed. He was also right.

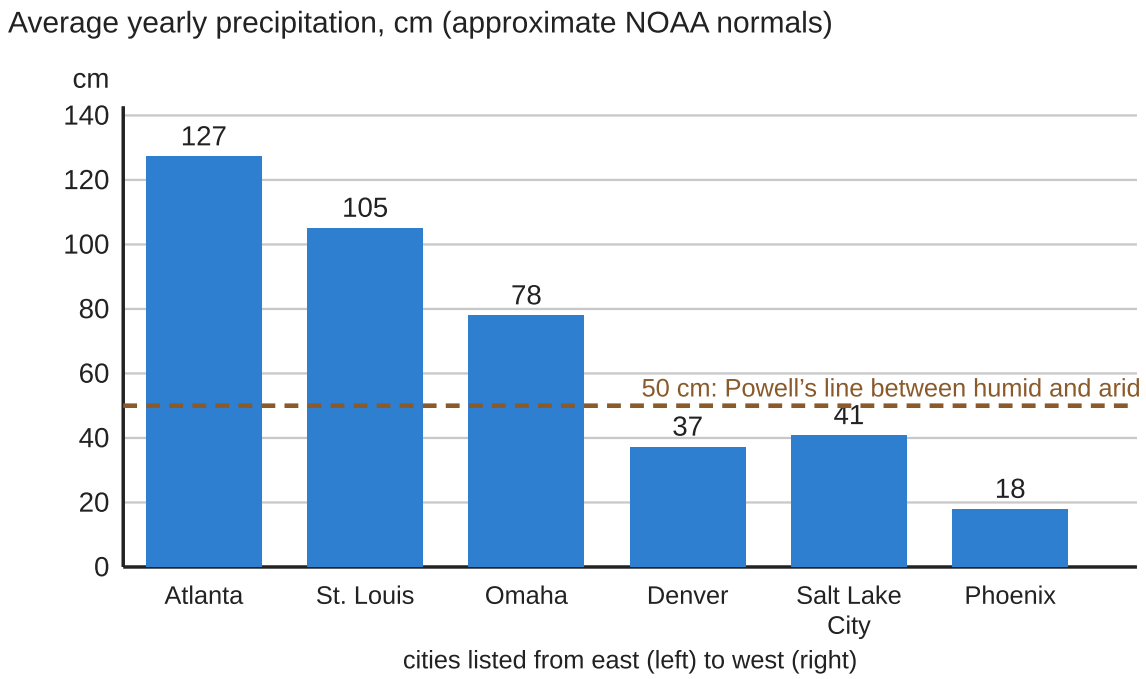
How they figured it out. The difference begins with rain. Atlanta receives roughly 127 cm a year, St. Louis about 105 cm, Omaha about 78 cm. Then the numbers fall off a cliff: Denver about 37 cm, Salt Lake City about 41 cm, Phoenix about 18 cm. Powell drew his line at about 50 cm (20 inches) a year, the least a grain crop can usually get by on without a ditch. Eastern settlers had brought English common law with them: **riparian rights**. Whoever owned land along a stream could use its water reasonably, had to return what was not used, and in a dry spell everyone on the bank took a smaller share. That works where rain falls on every field. It failed in the California gold camps of 1849, where miners on public land carried water in ditches far from any stream. They applied their rule for mining claims, the first to stake it and work it holds it, to water: **prior appropriation**. The first person to divert a measured flow and put it to **beneficial use** holds the senior right to it, even miles from the river. Colorado wrote the rule into its 1876 constitution, and in 1882 its Supreme Court, in *Coffin v. Left Hand Ditch Company*, held that an older ditch outranked a riparian landowner who came later. Most western states follow that Colorado Doctrine.

The big idea. Prior appropriation has four plain rules. First in time, first in right: every right carries a priority date. The right is for a measured amount, a flow in cubic meters or cubic feet per second or a yearly volume in acre-feet. The water must be put to beneficial use, and a right unused for years can be lost: “use it or lose it.” And the right can be sold separately from the land. In a dry summer the rules work like your warm-up pitcher. A water commissioner reads the stream gauge and “places a call”: the most senior right is filled first, then the next, until the water is gone, and the junior headgates are shut. Groundwater rules vary: Texas follows a rule of capture, while most western states now appropriate groundwater too, because a big well’s cone of depression (Lesson 2.3) can pull down a neighbor’s well or a nearby stream. When a river crosses state lines, the states make an **interstate compact**. The Colorado River Compact, signed at Santa Fe, New Mexico, on

November 24, 1922, with Herbert Hoover as chairman, split the river at Lees Ferry, Arizona, into an Upper Basin (Colorado, Wyoming, Utah, New Mexico) and a Lower Basin (Arizona, Nevada, California) and promised each 7.5 million acre-feet a year. A 1944 treaty added 1.5 million acre-feet for Mexico, and Hoover Dam, finished in 1936, stored spring floods so the division could work.

In the world today. The compact's negotiators had only about twenty years of gauge records, from unusually wet years, and they assumed the river carried more than the long record has since shown. Measurement, not argument, revealed the shortfall, and the states, the tribes and Mexico have been adjusting the details ever since. That is why the USGS runs more than 8,000 streamgages, many reporting every fifteen minutes, and why a career in western water begins with a tape, a current meter and a notebook. State engineers hire hydrographers to measure canals, commissioners to administer calls and hydrogeologists to model aquifers; irrigation districts hire ditch riders; law firms hire attorneys who read century-old decrees. A Colorado farmer can tell you her right to the tenth of a cubic foot per second and the day in 1880 it was first used. The numbers matter because they are what the neighbors agreed on, in writing, before the dry year came.

God's handiwork. Isaac knew about water quarrels. When his servants dug a well in the valley of Gerar, "the herdmen of Gerar did strive with Isaac's herdmen, saying, The water is ours" (Genesis 26:20). He named that well Esek, meaning contention, moved on, was fought again at Sitnah, and dug a third time; "for that they strove not," so he called it Rehoboth, meaning room: "For now the LORD hath made room for us" (Genesis 26:22). The Bible treats water as a gift to be shared under rules of peace, not seized. Powell's warning and the compacts that followed are human attempts at the same thing: to agree on who drinks first before the stream runs low, so that a dry year brings a ledger instead of a fight.



Approximate average yearly precipitation (NOAA normals, rounded). West of the Great Plains the totals fall below Powell's 50 cm line, and farming needs irrigation.

PICTURE STUDY



Boulder Dam from Across the Colorado River, Ansel Adams, 1941 · Photograph, made for the U.S. Department of the Interior · U.S. National Archives, College Park, Maryland (Ansel Adams photographs for the Department of the Interior)

In 1941 the Department of the Interior hired the photographer Ansel Adams to photograph national parks and the department's great works for murals in its new building in Washington. One of his subjects was Boulder Dam, now called Hoover Dam, finished in 1936 in Black Canyon on the Colorado River between Nevada and Arizona.

This dam is the piece of concrete that made the 1922 compact workable. Lake Mead behind it stores spring snowmelt from good years so it can be released in dry ones, and every acre-foot that goes in and comes out is measured and recorded like an entry in a ledger.

Look closely

- Find the dam and the canyon walls. Why would engineers choose a narrow rock canyon for a dam?
- Look at the river below the dam. Where is the water the dam is holding back?
- Notice how Adams uses light and shadow on the concrete and the rock. What does that make you feel about the size of the work?
- Look for power lines, towers or buildings. What else besides stored water does this dam give the West?

Talk about it

1. The compact of 1922 divided the river on paper. Why would a dam like this be needed to make that division work in a dry year?

2. Powell warned that there was not enough water for all the land. Does a dam make more water, or does it only move water from wet years to dry ones? Explain.
3. The water behind this dam fell as rain and snow in the mountains. Which lesson in this unit explains how some of that same rain ends up in wells instead of rivers?

> **Safety first.** Work outdoors or over a large tray; sand and water make floors slippery. Use washed sand and wash hands afterward. If you cut plastic sheeting, have an adult help with the scissors.

EXPERIMENT: DITCHES ON A DRY-YEAR RIVER

You will build a small river of sand with three farm ditches, run it as a water commissioner in a wet year and a dry year, and then test one thing western irrigation districts spend real money on: whether lining a ditch saves water.

Question: How much of the water poured into an unlined sand ditch reaches the end, compared with a ditch lined with plastic? Prediction: write yours as a percent. What we change: whether the ditch is lined. What we keep the same: the ditch length (50 cm), its slope, the water poured (500 mL), and how fast we pour. What we measure: milliliters collected at the end.

You will need

- A long shallow tray, planter box or a large baking pan at least 60 cm long, filled with 5 cm of damp play sand
- A 2 L pitcher, a measuring cup, three small cups labeled 1880, 1895 and 1910
- Plastic wrap or a strip of plastic bag (ditch lining), a small block to tilt the tray
- Modeling clay for headgates, a ruler, stopwatch, lab notebook

Steps

1. Tilt the tray slightly with the block. Carve a main river channel down the middle about 3 cm wide and 2 cm deep, ending at a drain hole or the low corner where a bowl can catch water. Carve three side ditches branching off, each leading to one of the labeled cups set into the sand. Give each ditch a clay headgate you can open or close.
2. Wet year: pour 1,500 mL slowly down the river over about one minute with all headgates open. Measure what each cup collected. Everyone has water.
3. Dry year under prior appropriation: pour only 600 mL. Open only the 1880 ditch until its cup reaches 150 mL, then open 1895, then 1910 if anything is left. Record each cup.
4. Dry year under riparian sharing: repeat with 600 mL and all three headgates open, adjusting the gates so the cups fill at about the same rate. Record each cup. Write two sentences comparing the two dry-year results.
5. Lining test: rebuild one straight ditch 50 cm long and 3 cm wide with a cup at the end. Pour 500 mL steadily over 30 seconds and measure what arrives. Repeat three times, moistening the sand the same way each time.

6. Line the same ditch with plastic pressed smooth into the channel. Pour 500 mL the same way and measure three times.
7. Compute the percent of water delivered for each condition and the average. Where did the missing water go? Write your conclusion and connect it to Lesson 2.2: seepage from an unlined ditch recharges the aquifer, which farmers downstream may be pumping.

Tips

- Pour from the same height and at the same speed each time; a stopwatch helps.
- Damp sand seeps far less than dry sand. Decide on one starting condition and keep it.
- Real canals lose a third or more of their water to seepage and evaporation in some districts, so a lined ditch is not a small matter.

Check your work

- I ran the dry-year river both ways and recorded every cup.
- I measured delivered water for the lined and unlined ditch, three trials each, and computed percents.
- I can explain where seepage water goes and why a state might count it.

FIELD NOTEBOOK

1. Draw a map of the Colorado River basin from memory of an atlas: the seven states, Lees Ferry as the dividing point, Hoover Dam, and the Gulf of California. Shade the Upper Basin and Lower Basin differently and write 7.5 million acre-feet on each.
2. Make a timeline of western water: 1847 (Mormon irrigation at Salt Lake), 1849 (gold camps), 1876 (Colorado constitution), 1878 (Powell’s report), 1882 (Coffin v. Left Hand Ditch), 1893 (Powell’s warning), 1922 (compact), 1936 (Hoover Dam), 1944 (Mexico treaty).
3. Copy the precipitation bar graph into your notebook and add your own town’s average yearly precipitation from NOAA as a seventh bar. Is your home east or west of the 50 cm line?

> **From history.** The first large irrigation in the Anglo-American West began on July 23, 1847, the day before Brigham Young reached the Salt Lake Valley. The advance party of Mormon pioneers dammed City Creek and turned its water over the baked valley floor so that their plows could break the ground, and within hours they were planting potatoes. The settlers dug community ditches, appointed watermasters, and divided the flow by turns measured in hours, a cooperative system that western states later borrowed when they wrote their water laws.

WORKED EXAMPLES

Example 1. The Colorado River Compact promised each basin 7.5 million acre-feet of water a year. One acre-foot is about 1,233 m^3. Express 7.5 million acre-feet in cubic meters and in cubic kilometers, and find the side of a cube that would hold it.

1. Cubic meters: 7,500,000 × 1,233 m^3 ≈ 9,250,000,000 m^3, about 9.25 billion cubic meters.
2. A cubic kilometer is 1,000 m × 1,000 m × 1,000 m = 1,000,000,000 m^3, so 9,250,000,000 ÷ 1,000,000,000 ≈ 9.25 km^3.
3. Cube root of 9.25 is about 2.1, so a cube about 2.1 km on each side would hold one basin’s yearly share.

Answer: About 9.25 billion m^3, or 9.25 km^3, a cube roughly 2.1 km on a side.

Example 2. Three rights on Dry Creek: Alpha Ditch, priority 1878, 2.0 m^3/s; Beta Canal, priority 1892, 3.0 m^3/s; Gamma Farm, priority 1915, 1.5 m^3/s. In August the gauge reads 4.0 m^3/s. How much does each get under prior appropriation? How would an equal-fraction riparian sharing differ?

1. Rank by date: Alpha (1878), Beta (1892), Gamma (1915). Total rights = 2.0 + 3.0 + 1.5 = 6.5 m^3/s, more than the 4.0 m^3/s flowing.
2. Alpha, most senior, takes its full 2.0 m^3/s. Remaining: 4.0 − 2.0 = 2.0 m^3/s.
3. Beta is next and is entitled to 3.0 but only 2.0 is left, so Beta gets 2.0 m^3/s. Remaining: 0.
4. Gamma, most junior, is called out and gets 0 m^3/s.
5. Riparian-style equal fraction: each gets 4.0 ÷ 6.5 ≈ 0.615 of its claim: Alpha 1.23, Beta 1.85, Gamma 0.92 m^3/s. Everyone has some water, but no one can count on a full supply.

Answer: Prior appropriation: Alpha 2.0, Beta 2.0, Gamma 0 m^3/s. Equal sharing: about 1.23, 1.85 and 0.92 m^3/s.

Example 3. An alfalfa field of 40 hectares needs about 90 cm of irrigation water over the growing season. How many cubic meters is that, how many acre-feet, and how many days would a canal headgate passing 0.5 m^3/s need to run to deliver it?

1. Area: 1 hectare = 10,000 m^2, so 40 ha = 400,000 m^2.
2. Volume: 400,000 m^2 × 0.90 m = 360,000 m^3.
3. Acre-feet: 360,000 ÷ 1,233 ≈ 292 acre-feet.
4. Time at 0.5 m^3/s: 360,000 ÷ 0.5 = 720,000 seconds. There are 86,400 seconds in a day, so 720,000 ÷ 86,400 ≈ 8.3 days of continuous flow.

Answer: 360,000 m^3, about 292 acre-feet, about 8.3 days of flow at 0.5 m^3/s.

PRACTICE

1. EASY State the rule of prior appropriation in six words or fewer, then explain it in one sentence.
2. EASY Which system of water law, riparian or prior appropriation, fits a region where rain falls on every field, and why?
3. EASY Define an acre-foot and give its size in cubic meters.
4. MEDIUM A town holds a right to 2,000 acre-feet a year. How many cubic meters is that? If the town uses 150 m^3 per household per year, how many households can it serve?
5. MEDIUM Three rights on a creek: A (1870) 1.5 m^3/s, B (1900) 2.0 m^3/s, C (1920) 1.0 m^3/s. The gauge reads 3.0 m^3/s. How much does each receive under prior appropriation?
6. MEDIUM Use the precipitation bar graph. (a) Which cities receive less than 50 cm a year? (b) About how many times more precipitation does Atlanta receive than Phoenix? (c) Which two of the six cities lie in states that follow the riparian doctrine, and does their rainfall fit that choice? (d) Omaha is close to Powell’s line. What would you expect farmers there to do in a dry year?
   (Use the map or drawing “Approximate average yearly precipitation, cm.” shown earlier in this lesson.)
7. MEDIUM Average monthly flow at a gauge on a mountain river, in m^3/s: January 20; March 45; May 160; June 190; July 90; September 30; November 22. The rights on the river total 100 m^3/s, of which the most junior 40 m^3/s belong to a ditch built in 1910. (a) In which months is the 1910 ditch fully supplied? (b) In which listed months does it get nothing at all? (c) What natural event explains the May and June peak? (d) What structure would let the river’s users move June water to September?
8. HARD A 25 hectare field needs 80 cm of irrigation water. How many cubic meters is that, and how many acre-feet?
9. HARD Western farmers lose water from irrigated soil to evaporation. Design an experiment to test whether a straw mulch reduces evaporation from a watered pan of soil. State the hypothesis, the independent and dependent variables, three controls, and how you would measure the result.

10. CHALLENGE In four or five sentences, explain why John Wesley Powell's 1893 warning came true for the Colorado River, and what the compact's negotiators lacked in 1922 that a hydrologist would insist on today.

COMMON MISTAKES

- Thinking the biggest or richest farm gets the water in a dry year. Under prior appropriation only the priority date matters: a small 1880 ditch is served before a huge 1950 canal.
- Thinking a water right means owning the water itself. It is a right to use a measured amount for a beneficial purpose; the water in the stream belongs to the public of the state.
- Thinking groundwater and streams are separate supplies. Pumping a well near a river can lower the river, and seepage from canals recharges aquifers, so most western states now manage them together.

Make it a game · Call on the River. Make six water-right cards, each with a priority year (1868, 1879, 1885, 1902, 1921, 1955) and a flow (1 to 3 m^3/s). Deal them out. The commissioner rolls two dice: the total is the river's flow today in m^3/s. Players lay down their cards in priority order and the commissioner fills each in turn until the river is empty; a card fully served scores 2, partly served scores 1, called out scores 0. Play seven rounds (seven years) and keep a ledger. Then reshuffle and give the newest card to the player who scored most. Does seniority or luck matter more over a decade?

Scripture. "And he removed from thence, and digged another well; and for that they strove not: and he called the name of it Rehoboth; and he said, For now the LORD hath made room for us, and we shall be fruitful in the land." (Genesis 26:22, KJV)

Isaac answered two water quarrels by digging again rather than fighting, and he thanked God for room. Water law at its best is a way for neighbors to make room for one another before the dry year comes.

Practice answers

1. "First in time, first in right." The person who first diverted water and put it to beneficial use has the senior right, and newer users are served only after older ones.
2. Riparian. Where rain is plentiful, landowners along a stream can share its water reasonably and all take a little less in a dry spell, because the stream is rarely the only source of water for crops.
3. The volume of water covering one acre to a depth of one foot, about 1,233 m^3 (about 1.23 million liters).
4. 2,000 × 1,233 = 2,466,000 m^3, about 2.5 million m^3. 2,466,000 ÷ 150 ≈ 16,400 households.
5. A takes 1.5 (remaining 1.5); B is entitled to 2.0 but gets the remaining 1.5; C gets 0.
6. (a) Denver, Salt Lake City and Phoenix. (b) 127 ÷ 18 ≈ 7 times. (c) Atlanta (Georgia) and St. Louis (Missouri); yes, at about 127 cm and 105 cm both are well above the line where rain-fed

farming works. (d) Rely on rain in most years but pump groundwater or irrigate in dry years, which is in fact common on the eastern Plains.

7. (a) May and June (flow of 160 and 190 exceeds the 100 m^3/s of total rights). (b) January, March, September and November, when flow is below the 60 m^3/s held by the senior rights (July, at 90, gives the 1910 ditch only part of its 40). (c) Snowmelt from the mountains. (d) A storage reservoir behind a dam, as Hoover Dam does for the Colorado.
8. 25 ha = 250,000 m^2; 250,000 × 0.80 = 200,000 m^3; 200,000 ÷ 1,233 ≈ 162 acre-feet.
9. Hypothesis: mulched soil loses less water to evaporation. Independent variable: mulch present or absent. Dependent variable: grams of water lost, found by weighing each pan at the start and after 24 hours. Controls: same pan size, same soil and amount, same 300 mL of water added, same sunny spot and time period, same thermometer location. Use at least three pans of each kind and compare average mass lost.
10. Powell said the arid lands held far more acres than the rivers could water, so settlers would end up fighting over water in court. The 1922 negotiators divided 15 million acre-feet a year between the basins using only about two decades of gauge records from unusually wet years, and later measurement showed the river’s average flow was smaller than they assumed. Promises on paper then exceeded the water in the river, and the states, tribes and Mexico have negotiated ever since. A hydrologist today would insist on a long gauge record, tree-ring and other evidence of past droughts, and a rule for sharing shortages before signing. Measurement first, then agreement.

Unit 2 review

Answer every question. Show your work for calculations with units, draw the diagram neatly with labels, and use complete sentences for explanations. The test is worth 60 points.

1. (4 pts) Multiple choice. In the speech of Jesus’ day, “living water” meant: (a) water that had been boiled; (b) water from a spring or well that renews itself from the ground; (c) rainwater stored in a cistern; (d) water carried from the Jordan River.

2. (5 pts) The Samaritan woman said, “the well is deep.” Using the geology of the valley at Shechem, explain in two or three sentences why Jacob’s well had to be cut about 40 m down to reach water, and why a well there gives water all year while a cistern can run dry.

3. (5 pts) A bucket holds 12 L and one round trip from a deep well takes 4 minutes. How many liters can one person draw in an hour? How long would it take to draw 180 L?

4. (4 pts) Multiple choice. Clay often has a porosity above 40 percent, yet it makes a confining layer rather than an aquifer because: (a) it holds no water at all; (b) its pores are too small and poorly connected for water to flow; (c) it dissolves in water; (d) it is always found below granite.

5. (5 pts) A student fills a cup with 500 mL of dry sand, then pours in water until it just reaches the sand surface. It takes 140 mL. Find the porosity. Then find how many cubic meters of water a sand aquifer with that porosity holds if its saturated volume is 2,000,000 m³.

6. (8 pts) Diagram. Draw a cross-section of the ground showing: a hill where rain recharges the ground, an unconfined sand aquifer with its water table, a clay confining layer, a confined aquifer beneath it, a water-table well, and an artesian well in which water rises above the aquifer. Label all six parts and mark the direction groundwater flows.

7. (4 pts) Multiple choice. The cement grout placed around the outside of the casing near the top of a well is there to: (a) make the pump run faster; (b) keep surface water, fertilizer and waste from trickling down along the casing into the aquifer; (c) hold the gravel pack in place at the bottom; (d) measure the water level.

8. (6 pts) Before pumping, the water in a well stands 15.0 m below ground. After an hour of pumping at 50 L per minute the level steadies at 20.0 m. (a) What is the static water level? (b) What is the drawdown? (c) What is the specific capacity? (d) A second well in the same aquifer gives 50 L/min with 2.5 m of drawdown. Which well is in more permeable material?

9. (5 pts) A new irrigation well 300 m from a family’s house well causes the house well’s water level to drop whenever the big pump runs. Explain what is happening using the term cone of depression, and name one thing the driller of the house well did that still protects its water quality.

10. (4 pts) Multiple choice. Under prior appropriation, in a dry year the water goes first to: (a) the largest farm; (b) the farm closest to the river; (c) the right with the earliest priority date that is being put to beneficial use; (d) whoever bids the most money that day.

11. (6 pts) Three rights on a creek: Ross Ditch (1874) 1.0 m^3/s; Valley Canal (1899) 2.5 m^3/s; Mesa Farm (1930) 1.5 m^3/s. The gauge reads 2.5 m^3/s. (a) How much does each receive? (b) Mesa Farm also holds a stored right of 400 acre-feet in a reservoir. How many cubic meters is that? (1 acre-foot ≈ 1,233 m^3.)
12. (4 pts) In two or three sentences, state what John Wesley Powell warned the Irrigation Congress in 1893 and what the Colorado River Compact of 1922 tried to do about the problem.

UNIT PROJECT: MY WELL REPORT: FROM MODEL AQUIFER TO WATER RIGHT

Assemble a hydrogeologist's report on the model well you built in Lesson 2.3. Include your driller's log and a scale cross-section of the layers in your tub; your porosity table and bar graph from Lesson 2.2; your pump-test table with static level, drawdown, recovery time and specific capacity for two pumping rates; and a one-page "water right" for your model well written like a state permit, stating a priority date, a measured amount in liters per minute and a beneficial use.

Finish with a page of reflection: what the Samaritan woman meant by "the well is deep," what Darcy, the Zigong drillers and Powell each contributed, and how Isaac's well called Rehoboth speaks to the sharing of water. Present the report to your family with your model tub beside you and demonstrate one pump test.

- **Measurement**: Porosity, drawdown, recovery and specific capacity are measured, recorded in tables with units, and calculated correctly.
- **Diagrams**: The cross-section and driller's log are to scale, neatly labeled, and show casing, screen, gravel pack, grout, water table and cone of depression.
- **Understanding**: The water right and reflection use the unit's terms correctly and explain prior appropriation, aquifers and the stories of the four lessons accurately.
- **Presentation**: The report is organized, dated and legible, and the live pump test is explained clearly to the audience.

Answer key

1. (b). Spring or well water moves and is renewed from the ground, unlike still cistern water.
2. The valley floor is fractured limestone, and the winter rain soaks down through the cracks, so the water table lies dozens of meters below the surface; the shaft had to be cut to reach it. Groundwater keeps seeping into a well from the saturated rock around it, so it is renewed through the dry summer, while a cistern is a sealed pit that holds only the rain poured into it and stays empty once that is used.
3. 60 ÷ 4 = 15 trips; 15 × 12 L = 180 L per hour. So 180 L takes one hour.
4. (b). Clay stores water but its tiny pores give it very low permeability.
5. Porosity = 140 ÷ 500 = 0.28 = 28 percent. Water = 0.28 × 2,000,000 m^3 = 560,000 m^3.
6. A correct drawing shows the land surface with a hill on one side and rain arrows; a dashed water table below the surface, higher under the hill and sloping down toward the low ground; a sand aquifer above a clay layer; a second aquifer under the clay; a well ending above the clay with water at the water-table level; and a well passing through the clay with water standing above the top of the confined aquifer (or flowing out at the surface). Flow arrows

point from the recharge hill toward the low ground. One point per labeled feature, one for flow direction, one for neatness and correct relative positions.

7. (b). The grout seals the gap between casing and ground against contamination from the surface.
8. (a) 15.0 m below ground. (b) 20.0 − 15.0 = 5.0 m. (c) 50 ÷ 5.0 = 10 L/min per meter. (d) The second well: 50 ÷ 2.5 = 20 L/min per meter, twice the specific capacity, so it draws from more permeable material.
9. The irrigation well pumps faster than water flows in, so the water table dips into a cone of depression around it that spreads out hundreds of meters; the house well lies inside the cone, so its level falls while the pump runs and recovers when it stops. The grout seal (or the casing and screen) still keeps surface contamination out of the house well even though its level is lower.
10. (c). First in time, first in right, for a measured beneficial use.
11. (a) Ross Ditch 1.0 m^3/s (remaining 1.5); Valley Canal gets the remaining 1.5 m^3/s of its 2.5; Mesa Farm gets 0 from the creek. (b) 400 × 1,233 = 493,200 m^3, about 490,000 m^3.
12. Powell warned that the arid West had far more land than water, so settlers were piling up a heritage of conflict and lawsuits over water rights. The 1922 compact tried to prevent that between states by dividing the Colorado River at Lees Ferry into an Upper and a Lower Basin and promising each 7.5 million acre-feet a year, with Hoover Dam later storing spring floods to make the division workable.

UNIT 3

Minerals and Mining

Moses told Israel they were going to “a land whose stones are iron, and out of whose hills thou mayest dig brass” (Deuteronomy 8:9). The metals in the hills are listed among God’s gifts, and digging them out is treated in Scripture as ordinary good work. This unit is about that work: how minerals are found and told apart, how a mine is laid out, how the men and women who go underground are kept alive, and how the ground is put back when the ore is gone. You will begin in the tailrace of a sawmill at Coloma, California, on January 24, 1848, where James Marshall picked up a flake the size of half a pea and tested it with a hammer and a rock.

From Sutter’s Mill you will learn why gold settles where it does and how density, hardness and streak separate it from fool’s gold. You will follow Daniel Jackling to Bingham Canyon, Utah, in 1906, where steam shovels proved that a mountain of low-grade copper could pay if you moved enough of it, and you will compare the open pit with the shaft, adit and room-and-pillar mine. You will stand in Monongah, West Virginia, on December 6, 1907, when 362 men died in an explosion, and trace the path from that morning to the Federal Mine Safety and Health Act of 1977 and the fans, rock dust and inspections that cut coal mining deaths from thousands a year to a handful. Finally you will watch President Carter sign the Surface Mining Control and Reclamation Act in August 1977 and learn how topsoil, slopes, limestone and counted plants return a mine to pasture or forest.

Along the way you will do the arithmetic of a working mining engineer: density from mass and volume, ore grade in grams per tonne and percent, strip ratio and extraction ratio, methane percentage, ventilation airflow, death rates per thousand workers, regrading volumes and ground-cover standards. You will pan a model placer, load a sugar-cube mine until it fails, ventilate a cardboard mine with a fan, and strip-mine and reclaim a tray of soil. The unit ends with your own mine plan, from discovery to reclamation, for an ore body you design.

BEFORE YOU BEGIN

- Can calculate a percent, a ratio and an average, and convert among grams, kilograms and tonnes and among centimeters, meters and kilometers
- Knows the soil horizons and the jar test from Unit 1, and understands that the A horizon holds the organic matter plants need
- Can read a bar graph and a data table and describe a trend in words
- Can plan a fair test with an independent variable, a dependent variable and controls, and record results in a notebook

MASTERY CHECKLIST

- I can tell the story of Sutter’s Mill and explain, using density, why placer gold collects where a stream slows.

- I can calculate density from mass and displaced water and use density, hardness and streak to tell gold from pyrite.
- I can describe an open-pit mine and an underground mine, name their parts, and use depth, size and grade to choose between them, including computing a strip ratio and an extraction ratio.
- I can name the main hazards of underground mining, explain the physics of methane, coal dust and ventilation, and tell what the Mine Act of 1977 and MSHA require.
- I can list the steps of reclamation in order, explain how acid mine drainage forms and is prevented, and compute topsoil volumes and ground-cover standards.
- I can explain from Deuteronomy 8:9, Job 28 and Genesis 2:15 how mining can be honest work and good stewardship at the same time.

OPTIONAL BOOKS AND RESOURCES

- **USGS Mineral Resources Program** (https://www.usgs.gov/programs/mineral-resources-program): Free. Mineral commodity summaries, maps of where minerals are mined in the United States, and plain-language pages on what each metal is used for. Look up copper, gold and coal production for your own state.
- **Mine Safety and Health Administration (MSHA)** (https://www.msha.gov/): Free. The federal agency created by the 1977 Mine Act. Its site has mining fatality statistics by year, safety alerts and training materials used by real miners; the data pages are the source for the graphs in Lesson 3.3.
- ***De re metallica* by Georgius Agricola, translated by Herbert and Lou Henry Hoover (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/38015): Free. The 1556 mining textbook with its famous woodcuts, in the 1912 Hoover translation. Browse the pictures of shafts, pumps and furnaces for Lesson 3.2; the text is for strong readers and parents.

3.1 Sutter's Mill (1848): Gold, Density and the Rush West ★

OBJECTIVES

- Tell the story of James Marshall's discovery at Sutter's Mill on January 24, 1848, and explain why placer gold collects where it does.
- Use density, hardness and streak to tell real gold from pyrite and other look-alikes, and calculate density from mass and volume.
- Explain the difference between a lode (vein) deposit and a placer deposit, and compute the grade of an ore in grams per tonne.

Warm-up. Fill a clear jar half full of water and drop in, one at a time, a small pebble, a steel nut or bolt, a wooden bead and a plastic button. Watch how fast each one sinks. Now swirl the jar so everything moves, and let it settle. Which object ends up on the bottom first, and which is last? Write one sentence predicting what would happen to a grain of gold mixed with sand in a moving stream.

Video. Coming soon. California Gold Rush, Sutter's Mill and how placer gold forms and is panned: search USGS, Smithsonian, California State Parks (Marshall Gold Discovery State Historic Park), PBS American Experience, SciShow and Moody Science classics.

KEY TERMS

mineral
A naturally occurring solid with a definite chemical makeup and an orderly crystal structure, such as gold, quartz or pyrite.

density
Mass divided by volume, measured in grams per cubic centimeter (g/cm³). Gold is about 19.3 g/cm³; quartz is about 2.65 g/cm³.

lode deposit
Gold or another metal still locked in the rock where it formed, usually in quartz veins. California's Mother Lode is a belt of such veins in the Sierra Nevada foothills.

placer deposit
Grains and nuggets of a heavy mineral that have weathered out of the rock and been concentrated by moving water in stream gravels.

streak
The color of the powder a mineral leaves when rubbed on an unglazed porcelain tile. Gold streaks golden yellow; pyrite streaks greenish black.

ore grade
How much valuable metal a rock contains, often given as grams per tonne (g/t) for gold or as a percent for copper.

CORE IDEAS

The story. On the morning of January 24, 1848, a carpenter named James W. Marshall walked along the tailrace of a sawmill he was building on the South Fork of the American River at Coloma, California. The mill belonged to John Sutter, a Swiss settler who hoped to sell lumber. Marshall had let water run through the ditch overnight to deepen it, and in the clear water he saw something glinting. He picked up a piece about half the size of a pea. He later wrote that it "made my heart thump, for I was certain it was gold." He hammered it flat with a rock, and it bent instead of shattering. A few days later Marshall carried the flakes to Sutter, who tested them with nitric acid and found them pure. Sutter wanted the news kept quiet until his mill was finished. It did not stay quiet. By the end of 1848 President Polk had told Congress the reports of gold were true, and in 1849 tens of thousands of people set out for California by ship and by wagon. California became a state in 1850, two years after Marshall's discovery.

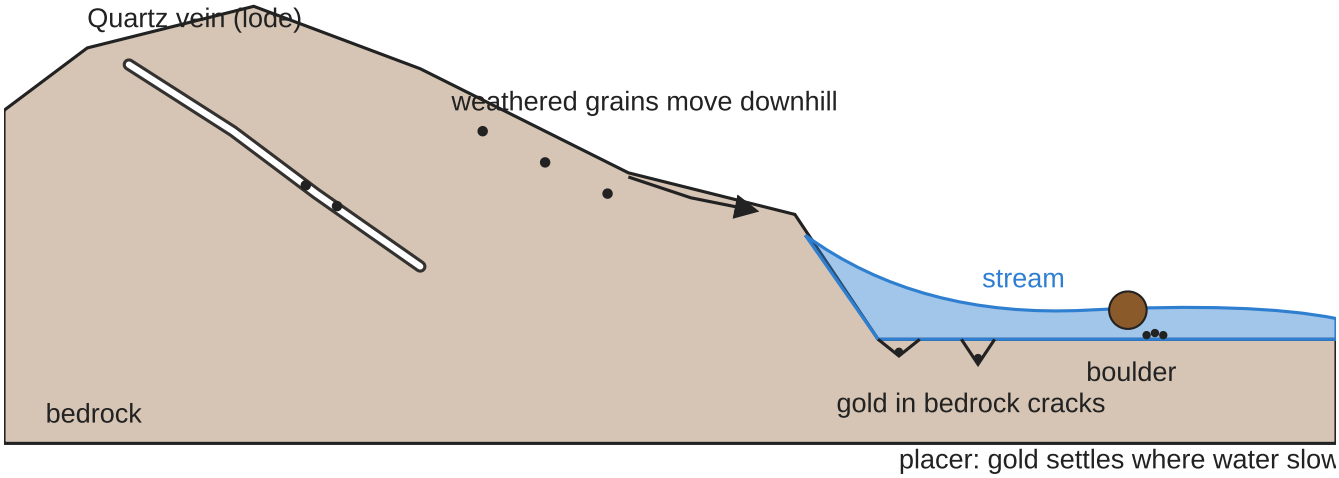
How they figured it out. Marshall and Sutter did not have a laboratory, but they did have three tests that any of us can still use. First, **malleability**: gold bends and flattens under a hammer, while pyrite (fool's gold) is brittle and crumbles. Second, **hardness**: gold is soft, about 2.5 to 3 on the Mohs scale, so a copper coin will scratch it, while pyrite is 6 to 6.5 and will scratch a steel knife. Third, **color and streak**: gold is the same yellow in shadow and in sunlight and leaves a golden streak on a porcelain tile; pyrite looks brassy, has flat crystal faces, and streaks greenish black. The best test of all is **density**. Gold has a density of about 19.3 grams per cubic centimeter, which means a piece of gold the size of a sugar cube has the mass of about seven sugar cubes of quartz. Pyrite is only about 5.0 g/cm³. If you can find a specimen's mass with a scale and its volume by the water it pushes aside, you can tell gold from everything that merely looks like it.

The big idea. Density is also why the gold was lying in Marshall's ditch in the first place. The gold of the Sierra Nevada formed in **lode deposits**, veins of white quartz threading through the hard rock of the foothills. Over time the rock at the surface weathers and crumbles, and rain and streams carry the broken pieces downhill. Quartz grains and gold grains travel together, but not for long. Water moving fast enough to roll a grain of quartz is far too weak to move a grain of gold of the same size, because the gold grain is more than seven times as heavy. So gold drops out of the current first: on the inside of river bends, behind boulders, in cracks of the bedrock, and in the gravel bars where the water slows. These are **placer deposits**. A miner with a pan copies the river. He swirls gravel and water, lets the light sand wash over the rim, and the heavy gold stays at the bottom. The same principle, heavy things settle out of slow water, is how sluice boxes, long toms and the great modern gold mills all work.

Try it and see. Geologists describe how rich a deposit is by its **grade**. For gold, grade is usually given in grams of gold per tonne of rock (one tonne is 1,000 kg). One gram per tonne is the same as one part per million. Many large gold mines today profitably dig and crush rock that holds only about 1 g/t, which means a tonne of ore the size of a kitchen table yields a flake of gold about the size of a pea. The gravels of 1848 were far richer. Early miners sometimes washed out an ounce of gold (31.1 grams) from a few hundred kilograms of

gravel, which is a grade of more than 100 g/t. That is why the richest placers were worked out within a few years, and why by the 1850s mining in California turned to tunneling into the lode veins and to large companies with machines. Marshall himself never grew rich. Sutter's workers abandoned the mill to dig for gold, squatters overran his land, and the man whose name is on the famous mill died poor in 1880.

God's handiwork. Gold is one of the first things the Bible names in describing the lands around Eden: "And the gold of that land is good" (Genesis 2:12). Gold is good because of what it is: it does not rust or tarnish, it can be beaten thinner than paper, it conducts electricity, and it shines. A flake found in a California stream in 1848 would look exactly the same today. The Book of Job notices that gold must be searched out: "Surely there is a vein for the silver, and a place for gold where they fine it" (Job 28:1). The miner finds the vein, the stream sorts the grains, and the one who learns how density works can read the riverbed like a page. That ordered behavior, the same every time, is part of why a created world can be studied at all.



From lode to placer. Gold weathers out of quartz veins in the hills, travels downstream with sand and gravel, and settles first wherever the water slows.

PICTURE STUDY



Miners in the Sierras, Charles Christian Nahl and August Wenderoth, 1851–1852 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C.

Charles Nahl came to California from Germany in 1851 and tried gold mining himself before he went back to painting. With his partner August Wenderoth he painted this scene from his own experience of the diggings: a small company of miners shoveling gravel into a long wooden trough called a long tom, while diverted stream water washes the light sand away and leaves the heavy gold behind.

Look at the picture as a scientist as well as an art lover. Everything in it depends on moving water and on the fact that gold is denser than sand.

Look closely

- Find the wooden trough. Where does its water come from, and where does the muddy water go when it leaves?
- Count the miners and notice what each one is doing. Which jobs move gravel, and which job sorts it?
- Look at the stream and the valley walls. Where would you expect placer gold to have settled before the miners arrived?
- Notice the light. Nahl painted the Sierra in bright sun; how does the light make the water and the men’s shirts stand out?

Talk about it

1. Why do the miners need running water to find gold, and what property of gold are they relying on?

2. What do the cabin and the stacked tools tell you about how long this company planned to stay?
3. Nahl had been a miner before he painted this. What details in the painting might only a person who had done the work notice?

> **Safety first.** The panning project uses water and small heavy objects; keep steel nuts and BBs away from young children and work over a tray or outdoors so spilled sand does not go down a drain.

EXPERIMENT: PANNING FOR GOLD: DOES DENSITY DECIDE WHAT STAYS IN THE PAN?

You will build a model placer deposit and pan it the way a forty-niner did. Your “gold” will be small steel nuts or BBs, which are denser than sand but much less dense than gold, so you will also test a prediction about what happens when the density difference is smaller.

Question: does a denser object stay in the pan more reliably than a less dense one of the same size? Prediction: write yours before you start.

You will need

- A pie plate or shallow metal or plastic bowl (the pan)
- About 1 liter of play sand or garden sand and a handful of small gravel
- 20 small steel hex nuts or copper-coated BBs (dense “gold”)
- 20 small plastic beads or dried peas of about the same size (less dense look-alikes)
- A dishpan or tray of water, a kitchen scale, a measuring cup
- Notebook, pencil, stopwatch

Steps

1. Weigh 10 of the nuts and 10 of the beads on the kitchen scale. Find the volume of each group by dropping them into a measuring cup of water and reading how much the water rises (1 mL = 1 cm^3). Calculate the density of each material in g/cm^3 and record it.
2. Mix the sand, gravel, 20 nuts and 20 beads in the pan. This is your model gravel bar. Keep the same recipe for every trial.
3. Lower the pan into the water and swirl it so the sand floats up and over the rim. Tilt and swirl for exactly 60 seconds. Keep the time and the swirling speed the same each trial.
4. Count how many nuts and how many beads remain in the pan. Record them in a table with columns: trial, nuts recovered out of 20, beads recovered out of 20.
5. Repeat for three trials and find the average recovery for each material. Recovery percent = recovered ÷ 20 × 100.
6. Change one variable: use smaller nuts or BBs instead of the hex nuts, keep everything else the same, and run three more trials. Does size change recovery?

7. Write a conclusion: which material stayed in the pan, and does your density measurement explain why? What would you predict for real gold at 19.3 g/cm³?

Tips

- If everything washes out, you are swirling too hard. Real panning is slow and patient.
- If you have a magnet, you can check that you recovered all the steel nuts from the waste sand afterward.

Check your work

- I can calculate the density of a material from its mass and the water it displaces.
- I can name the independent variable (material or size), the dependent variable (recovery percent) and the controls (time, swirl speed, recipe) in my experiment.
- I can explain why the heavy grains stay in the pan and the light grains wash out.

FIELD NOTEBOOK

1. Draw the cross-section from lode to placer in your notebook: a quartz vein in the hills, a stream, and the four places gold settles (inside bend, behind a boulder, bedrock cracks, gravel bar). Label each one.
2. Make a three-column chart titled “Gold or Fool’s Gold?” comparing gold and pyrite by hardness, streak, density and how each behaves under a hammer.
3. Write a dated notebook entry as if you were James Marshall on the evening of January 24, 1848. Describe exactly what you saw, the two tests you did and what you plan to do next.

> **From history.** The gold at Sutter’s Mill was found just nine days before Mexico and the United States signed the Treaty of Guadalupe Hidalgo on February 2, 1848, which transferred California to the United States. Neither government knew about the gold when they signed. The rush that followed was so large that San Francisco, a village of about 1,000 people in early 1848, grew to roughly 25,000 within two years, and California skipped the usual territory stage and was admitted as a state on September 9, 1850.

WORKED EXAMPLES

Example 1. A hiker finds a shiny brassy lump in a creek. Its mass on a kitchen scale is 15.0 g. When dropped into a measuring cup, it raises the water level from 50.0 mL to 53.0 mL. Is it gold?

1. Volume is the water it displaced: 53.0 mL − 50.0 mL = 3.0 mL = 3.0 cm^3.
2. Density = mass ÷ volume = 15.0 g ÷ 3.0 cm^3 = 5.0 g/cm^3.
3. Compare with known densities: gold about 19.3 g/cm^3, pyrite about 5.0 g/cm^3, quartz about 2.65 g/cm^3.
4. A 3.0 cm^3 piece of real gold would have a mass of about 19.3 × 3.0 = 58 g, almost four times what the scale shows.

Answer: No. Its density is about 5.0 g/cm^3, which matches pyrite (fool’s gold). Real gold of that size would weigh about 58 g.

Example 2. In the summer of 1848 a miner washes 50 pans of gravel in a day, about 5 kg of gravel per pan, and recovers 31 g of gold (about one troy ounce). What is the grade of this gravel in grams per tonne, and how does it compare with a modern large gold mine working ore of about 1 g/t?

1. Total gravel washed: 50 pans × 5 kg = 250 kg = 0.25 tonne.
2. Grade = gold ÷ rock = 31 g ÷ 0.25 t = 124 g/t.
3. Compare: 124 g/t ÷ 1 g/t = 124. The 1848 gravel was more than 100 times as rich as ore many modern mines dig profitably.
4. Because 1 g/t equals 1 part per million, 124 g/t is 124 parts per million, still only about 0.01 percent of the gravel by mass.

Answer: About 124 g/t (124 parts per million), well over 100 times the grade of typical modern gold ore. Even so, gold was only about one ten-thousandth of the gravel.

Example 3. A student has a fingernail (Mohs hardness about 2.5), a copper coin (about 3) and a steel nail (about 5.5). A yellow mineral specimen cannot be scratched by the fingernail but is scratched by the copper coin. What range of hardness does the specimen have, and is it more likely gold or pyrite?

1. Not scratched by fingernail means hardness is greater than about 2.5.
2. Scratched by copper means hardness is less than about 3.
3. So the hardness lies between 2.5 and 3 on the Mohs scale.
4. Gold is 2.5 to 3; pyrite is 6 to 6.5. Pyrite would not be scratched by the copper coin or even by the steel nail.

Answer: Hardness between 2.5 and 3. That fits gold, not pyrite. A streak test (golden yellow for gold, greenish black for pyrite) would confirm it.

PRACTICE

1. EASY Who found gold at Sutter’s Mill, on what river, and in what year?
2. EASY Define a placer deposit and a lode deposit in one sentence each.
3. EASY A sample has a mass of 38.6 g and a volume of 2.0 cm^3. What is its density, and could it be gold?
4. MEDIUM Explain in two sentences why gold grains settle on the inside of a river bend while quartz sand of the same size keeps moving.
5. MEDIUM A mine processes 2,000 tonnes of ore per day at a grade of 1.5 g/t. How many grams of gold does it produce per day if it recovers all of the gold? How many troy ounces (31.1 g each)?
6. MEDIUM Data reading. A student tested four yellow minerals and recorded: Sample A: hardness 6.5, streak greenish black, density 5.0. Sample B: hardness 2.5, streak golden yellow, density 19.2. Sample C: hardness 3.5, streak white, density 3.4. Sample D: hardness 7, streak white, density 2.65. Which sample is most likely gold, which is pyrite, and which is quartz? Which single measurement was most decisive?
7. MEDIUM Data reading. The table shows how far a stream carried grains of equal size in one minute in a classroom flume: quartz 240 cm, pyrite 85 cm, gold-colored tungsten shot (density about 19) 6 cm. Based on the pattern, what relationship between density and distance carried does the data support? What would you predict for a magnetite grain (density 5.2)?
8. HARD Experiment design. You want to find out whether grain SIZE affects how far the stream carries gold-colored tungsten shot. Describe the independent variable, the dependent variable, two things you would keep the same, and how many trials you would run.
9. HARD A nugget-shaped object has a mass of 50 g and a volume of 5 cm^3. A friend says it must be gold mixed with quartz. Calculate the density and explain whether the friend could be right.

10. CHALLENGE Write a paragraph explaining why the richest placer gravels of California were worked out within a few years while lode mining in the same hills went on for decades. Use the words density, grade and lode.

COMMON MISTAKES

- Thinking that anything shiny and yellow in a stream is gold. Pyrite and mica are the usual culprits; a streak test or a density measurement settles it in a minute.
- Believing gold sinks because it is “heavy.” A big quartz boulder is heavier than a gold flake. Gold settles out first because it is denser: more mass in the same volume.
- Imagining that Marshall or Sutter grew rich. Neither did. The discovery brought hundreds of thousands of people to California, but the men at the mill lost their workers, their land and their mill.

> **Make it a game · Pan or Pass.** A parent reads out a mineral’s clues one at a time (density, hardness, streak, how it behaves under a hammer). After each clue, players may shout “Pan!” if they are sure it is gold or “Pass!” if they are sure it is not. A correct early call scores 3 points, a correct call after all clues scores 1, and a wrong call loses 2. Use gold, pyrite, quartz, mica and copper. First to 12 points wins.

> **Scripture.** “And the gold of that land is good: there is bdellium and the onyx stone.” (Genesis 2:12, KJV)

The first mention of gold in Scripture calls it good. Gold does not rust, it can be shaped and it endures, and finding it takes patience and knowledge of how God’s world is ordered. Wealth from the ground is a gift to be used well, not an end in itself.

Practice answers

1. James W. Marshall, on the South Fork of the American River at Coloma, California, in January 1848 (January 24).
2. A lode deposit is metal still in the rock where it formed, such as gold in a quartz vein. A placer deposit is grains of a heavy mineral that have weathered out and been concentrated by moving water in stream gravels.
3. 38.6 ÷ 2.0 = 19.3 g/cm³. Yes, that matches the density of gold.
4. Water slows on the inside of a bend, and slower water can carry less. Because gold is more than seven times as dense as quartz, the slowed water can still move the quartz grains but not the gold grains, so gold drops out there.
5. 2,000 × 1.5 = 3,000 g per day. 3,000 ÷ 31.1 ≈ 96 troy ounces.
6. B is gold (soft, yellow streak, density near 19.3). A is pyrite (hard, greenish-black streak, density 5.0). D is quartz (hardness 7, density 2.65). C is none of the three. Density was most decisive because only gold is near 19 g/cm³.
7. The denser the grain, the shorter the distance the water carried it. Magnetite at 5.2 g/cm³ should travel about as far as pyrite (5.0 g/cm³), roughly 80 cm.
8. Independent variable: diameter of the shot (for example 1 mm, 2 mm, 4 mm). Dependent variable: distance carried in a set time. Keep the same: water speed and depth, the material

of the shot, the starting point and the timing. Run at least three trials per size and average them.

9. Density is 50 ÷ 5 = 10 g/cm³. Pure gold is 19.3 and quartz is 2.65, so a mixture of the two could have a density between them, including 10 g/cm³. The friend could be right; the object could be a quartz piece with gold in it. A streak test on a cut surface or looking for visible gold would help.
10. A good answer explains that placers are concentrated by water over long stretches of stream, so the river had already done the sorting; a miner with a pan could recover high-grade gold quickly, and the limited supply of such concentrated gravel was soon exhausted. Lode gold was spread thinly through hard quartz veins at a lower grade, so it required tunnels, crushing machinery and capital, which took far longer but could continue as long as the veins lasted. Density explains why placers were rich and easy; grade explains why lodes were slow and costly.

3.2 Open-Pit and Underground Mines: Bingham Canyon (1906) ★

OBJECTIVES

- Describe how an open-pit mine and an underground mine are laid out, naming benches, haul roads, shafts, adits, drifts and room-and-pillar workings.
- Explain how depth, shape and grade of an ore body decide which mining method is used, and calculate strip ratio and the metal content of an ore from its grade.
- Tell how Daniel Jackling's 1906 experiment at Bingham Canyon, Utah, made it possible to mine very low-grade copper ore profitably.

Warm-up. Push ten chocolate chips (the ore) into a block of modeling clay or a cup of damp sand (the rock). Put three of them near the top and spread out, and seven deep in the middle in a tight cluster. Now recover them two ways: scrape the whole top away to reach the shallow chips, then poke a single narrow tunnel to reach the deep cluster. Which method moved more clay? Which left the block more intact? Write one sentence about when each method makes sense.

Video. Coming soon. Open-pit copper mining at Bingham Canyon and underground room-and-pillar and longwall mining explained: search USGS, Smithsonian, Kennecott/Rio Tinto Kennecott visitor videos, Practical Engineering, Science Channel and Moody Science classics.

KEY TERMS

ore
Rock that contains enough of a valuable mineral to be worth mining at a profit. Rock that does not is called waste rock.

open-pit mine
A surface mine dug downward as a huge bowl of stepped ledges (benches), used when the ore body is large and near the surface.

bench
One of the flat steps cut around the walls of an open pit; trucks drive on them and drills and shovels work from them. Each is typically 10 to 15 m tall.

shaft and adit
A shaft is a vertical opening down to underground workings; an adit is a nearly level tunnel driven into a hillside. Horizontal tunnels that follow the ore are called drifts.

room-and-pillar
An underground method in which miners remove ore in rooms and leave pillars of rock standing to hold up the roof, common in coal, salt and limestone mines.

strip ratio

The tonnes of waste rock that must be removed for every tonne of ore mined in a surface mine, such as 3:1.

CORE IDEAS

The story. In 1906, in a steep canyon in the Oquirrh Mountains southwest of Salt Lake City, Utah, a young mining engineer named Daniel C. Jackling started up steam shovels to dig copper ore that nearly every expert said was worthless. The copper at Bingham Canyon was real, but it was scattered through the rock at about two percent or less, far too thin for the tunnels and hand labor of the day. Jackling's idea was to treat the mountain like a gravel pit: dig the whole hillside with steam shovels, load it onto railcars, crush it in a giant mill, and let the sheer volume make up for the low grade. Investors laughed, then invested. Within a few years the low-grade ore was paying handsomely. Today the Bingham Canyon Mine is about 4 km across and about 1.2 km deep, one of the largest man-made excavations in the world, and the method Jackling proved there is how most of the world's copper, iron and gold are mined.

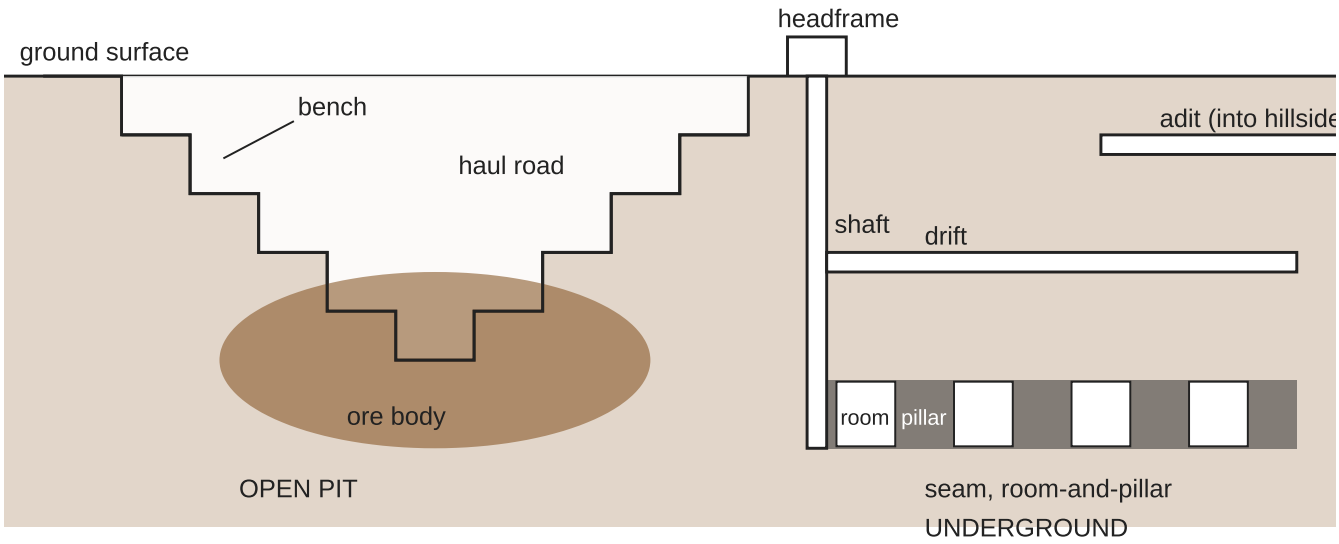
How they figured it out. Jackling was solving a geometry problem as much as a chemistry one. There are two basic ways to reach ore. A **surface mine** removes everything above the ore. An **open pit** is dug as a series of stepped ledges called **benches**, each about 10 to 15 m tall, spiraling down with a haul road so that trucks the size of houses can drive to the bottom and back. Strip mines, quarries and placer dredges are other kinds of surface mining. An **underground mine** leaves the overlying rock in place and reaches the ore through openings. A **shaft** drops straight down, with an elevator called a cage or skip. An **adit** is a level tunnel driven into a hillside. From these, **drifts** follow the ore sideways, and **stopes** are the rooms where ore is actually broken out. In flat deposits such as coal, salt or limestone, miners use **room-and-pillar**, removing the rock in a checkerboard of rooms and leaving pillars standing to hold up the roof. In long flat coal seams a **longwall** machine shears off the seam while hydraulic shields hold the roof above the miners and let it fall behind them.

The big idea. The choice between surface and underground comes down to three measurements: how deep the ore is, how big and what shape it is, and how rich it is. Mining engineers compare the cost of moving waste rock with the value of the ore beneath. The key number for a surface mine is the **strip ratio**: tonnes of waste removed per tonne of ore. A strip ratio of 3:1 means three tonnes of rock must be dug and hauled to waste piles for every tonne that goes to the mill. As a pit deepens, the walls must be cut back to stay stable, so the strip ratio rises. At some depth it becomes cheaper to tunnel than to keep widening the bowl, and the mine goes underground. That is why Bingham's copper, spread through a huge shallow body of rock, is an open pit, while a narrow gold vein a kilometer down in the same state is reached by shaft and drift. The **grade** sets the other side of the balance. Copper ore today is often about 0.5 percent copper, which means a tonne of ore (1,000 kg) yields only about 5 kg of metal, and 995 kg of ground rock becomes tailings. Only huge scale makes that pay.

Try it and see. Underground, the rock itself is the structure, and the engineer's job is to leave enough of it standing. In room-and-pillar mining, the **extraction ratio** is the fraction of

the seam actually removed. If rooms are 6 m wide and pillars 6 m wide in both directions, each 12 m by 12 m block holds a 6 m by 6 m pillar, so the pillar is 36 of 144 square meters, or 25 percent, and the extraction ratio is 75 percent. Take out more and the pillars must carry more load each; take out too much and the roof comes down. In this lesson’s project you will build a room-and-pillar model from sugar cubes and load it until it fails, then change the pillar spacing and see what the rock is telling you. A good mine plan is a kind of stewardship: taking what is useful while leaving the ground stable and the miners safe.

God’s handiwork. Deuteronomy describes the Promised Land as “a land whose stones are iron, and out of whose hills thou mayest dig brass” (Deuteronomy 8:9). Metals in the hills are listed among God’s gifts, and the digging of them is treated as ordinary good work. Job 28 describes a miner’s world in detail: “Iron is taken out of the earth, and brass is molten out of the stone” (Job 28:2), and “He putteth forth his hand upon the rock; he overturneth the mountains by the roots” (Job 28:9). The chapter ends, though, by saying that wisdom is harder to find than any ore and that “the fear of the Lord, that is wisdom” (Job 28:28). The mine is a picture of searching with skill for what is hidden, and the Bible uses it to point to a search that matters even more.



Two ways to reach ore. Left: an open pit with benches and a spiral haul road dug into a large shallow ore body. Right: a shaft, an adit and drifts reaching a deep seam mined by room-and-pillar.

PICTURE STUDY



Woodcut of a mine shaft, from De re metallica, Woodcut made for Georgius Agricola's De re metallica, 1556 · Woodcut illustration in a printed book · First printed in Basel; copies in many libraries. English translation by Herbert and Lou Henry Hoover, 1912 (free at Project Gutenberg)

Georgius Agricola was a German physician in the mining towns of Saxony and Bohemia who spent about twenty years writing the first great textbook of mining, De re metallica (On the Nature of Metals). It was printed in Basel in 1556, a year after he died, with 292 woodcuts so that a reader who had never been underground could see exactly how shafts were sunk, tunnels timbered, water pumped and ore raised.

The woodcuts cut the ground open like a cake so you can see the shaft and the men at once. That trick, the cross-section, is still how engineers draw mines today.

Look closely

- Find the shaft. How deep does the artist suggest it goes, and how is it kept from caving in?
- Look for the rope, bucket, ladder or machine used to move men and ore. Who or what supplies the power?
- Many of Agricola's woodcuts carry letters (A, B, C) that are explained in his text. If you find letters here, what do you think each one marks?
- Compare the size of the openings with the size of the men. How does this compare with a modern open pit that is four kilometers across?

Talk about it

1. Why did Agricola think pictures were necessary in a book about mining?

2. Which parts of this 1556 mine would you still find in an underground mine today, and which have been replaced by machines?
3. Herbert Hoover, a mining engineer who later became President, spent five years translating this book with his wife. Why might a working engineer have thought a 350-year-old book worth that effort?

EXPERIMENT: ROOM-AND-PILLAR: HOW MUCH ROOF CAN THE PILLARS HOLD?

You will build a model room-and-pillar mine from sugar cubes and a cardboard roof, load it with books until it fails, and measure how the extraction ratio changes the load the pillars can carry.

Question: how does leaving fewer pillars affect the load the roof can bear before collapse? Prediction: write what you expect, and whether you think the relationship is a straight line.

You will need

- A box of sugar cubes (about 100)
- Two squares of stiff cardboard, about 30 cm by 30 cm (the floor and the roof)
- A stack of books of similar size and a kitchen or bathroom scale
- Ruler, pencil, notebook

Steps

1. Draw a 30 cm by 30 cm grid on the floor cardboard with 6 cm squares (a 5 by 5 grid). Each square is a “block” of your seam.
2. Layout A: place one sugar-cube pillar in every square (25 pillars). Set the roof on top. Count the pillars and compute the extraction ratio: pillar area ÷ total area, then 1 minus that fraction. Each cube is about 1.5 cm wide, so one cube in a 6 cm square covers about 2.25 ÷ 36 = 6 percent.
3. Add books one at a time to the roof, centered, until the roof tilts or a pillar crushes. Weigh the books that were held before failure. Record the load in kilograms.
4. Layout B: use pillars only in every other square (13 pillars in a checkerboard). Repeat the loading test. Layout C: pillars only at the corners and center (5 pillars). Repeat.
5. Make a table: layout, number of pillars, load held (kg), load per pillar (kg ÷ pillars). Plot number of pillars on the horizontal axis and load held on the vertical axis.
6. Describe the shape of your graph. Did halving the pillars halve the load, or did the roof fail sooner because of tilting?
7. Write a conclusion a mine planner could use: how many pillars would you leave if you wanted to hold at least a certain load with a safety margin of two times?

Tips

- Use a second person to steady the roof while you add books; failures are sudden.
- Keep the roof the same cardboard for every layout; a stiffer roof spreads the load and changes the result.

Check your work

- I can compute an extraction ratio from the pillar layout.
- I can identify the independent variable (number of pillars), the dependent variable (load held) and my controls.
- I can explain why a real mine leaves far more rock standing than the minimum that held up my model.

FIELD NOTEBOOK

1. Draw the two-part cross-section from the figure in your notebook and label: bench, haul road, waste dump, ore body, shaft, adit, drift, room, pillar.
2. Make a decision chart titled “Surface or Underground?” with three rows (depth, size and shape, grade) and write under each what points toward each method.
3. Record your sugar-cube experiment: a labeled drawing of each layout, your data table and your graph of pillars versus load.

> **From history.** Agricola’s De re metallica stayed the standard mining textbook in Europe for well over a century, and its woodcuts were copied into other books for generations. In 1912 the American mining engineer Herbert Hoover and his wife Lou Henry Hoover, a geology graduate, published the first complete English translation after five years of work, including testing some of Agricola’s recipes themselves to be sure of the meaning. Seventeen years later Hoover became the thirty-first President of the United States.

WORKED EXAMPLES

Example 1. An open-pit copper mine has a strip ratio of 3:1 and sends 100,000 tonnes of ore to its mill each day. How much waste rock does it move per day, and how much rock in total?

1. Strip ratio 3:1 means 3 tonnes of waste for every 1 tonne of ore.
2. Waste per day = 3 × 100,000 t = 300,000 t.
3. Total rock moved = ore + waste = 100,000 t + 300,000 t = 400,000 t per day.
4. Only one quarter of everything dug (100,000 ÷ 400,000) is ore.

Answer: 300,000 tonnes of waste rock per day and 400,000 tonnes of rock in total; three quarters of what is dug goes to the waste dumps.

Example 2. Copper ore at a mine has a grade of 0.6 percent copper. (a) How many kilograms of copper are in one tonne of ore? (b) How many tonnes of ore must be mined to produce one tonne of copper if the mill recovers 85 percent of the copper?

1. (a) 0.6 percent of 1,000 kg = 0.006 × 1,000 kg = 6 kg of copper per tonne of ore.
2. (b) With perfect recovery: 1,000 kg ÷ 6 kg per tonne = 166.7 tonnes of ore per tonne of copper.
3. With 85 percent recovery, each tonne of ore gives only 6 × 0.85 = 5.1 kg of copper.
4. 1,000 kg ÷ 5.1 kg per tonne = 196 tonnes of ore.

Answer: (a) 6 kg of copper per tonne of ore. (b) About 196 tonnes of ore for each tonne of copper when recovery is 85 percent. The other 195 tonnes become tailings.

Example 3. You want to build a tabletop model of the Bingham Canyon pit, which is about 4 km wide and 1.2 km deep. If the model is 40 cm wide, what scale are you using and how deep should the model be?

1. Convert to the same units: 4 km = 4,000 m = 400,000 cm.
2. Scale = model ÷ real = 40 cm ÷ 400,000 cm = 1 ÷ 10,000, written 1:10,000.
3. Real depth 1.2 km = 120,000 cm. Model depth = 120,000 cm ÷ 10,000 = 12 cm.
4. Check the ratio: real depth ÷ width = 1.2 ÷ 4 = 0.3, and model 12 ÷ 40 = 0.3. The proportions match.

Answer: Scale 1:10,000; the model should be 12 cm deep. The pit is wide and shallow in proportion, about three times as wide as it is deep.

PRACTICE

1. EASY Name the two basic ways of reaching ore and give one example of a mine type for each.
2. EASY What is the difference between a shaft and an adit?
3. EASY A mine has a strip ratio of 5:1 and mines 20,000 tonnes of ore a day. How many tonnes of waste does it remove each day?
4. MEDIUM Iron ore at a mine is 60 percent iron. How many kilograms of iron are in 1 tonne of ore? How does this compare with 1 tonne of 0.5 percent copper ore?
5. MEDIUM In a room-and-pillar mine the rooms are 8 m wide and the pillars are 8 m wide in both directions. What fraction of the seam is removed (the extraction ratio)?
6. MEDIUM Data reading. A planning table for a pit lists depth and strip ratio: 100 m, 1.5:1; 200 m, 2.5:1; 300 m, 4:1; 400 m, 6:1; 500 m, 9:1. Describe the trend. At which depth does the strip ratio first exceed 5:1? If the company switches to underground mining when the ratio passes 8:1, at roughly what depth does it switch?

7. MEDIUM Data reading. The bar graph in a report shows ore mined per day by method at one company: open pit 150,000 t, room-and-pillar 12,000 t, longwall 25,000 t, shaft-and-drift vein mine 2,000 t. Which method moves the most ore, and about how many times more than the vein mine? Why might the vein mine still be worth operating?
8. HARD Experiment design. Design a test of whether pillar SHAPE (square versus long rectangular pillars of equal area) changes the load a model roof can hold. State the independent variable, the dependent variable, three controls and how you would judge failure.
9. HARD A copper ore body is 2 km across and begins 50 m below the surface. A gold vein is 2 m wide and lies 800 m deep. Which would be mined by open pit and which underground? Explain using depth, shape and grade.
10. CHALLENGE Write a paragraph explaining why Daniel Jackling's 1906 method was called revolutionary even though digging a hole with a shovel is not new. Use the words grade, scale and strip ratio.

COMMON MISTAKES

- Thinking an open pit is just a big hole. The benches, haul roads and wall angles are engineered so that trucks can reach the bottom and the walls stay stable as the pit deepens.
- Assuming high grade always means a better mine. A huge low-grade body near the surface can be worth far more than a tiny rich vein that is deep and hard to reach.
- Believing miners take all the rock in an underground seam. Pillars or shields must hold up the roof, so a large share of the seam is left behind on purpose.

> **Make it a game · Mine Planner.** A parent describes an ore body in three clues: depth, size and shape, and grade (for example: 30 m deep, 1 km wide, 0.4 percent copper). Players have ten seconds to call "Pit!" or "Shaft!" and give one reason. A correct call with a correct reason scores 2; a correct call with no reason scores 1. Add bonus rounds where players must estimate the strip ratio or the kilograms of metal in one tonne. Play to 15.

> **Scripture.** "A land wherein thou shalt eat bread without scarceness, thou shalt not lack any thing in it; a land whose stones are iron, and out of whose hills thou mayest dig brass." (Deuteronomy 8:9, KJV)

Moses lists iron and copper in the hills among the blessings of the Promised Land, alongside bread. Mining is treated in Scripture as honest, useful work with the gifts God placed in the ground.

Practice answers

1. Surface mining (for example, an open pit, a strip mine or a quarry) and underground mining (for example, a shaft mine with drifts, or a room-and-pillar coal mine).
2. A shaft is a vertical opening down into the mine; an adit is a nearly level tunnel driven into a hillside.

3. 5 × 20,000 = 100,000 tonnes of waste per day.
4. 600 kg of iron per tonne. Copper ore at 0.5 percent holds only 5 kg of copper per tonne, 120 times less metal by mass.
5. Each 16 m by 16 m block (256 m²) has one 8 m by 8 m pillar (64 m²). Pillar fraction 64 ÷ 256 = 25 percent, so the extraction ratio is 75 percent.
6. The strip ratio rises faster and faster with depth (the increase per 100 m grows from 1 to 1.5 to 2 to 3). It first exceeds 5:1 at 400 m (6:1). It passes 8:1 between 400 m and 500 m, so the switch would come at roughly 470 to 500 m.
7. The open pit, 150,000 ÷ 2,000 = 75 times more than the vein mine. The vein mine may be worth it because its ore is much higher grade (for example gold at many grams per tonne), so each tonne is worth far more.
8. Independent variable: pillar shape (square 2 by 2 cubes versus rectangular 1 by 4 cubes, same area). Dependent variable: load in kg at failure. Controls: same number of pillars and total pillar area, same roof cardboard, same book sizes and loading order, same floor grid. Failure is judged by the first visible roof tilt or crushed cube, with three trials per shape averaged.
9. The copper body would be an open pit: it is large and shallow, so the strip ratio is low and the huge volume makes a low grade pay. The gold vein would be underground: it is narrow and deep, so removing 800 m of rock to reach a 2 m vein would mean an enormous strip ratio, while its high grade makes a shaft and drifts worthwhile.
10. A good answer explains that the ore at Bingham Canyon was too low in grade to pay by hand or tunnel mining, and that Jackling’s insight was scale: by moving an enormous tonnage with steam shovels, rail and a giant mill, the small value per tonne multiplied into a large total. Because the ore body was shallow and broad, the strip ratio was low enough that surface mining paid. The revolution was in the economics and engineering of scale, not in the shovel itself, and it made most of the world’s low-grade copper deposits minable.

3.3 Mine Safety: From Monongah (1907) to the Mine Act (1977)

OBJECTIVES

- Name the main hazards of underground mining (methane, coal dust, roof falls, bad air and dust disease) and explain the physical reason each one is dangerous.
- Tell how the Monongah explosion of 1907 and the Farmington disaster of 1968 led to the Bureau of Mines, the 1969 Coal Act and the Federal Mine Safety and Health Act of 1977, which created MSHA.
- Calculate a methane percentage, a fatality rate per 1,000 workers and a ventilation airflow, and read a graph of mining deaths over time.

Warm-up. Hold a sheet of paper flat and blow across its top edge; then roll it into a tube and blow through it. Which way moves the air farther? Now think about a tunnel two kilometers long with a dead end. Write one sentence about how you would get fresh air to the men at the end of it, and one sentence about how you would know whether the air there was safe.

Video. Coming soon. Coal mine safety, methane and coal dust explosions, Monongah 1907 and the Quecreek rescue of 2002: search MSHA (U.S. Department of Labor), NIOSH, Smithsonian, PBS American Experience, West Virginia Public Broadcasting and Practical Engineering.

KEY TERMS

methane (firedamp)
A colorless, odorless gas (CH_4) that seeps out of coal seams. It explodes when it makes up about 5 to 15 percent of the air and meets a spark or flame.

coal dust explosion
A blast caused when fine coal dust hanging in the air is ignited, often by a methane explosion. Mines spread powdered limestone (rock dust) so the dust on the floor and walls will not burn.

ventilation
Moving fresh air through a mine with large fans so that methane is diluted below 1 percent and oxygen stays high. Airflow equals air speed times the cross-section area of the tunnel.

roof support
Pillars, timber, steel roof bolts and hydraulic shields that hold up the rock above a mine opening. Roof falls have long been the leading cause of underground mining deaths.

black lung

Coal workers' pneumoconiosis, a disease caused by years of breathing fine coal dust. It is prevented by water sprays, ventilation and limits on dust in the air.

MSHA

The Mine Safety and Health Administration, created by the Federal Mine Safety and Health Act of 1977. Its inspectors must visit every underground mine four times a year and every surface mine twice.

CORE IDEAS

The story. At about 10:30 on the morning of December 6, 1907, the ground shook in the small town of Monongah, West Virginia. An explosion had torn through two connected coal mines of the Fairmont Coal Company, No. 6 and No. 8. The blast wrecked the ventilation fans and filled the tunnels with poisonous afterdamp. Rescuers could work only in short shifts because the air would not support a lamp flame, much less a man. The official death toll was 362, the worst mining disaster in American history, and many of the dead were immigrants from Italy, Poland and Hungary who had come to the coalfields for work. Monongah was not alone. In that single year, 1907, more than 3,200 coal miners died in the United States. The shock moved Congress to create the U.S. Bureau of Mines in 1910, the first federal agency devoted to studying how mine disasters happen and how to stop them.

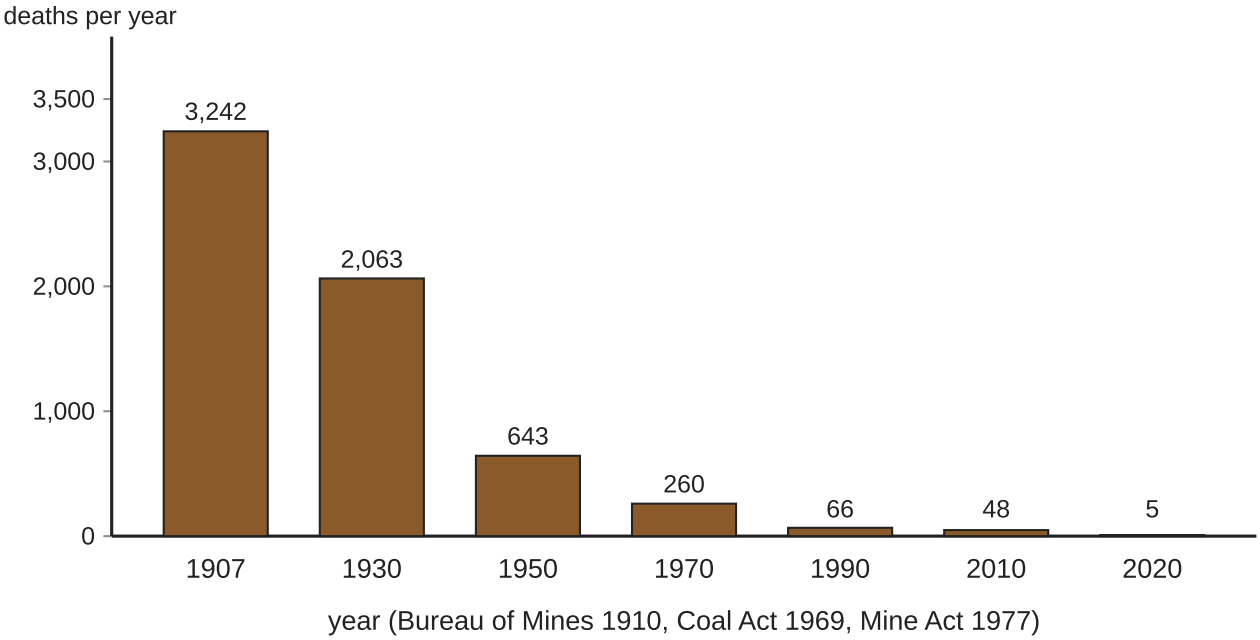
How they figured it out. Engineers already understood the physics of the danger; the task was to make mines obey it. Coal seams release **methane**, which miners called firedamp. In open air it drifts away harmlessly, but in a closed tunnel it builds up, and when it reaches roughly 5 to 15 percent of the air any spark will set it off. The first defense was the **safety lamp** of Humphry Davy in 1815, a flame wrapped in fine wire gauze that cooled the flame's gases so they could not ignite the methane outside, and whose flame grew a blue cap when methane was present, making the lamp a detector as well as a light. Caged canaries, which collapse from carbon monoxide long before a man does, were carried into mines for the same reason until electronic sensors replaced them. The second danger is **coal dust**. A small methane explosion raises fine dust from the floor and walls, and that dust can explode far more violently than the gas, racing through kilometers of tunnel. Bureau of Mines experiments showed that mixing the dust with powdered limestone, which cannot burn, stops the chain. Today U.S. mines must keep the dust on their surfaces at least 80 percent incombustible. The third defense is **ventilation**: giant fans pull fresh air through the mine so that methane is diluted long before it reaches a dangerous level. Under current rules, when a reading shows 1.0 percent methane the ventilation must be fixed, and at 1.5 percent everyone leaves and the electric power is cut.

The big idea. Knowing how to prevent disasters is not the same as making sure every mine does it. On November 20, 1968, an explosion at the Consol No. 9 mine near Farmington, West Virginia, killed 78 men, and the nation watched the smoke on television. Congress passed the Federal Coal Mine Health and Safety Act of 1969, which set the first strict limits on dust in mine air, required regular federal inspections and recognized **black lung** as a disease deserving compensation. Then came the **Federal Mine Safety and Health Act of 1977**, signed on November 9, 1977. It brought every mine in the country, coal and metal and

quarry alike, under one law and created the **Mine Safety and Health Administration (MSHA)** in the Department of Labor in 1978. MSHA inspectors must inspect every underground mine four times a year and every surface mine twice, and they can close a section of a mine on the spot. Every new miner must receive safety training before going underground, and a miner who refuses unsafe work is protected by law. Later disasters brought more rules: after Sago in 2006 Congress passed the MINER Act of 2006, which requires emergency air supplies, refuge chambers and tracking systems so rescuers can find trapped men, and after Upper Big Branch in 2010 the rock-dust standard was raised to the 80 percent rule described above.

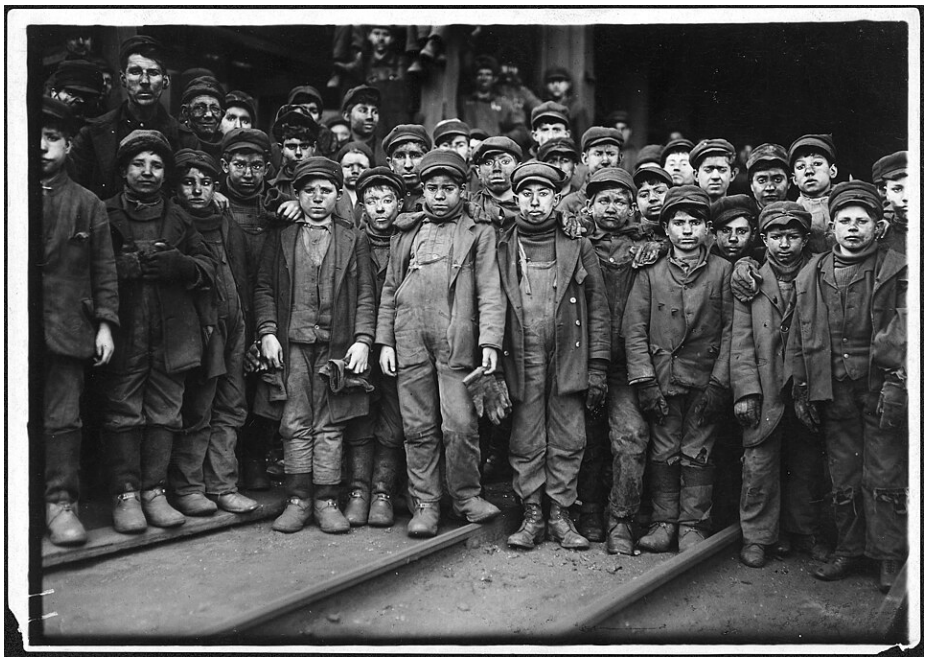
Try it and see. The results can be read on a graph. In 1907 about 3,242 coal miners died among roughly 680,000 coal workers, close to five deaths for every thousand men in a single year. By 1950 the yearly toll was in the hundreds, by 1990 it was 66, and in 2020 it was 5, even though machines now dig far more coal per miner than picks and shovels ever did. In recent years the total deaths in all American mining, coal, metal and stone together, have been a few dozen a year. Each one is still a grief to a family, and the goal is zero, but the drop is one of the great quiet successes of applied science. The tools are not glamorous: fans, limestone dust, roof bolts, gas meters and training. In this lesson you will build a model mine and see for yourself why air will not go down a dead-end tunnel unless you make it.

God’s handiwork. The law of Moses includes a safety rule for builders: “When thou buildest a new house, then thou shalt make a battlement for thy roof, that thou bring not blood upon thine house, if any man fall from thence” (Deuteronomy 22:8). A railing on a flat roof is a small thing, but God’s law counts a preventable death as the owner’s responsibility. The miner is made in God’s image (Genesis 1:27), and his life is worth more than the coal he digs. Mine safety law, for all its paperwork, rests on the same idea as the battlement: those who send others into danger must do what can be done to bring them home. The men and women who studied dust explosions in Bureau of Mines test tunnels, and the inspectors who still walk the dark headings today, do a kind of neighbor-love that most of us never see.



Coal mining deaths in the United States in selected years, from Mine Safety and Health Administration records (approximate). The bars for 1990 and later are so small they are hard to see at this scale.

PICTURE STUDY



Breaker Boys at the Ewen Breaker, Pennsylvania Coal Company, South Pittston, Pennsylvania, Lewis W. Hine, January 10, 1911 · Gelatin silver print photograph · U.S. National Archives, College Park, Maryland (National Child Labor Committee photographs; prints also at the Library of Congress)

Lewis Hine was a schoolteacher who became a photographer for the National Child Labor Committee in 1908. He traveled to mills, canneries and mines with a heavy camera and recorded, with names, ages and dates, the children he found working. At the Ewen Breaker

in South Pittston he photographed the boys who sat all day over chutes of moving coal, picking out slate and rock by hand in air thick with dust.

Hine’s photographs were used in reports and lantern-slide lectures and helped persuade states and later Congress to pass child labor and safety laws. He said he wanted to show things that had to be corrected and things that had to be appreciated. Both are in this picture.

Look closely

- Look at the faces and the hands. How can you tell what their work was from the photograph alone?
- Notice the light. Where is it coming from, and what does that tell you about the building they worked in?
- Count the boys you can see clearly. Hine often recorded their ages; most breaker boys were between about 8 and 14. What does the picture tell you about safety conditions before the laws you studied in this lesson?
- Hine made several pictures in this breaker. What does this one show about where the boys sat and what they handled all day?

Talk about it

1. What hazards from this lesson (dust, machinery, bad air) would these boys have faced every day?
2. Hine wrote down names, places and dates for his pictures. Why would a careful record matter more than a dramatic picture if you wanted to change a law?
3. How is a photographer who documents a danger honestly doing a kind of work that resembles a scientist’s?

> **Safety first.** The ventilation model uses a small electric fan or a hair dryer on its cool setting. Keep fingers and paper streamers away from fan blades, do not use candles, incense or smoke in the model, and keep the fan cord away from any water. An adult should do all cutting with the utility knife.

EXPERIMENT: VENTILATING A MODEL MINE: CAN FRESH AIR REACH THE DEAD END?

You will build a cardboard model of a mine with a main tunnel and side headings, blow air into it with a fan, and measure how many places the air actually reaches. Then you will add stoppings (walls) the way a mine ventilation engineer does and test whether forcing the air around a loop reaches more of the mine.

Question: does adding stoppings increase the number of headings that receive moving air? Prediction: write yours and your reason.

You will need

- A large flat box with a lid, such as a shirt box or a cut-down shipping box, about 40 cm by 60 cm
- Extra cardboard for partitions, a utility knife (adult use), tape
- Eight small strips of lightweight tissue paper, about 1 cm by 5 cm, as streamers
- A small desk fan or a hair dryer on the cool setting
- Clear plastic wrap for a window in the lid, a ruler, a stopwatch, notebook

Steps

1. Using the box as the rock, tape cardboard partitions inside to make a main tunnel down the middle with four short side headings branching off each side, each ending in a dead end (eight headings total). Cut an intake opening at one end of the main tunnel and a return opening at the other end.
2. Tape one tissue streamer hanging from the lid at the far end of each heading, so it will flutter if air moves there. Replace part of the lid with plastic wrap so you can see inside.
3. Trial A (no stoppings): run the fan at the intake for 30 seconds. Count how many of the eight streamers are moving. Record it. Repeat three times.
4. Trial B: tape short cardboard stoppings partway across the main tunnel just past each pair of headings, leaving a gap on alternate sides so the air must zigzag through the headings. Run the same test three times and record.
5. Measure the speed of the air at the return opening by timing how long a small scrap of tissue takes to travel a marked 30 cm. Speed = distance ÷ time. Measure the opening's height and width, and compute airflow = speed × area.
6. Make a table comparing trials A and B: streamers moving, average, and airflow at the return. Draw the layout of your mine for each trial with arrows showing where the air went.
7. Write a conclusion a ventilation engineer would recognize: what did the stoppings change, and why would a real mine need its air to reach every working face?

Tips

- If no streamer moves, your box is leaking air. Tape the seams.
- The dead ends are the point. Air takes the easiest path, so without stoppings it goes straight from intake to return and skips the headings.

Check your work

- I can explain why air does not naturally enter a dead-end heading.
- I can compute airflow from speed and area in cubic meters per second.
- I can name the independent variable (stoppings or none), the dependent variable (streamers moving) and my controls.

FIELD NOTEBOOK

1. Draw a cross-section of an underground coal mine and label the five hazards from the key terms, plus the defense against each (lamp or sensor, rock dust, fan, roof bolts, water sprays).
2. Copy the bar graph of coal mining deaths into your notebook and add a one-sentence caption that a museum would accept, naming the source and the trend.
3. Make a timeline from 1815 (Davy lamp) to 2006 (MINER Act) with at least six dated events from this lesson.

From history. In July 2002, water from an abandoned, flooded mine broke into the Quecreek Mine in Somerset County, Pennsylvania, trapping nine miners 73 m underground in rising water. Rescuers drilled a 15 cm hole to pump in warm compressed air, which kept the men alive and held back the water, then bored a 75 cm rescue shaft. After 77 hours all nine men were lifted out alive in a steel capsule, one at a time. The rescue used careful survey maps, air pressure and drilling: the same ordinary tools of mining turned to saving lives.

WORKED EXAMPLES

Example 1. A gas meter in a working heading reports that 100 liters of mine air contain 1.2 liters of methane. What is the methane percentage, and what does the law require?

1. Percent = part ÷ whole × 100 = 1.2 L ÷ 100 L × 100 = 1.2 percent.
2. Compare with the rules: at 1.0 percent, ventilation changes must be made; at 1.5 percent, miners are withdrawn and power is cut off.
3. 1.2 percent is above 1.0 but below 1.5, so work on the ventilation is required but the men need not leave yet.
4. Compare with the explosive range: 5 to 15 percent. The reading is far below it, which is exactly the point of acting early.

Answer: 1.2 percent methane. The crew must improve ventilation at once (above the 1.0 percent action level) but withdrawal is not yet required (below 1.5 percent). Acting at 1 percent keeps the air far from the 5 percent explosive limit.

Example 2. In 1907 about 3,242 coal miners died among roughly 680,000 coal workers. In 2020, 5 died among roughly 40,000. Compute the death rate per 1,000 workers for each year and compare them.

(Use the map or drawing "The raw counts fall steeply. Dividing by the number of workers shows the risk to" shown earlier in this lesson.)

1. 1907 rate = 3,242 ÷ 680,000 × 1,000 = 4.77 deaths per 1,000 workers, about 4.8.
2. 2020 rate = 5 ÷ 40,000 × 1,000 = 0.125 deaths per 1,000 workers.
3. Ratio = 4.77 ÷ 0.125 ≈ 38.
4. Using a rate rather than the raw count matters because the workforce shrank by about 17 times; the rate shows the mine itself became safer, not only smaller.

Answer: About 4.8 per 1,000 in 1907 and about 0.13 per 1,000 in 2020. A miner in 1907 was roughly 38 times as likely to die on the job in a year as a miner in 2020.

Example 3. A mine tunnel is 3.0 m high and 6.0 m wide. Fresh air moves through it at 2.0 meters per second. How much air passes through per second and per minute?

1. Cross-section area = height × width = 3.0 m × 6.0 m = 18 m^2.
2. Airflow = speed × area = 2.0 m/s × 18 m^2 = 36 m^3/s.
3. Per minute: 36 m^3/s × 60 s = 2,160 m^3/min.
4. That is enough air to fill a classroom of about 200 m^3 more than ten times every minute.

Answer: 36 cubic meters per second, or 2,160 cubic meters per minute.

PRACTICE

1. EASY What happened at Monongah, West Virginia, on December 6, 1907, and what federal agency was created three years later?
2. EASY What law created MSHA, and in what year was it signed? What department is MSHA part of?
3. EASY Between what two percentages of the air does methane explode? Why do mines act at 1 percent?
4. MEDIUM A sample of 250 liters of mine air contains 4 liters of methane. What percentage is that, and what must happen under MSHA rules?
5. MEDIUM Explain in two or three sentences how a Davy safety lamp works and why the flame's appearance was useful.
6. MEDIUM Data reading. Methane readings at a working face were taken each hour: 7:00, 0.4%; 8:00, 0.6%; 9:00, 0.8%; 10:00, 1.0%; 11:00, 1.3%. Describe the trend, state the hour at which MSHA's action level was reached, and predict the reading at noon if nothing is changed. What should the crew do?

7. MEDIUM Data reading. A table lists U.S. coal mining deaths and coal workers: 1950, 643 deaths, 480,000 workers; 1970, 260 deaths, 140,000 workers; 1990, 66 deaths, 130,000 workers. Compute the deaths per 1,000 workers for each year. Did the risk to each miner fall between 1970 and 1990, even though the workforce barely changed?
8. HARD Experiment design. You want to test whether the WIDTH of the gap left beside each stopping in your model mine affects how many headings receive air. Describe the independent variable, the dependent variable, three controls and your procedure.
9. HARD A tunnel is 2.5 m high and 5.0 m wide. The ventilation plan requires at least 20 m^3/s of air. If the measured air speed is 1.4 m/s, is the plan being met? If not, what speed is needed?
10. CHALLENGE Write a paragraph answering this question: if engineers already understood methane, coal dust and ventilation in the 1920s, why did a law like the 1977 Mine Act still matter? Use the words inspection, training and rate.

COMMON MISTAKES

- Thinking methane is poisonous. Pure methane is not toxic; it is dangerous because it explodes between about 5 and 15 percent in air and because it can displace oxygen. Carbon monoxide after a fire is the poison.
- Believing the dust explosion is a small matter compared with the gas. In most great mine disasters the methane only lit the fuse; the coal dust did most of the destruction.
- Judging safety by the number of deaths alone. The number of miners changed enormously over the century, so the fair comparison is the rate per thousand workers.

> **Make it a game · Safety Inspector.** One player is the mine foreman and describes a scene with one hidden hazard, such as “the methane meter reads 1.3 percent and the fan is on low,” or “the floor is black with dust and the rock dust bags are unopened.” The other players are MSHA inspectors who have fifteen seconds to name the hazard, say what the law requires and name the physical reason it is dangerous. Three correct parts earn 3 points. Switch roles every round. Play to 15.

> **Scripture.** “When thou buildest a new house, then thou shalt make a battlement for thy roof, that thou bring not blood upon thine house, if any man fall from thence.” (Deuteronomy 22:8, KJV)

God’s law requires a railing on a flat roof so that no one falls. The principle is that those who build and employ are responsible for preventable harm to others. Mine safety law applies that same principle a kilometer underground.

Practice answers

1. An explosion in two coal mines killed 362 men, the worst mining disaster in U.S. history. Congress created the U.S. Bureau of Mines in 1910.
2. The Federal Mine Safety and Health Act of 1977, signed November 9, 1977. MSHA is part of the U.S. Department of Labor.

3. About 5 to 15 percent. Mines act at 1 percent so that the methane level never comes near the explosive range.
4. 4 ÷ 250 × 100 = 1.6 percent. That is above 1.5 percent, so everyone must be withdrawn from the area and electric power disconnected until the level is reduced.
5. The flame is enclosed in fine wire gauze; the gauze conducts heat away so the burning gases cool below the ignition temperature of methane before they pass outside, so the flame cannot set off the firedamp. If methane is present, it burns inside the gauze as a blue cap on the flame, so the lamp also warns the miner.
6. Methane rises steadily by about 0.2 to 0.3 percent per hour. The 1.0 percent action level was reached at 10:00, when ventilation changes were required. If nothing changes the noon reading would be about 1.5 to 1.6 percent, the withdrawal level. The crew should have increased ventilation at 10:00 and must withdraw if 1.5 percent is reached.
7. 1950: 643 ÷ 480 = 1.34 per 1,000. 1970: 260 ÷ 140 = 1.86 per 1,000. 1990: 66 ÷ 130 = 0.51 per 1,000. Yes: between 1970 and 1990 the workforce stayed about the same but the rate fell to less than a third, which matches the years after the 1969 and 1977 laws.
8. Independent variable: gap width (for example 2 cm, 4 cm, 8 cm). Dependent variable: number of streamers moving out of eight (or air speed at the far heading). Controls: same fan setting and distance, same box and layout, same streamer size and position, same 30-second run. Procedure: run three trials at each gap width, average, and graph gap width against streamers moving.
9. Area = 12.5 m^2. Airflow = 1.4 × 12.5 = 17.5 m^3/s, which is below 20 m^3/s, so the plan is not met. Needed speed = 20 ÷ 12.5 = 1.6 m/s.
10. A good answer explains that knowledge alone does not protect a miner at a mine that skips rock dusting or ignores a gas reading. The 1977 Act made the known defenses mandatory everywhere, with four inspections a year underground so that violations were found and corrected, required training so every new miner knew the hazards, and gave miners the right to refuse unsafe work. The death rate per thousand workers fell sharply in the years after the 1969 and 1977 laws, showing that enforcement turned knowledge into results.

3.4 Reclamation: Putting the Land Back (SMCRA, 1977)

OBJECTIVES

- Describe the steps of reclaiming a surface mine in order: mapping, stripping and stockpiling topsoil, removing overburden, regrading to approximate original contour, replacing topsoil, seeding and monitoring.
- Explain how acid mine drainage forms from pyrite, water and oxygen, read pH data from a stream, and name two ways reclamation prevents or treats it.
- Tell what the Surface Mining Control and Reclamation Act of 1977 requires (bonds, the reference-area standard, the Abandoned Mine Land fund) and calculate topsoil volumes, regrading volumes and ground-cover percentages.

Warm-up. Scoop a cup of garden soil from the surface and a cup from about 20 cm down and set them side by side on newspaper. Compare color, smell and crumbliness. Now imagine a bulldozer mixed both cups together and spread the mixture over a bare hillside. Write one sentence predicting how well grass seed would grow in the mixture compared with the surface soil alone, and one sentence about which cup you would want on top if you were rebuilding the hill.

Video. Coming soon. Surface mine reclamation, topsoil replacement and acid mine drainage treatment explained: search the Office of Surface Mining Reclamation and Enforcement (OSMRE), USGS, state geological surveys, Pennsylvania DEP abandoned mine videos, Practical Engineering and university extension channels.

KEY TERMS

reclamation
Restoring mined land to a stable, useful condition: regrading the ground, replacing topsoil, controlling water and establishing plants so that the land can be pasture, forest, wetland, cropland or a park.

overburden (spoil)
The rock and subsoil that lie above an ore body or coal seam and must be removed to reach it. Once it is dug up and piled, it is called spoil.

topsoil stockpile
The A horizon stripped from the mine site before digging and stored in a separate seeded pile so it can be spread back on top at the end. Mixing it with spoil ruins it.

approximate original contour
The shape the law requires reclaimed land to have: highwalls and spoil piles eliminated and slopes regraded so the land closely resembles its shape before mining and drains the way it did.

acid mine drainage

Acidic, iron-rich water that forms when pyrite (iron sulfide, FeS_2) in coal or overburden is exposed to oxygen and water. It can drop a stream's pH below 4 and coat the bed with orange iron hydroxide.

reclamation bond

Money a mining company must deposit before it digs, enough to pay for reclamation if the company fails to do it. The bond is returned in stages only after the land is regraded, replanted and proven to hold its vegetation.

CORE IDEAS

The story. On August 3, 1977, in the Rose Garden of the White House, President Jimmy Carter signed the Surface Mining Control and Reclamation Act, called SMCRA for short. Congress had passed similar bills in 1974 and 1975, and President Ford had vetoed both. The problem could be seen from any car window in the coal country of Appalachia, Illinois or Pennsylvania: hillsides cut into bare rock walls, loose spoil slumping into creeks after every rain, and orange water seeping from old pits where nothing grew. Some companies reclaimed their land well, and several states required it, but the rules differed from state to state, and thousands of hectares of abandoned mines belonged to no one who could be made to fix them. The new law said that a company that opened the ground had to close it again, and it created the Office of Surface Mining Reclamation and Enforcement in the Department of the Interior to make sure it happened. It also placed a fee on every ton of coal mined, 35 cents for surface-mined coal and 15 cents for underground coal, to build an Abandoned Mine Land fund for repairing the old scars.

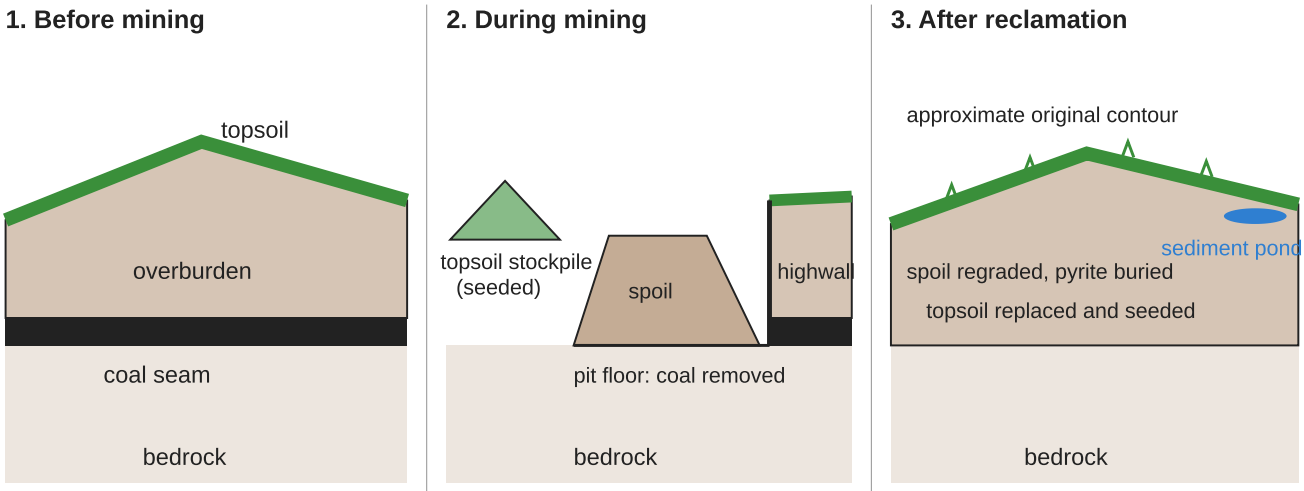
How they figured it out. Reclamation is the soil science of Unit 1 run in reverse, and it starts before the first shovel. Engineers map the site, measure the depth of the topsoil and drill the overburden to learn what it is made of. The **topsoil** is stripped first, on its own, and placed in a **stockpile** away from the pit, seeded with grass so it does not wash or blow away, because that dark A horizon holds the seeds, roots, fungi and nutrients the whole plan depends on. Next the **overburden** is removed to reach the coal. When a section is finished, bulldozers push the spoil back into the cut, bury any pyrite-bearing rock deep where water and air cannot reach it, and regrade the surface to **approximate original contour**, which means no vertical highwalls are left and the slopes blend into the hills around them. Only then is the topsoil spread back on top, usually to a planned depth such as 30 cm, and seeded with grasses, legumes and trees chosen for the region. Ditches and sediment ponds catch muddy runoff until the plants take hold.

The big idea. The hardest problem in reclamation is chemistry, not earthmoving. Coal and the shale around it often contain **pyrite**, the fool's gold of Lesson 3.1. Buried and dry, pyrite does nothing. Dug up and exposed to oxygen and rainwater, it slowly reacts to form sulfuric acid and dissolved iron, and the water running out of such a pile is **acid mine drainage**. Its pH can fall to 3 or lower, about as acidic as vinegar, and when it reaches a stream the iron comes out of solution as a rusty orange coating that miners call yellow boy. Fish, insects and plants cannot live in it. Remember that pH is a scale of tens: a stream at pH 4 has ten times the hydrogen-ion concentration of one at pH 5 and one hundred times that of one at pH 6.

Reclamation attacks the problem at both ends. Prevention means keeping pyritic rock covered and wet, under compacted clay, spoil and topsoil, so oxygen cannot reach it. Treatment means running the drainage over crushed limestone, which neutralizes the acid, or through built wetlands where bacteria and plants settle the iron out. Water that enters a limestone channel at pH 3 can leave it near pH 6.

Try it and see. How does anyone know the reclamation worked? SMCRA answers with a **bond** and a measurement. Before mining, the company deposits a bond large enough to pay someone else to reclaim the site. The bond is released in stages: part when the land is regraded and topsoiled, part when it is seeded, and the rest only after the plants have survived without help for five years in the wetter East (where rainfall is above about 660 mm a year) or ten years in the drier West. During that time inspectors measure ground cover in sample squares called quadrats on the reclaimed land and on a nearby unmined **reference area** with the same soil and slope. The reclaimed land must reach at least 90 percent of the reference area's cover: if the reference pasture is 80 percent covered, the reclaimed field must reach 72 percent. If it does not, the company plants again and the clock keeps running. Meanwhile the Abandoned Mine Land fund pays for sealing open shafts, putting out underground fires, regrading dangerous highwalls and treating acid water at old sites, worst dangers first. SMCRA applies to coal; mines for copper, gold and stone are reclaimed under state laws and federal land rules, and most follow the same steps.

God's handiwork. The first job God gave to man was to tend a piece of ground: "the LORD God took the man, and put him into the garden of Eden to dress it and to keep it" (Genesis 2:15). The law of Moses later commanded that even farmed land be given a rest, "a sabbath of rest unto the land" every seventh year (Leviticus 25:4). Mining is honest work with gifts God placed in the hills, as Deuteronomy 8:9 says, but the hills are still His, and the people downstream are our neighbors. A reclaimed mine is dominion done rightly: the coal or copper is taken and used, and the land is handed back able to grow grass and hold a creek clean. The careful order of the work, topsoil last off and first back on, pyrite buried from the air, plants counted square by square, is obedience to the way the Creator made soil, water and chemistry to behave.



Topsoil comes off first and goes back last; the highwall becomes a gentle slope; plants are counted before the bond is released.

Reclaiming a surface coal mine. Topsoil comes off first and goes on last. Spoil is regraded to approximate original contour, pyrite-bearing rock is buried away from air, and plants must be measured before the bond is released.

PICTURE STUDY



Bibémus Quarry, Paul Cézanne, about 1895 · Oil on canvas · Museum Folkwang, Essen, Germany

A few kilometers east of Aix-en-Provence in southern France lies Bibémus, a quarry of warm orange stone that had been worked since Roman times and was abandoned in the 1800s. Paul Cézanne rented a small stone hut there in 1895 and painted the quarry again and again over the next several years. He loved the way the cut blocks and the natural rock met at odd angles, and the way pines had rooted in the cracks and begun to take the place back.

No law required anyone to reclaim Bibémus. What you see is what happens when a mine is simply left: the walls stand sharp for a century while trees, slowly, do the work by themselves.

Look closely

- Find the straight edges cut by the quarrymen and the rounded edges weathered by rain. Which are there more of?
- Look at where the trees are growing. Why would roots find a foothold on a ledge or in a crack rather than on a flat cut face?
- Notice how Cézanne built the rock from patches of orange and ochre. What does the color tell you about iron in the stone?
- Compare the amount of bare rock with the amount of green. If this were a coal mine in Pennsylvania, what would the law require before the company could leave?

Talk about it

1. The quarry was abandoned long before Cézanne arrived, yet the walls are still bare. What does that suggest about how fast unreclaimed ground recovers on its own?
2. Which steps of modern reclamation (regrading, topsoil, seeding, water control) would have changed this view the most?
3. Cézanne found beauty in an abandoned mine. Can a reclaimed mine be both useful and beautiful? Give an example from your own area if you can.

EXPERIMENT: STRIP-MINE A TRAY AND PUT IT BACK: DOES TOPSOIL ORDER MATTER?

You will build a layered model of a hillside in two trays, mine the “coal” out of both, and reclaim them two different ways: one by the law’s method (topsoil set aside and replaced on top) and one by careless mixing. Then you will seed both and count what grows.

Question: does replacing the topsoil as the top layer give better plant cover than mixing it with the spoil? Prediction: write yours and give a reason from Unit 1.

You will need

- Two identical shallow trays or baking pans, about 30 cm by 20 cm and at least 6 cm deep
- Potting soil or dark garden topsoil (about 2 liters) for the A horizon
- Pale sand or sandy subsoil (about 3 liters) for the overburden
- A thin layer of dried black beans or crushed charcoal briquettes (about 1 cup) for the coal seam
- Fast-sprouting seed such as grass, radish or wheat; a spray bottle; a spoon or small trowel
- Ruler, notebook, pencil and a 5 cm by 5 cm cardboard square (the quadrat)

Steps

1. Build both trays the same: 1 cm of sand on the bottom (bedrock), then the “coal seam” of beans, then 3 cm of sand (overburden), then 1.5 cm of dark topsoil. Measure the layers with the ruler and record them.
2. Mine both trays. Tray A (law’s method): scoop the topsoil off first into a separate bowl, then scoop the sand overburden into a second bowl, then remove the beans. Tray B (careless): dig straight down with the spoon, piling everything you remove into one bowl, and remove the beans.
3. Reclaim Tray A: spread the sand back, level it to about the original shape, then spread the topsoil evenly on top. Reclaim Tray B: stir its single bowl so the topsoil and sand are mixed, then spread the mixture back and level it.
4. Seed both trays with the same number of seeds (count 60 seeds each) spread the same way, and mist them with the same number of sprays. Keep both trays side by side in the same light.
5. Each day for ten days mist both trays equally and count the sprouts. On day 10, drop the 5 cm quadrat on four spots in each tray and count the sprouts inside each square; average them.
6. Make a table: tray, treatment, total sprouts by day, average sprouts per quadrat on day 10. Draw a line graph of sprouts versus days for both trays.
7. Write a conclusion: which tray met a “reference area” standard of 90 percent of the better tray’s count? Explain, using what you know about the A horizon, why order mattered.

Tips

- If both trays sprout equally well, your topsoil and sand may be too similar. Use a paler, nutrient-poor sand for the overburden next time.
- For an extension, pour 100 mL of a vinegar-and-water mix (1 part vinegar to 4 parts water) through a cup of crushed limestone or marble chips and test the pH before and after with pH strips. That is the limestone channel in miniature.

Check your work

- I can name the independent variable (topsoil replaced on top versus mixed), the dependent variable (sprout count) and three things I kept the same.
- I can count ground cover in a quadrat and compare it with a reference standard.
- I can explain why reclamation strips the topsoil first and replaces it last.

FIELD NOTEBOOK

1. Draw the three-panel figure (before, during, after) in your notebook and label: topsoil, overburden, coal seam, topsoil stockpile, highwall, spoil, approximate original contour, sediment pond.
2. Make a flow chart titled “Acid Mine Drainage” with three boxes for the causes (pyrite, oxygen, water), two for the results (low pH, orange iron) and two for the cures (bury and cover, limestone or wetland). Color the water orange where it is acidic.

3. Record your tray experiment: a labeled drawing of each tray's layers before mining and after reclamation, your daily sprout table and your line graph.

From history. States tried to solve the problem first. West Virginia passed the first state law requiring surface-mine operators to reclaim their land in 1939, and Indiana, Illinois and Pennsylvania followed in the 1940s. But a company could mine carefully in a strict state and carelessly across the border, and old mines abandoned before the laws belonged to no one. Congress passed a national bill in 1974 and again in 1975; President Ford vetoed both, saying they would cost too much coal. The 1977 Act finally set one standard for the whole country and used the coal fee to begin fixing the old abandoned sites, worst dangers first.

WORKED EXAMPLES

Example 1. A surface mine will disturb 20 hectares of pasture where the topsoil averages 30 cm deep. How many cubic meters of topsoil must be stripped and stockpiled? If a dump truck carries 20 m^3, how many loads is that, and what is the mass of the topsoil at 1.3 tonnes per cubic meter?

1. Convert the area: 1 ha = 10,000 m^2, so 20 ha = 200,000 m^2.
2. Volume = area × depth = 200,000 m^2 × 0.30 m = 60,000 m^3.
3. Truck loads = 60,000 m^3 ÷ 20 m^3 per load = 3,000 loads.
4. Mass = 60,000 m^3 × 1.3 t/m^3 = 78,000 tonnes.

Answer: About 60,000 m^3 of topsoil, or 3,000 truckloads, with a mass of about 78,000 tonnes. All of it must go back on top at the end.

Example 2. A finished cut leaves a vertical highwall 24 m high and 500 m long. To reach approximate original contour the company must push spoil against it to make a slope of 3:1 (3 m horizontal for every 1 m of rise). How far out from the wall will the slope reach, what is its angle, and how much spoil is needed?

(Use the map or drawing "The highwall in the middle panel is pushed down into the gentle regraded slope o" shown earlier in this lesson.)

1. Horizontal run = 3 × height = 3 × 24 m = 72 m.
2. Angle: tan θ = 1 ÷ 3 = 0.333, so θ ≈ 18°, a gentle slope that grass can hold.
3. The fill is a triangle in cross-section: area = ½ × 24 m × 72 m = 864 m^2 for every meter of wall length.
4. Volume = 864 m^2 × 500 m = 432,000 m^3 of spoil.

Answer: The slope reaches 72 m out from the old wall at about 18 degrees, and the company must place about 432,000 m^3 of spoil to build it.

Example 3. An inspector measures ground cover in five quadrats on an unmined reference pasture: 82%, 78%, 85%, 80% and 75%. On the reclaimed field five quadrats give 69%, 73%, 66%, 74% and 68%. SMCRA requires the reclaimed land to reach 90 percent of the reference cover. Does the field pass?

1. Reference mean = (82 + 78 + 85 + 80 + 75) ÷ 5 = 400 ÷ 5 = 80%.
2. Required cover = 90% of 80% = 0.90 × 80 = 72%.
3. Reclaimed mean = (69 + 73 + 66 + 74 + 68) ÷ 5 = 350 ÷ 5 = 70%.
4. Compare: 70% is less than the 72% standard.

Answer: No. The reclaimed field averages 70 percent cover and needs 72 percent, so the bond is not released and the company must improve the stand and be measured again.

PRACTICE

1. EASY What law was signed on August 3, 1977, who signed it, and what office did it create?
2. EASY List the reclamation steps in the correct order, from stripping topsoil to bond release.
3. EASY A stream below an old mine has pH 3, and an unaffected stream nearby has pH 6. How many times greater is the hydrogen-ion concentration in the mine stream?
4. MEDIUM A mine will disturb 8 hectares with 25 cm of topsoil. How many cubic meters of topsoil must be stockpiled?
5. MEDIUM Explain in two or three sentences why the topsoil is stripped first, stored in its own pile and seeded, rather than being pushed aside with the overburden.
6. MEDIUM Data reading. A stream survey records pH at four stations: A, upstream of all mining, pH 6.8; B, just below an abandoned 1950s strip pit, pH 3.4; C, 2 km downstream of B after a limestone channel, pH 5.9; D, below a mine reclaimed in 2015, pH 6.5. (a) Which station shows acid mine drainage? (b) About how many times more acidic is B than A, to the nearest power of ten? (c) What do stations C and D together suggest about treatment and prevention?
7. MEDIUM Data reading. Ground cover measured on a reclaimed field each year after seeding: year 1, 35%; year 2, 55%; year 3, 66%; year 4, 71%; year 5, 74%. The reference area holds 80%. (a) Describe the trend. (b) In which year does the field first meet the 90-percent-of-reference standard? (c) Why does the law in the East wait five years rather than releasing the bond in year 2?
8. HARD Experiment design. You want to test whether the AMOUNT of crushed limestone affects how much the pH of model mine drainage (1 part vinegar to 4 parts water) rises. State the independent variable, the dependent variable, three controls and your procedure, including how many trials.
9. HARD A highwall is 15 m high and 200 m long. The reclamation plan calls for a 2.5:1 slope. Find the horizontal distance the slope will reach, the fill area per meter of wall and the total spoil volume.

10. CHALLENGE Write a paragraph explaining why SMCRA makes a company post money before it digs and then waits years to return it, instead of simply writing a rule that says “reclaim the land.” Use the words bond, reference area and revegetation.

COMMON MISTAKES

- Thinking reclamation means scattering grass seed on a spoil pile. Without topsoil on top, regrading and water control, most of the seed dies, the pile erodes and pyrite in the spoil keeps making acid.
- Believing the orange color in a mine stream is rust from old machinery. It is iron that came out of pyrite in the rock when air and water reached it; the cure is chemistry (burial, limestone, wetlands), not hauling away scrap.
- Assuming SMCRA covers every mine. It governs coal mining; copper, gold, stone and gravel operations are reclaimed under state laws and federal land rules, which often follow the same steps but are not the same law.

> **Make it a game · Bond Release.** A parent is the inspector and describes a reclaimed site in four or five details, leaving out or breaking one rule, such as “the spoil was regraded, the field was seeded last spring, the highwall still stands 10 m tall, and the pond is clear.” Players have fifteen seconds to name the missing or broken step and say what must be done before the bond is released. A correct catch scores 2; naming the measurement the inspector would make (quadrats, pH, slope) earns 1 more. Switch inspectors every round. Play to 15.

> **Scripture.** “And the LORD God took the man, and put him into the garden of Eden to dress it and to keep it.” (Genesis 2:15, KJV)

The first task given to man was to work a piece of ground and to keep it. Taking coal or metal from the hills is part of dressing the earth; putting the land back so it can grow grass and hold clean water is part of keeping it.

Practice answers

1. The Surface Mining Control and Reclamation Act (SMCRA), signed by President Jimmy Carter. It created the Office of Surface Mining Reclamation and Enforcement in the Department of the Interior.
2. Map and sample the site; strip and stockpile the topsoil separately; remove overburden and mine the coal; regrade the spoil to approximate original contour, burying pyritic rock; replace the topsoil; seed and plant; control water with ditches and ponds; monitor ground cover for five or ten years; release the bond in stages.
3. Three pH units lower means 10^3 = 1,000 times more hydrogen ions.
4. 8 ha = 80,000 m². Volume = 80,000 × 0.25 = 20,000 m³.
5. The topsoil (A horizon) holds the organic matter, nutrients, seeds and soil life that plants need; mixing it with pale subsoil and rock dilutes all of that. Storing it separately keeps it ready to go back on top. Seeding the pile keeps the soil from eroding and keeps it alive while it waits.

6. (a) Station B. (b) 6.8 − 3.4 = 3.4 pH units, so between 10^3 and 10^4, roughly a few thousand times more hydrogen ions (about 2,500). (c) The limestone channel raised the pH from 3.4 to 5.9, so treatment works but did not fully restore the stream; the reclaimed mine at D is close to the upstream value, so prevention by proper reclamation works better than treating the water afterward.
7. (a) Cover rises every year but by smaller amounts each time (20, 11, 5, 3 points). (b) The standard is 72%; the field first meets it in year 5 (74%). (c) Early growth can come from fertilizer and a mild year; the waiting period shows whether the plants can survive drought, winter and poor years on their own without the company's help.
8. Independent variable: mass of limestone chips (for example 0 g, 25 g, 50 g, 100 g). Dependent variable: pH of the water after passing through, measured with pH strips or a meter. Controls: same volume and strength of vinegar mix, same contact time (for example 5 minutes), same chip size, same temperature, same container. Procedure: pour 100 mL of the mix through each amount of limestone, wait the set time, measure pH, run three trials per amount and graph limestone mass against pH.
9. Run = 2.5 × 15 = 37.5 m. Area = ½ × 15 × 37.5 = 281.25 m^2 per meter. Volume = 281.25 × 200 = 56,250 m^3.
10. A good answer explains that a rule with no money behind it can be ignored by a company that goes bankrupt or walks away, which is exactly what left thousands of abandoned mines before 1977. The bond guarantees that funds exist to do the work even if the company fails. Releasing it in stages ties the money to measurable results: regrading, topsoil, and finally revegetation measured against a reference area, so that success is judged by counted plants rather than by promises. Waiting five or ten years proves the plants can survive on their own.

Unit 3 review

Answer each question. Show your work for calculations and use complete sentences for explanations. Use metric units. The test is worth 60 points.

1. (5 pts) Multiple choice. Which property most reliably tells real gold from pyrite? (a) Both are yellow, so color. (b) Density: gold is about 19.3 g/cm³ and pyrite about 5.0 g/cm³. (c) Both are found in streams, so location. (d) Pyrite is softer than gold.
2. (5 pts) A specimen has a mass of 38.6 g. Dropped into a measuring cup, it raises the water from 40.0 mL to 42.0 mL. Calculate its density and state whether it could be gold.
3. (5 pts) Explain in two or three sentences how gold gets from a lode deposit to a placer deposit, and why it settles on the inside of a river bend while quartz sand keeps going.
4. (5 pts) Diagram item. Draw a cross-section showing an open-pit mine on the left and an underground mine on the right. Label at least six of these: bench, haul road, ore body, waste dump, shaft, adit, drift, room, pillar.
5. (5 pts) An open pit has a strip ratio of 4:1 and sends 50,000 tonnes of ore to the mill each day. How much waste rock is moved per day, and what total mass of rock is dug? If the ore grades 0.5 percent copper, how many kilograms of copper does one day’s ore contain?
6. (5 pts) Multiple choice. A narrow silver vein 1 m wide lies 600 m below the surface. Which method would an engineer choose, and why? (a) Open pit, because all mines start at the surface. (b) Open pit, because silver is valuable. (c) Underground by shaft and drift, because removing 600 m of rock to reach a 1 m vein would give an enormous strip ratio. (d) Room-and-pillar, because it works for every deposit.
7. (5 pts) A gas meter shows that 200 liters of mine air contain 3.2 liters of methane. Calculate the percentage and state what MSHA rules require at that level. Between what percentages does methane explode?
8. (5 pts) Name the law that created MSHA and the year it was signed, and describe three things the law or the agency requires of mines.
9. (5 pts) Data reading. In 1907 about 3,242 coal miners died among roughly 680,000 workers. In 1990, 66 died among roughly 130,000. Calculate deaths per 1,000 workers for each year and explain why the rate is a fairer comparison than the raw count.
10. (5 pts) Multiple choice. Orange, acidic water flows from an old spoil pile. The cause is: (a) rust from abandoned machinery; (b) pyrite in the spoil reacting with oxygen and water to make sulfuric acid and dissolved iron; (c) fertilizer from the reclamation seeding; (d) limestone dissolving in rain.
11. (5 pts) A mine will disturb 12 hectares with 20 cm of topsoil. (a) How many cubic meters of topsoil must be stockpiled? (b) After reclamation, a reference pasture has 75 percent ground cover. What cover must the reclaimed field reach to meet SMCRA’s 90-percent-of-reference standard, and does a field averaging 65 percent pass?
12. (5 pts) Short essay. In five or six sentences, describe the steps of reclaiming a surface coal mine in order and explain how the Surface Mining Control and Reclamation Act of

1977 makes sure the work is done. Use the words topsoil, approximate original contour, bond and reference area.

UNIT PROJECT: MY MINE PLAN: FROM DISCOVERY TO RECLAMATION

Design a complete plan for a mine on paper, as a mining engineer would present it. Invent or choose a realistic ore body (for example a copper body 1 km wide beginning 40 m down at 0.6 percent, a gold vein 2 m wide at 500 m, or a coal seam 2 m thick under 20 m of overburden) and give its depth, size, shape and grade. Include: a labeled cross-section drawing of the deposit and your chosen mining method with a one-paragraph justification using strip ratio or extraction ratio; a grade calculation showing how much metal or coal one day's production contains; a safety page naming the three main hazards for your mine, the defense against each and a ventilation airflow calculation if the mine is underground; and a reclamation page with the topsoil volume to be stockpiled, the regraded slope and its fill volume, and the ground-cover standard you must meet.

Attach the data table and graph from at least one of the unit's four experiments (panning, sugar-cube pillars, the cardboard mine ventilation or the reclamation trays) and finish with a short paragraph on how your plan takes the ore while keeping the miners safe and the land fit to hand back, connecting it to Deuteronomy 8:9 or Genesis 2:15.

- **Geology and method**: The ore body is described with depth, size, shape and grade in metric units; the cross-section is labeled correctly and the method choice is justified with a correct strip ratio or extraction ratio.
- **Calculation**: Grade, airflow, topsoil volume, regrading volume and ground-cover standard are computed correctly with units and work shown.
- **Safety and reclamation**: Hazards and defenses match the mine type and the law; the reclamation steps are in the right order and address acid mine drainage, bonding and the reference-area standard.
- **Experiment and care**: The attached experiment states its question, variables and controls with a complete data table and graph; the whole plan is neat, labeled and easy to follow.

Answer key

1. (b). Gold is nearly four times as dense as pyrite. Pyrite is actually much harder than gold (6 to 6.5 versus 2.5 to 3), so (d) is backward.
2. Volume = 2.0 cm^3. Density = 38.6 ÷ 2.0 = 19.3 g/cm^3. Yes, that matches gold.
3. Gold in quartz veins is freed as the rock weathers and is carried downhill by streams with sand and gravel. Water slows on the inside of a bend, and the slower water can still move quartz grains but not gold grains of the same size, because gold is more than seven times as dense, so the gold drops out there and collects as a placer.
4. A stepped bowl with benches and a spiral haul road dug into a broad shallow ore body, with a waste dump beside it; on the right a vertical shaft from the surface, a level adit into the hillside, a horizontal drift following the seam, and a seam mined in rooms with pillars left standing. Full credit for a clear drawing with six correct labels.

5. Waste = 4 × 50,000 = 200,000 t. Total = 250,000 t. Copper = 0.005 × 50,000,000 kg = 250,000 kg (250 t).
6. (c).
7. 3.2 ÷ 200 × 100 = 1.6 percent. That is above 1.5 percent, so miners must be withdrawn and electric power cut off until the level is reduced. Methane explodes at about 5 to 15 percent in air.
8. The Federal Mine Safety and Health Act of 1977. Any three: four inspections a year of every underground mine and two of every surface mine; safety training for every new miner before going underground; the right of miners to refuse unsafe work; the power of inspectors to close a dangerous section of a mine; coverage of all mines, coal and metal and quarry, under one law.
9. 1907: 3,242 ÷ 680 ≈ 4.8 per 1,000. 1990: 66 ÷ 130 ≈ 0.5 per 1,000. The workforce shrank by about five times, so fewer deaths could simply mean fewer miners; the rate shows the risk to each miner, which fell by about nine times.
10. (b).
11. (a) 120,000 m^2 × 0.20 m = 24,000 m^3. (b) 0.90 × 75 = 67.5 percent required; 65 percent does not pass.
12. A good answer: the topsoil is stripped first and stockpiled separately and seeded; overburden is removed and the coal mined; spoil is pushed back and regraded to approximate original contour with pyritic rock buried away from air; topsoil is spread back on top and the land is seeded; ditches and ponds control runoff. SMCRA requires the company to post a bond before mining that is released only in stages, the last stage after five or ten years when ground cover reaches 90 percent of a nearby unmined reference area; it created the Office of Surface Mining to inspect, and a fee on coal funds reclamation of abandoned mines.

UNIT 4

Oil, Gas and Coal

For most of history the oil that seeped from the ground was a curiosity and a medicine. Then, in the space of two generations, it lit the world's lamps, fueled its cars and ships, paved its roads and fed its fields. This unit follows that story from a muddy creek bank in Pennsylvania in 1859 to a Texas hill in 1901, and then underground, to the folded, porous, sealed rocks where oil and natural gas collect, and finally into the refinery, where a single barrel is sorted into gasoline, diesel, jet fuel, asphalt and the raw material for plastics and medicines. Coal, the black rock that still makes our steel and much of our electricity, has its place beside them.

You will meet Edwin Drake and Uncle Billy Smith, who drove an iron pipe through caving gravel and struck oil at 21 meters; Pattillo Higgins and Anthony Lucas, who reasoned from gas seeps and salt to the greatest gusher the world had seen; the geologists who worked out why oil gathers under arched rock; and William Burton, who taught a refinery to break big molecules into small ones. Along the way you will measure porosity, compute flow rates and pressures, read production tables, build a trap in a jar and model a distillation tower with three drops on a plate.

The oil, gas and coal under our feet are part of the **fulness** of an earth that "is the LORD'S" (Psalm 24:1). Finding them takes patient observation; using them well takes skill and restraint. Where museum signs and textbooks give long ages for how these fuels formed, you will learn to separate what is measured from what is interpreted, to state the mainstream view fairly, and to set the young-earth creation reading beside it with respect.

BEFORE YOU BEGIN

- Can convert units with a conversion factor (feet to meters, gallons to liters) and work with percents and ratios
- Knows the three rock families and that sandstone and shale are sedimentary rocks made of grains
- Can compute density as mass divided by volume and explain why less dense fluids float
- Can identify independent and dependent variables and controls in a simple experiment (Units 1 to 3)

MASTERY CHECKLIST

- I can tell the stories of Drake's well (1859) and Spindletop (1901), name the key people, and explain the drive pipe, rotary drilling and drilling mud.
- I can convert between barrels, liters and kilograms, and between barrels per day and liters per second.
- I can name the four parts of a petroleum system, sketch an anticline, fault and salt-dome trap, and explain why gas, oil and water stack in that order.

- I can measure porosity, explain how it differs from permeability, and estimate the oil in a reservoir from its dimensions.
- I can list the main products of a barrel of oil with approximate volumes, describe fractional distillation and cracking, and name the uses of natural gas and the ranks of coal.
- I can separate what is observed about how oil and coal formed from what is interpreted, and state the mainstream and young-earth readings fairly.

OPTIONAL BOOKS AND RESOURCES

- **Energy Kids, from the U.S. Energy Information Administration** (https://www.eia.gov/kids/): Free. Clear pages on oil, natural gas and coal: where they come from, how they are refined and used, with current data tables. Use it to check the barrel-yield and energy-share figures in Lesson 4.4.
- **Drake Well Museum and Park, Titusville, Pennsylvania** (https://www.drakewell.org/): Free to browse online. The museum stands on the site of the 1859 well and has a working replica engine house. Its history pages and photographs support Lesson 4.1, and a visit is a fine Field Lab trip for families in the Northeast.
- **USGS Energy Resources Program** (https://www.usgs.gov/programs/energy-resources-program): Free. Maps and plain-language pages on where oil, gas and coal are found in the United States. Useful for finding whether your own county has producing fields for the Unit 8 capstone.

4.1 Drake's Well (1859): The First Oil Well Drilled on Purpose ★

OBJECTIVES

- Tell the story of Edwin Drake's well at Titusville, Pennsylvania, on August 27, 1859, and explain why the drive pipe was the idea that made it work.
- Define petroleum, kerosene and the 42-gallon (159-liter) barrel, and convert between barrels, liters and kilograms.
- Calculate drilling rates in meters per day from a depth log and read a table of early oil production.

Warm-up. Fill a cup with dry sand or sugar and try to bore a narrow hole to the bottom with a pencil. Pull the pencil out and watch what happens to the sides of the hole. Now push a drinking straw into the sand first and scoop out the inside with a toothpick. Which hole stays open? Write one sentence about why. You have just discovered Edwin Drake's problem and his solution.

Video. Coming soon. Drake Well 1859 Titusville Pennsylvania first oil well history and how cable-tool drilling worked; look for the Drake Well Museum (Pennsylvania Historical and Museum Commission), Smithsonian, PBS and state public-television history segments, the U.S. Energy Information Administration Energy Kids pages, and Homeschool Pop (Alternate).

KEY TERMS

petroleum
Natural crude oil, a dark liquid mixture of hydrocarbons found in the pore spaces of rock. From Latin petra (rock) and oleum (oil).

seep
A place where oil or gas leaks naturally out of the ground, often into a creek or spring.

kerosene
A clear lamp oil made by distilling crude oil (or, before 1859, coal). It burned brighter and cheaper than whale oil or candles.

cable-tool drilling
Drilling by lifting a heavy iron bit on a cable and dropping it again and again to pound a hole into rock, then scooping out the chips.

drive pipe (casing)
An iron pipe driven down through loose soil and gravel to bedrock so the hole will not cave in. Every modern well is still lined with steel casing.

barrel

The standard unit of oil: 42 U.S. gallons, about 159 liters. Pennsylvania producers agreed on it in 1866.

CORE IDEAS

The story. Oil Creek winds through the hills of northwestern Pennsylvania, and for as long as anyone remembered, a dark, smelly oil had floated on its springs. Seneca Indians had skimmed it for medicine and paint. Settlers soaked blankets in it and sold the squeezings in bottles as “Seneca Oil,” a cure for everything. In the early 1850s a New York lawyer named George Bissell wondered whether this “rock oil” might be worth more as a lamp fuel than as a medicine. He paid Professor Benjamin Silliman Jr. of Yale to study it, and Silliman reported that it could be distilled into a fine, bright-burning lamp oil. The question was how to get enough of it. Skimming creeks gave a few gallons a day. Bissell had a bolder thought: salt makers in Pennsylvania drilled wells hundreds of feet deep to reach brine, and their wells often filled with annoying oil. Why not drill for the oil itself?

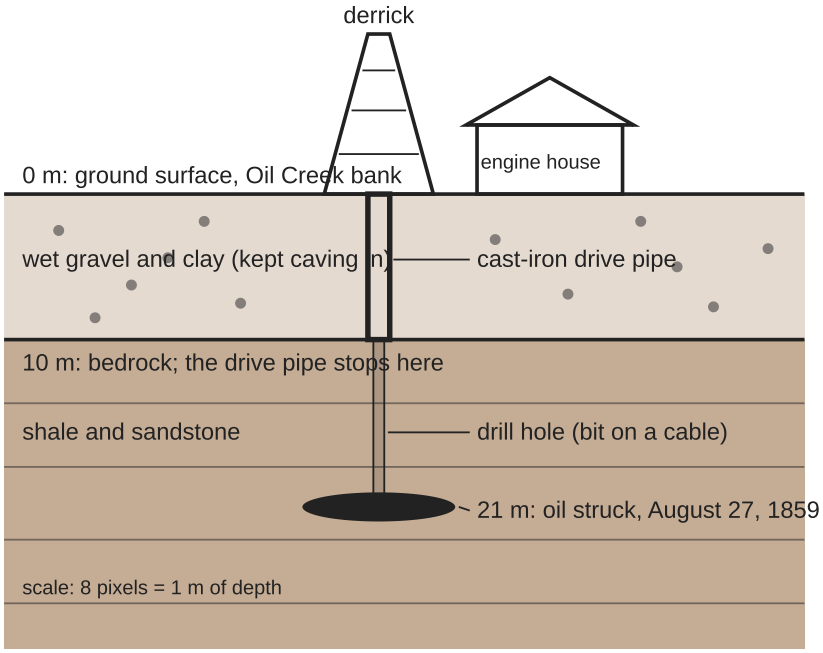
How they figured it out. The company hired Edwin L. Drake, a retired railroad conductor with no training in geology, partly because he still had a free railroad pass. The company called him “Colonel” in its letters to impress the townspeople of Titusville. Drake moved to Titusville in the spring of 1858, hired a blacksmith and salt-well driller named William “Uncle Billy” Smith, bought a small steam engine and built a wooden derrick. The first attempts failed for a plain reason: the ground near the creek was loose gravel soaked with water, and every hole they dug caved in before it reached bedrock. Drake’s answer was simple and new. He drove lengths of cast-iron pipe down through the gravel, about 10 meters, until the pipe stood on solid rock, and then drilled *inside* the pipe. From there Uncle Billy’s bit pounded down at about 1 meter a day. The money ran out. Townspeople called the project “Drake’s Folly,” and a letter ordering him to quit was already in the mail. On Saturday, August 27, 1859, at a depth of 69.5 feet (about 21 meters), the bit dropped into a crevice. On Sunday afternoon Uncle Billy peered down the pipe and saw oil standing a few feet below the top. A hand pump brought up about 20 barrels a day, so much that they ran out of whiskey barrels and washtubs to hold it.

The big idea. Petroleum does not sit in underground lakes. It fills the tiny pore spaces between the grains of sandstone and limestone, the way water fills a sponge, and it is usually held down by a layer of tight rock above it. A well is simply a controlled path from the surface into that oil-soaked rock. Drake did not invent drilling; salt drillers had done it for decades, and Chinese brine drillers had done it for centuries. What he did was drill *for oil on purpose* and solve the caving problem with casing. Within a few years the oil business needed a standard measure, and in 1866 the Pennsylvania producers settled on the 42-gallon barrel, about 159 liters, which is still the unit the whole world uses to count oil. Crude oil is lighter than water, with a density around 0.85 grams per cubic centimeter, so it floats on water in the ground and in a bucket.

In the world today. The kerosene that came from Drake’s oil changed ordinary life. Whale oil was growing scarce and costly, and candles were dim. A kerosene lamp lit a farm kitchen for a few cents a night, and people could read after dark. Lamps, not cars, were the first

reason the world wanted oil; gasoline was at first a dangerous leftover. Titusville became the first oil boomtown, and towns like Pithole sprang up and vanished within two years. Drake never patented his drive pipe and never got rich. He lost his money and grew ill; the state of Pennsylvania later voted him a pension. Today the Drake Well Museum stands on the site with a working replica of his engine house, and the people who find and drill for oil still carry the old names: driller, roustabout, tool pusher, and well-site geologist, who reads the rock chips as they come up.

God’s handiwork. The oil under Oil Creek had been there long before anyone knew what to do with it. A resource is a gift of creation plus the knowledge to use it well. Moses sang that God made Israel “to suck honey out of the rock, and oil out of the flinty rock” (Deuteronomy 32:13). He meant olive oil from trees rooted in stony hillsides, but the verse fits the oil country well. The deeper truth holds: the earth is stocked with good things, and finding them takes patience, skill and a willingness to be laughed at for a while.



Drake’s well in cross-section. The drive pipe held back the caving gravel; the cable-tool bit pounded the rest of the way to oil at about 21 meters.

PICTURE STUDY



Drake Well, Titusville, Pennsylvania (Edwin Drake, in the top hat, with Peter Wilson), John A. Mather, 1861 · Photograph · Drake Well Museum, Titusville, Pennsylvania (Mather collection)

John A. Mather was an English-born photographer who settled in Titusville in 1860 and spent the rest of his life photographing the Pennsylvania oil region: derricks, boomtowns, flatboats loaded with barrels, and the men who worked them. This picture, taken in 1861, is the best-known photograph of the first oil well. Edwin Drake stands at the right in his top hat; the man beside him is usually identified as Peter Wilson, a Titusville druggist who had helped Drake when money ran short.

Look closely and you will see that there is nothing grand about the place. The engine house is rough boards, the derrick is a simple tower, and the creek bank is muddy. From this small shed came the oil industry.

Look closely

- Find the derrick rising above the engine house. Why did the drillers need a tall tower to lift and drop a bit?
- Look at the ground around the building. Does it look like solid rock or loose, wet soil? What problem would that cause?
- Find the barrels, if any are visible, and notice the two men’s clothing. Do they look like laborers or like gentlemen posing for a picture?
- Notice how close the well is to the water. Why did early drillers work right beside the creek?

Talk about it

1. Why do you think Mather thought this plain shed worth photographing in 1861?

2. What does Drake’s top hat tell you about how he wanted to be seen, and how does that fit the company’s title “Colonel”?
3. If you could ask Uncle Billy Smith one question about the morning he saw oil in the pipe, what would it be?

EXPERIMENT: DRAKE’S PROBLEM: DOES A DRIVE PIPE KEEP A HOLE OPEN?

Drake lost months to caving gravel before he thought of driving a pipe to bedrock. In this experiment you will model wet gravel over rock, drill with and without casing, and measure how deep a hole stays open.

Question: Does lining a hole with a pipe let you drill deeper through loose, wet material? Prediction: write yours before you begin.

You will need

- A clear plastic cup or jar, at least 12 cm tall
- A flat stone, tile or thick coin to serve as bedrock at the bottom
- Aquarium gravel or coarse sand, enough to fill the cup to within 2 cm of the top
- Water
- A pencil or chopstick as the drill bit
- A wide straw or a rolled strip of stiff plastic (a cut-up water bottle) as the drive pipe
- A ruler, a spoon, a tray to catch spills, and your lab notebook

Steps

1. Place the stone flat in the bottom of the cup. Pour in gravel or sand until it is 8 to 10 cm deep over the stone. Measure and record the depth of the loose layer.
2. Add water slowly until the gravel is soaked but not flooded, like a creek bank. Keep the amount of water the same for every trial.
3. Trial A, no casing: push the pencil straight down and wiggle it to open a hole. Pull it out and immediately measure how deep the open hole stays before the sides slump. Record the depth. Repeat three times in fresh spots and find the average.
4. Trial B, with casing: push the straw straight down until it touches the stone (bedrock). Use the pencil to scoop or push the gravel up out of the inside of the straw. Measure how deep the open hole reaches. Repeat three times and average.
5. Record both averages in a table with columns: Trial, Depth 1, Depth 2, Depth 3, Average, Reached bedrock?
6. Change one variable only and test again: try dry gravel instead of wet, or fine sand instead of gravel. Predict first, then measure.
7. Write a conclusion in two or three sentences. Use the words casing, cave in and bedrock, and state whether your prediction held.

Tips

- Push the casing in slowly and straight. A pipe pushed at an angle binds and tears the sides, which happened to Drake as well.
- What we change: casing or no casing (then wet or dry). What we keep the same: the cup, the gravel depth, the amount of water, the drill. What we measure: the depth of open hole in centimeters.

Check your work

- I kept every variable the same except the one I was testing.
- I recorded three trials for each condition and averaged them.
- I can explain in my own words why Drake’s drive pipe worked.

FIELD NOTEBOOK

1. Draw a labeled cross-section of Drake’s well like the figure: surface, gravel, drive pipe, bedrock, drill hole, oil. Mark the depths in meters.
2. Make a two-column table titled “Lamp Light Before and After 1859” with columns for fuel (candles, whale oil, coal oil, kerosene) and one fact about each.
3. Copy the data table from your casing experiment neatly, and draw a simple bar graph comparing the average depth with and without casing.

> **From history.** Drake had no military rank. The Seneca Oil Company addressed its letters to “Colonel E. L. Drake” before he arrived in Titusville so that the townspeople would take the stranger seriously, and the name stuck for the rest of his life. It did not make him rich. He failed to patent the drive pipe, lost his savings speculating in oil, and spent his last years in poor health. In the early 1870s Pennsylvania voted him a yearly pension of $1,500 in gratitude for what his stubborn little well had started.

WORKED EXAMPLES

Example 1. Drake’s drive pipe reached bedrock at 32 feet. The well struck oil at 69.5 feet. Uncle Billy’s cable-tool bit advanced about 3 feet per day through rock. Convert these figures to meters (1 foot = 0.3048 m) and estimate how many working days the rock drilling took.

(Use the map or drawing “Use the depth scale on the left to check the numbers in this example.” shown earlier in this lesson.)

1. Convert the depths: 32 ft × 0.3048 = 9.75 m, about 9.8 m. 69.5 ft × 0.3048 = 21.18 m, about 21.2 m.
2. Find the thickness of rock actually drilled: 21.2 m − 9.8 m = 11.4 m.
3. Convert the drilling rate: 3 ft/day × 0.3048 = 0.91 m/day.
4. Divide distance by rate: 11.4 m ÷ 0.91 m/day ≈ 12.5 days.

Answer: About 9.8 m of drive pipe and 11.4 m of drilled rock; the rock drilling took roughly 12 to 13 working days at 0.9 m per day.

Example 2. Drake’s pump brought up about 20 barrels of oil a day. One barrel is 159 liters, and the crude oil had a density of about 0.85 kg per liter. How many liters per day was that, how many liters per hour, and about how many kilograms of oil came up each day?

1. Liters per day: 20 barrels × 159 L/barrel = 3,180 L per day.
2. Liters per hour: 3,180 L ÷ 24 h = 132.5 L per hour, about 130 L per hour, or a 10-liter bucket every 4 to 5 minutes.
3. Mass per day: 3,180 L × 0.85 kg/L = 2,703 kg, about 2.7 metric tons.
4. Check the sense of it: oil is lighter than water (1.00 kg/L), so the mass in kilograms should be a little less than the volume in liters. It is.

Answer: About 3,180 L per day, about 130 L per hour, and about 2,700 kg (2.7 t) of oil per day.

Example 3. Historians give these approximate figures for U.S. crude oil production in the first years after Drake's well: 1859, about 2,000 barrels; 1860, about 500,000 barrels; 1862, about 3,000,000 barrels. By what factor did production grow from 1859 to 1860, and from 1860 to 1862? Express the 1862 total in liters.

1. Factor 1859 to 1860: 500,000 ÷ 2,000 = 250. Production grew 250 times in one year.
2. Factor 1860 to 1862: 3,000,000 ÷ 500,000 = 6. Production grew 6 times in two years.
3. Liters in 1862: 3,000,000 barrels × 159 L = 477,000,000 L, about 4.8×10^8 L, or 477,000 cubic meters (1 m^3 = 1,000 L).
4. Notice that the biggest jump by factor came first, when the industry went from one well to hundreds; later growth was still huge in barrels but smaller as a multiple.

Answer: Growth factors of about 250 (1859 to 1860) and 6 (1860 to 1862); the 1862 total is about 477 million liters, or 477,000 m^3.

PRACTICE

1. EASY Where and when did Drake's well strike oil, and at about what depth in meters?
2. EASY What was the drive pipe, and what problem did it solve?
3. EASY Convert 100 barrels of oil to liters, and 5,000 liters to barrels (round to one decimal place).
4. MEDIUM Why did people in 1859 want oil? Name the main product and the two older light sources it replaced.
5. MEDIUM A bucket holds 2.0 kg of crude oil with a density of 0.85 kg/L and 2.0 kg of water. Which takes up more space, and by how many liters?
6. MEDIUM Data reading. A model drilling log for Drake's well is given in meters below the surface. Day 0: 9.8 m (drive pipe finished). Day 4: 13.4 m. Day 8: 17.0 m. Day 12: 20.6 m. Day 13: 21.2 m (oil). (a) What was the average drilling rate in meters per day from Day 0 to Day 12? (b) Was the rate steady, or did it change? Support your answer with two numbers from the table. (c) If the rate from Day 0 to Day 12 had continued, on what day would the hole have reached 25 m?
7. MEDIUM Data reading. Approximate U.S. oil production and price, as historians report them: 1859, 2,000 barrels, about $16 per barrel. 1860, 500,000 barrels, about $10 per barrel. 1861, 2,100,000 barrels, less than $1 per barrel. (a) Describe the relationship between the amount produced and the price. (b) Which of these is the best explanation? (i) Oil became harder to burn. (ii) Supply grew far faster than the number of buyers. (iii) Barrels became smaller. (c) What happened to the total barrels from 1860 to 1861, as a percent increase?
8. HARD Experiment design. You want to find out whether a wider drive pipe or a narrower one lets you dig a deeper open hole in wet sand. Name the independent variable, the

dependent variable, two things you must keep the same, and how many trials you would run and why.

9. HARD Drake's well produced about 20 barrels a day at first. A modern well in the same region might produce 2 barrels a day, while a good well in Texas might produce 500 barrels a day. Write the three rates as a ratio in simplest form, and explain why a 2-barrel-a-day well might still be worth running.
10. CHALLENGE Written explanation. Drake was called a fool in 1859 and a pioneer by 1865. In four or five sentences, explain what Drake did that others had not done, what idea actually solved his problem, and what this teaches about how new knowledge about the earth is usually won.

COMMON MISTAKES

- Picturing oil in big underground lakes or caves. Oil fills the tiny pore spaces between grains in rock, like water in a sponge.
- Thinking Drake invented drilling. Salt-well drillers in Pennsylvania and brine drillers in China drilled deep holes long before 1859. Drake's new ideas were drilling on purpose for oil and casing the hole with a drive pipe.
- Thinking the first oil was wanted for cars. There were no cars in 1859. The prize was kerosene for lamps; gasoline was a dangerous leftover for decades.

Make it a game · Drake's Folly. Each player needs a die and a scorecard with a depth line from 0 to 21 meters. Each turn is one drilling day: roll the die and advance that many meters. But if you roll a 1 and you have not yet spent a turn to "set casing," your hole caves in and you go back to 0. Spending one turn to set casing protects you for the rest of the game. First to reach 21 meters strikes oil and shouts "Uncle Billy!" Play three rounds and discuss: was it worth losing a day to set the casing?

Scripture. "He made him ride on the high places of the earth, that he might eat the increase of the fields; and he made him to suck honey out of the rock, and oil out of the flinty rock;" (Deuteronomy 32:13, KJV)

Moses was singing of olive oil from trees that grow in stony ground, not petroleum. But the picture is the same: God stocked the hard earth with good things and gives people the wit to draw them out.

Practice answers

1. Near Titusville, Pennsylvania, on Oil Creek, on August 27, 1859, at 69.5 feet, about 21 meters.
2. A cast-iron pipe driven down through the loose, water-soaked gravel to bedrock. It kept the hole from caving in so the drillers could drill inside it to reach solid rock.
3. 100 × 159 = 15,900 L. 5,000 ÷ 159 ≈ 31.4 barrels.
4. For kerosene lamp oil. It replaced costly whale oil and dim candles (and coal-oil kerosene distilled from coal). Gasoline was at first a dangerous leftover, since there were no cars.
5. Oil: 2.0 ÷ 0.85 = 2.35 L. Water: 2.0 ÷ 1.00 = 2.0 L. The oil takes up about 0.35 L more, which is why oil floats on water.

6. (a) (20.6 − 9.8) ÷ 12 = 10.8 ÷ 12 = 0.9 m/day. (b) Steady: each 4-day span gained 3.6 m (13.4 − 9.8 = 3.6; 17.0 − 13.4 = 3.6; 20.6 − 17.0 = 3.6). (c) 25 − 9.8 = 15.2 m; 15.2 ÷ 0.9 ≈ 16.9, so during Day 17.
7. (a) As production rose, price fell sharply; they move in opposite directions. (b) (ii). Hundreds of wells flooded the market before refineries, railroads and lamp buyers could catch up. (c) (2,100,000 − 500,000) ÷ 500,000 = 3.2, a 320 percent increase.
8. Independent variable: the pipe’s diameter. Dependent variable: the depth of open hole in centimeters. Keep the same: the sand type and depth, the amount of water, the digging tool, the person pushing and the pushing speed. At least three trials per pipe, averaged, because single trials vary with how the sand happens to settle.
9. 20 : 2 : 500 = 10 : 1 : 250. A small well can still pay if the pump is already in place, the oil price is high enough and the costs of running it are low; many Pennsylvania “stripper” wells have pumped for decades.
10. A strong answer says: others skimmed seeps or drilled for salt, but Drake drilled on purpose for oil; the drive pipe through gravel to bedrock solved the caving problem; he persisted for more than a year while the money ran out; and new knowledge of the earth usually comes from patient, careful trial and error, often by people willing to be laughed at, who then share what they learned so others can build on it.

4.2 Spindletop (1901): The Gusher That Changed Texas

OBJECTIVES

- Tell the story of the Lucas gusher at Spindletop Hill near Beaumont, Texas, on January 10, 1901, and name the people who made it happen.
- Explain how rotary drilling and drilling mud differ from cable-tool drilling, and why a salt dome can hold oil.
- Convert flow rates between barrels per day and liters per second, compute pressure at depth, and read production data to explain why a field can decline quickly.

Warm-up. Shake a sealed bottle of carbonated water for ten seconds, then set it on the counter. Do not open it. Look at the bubbles pressing against the cap and think: what is holding that gas in, and what would happen if the cap were a layer of loose sand instead of a screw top? Write one sentence predicting what a driller would see if the bit broke through a cap like that.

Video. Coming soon. Spindletop Lucas gusher 1901 Beaumont Texas history, rotary drilling and drilling mud explained; look for the Spindletop-Gladys City Boomtown Museum at Lamar University, Texas State Historical Association, Smithsonian, PBS and Texas public-television history segments, the U.S. Energy Information Administration Energy Kids pages, and Homeschool Pop (Alternate).

KEY TERMS

gusher
A well in which underground pressure shoots oil and gas uncontrolled out of the top. Today it is called a blowout and is prevented with heavy mud and steel valves.

salt dome
A thick plug of rock salt that has pushed upward through the layers above it, bending them up and making traps for oil along its sides and over its cap.

rotary drilling
Drilling by spinning a toothed bit on the end of a turning pipe while fluid is pumped down the pipe to carry the rock chips back up.

drilling mud
A heavy mixture of water, clay and minerals pumped down a well. It cools the bit, carries chips up, plasters the hole’s walls, and its weight holds back oil and gas.

boomtown
A town that grows very fast when a resource is found nearby. Beaumont grew from about 9,000 people to about 50,000 within months of the gusher.

reservoir pressure
The push of fluid in the pores of a rock, which drives oil up a well. When too many wells drain a field, pressure drops and the wells slow.

CORE IDEAS

The story. South of Beaumont, Texas, a low hill rose a few meters above the flat coastal prairie. Locals called it Spindletop. Gas bubbled from its springs, and the water smelled of sulfur. Pattillo Higgins, a Beaumont businessman and Sunday school teacher who had lost his left arm as a teenager, took his class there for picnics and noticed the bubbling. He taught himself geology from books and became convinced there was oil under the hill. In 1892 he formed a company, named for a girl in his class, Gladys Bingham, and drilled three shallow wells that all failed in loose sand. Higgins advertised for help, and in 1899 an answer came from Anthony F. Lucas, an Austrian-born mining engineer who had worked in the salt mines of Louisiana. Lucas knew that the Gulf Coast hills were the tops of huge salt plugs, and he believed oil might be trapped around them. His first well reached about 175 meters and collapsed. With money from the Pittsburgh oil men Guffey and Galey, he hired three brothers from Corsicana, Al, Curt and Jim Hamill, who drilled a different way.

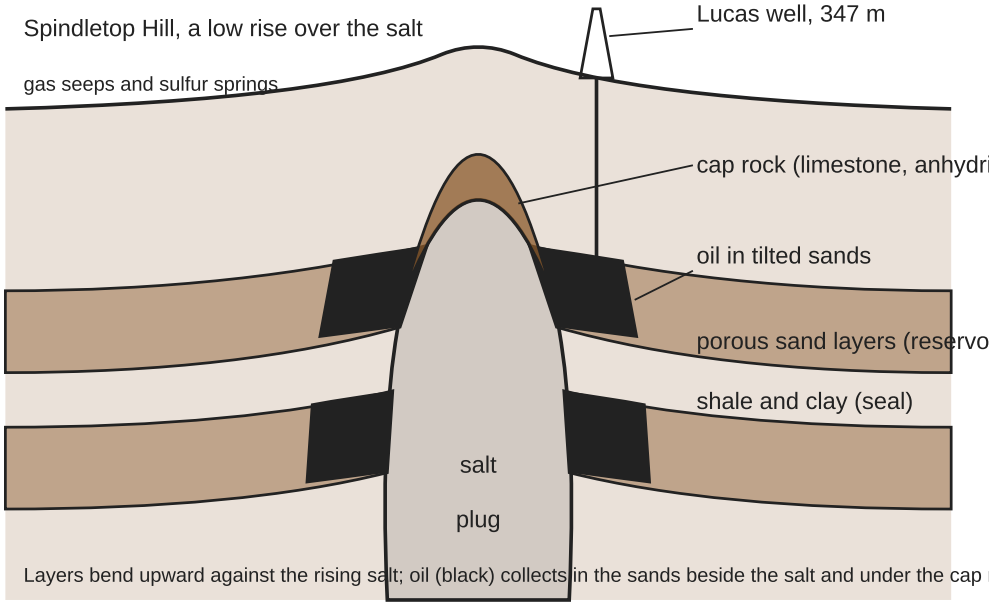
How they figured it out. Drake's crews had pounded with a bit on a cable. The Hamills used a rotary rig: a turning bit on the end of a rotating pipe, with water pumped down the pipe to flush the chips up. But at Spindletop the loose sand kept slumping into the hole and the water pumped straight into it. The brothers tried mud instead of water. Beaumont tradition says they drove cattle through a pit of water to churn it into mud. The mud plastered the walls of the hole, held back the sand, and let the bit go deeper. Drilling mud is still the heart of every well drilled today. On the morning of January 10, 1901, at about 347 meters (1,139 feet), the well began to belch mud, then the drill pipe itself shot out of the hole and over the derrick. Everything went quiet. Then, with a roar, a column of oil and gas burst more than 45 meters into the air, well above the derrick, and kept roaring for nine days before the Hamills could cap it. Estimates put the flow at about 100,000 barrels a day, far more than any single well in the world had ever flowed, and five thousand times Drake's 20 barrels a day.

The big idea. Spindletop taught the world three things. First, oil is found by thinking about *structures*. A salt dome is a plug of rock salt that has risen through the overlying layers like a slow bubble, bending them upward. Sandy layers tilted against the salt, sealed above by hard cap rock, make natural traps where oil gathers. Lucas was looking for a shape, not just a seep. Second, underground fluids are under great pressure. At 347 meters the weight of the column of water filling the pores above presses with about 3.4 million pascals, about 34 times air pressure, and gas dissolved in the oil adds to the push. A column of heavy mud in the hole balances that pressure; when the mud is lost, the well blows. Third, pressure is a shared account. By the end of 1901 more than two hundred wells crowded onto the hill. Each new well drew down the same pressure. The field gave 3.6 million barrels in 1901 and 17.4 million in 1902, then fell off sharply; by 1904 it was yielding only about 10,000 barrels a day. Too many straws in one glass empty it fast and waste what might have flowed for decades.

In the world today. Beaumont became a boomtown overnight. The population swelled from about 9,000 to about 50,000, and tent camps, saloons and hotels sprang up where cattle had grazed. Out of the scramble came Gulf Oil and Texaco, and older firms such as Sun Oil grew large on Texas crude. More important, Spindletop made oil cheap and plentiful just as the

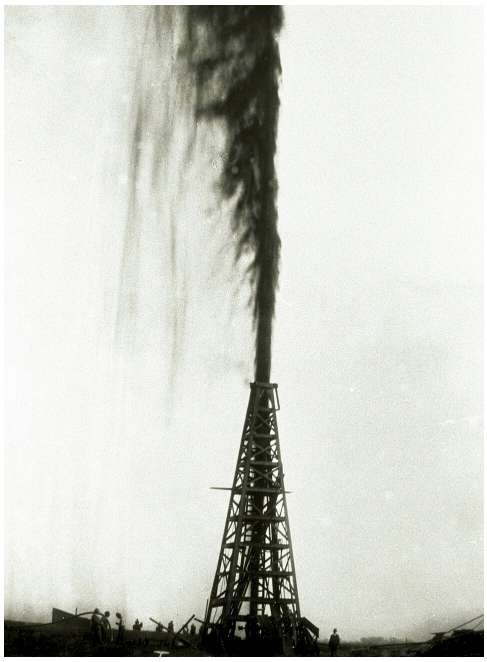
gasoline automobile and the oil-burning ship and locomotive arrived. Texas became the center of the industry. Rotary rigs and mud now drill wells many kilometers deep, and the blowout preventer, a stack of steel valves at the wellhead, prevents gushers. The jobs remain: driller, derrickhand, mud engineer, geologist, landman.

God's handiwork. Higgins read a few library books and looked carefully at bubbling springs that everyone else had walked past. Lucas studied salt and thought about what lay beside it. The Hamills watched sand slump and reasoned their way to mud. None of them made the oil; they discerned an order already there and worked with it. "O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches" (Psalm 104:24). The same lesson cuts the other way: the waste on Spindletop Hill shows that riches handled greedily are soon spent. Dominion means care.



A salt dome trap like Spindletop. Rising salt bends the layers upward; oil gathers in tilted sands against the salt and under the cap rock.

PICTURE STUDY



The Lucas Gusher at Spindletop, January 1901, John Trost (attributed), January 1901 · Photograph · American Petroleum Institute collection; widely reproduced

Beaumont photographer John Trost is credited with this photograph of the Lucas gusher, taken while oil was still roaring out of the well in January 1901. It became the best-known image of the Texas oil boom and was printed on postcards and in newspapers across the country.

Notice that the oil column rises far above the derrick. No one planned this. The drillers had lost control of the well, and for nine days the oil poured onto the prairie and into hastily dug pits until the well could be capped.

Look closely

- Compare the height of the oil column with the derrick. About how many derricks tall is the gusher?
- Find the people. How close are they standing, and what does that tell you about the danger?
- Look at the ground around the well. Where do you think all that oil went?
- Look for other derricks or buildings. Was this taken before or after the boom crowded the hill?

Talk about it

1. What underground conditions pushed the oil this high?
2. Why is a gusher a sign of a well out of control rather than a well done right?
3. Within a year more than two hundred wells crowded this hill. How would that change the picture, and the reservoir pressure?

> **Safety first.** Do the gusher model outdoors or in a sink, wear safety glasses, point the bottle away from faces, and use only vinegar and baking soda. Never use a glass bottle, and never try to seal a pressurized container tightly.

EXPERIMENT: GUSHER IN A BOTTLE: CAN HEAVIER MUD HOLD BACK THE PRESSURE?

At Spindletop, gas pressure in the trap shot oil 45 meters into the air once the drillers lost their mud. In this experiment you will make a small pressure source with vinegar and baking soda, let it push liquid up a straw, and test whether a heavier fluid in the "well" holds it down.

Question: Does a denser column of fluid in the well reduce how high the gusher rises? Prediction: write yours first.

You will need

- A clean 500 mL plastic bottle (never glass)
- A clear drinking straw and modeling clay or putty to seal it in the bottle's mouth
- White vinegar, baking soda, a small square of tissue paper
- Water, cooking oil (a few spoonfuls), and cornstarch or flour to make a thick "mud"
- Food coloring, a ruler or meter stick taped to a wall or stake, safety glasses, a tray or a sink
- Lab notebook and a stopwatch

Steps

1. Pour 150 mL of vinegar into the bottle and add a thin layer of cooking oil (about 2 tablespoons) so it floats on top. This oil layer is your trapped oil.
2. Wrap 1 level teaspoon of baking soda in a small twist of tissue paper. This is the gas source; the paper delays the reaction a few seconds so you can seal the top.
3. Trial A, water in the well: drop the packet in, quickly push the straw through a plug of clay into the bottle mouth so the straw's bottom is below the oil, and press the clay to seal. Pour a few drops of colored water into the straw to be the fluid in the well. Stand back and watch the straw.
4. Measure the highest point the fluid reaches up the straw, or the height of any spray above the straw, against the ruler. Record it. If the clay pops off, record that too: your well blew out.
5. Rinse and repeat Trial A twice more, keeping the vinegar, baking soda, oil and straw depth exactly the same. Average the three heights.
6. Trial B, mud in the well: mix cornstarch or flour with a little water into a thick paste. Fill the straw about one third full with this mud before you seal it. Repeat three trials and average.
7. Record in a table: Trial, Fluid in well, Height 1, Height 2, Height 3, Average, Blowout? Write a conclusion that uses the words pressure, density and mud, and compare your result to what the Hamill brothers found.

Tips

- What we change: the fluid in the well (water or heavy mud). What we keep the same: the vinegar and baking soda amounts, the bottle, the straw depth, the seal. What we measure: how high the fluid rises in centimeters.
- If nothing happens, your seal is leaking or the straw is above the liquid. If the clay pops off every time, use half the baking soda. Real drillers face the same balance: too little mud weight and the well blows, too much and the mud cracks the rock.

Check your work

- I wore safety glasses and used only vinegar and baking soda in a plastic bottle.
- I averaged three trials for each fluid and recorded blowouts honestly.
- I can explain why heavier drilling mud helps prevent a gusher.

FIELD NOTEBOOK

1. Draw the salt dome cross-section from the figure and label the salt, the cap rock, the tilted sands, the trapped oil and the Lucas well with its depth of 347 m.
2. Make a timeline strip for Spindletop Hill with at least six dates: Higgins's picnics (about 1890), Gladys City company (1892), Lucas arrives (1899), gusher (January 10, 1901), capped (nine days later), peak year (1902), decline (1904).
3. Draw a bar graph of Spindletop production: 1901, 3.6 million barrels; 1902, 17.4 million barrels. Add a bar for Texas in 1900, 0.84 million barrels, for comparison.

> **From history.** The hill's name is usually explained by a tall tree there whose shape reminded settlers of a spindle (other stories are told too), and the field was not finished in 1904. In 1925 drillers tried deeper wells on the flanks of the salt dome, below the old shallow production, and started a second boom that peaked in 1927. A tall granite monument to the Lucas gusher was dedicated in 1941, and today it stands beside the Spindletop-Gladys City Boomtown Museum at Lamar University in Beaumont, where a replica of the 1901 boomtown has been rebuilt, with wooden derricks and a replica gusher that sprays water.

WORKED EXAMPLES

Example 1. The Lucas gusher is estimated at 100,000 barrels per day. Convert this to liters per second (1 barrel = 159 L; 1 day = 86,400 s). Then compare it to Drake's well at 20 barrels per day.

1. Liters per day: 100,000 × 159 L = 15,900,000 L per day.
2. Liters per second: 15,900,000 L ÷ 86,400 s ≈ 184 L/s.
3. Picture it: a bathtub holds about 150 L, so the gusher filled more than one bathtub every second.
4. Ratio to Drake's well: 100,000 ÷ 20 = 5,000. The Lucas well flowed 5,000 times faster.

Answer: About 184 liters per second, roughly a bathtub a second, and 5,000 times the rate of Drake's well.

Example 2. At the bottom of the Lucas well, 347 m down, the pores of the rock were full of water. Estimate the fluid pressure there using $P = \rho g h$ with water density 1,000 kg/m³ and g = 9.8 m/s². Express it in megapascals and in atmospheres (1 atm ≈ 101,000 Pa). Then find the pressure that a column of drilling mud with density 1,200 kg/m³ would exert at the same depth.

1. Water pressure: P = 1,000 × 9.8 × 347 = 3,400,600 Pa ≈ 3.4 MPa.
2. In atmospheres: 3,400,600 ÷ 101,000 ≈ 33.7, about 34 atm.
3. Mud pressure: P = 1,200 × 9.8 × 347 = 4,080,720 Pa ≈ 4.1 MPa.
4. Compare: the mud column pushes down with about 0.7 MPa more than the water in the rock pushes up, which is the margin that keeps oil and gas in the ground. Replace the mud with plain water and that margin disappears.

Answer: About 3.4 MPa (34 atm) of water pressure at 347 m; a 1,200 kg/m³ mud column gives about 4.1 MPa, enough to hold the formation back.

Example 3. Spindletop produced about 3.59 million barrels in 1901 and about 17.4 million barrels in 1902. All of Texas produced about 0.84 million barrels in 1900. (a) By what factor did Spindletop’s output grow from 1901 to 1902? (b) How many times larger was Spindletop’s 1902 output than all of Texas in 1900? (c) What was the average daily output of the field in 1902?

1. (a) 17.4 ÷ 3.59 ≈ 4.85, so output grew nearly fivefold in one year as hundreds of wells were added.
2. (b) 17.4 ÷ 0.84 ≈ 20.7. One hill in 1902 gave about 21 times what the whole state gave two years before.
3. (c) 17,400,000 barrels ÷ 365 days ≈ 47,700 barrels per day, average for the field.
4. Compare with the single Lucas well in January 1901 at about 100,000 barrels per day: the whole field’s average in its best year was less than half the first well’s first flow, because the shared pressure was already falling.

Answer: (a) About 4.9 times. (b) About 21 times. (c) About 47,700 barrels per day.

PRACTICE

1. EASY Give the date of the Lucas gusher, the town nearest to it, and the approximate depth of the well in meters.
2. EASY Match each person to his part: Pattillo Higgins, Anthony Lucas, the Hamill brothers. Parts: drilled the well with a rotary rig and mud; believed there was oil under the hill because of gas seeps; salt-mine engineer who understood salt domes and raised the money.
3. EASY Name two jobs drilling mud does in a well.
4. MEDIUM A well flows 2,000 barrels per day. Express this in liters per hour and liters per minute.
5. MEDIUM Explain the difference between cable-tool drilling (Drake) and rotary drilling (Spindletop) in two sentences.
6. MEDIUM Data reading. Approximate production, as reported by historians: Texas, 1900: 0.84 million barrels. Texas, 1901: 4.4 million barrels. Texas, 1902: 18.1 million barrels. Spindletop field, 1901: 3.6 million barrels. Spindletop field, 1902: 17.4 million barrels. (a) What fraction of Texas production in 1902 came from Spindletop alone? (b) Which statement is best supported? (i) Texas production outside Spindletop fell to zero. (ii) Nearly all of Texas’s growth from 1900 to 1902 came from Spindletop. (iii) Spindletop produced more than the rest of the United States combined in 1902. (c) Explain why you cannot decide statement (iii) from this table.
7. MEDIUM Data reading. Average daily output of Spindletop Hill, approximate: January 1901, one well, 100,000 barrels/day. 1902 average, about 47,700 barrels/day. 1904, about 10,000 barrels/day. (a) By what percent did daily output fall from 1902 to 1904? (b) Historians say that by late 1901 more than 200 wells crowded the hill. Which hypothesis best explains the decline? (i) The oil turned to water. (ii) Many closely

spaced wells drained the shared reservoir pressure quickly. (iii) The drillers forgot how to use mud. (c) What one piece of data would you collect to test your hypothesis?

8. HARD Experiment design. You want to test whether the spacing between wells affects how long a model reservoir keeps flowing. Describe a setup using a sponge soaked with colored water, several straws and a timer. Name the independent variable, the dependent variable, two controls, and one source of error.
9. HARD A well is 1,500 m deep. Using $P = \rho g h$, find the pore-water pressure at the bottom in MPa (ρ = 1,000 kg/m^3, g = 9.8 m/s^2). What minimum mud density would be needed to equal that pressure if the mud fills the whole 1,500 m hole? Why in practice would the mud engineer use a somewhat heavier mud?
10. CHALLENGE Written explanation. In four or five sentences, explain how Spindletop was both a triumph and a warning. Use the words salt dome, pressure and boomtown.

COMMON MISTAKES

- Thinking a gusher is a sign of a well done right. A gusher is a blowout: wasted oil, a fire hazard and a danger to the crew. Modern wells are designed so it never happens.
- Thinking the salt itself holds the oil. Salt is nearly impermeable; the oil is in the porous sand layers tilted against the salt and sealed above by cap rock.
- Thinking the oil ran out at Spindletop. The oil did not vanish; the reservoir pressure fell because too many wells drained it too fast, leaving much oil behind. Deeper flank wells in the 1920s found more.

> **Make it a game · Boomtown Rush.** Draw a 5 by 5 grid on paper: this is Spindletop Hill. The hill starts with 100 pressure points. Players take turns placing a derrick (an X) on any square and collecting barrels: a well earns 10 barrels times the number of pressure points, divided by 100, rounded down (so 10 barrels at full pressure). Every well placed lowers the hill's pressure by 8 points, and a well placed next to an existing well lowers it by 12. Play until pressure reaches 0. Add up each player's barrels, then play again with a rule that wells must be at least two squares apart. Which game produced more total barrels for everyone?

> **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)

The psalmist looks at the earth and sees not luck but wisdom and plenty. Higgins and Lucas found riches under a hill because they studied how the layers were arranged. The same psalm reminds us that the riches are God's, to be used with care.

Practice answers

1. January 10, 1901; Beaumont, Texas; about 347 m (1,139 feet).
2. Higgins: believed there was oil because of the gas seeps. Lucas: salt-mine engineer who understood salt domes and raised the money. Hamill brothers: drilled the well with a rotary rig and mud.

3. Any two: carries rock chips up out of the hole, cools the bit, plasters and supports the walls so they do not cave, and its weight holds back the pressure of oil and gas.
4. 2,000 × 159 = 318,000 L/day; ÷ 24 = 13,250 L/h; ÷ 60 ≈ 221 L/min.
5. Cable-tool drilling lifts and drops a heavy bit on a cable to pound the rock, then stops to scoop out chips. Rotary drilling spins a toothed bit on a turning pipe while mud pumped down the pipe carries the chips up continuously, so it is faster and the mud supports the hole.
6. (a) 17.4 ÷ 18.1 ≈ 0.96, about 96 percent. (b) (ii). Texas grew by about 17.3 million barrels, and Spindletop alone added 17.4 million, so essentially all of the growth was Spindletop. (c) The table gives no figure for the rest of the United States, so (iii) cannot be checked from these data.
7. (a) (47,700 − 10,000) ÷ 47,700 ≈ 0.79, a fall of about 79 percent. (b) (ii). (c) Reservoir pressure measured in the wells over time; if pressure fell as wells were added, the hypothesis is supported.
8. Soak identical sponges with the same amount of colored water. Insert straws as “wells” and draw with the same gentle suction or let the water drain into cups. Independent variable: the distance between straws (or the number of straws per sponge). Dependent variable: how long water keeps flowing, or the total volume collected per straw. Controls: same sponge size, same water amount, same straw size, same suction. Source of error: uneven suction by hand, or a sponge not soaked evenly.
9. P = 1,000 × 9.8 × 1,500 = 14,700,000 Pa = 14.7 MPa. To equal it with the same column height the mud needs at least 1,000 kg/m³ (the same as water). In practice gas in the pores and extra pressure in the rock mean the engineer uses heavier mud, perhaps 1,100 to 1,300 kg/m³, to keep a safety margin against a blowout.
10. A strong answer: it was a triumph because Higgins and Lucas reasoned from gas seeps and the shape of a salt dome to find oil where experts said there was none, and the Hamills’ rotary rig and mud proved a new way to drill; the gusher made oil cheap just as cars and oil-burning ships arrived. It was a warning because the boomtown rush crowded hundreds of wells on one hill, the shared pressure was drained in a few years, and much oil and gas was wasted; good stewardship means spacing wells and managing pressure so a field lasts.

4.3 Traps and Reservoirs: Where Oil and Gas Hide

OBJECTIVES

- Name the four parts of a petroleum system (source rock, reservoir rock, seal and trap) and identify anticline, fault, salt dome and stratigraphic traps in a cross-section.
- Define porosity and permeability, measure the porosity of a sample, and explain why gas, oil and water stack in that order in a trap.
- Estimate the oil in a reservoir from its area, thickness, porosity and saturation, and read a table of rock properties to pick a reservoir and a seal.

Warm-up. Take a dry kitchen sponge and a smooth stone of about the same size. Drop ten drops of water on each. Where does the water go? Now hold the wet sponge sideways: does the water run out the side, or stay? The sponge is a reservoir rock. The stone is a seal. Write one sentence about what would happen if you laid the stone on top of the sponge and poured water into the sponge from below.

Video. Coming soon. How oil and gas traps work: anticline, fault, salt dome, source rock, reservoir, seal, porosity and permeability; look for USGS Energy Resources Program, U.S. Energy Information Administration Energy Kids, state geological surveys (Kansas, Oklahoma, Texas Bureau of Economic Geology), Smithsonian, and classroom geology channels with porosity demonstrations.

KEY TERMS

source rock
A dark, organic-rich rock, usually shale, from which oil and natural gas were generated by heat and pressure.

reservoir rock
A rock with connected pore spaces, such as sandstone or porous limestone, that holds oil, gas or water the way a sponge holds water.

porosity
The fraction of a rock’s volume that is open space, given as a percent. Good reservoir sandstones are often 10 to 30 percent pores.

permeability
How easily fluid can flow through a rock, which depends on whether the pores are connected. Gravel is very permeable; shale is nearly impermeable.

seal (cap rock)
A layer of tight rock, such as shale, salt or anhydrite, that fluids cannot pass through, which keeps oil and gas from rising to the surface.

trap
An arrangement of rock layers, such as an upfold (anticline), a fault, a salt dome or a layer that pinches out, that gathers oil and gas in one place under a seal.

CORE IDEAS

The story. In the spring of 1861, two years after Drake's well, a crew near Rouseville, Pennsylvania, drilled into something no one on Oil Creek had met before. The Little and Merrick well did not need a pump. Gas and oil roared up on their own, and within minutes the spray reached the engine fire. The explosion and blaze killed about nineteen men, among them Henry Rouse, one of the region's leading oil men. The marine painter James Hamilton painted the well burning at night. The drillers had learned a hard lesson: oil underground is not sitting quietly. It is pressed into the pores of rock, often with gas, and held down by a lid. Break the lid and the pressure answers. Over the next century geologists worked out what that lid is and why oil gathers in some places and not others. That knowledge is the business of finding oil, and it is fine detective work.

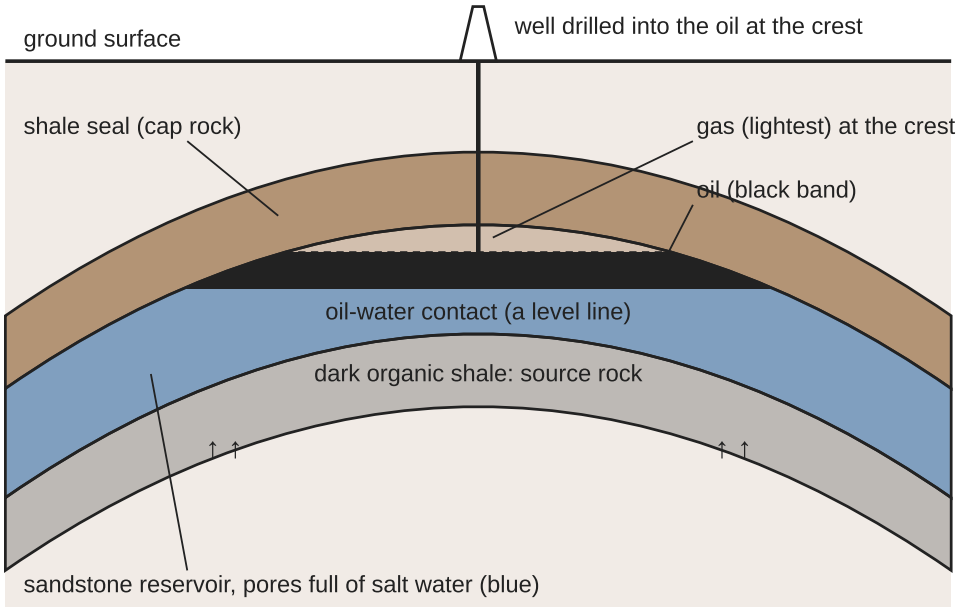
How they figured it out. Early drillers noticed that wells on the crests of gentle upfolds in the rock, called **anticlines**, were far more likely to strike oil than wells in the troughs. In 1861 T. Sterry Hunt of the Geological Survey of Canada, and then others put the pieces together into what became the **anticlinal theory**: oil is lighter than water, so it rises through water-filled pores until it meets a layer it cannot pass, and under an arched seal it has nowhere to go but to collect at the top. Rock samples from wells showed the pattern: oil-bearing sandstones and porous limestones, tight shales above them, and far below, dark organic-rich shales that smelled of oil when broken. The modern picture has four parts. A **source rock** generates oil and gas. The fluids migrate upward and sideways into a **reservoir rock** with connected pores. A **seal** stops them. And a **trap**, the shape of the layers, gathers them in one place. Within the trap the fluids sort by density: natural gas (lightest) on top, oil below it, and salty water at the bottom.

The big idea. Two properties decide whether a rock can be a reservoir. **Porosity** is how much of the rock is open space. Saturate a dry 500 cm^3 sandstone block, and if it drinks 90 mL of water it is 18 percent pores. **Permeability** is how easily fluid moves through those pores, which depends on whether they connect. A fine clay can be very porous and still nearly impermeable, because its pores are tiny and poorly linked; that is exactly why shale makes a good seal. Traps come in a few shapes. An anticline is an arch. A fault trap forms where a break in the rock slides a porous layer against a tight one. A salt dome, as at Spindletop, bends layers up against impermeable salt. A stratigraphic trap forms where a sandy layer pinches out inside shale, or where a buried reef lies in mud. The geologist finds these shapes from outcrops, seismic echoes bounced off the layers and the logs of earlier wells, then drills where the seal is tight and the pores are full.

Try it and see. Fill a clear jar one third with coarse gravel, then a layer of damp clay pressed flat and domed up in the middle, then more gravel on top. Push a straw down through the top gravel and the clay into the lower gravel and pour in colored water, then a little cooking oil. Watch where the oil goes. It rises through the water-filled gravel and gathers under the highest part of the clay: you have built an anticline trap. Now poke a second hole in the clay off to one side. Does oil escape? Real seals leak too; seeps at the surface are how the people on Oil Creek found oil in the first place. The ratios matter as well. A reservoir sandstone 2 km by 3 km and 20 m thick, with 18 percent porosity and 70

percent of its pores filled with oil, holds about 15 million cubic meters of oil, roughly 95 million barrels, though usually only a third or so can be brought to the surface.

God's handiwork. Job describes a God who "cutteth out rivers among the rocks; and his eye seeth every precious thing," and who brings "the thing that is hid" to light (Job 28:10–11). Oil and gas are hidden things. The arrangement that keeps them in place is not haphazard: porous rock beneath, tight rock above, folds and faults that gather rather than scatter. Geologists read that order the way a careful reader follows a well-made story, and the better they read it, the fewer dry holes they drill. The measured properties of rock, porosity, permeability, density, are the same for everyone who measures them.



Arrows: oil and gas migrate up from the source rock into the reservoir and stop under the seal. Not to scale.

An anticline trap. Oil and gas rise from the source rock into the porous sandstone, stop under the shale seal, and sort by density: gas on top, oil, then water.

⏳ Thinking About Time

What the sign says. Textbooks and museum signs say that petroleum formed from countless microscopic sea creatures and algae buried in mud and cooked slowly by the earth's heat, mostly tens to hundreds of millions of years ago, and that most coal formed from swamp forests about 300 million years ago, in what the signs call the Carboniferous period.

What we observe. What we can actually observe and measure: oil contains molecules clearly derived from living things, such as porphyrins related to chlorophyll; source rocks are rich in organic carbon; rock gets hotter with depth, about 25 °C for every kilometer; and in laboratories, algae and plant material under heat and pressure have been turned into crude-like oil in hours and into coal-like material in weeks to months. The temperatures and chemistry are observed. The time is not observed; it is calculated from assumed slow rates of burial and heating.

How Christians read it. Many Christians who hold to a recent creation read the oil and coal as largely the work of the Flood of Genesis 6–9: vast masses of plants, algae and sea life were buried quickly under thick sediment, and the heat and pressure of those sediments produced oil and coal in the centuries that followed, not over hundreds of millions of years. Other Christians accept the long ages and see them as God's slow providence. Both agree on the chemistry and both honor God as the Maker; the dates are an interpretation to be weighed, not a measurement read directly from the rock.

Try it. Break a lump of coal (or look at one under a hand lens) and search for the flattened plant fragments or bark patterns that show what it was made from.

Genesis 7:11

PICTURE STUDY



Burning Oil Well at Night, near Rouseville, Pennsylvania, James Hamilton, about 1861 · Oil on paperboard · Smithsonian American Art Museum, Washington, D.C.

James Hamilton was born in Ireland and grew up in Philadelphia, where he became known for stormy, glowing seascapes. Around 1861 he turned to a new kind of spectacle: the oil fields of western Pennsylvania, where the fire at the Little and Merrick well near Rouseville had just killed about nineteen men. Hamilton painted the burning well at night, the flame towering over the derrick and the smoke rolling into the clouds.

The painting is beautiful and terrible at once. It shows what reservoir pressure looks like when the seal is broken and nothing is ready to hold it back.

Look closely

- Find the base of the flame. Is it coming from the ground, or from the top of a structure? What does that tell you about the well?
- Look at the sky. How much of the picture is lit by the fire rather than by the moon or stars?
- Find the people. How large are they compared with the flame, and what are they doing?
- Notice the colors Hamilton chose for the ground and water. Where is the oil in this picture?

Talk about it

1. What underground conditions made this fire possible: what was pushing the oil and gas up?
2. Hamilton usually painted ships in storms. Why might a painter of storms have been drawn to this subject?
3. What would a modern driller have at the top of the well to prevent what the painting shows?

> **Safety first.** Use only water, cooking oil and food coloring in the trap model. Clean up oil spills on floors at once so no one slips, and do not pour used oil down the drain; wipe it up with paper towels and throw it away.

EXPERIMENT: RESERVOIR OR SEAL? MEASURING POROSITY AND PERMEABILITY

Geologists decide which layers can hold oil and which can seal it by measuring two numbers. You will measure both for three materials and then use your results to build a working trap.

Question: Which of three earth materials has the highest porosity, and is the most porous one also the most permeable? Prediction: rank them before you start.

You will need

- Three identical clear cups or jars (about 250 mL) with the volume marked, plus a measuring cup or graduated cylinder
- Aquarium gravel, play sand, and potting clay or soil with a lot of clay (or flour mixed with a little water and pressed firm)
- Water, food coloring, cooking oil (a few spoonfuls)
- A funnel, a coffee filter or a cup with small holes punched in the bottom, and a stopwatch
- A larger clear jar and a straw for the trap model
- Lab notebook, ruler and pencil

Steps

1. Fill each cup level to the 200 mL mark with one material: gravel, sand, clay. Tap gently to settle, then refill to the mark. Record the bulk volume (200 mL) for each.

2. Porosity: slowly pour measured water into the gravel until the water just reaches the top of the material. Record the milliliters added. Porosity = water added ÷ 200 mL × 100 percent. Repeat for sand and clay (the clay will take a long time to soak; give it five minutes and record what it accepted).
3. Permeability: put 100 mL of each dry material into the filter cup or funnel over an empty measuring cup. Pour 100 mL of water on top all at once and time how long it takes for 50 mL to drain through. Record the time; if it has not reached 50 mL after 5 minutes, record “more than 300 s” and the amount collected.
4. Make a table: Material, Water held (mL), Porosity (%), Time for 50 mL to drain (s). Rank the materials on each measure. Does the most porous one drain fastest?
5. Build the trap: in the large jar, put 5 cm of gravel, then shape a 1 cm layer of damp clay into a dome that seals against the jar walls, then 3 cm more gravel on top. Push the straw down through the top gravel and clay into the lower gravel.
6. Pour colored water down the straw until the lower gravel is nearly full, then pour in about 20 mL of cooking oil. Watch for several minutes and sketch where the oil gathers. Then poke a small hole in the clay dome away from the straw and record what happens.
7. Conclusion: in three or four sentences, state which material would make the best reservoir rock and which the best seal, using your porosity and permeability numbers, and explain what your trap model showed.

Tips

- What we change: the material. What we keep the same: the cup volume, the amount of water poured, the way we tap and level, the timing method. What we measure: milliliters of water held and seconds to drain.
- Real sandstone reservoirs are about 10 to 30 percent porous, less than your loose sand, because the grains are cemented. Shale can be 5 to 10 percent porous yet still seal, because its pores are tiny and poorly connected.

Check your work

- I measured porosity as a percent and permeability as a drain time for all three materials.
- I kept the volumes and procedure the same for each material.
- I can explain why a good seal can be porous but not permeable, and I built a trap that held oil under a dome.

FIELD NOTEBOOK

1. Copy the anticline trap figure and label source rock, reservoir, seal, gas, oil, water and the well. Then draw and label the three other trap types in small boxes: fault trap, salt dome, pinch-out.
2. Record your porosity and permeability table neatly and add a bar graph of porosity for gravel, sand and clay.

3. Draw your jar trap before and after you poked the hole in the clay, with arrows showing where the oil moved.

From history. The anticlinal theory had several fathers. In 1861 the chemist and geologist T. Sterry Hunt of the Geological Survey of Canada, writing about the oil springs of Ontario, pointed out that oil gathered along the crests of folds in the rock. In the same year E. B. Andrews in Ohio made similar observations, and by the 1880s I. C. White was using the theory on purpose to pick drilling sites in Pennsylvania and West Virginia, with great success. It was one of the first times a geological idea was used to predict where a valuable resource would be found, and it turned oil hunting from a gamble into a profession.

WORKED EXAMPLES

Example 1. A dry block of sandstone has a volume of 500 cm³. When slowly saturated, it takes in 90 mL of water. What is its porosity? If the same block were shale that took in 30 mL, what would its porosity be? Which is the better reservoir, and why does porosity alone not decide which is the better seal?

1. Porosity = pore volume ÷ bulk volume. For the sandstone: 90 cm³ ÷ 500 cm³ = 0.18 = 18 percent. (1 mL = 1 cm³.)
2. For the shale: 30 ÷ 500 = 0.06 = 6 percent.
3. The sandstone holds three times as much fluid per cubic meter, so it is the better reservoir.
4. Sealing depends on permeability, not porosity. Shale pores are tiny and poorly connected, so fluids cannot move through it, which makes it a seal even though it has some pore space.

Answer: Sandstone 18 percent, shale 6 percent. The sandstone is the better reservoir; the shale seals because of its very low permeability, not its porosity.

Example 2. A reservoir sandstone under an anticline covers 2 km by 3 km and averages 20 m thick. Its porosity is 18 percent and 70 percent of the pore space holds oil (the rest is water). Estimate the oil in place in cubic meters and in barrels (1 m^3 = 6.29 barrels). If about one third can be recovered, how many barrels can be produced?

(Use the map or drawing "The oil zone is the dark band in the sandstone; its area times thickness times p" shown earlier in this lesson.)

1. Area: 2,000 m × 3,000 m = 6,000,000 m^2.
2. Bulk rock volume: 6,000,000 m^2 × 20 m = 120,000,000 m^3.
3. Pore volume: 120,000,000 × 0.18 = 21,600,000 m^3.
4. Oil volume: 21,600,000 × 0.70 = 15,120,000 m^3 of oil in place.
5. In barrels: 15,120,000 × 6.29 ≈ 95,100,000 barrels, about 95 million.
6. Recoverable: 95,100,000 ÷ 3 ≈ 31,700,000, about 32 million barrels. The rest clings to the grains or is left behind when pressure falls.

Answer: About 15 million m^3 of oil in place, roughly 95 million barrels, of which about 32 million barrels might be recovered.

Example 3. A well log shows three fluids in a trap. Their densities: natural gas about 0.2 g/cm^3 at reservoir pressure, crude oil 0.85 g/cm^3, and salty formation water 1.03 g/cm^3. (a) In what order, top to bottom, will they stack? (b) How much does 1 m^3 of each weigh in kilograms? (c) By how many kilograms per cubic meter is oil lighter than the brine, and what does that difference do?

1. (a) Lighter fluids float on heavier ones: gas on top, then oil, then water at the bottom.
2. (b) 1 m^3 = 1,000,000 cm^3, so 1 g/cm^3 = 1,000 kg/m^3. Gas: 0.2 × 1,000 = 200 kg. Oil: 850 kg. Brine: 1,030 kg.
3. (c) 1,030 − 850 = 180 kg per m^3. That difference is the buoyant push that drives oil upward through water-filled pores until a seal stops it; it is why oil migrates to the top of the trap and why the oil-water contact is a nearly level line.

Answer: (a) Gas, oil, water. (b) 200 kg, 850 kg, 1,030 kg. (c) 180 kg/m^3; the buoyancy drives oil up to the crest of the trap and makes a level oil-water contact.

PRACTICE

1. EASY Name the four parts of a petroleum system and give one rock type for each of the first three.
2. EASY A 400 cm^3 rock sample soaks up 60 mL of water. What is its porosity?
3. EASY In a trap, which fluid is on top, which in the middle, and which on the bottom? Why?

4. MEDIUM Explain the difference between porosity and permeability using a sponge and a brick of clay as examples.
5. MEDIUM Sketch and label an anticline trap and a fault trap. In each, mark where a geologist should drill to find oil.
6. MEDIUM Data reading. A table of rock properties from a well: Layer A, shale, porosity 6 percent, permeability very low. Layer B, sandstone, porosity 22 percent, permeability high. Layer C, limestone, porosity 12 percent, permeability moderate. Layer D, rock salt, porosity near 0, permeability near 0. Layer E, dark organic shale, porosity 8 percent, permeability very low, high organic carbon. (a) Which layer is the best reservoir? (b) Which two could serve as seals? (c) Which is most likely the source rock, and what property tells you? (d) A student says Layer A cannot be a seal because it has 6 percent porosity. Explain the error.
7. MEDIUM Data reading. A student measured how long 50 mL of water took to drain through 100 mL of each material: gravel, 4 s; coarse sand, 15 s; fine sand, 48 s; silt, 210 s; clay, more than 300 s (only 5 mL drained). Porosity measured: gravel 38 percent, coarse sand 36 percent, fine sand 40 percent, silt 42 percent, clay 45 percent. (a) Describe the trend between grain size and drain time. (b) Describe the trend between grain size and porosity. (c) Which conclusion do the data support? (i) Higher porosity always means higher permeability. (ii) Permeability depends mainly on grain size, not on porosity. (iii) Clay has the lowest porosity.
8. HARD Experiment design. You want to know whether packing a sand sample tightly changes its porosity. Describe your procedure, name the independent and dependent variables, and list two variables you must keep the same. Predict the result and explain your prediction.
9. HARD A reservoir 1.5 km by 2 km, 10 m thick, has 20 percent porosity and 60 percent oil saturation. Compute the oil in place in m^3 and in barrels (1 m^3 = 6.29 barrels).
10. CHALLENGE Written explanation. Suppose a museum sign reads: “This oil formed from marine algae buried 150 million years ago.” In four or five sentences, separate what in that sentence is observed from what is interpreted, and state briefly how a young-earth Christian geologist might read the same evidence. Be fair to both.

COMMON MISTAKES

- Thinking oil sits in underground caverns or lakes. It saturates the connected pores of rock; a reservoir looks like solid stone in your hand.
- Thinking a porous rock is always permeable. Clay and shale can be quite porous yet nearly impermeable because their pores are tiny and poorly connected, which is why they seal.
- Thinking oil is found where the source rock is. Oil migrates, sometimes many kilometers, from the source rock into a reservoir and stops only where a seal and trap catch it.

> **Make it a game · Trap or Leak?.** The parent draws quick cross-sections on scrap paper, one at a time: an arch with shale on top; an arch with sandstone on top and no seal; a

tilted sandstone cut by a fault against shale; a tilted sandstone that runs all the way to the surface; a salt plug with sands tilted against it; a flat stack of layers with no fold or fault. The student has ten seconds to call “Trap!” or “Leak!” and name the reason: which part is missing or present (seal, reservoir, shape). One point for the right call, two for the right reason. Switch roles after six drawings.

Scripture. “He cutteth out rivers among the rocks; and his eye seeth every precious thing. He bindeth the floods from overflowing; and the thing that is hid bringeth he forth to light.” (Job 28:10–11, KJV)

Job 28 is a chapter about mining and the search for hidden things in the earth. God sees every precious thing already; we search patiently for what He has placed. The verse about binding the floods reminds us that the earth’s waters, like its oil, are under His order.

Practice answers

1. Source rock (organic-rich shale), reservoir rock (sandstone or porous limestone), seal or cap rock (shale, salt or anhydrite), and trap (a shape such as an anticline, fault, salt dome or pinch-out).
2. 60 ÷ 400 = 0.15 = 15 percent.
3. Gas on top, oil in the middle, water on the bottom, because they sort by density: the least dense rises highest.
4. Porosity is how much open space there is; permeability is how easily fluid moves through connected spaces. A sponge has high porosity and high permeability. Clay can hold a fair amount of water in tiny pores (some porosity) but the pores are so small and poorly connected that water barely moves through it (very low permeability).
5. Anticline: layers arched up; oil collects at the crest under the seal, so drill at the top of the arch. Fault trap: a porous layer offset by a fault so it butts against a tight layer; oil collects in the porous layer up against the fault beneath the seal, so drill just on the up-dip side of the fault in the porous bed.
6. (a) B, the sandstone: highest porosity and permeability. (b) A and D (shale and salt); E would also seal. (c) E, because of its high organic carbon content. (d) Sealing depends on permeability, not porosity; shale with 6 percent porosity still seals because its pores are not connected.
7. (a) As grain size decreases, drain time increases sharply, so permeability falls. (b) Porosity changes little and actually rises slightly as grains get finer. (c) (ii). The finest material had the highest porosity but the lowest permeability, so (i) and (iii) are contradicted.
8. Fill identical cups to 200 mL with the same sand, one poured loosely, one tapped firmly 50 times and refilled to the mark; saturate each with measured water and compute porosity. Independent variable: how tightly the sand is packed. Dependent variable: porosity (percent). Keep the same: the sand type and grain size, the cup volume, the water-pouring method, the person judging “full.” Prediction: the packed sand will have lower porosity because grains settle into the gaps; in nature, deep burial and cementing lower porosity the same way.
9. Area 1,500 × 2,000 = 3,000,000 m^2; bulk 3,000,000 × 10 = 30,000,000 m^3; pore 30,000,000 × 0.20 = 6,000,000 m^3; oil 6,000,000 × 0.60 = 3,600,000 m^3; barrels 3,600,000 × 6.29 ≈ 22,600,000, about 23 million barrels.

10. A strong answer: Observed: the oil contains molecules from living things such as algae, the source rock is organic-rich marine shale, and heat and pressure can turn such material into oil, as laboratory experiments show in hours to weeks. Interpreted: the 150 million years, which is calculated from assumed slow rates of burial and heating that no one measured over that span. A young-earth geologist would agree about the algae and the chemistry but read the burial as rapid, during the Flood of Genesis, with the oil forming over centuries under thick, hot sediment. Both readings should be stated fairly; the date is a conclusion from assumptions, not a measurement on the rock.

4.4 What a Barrel of Oil Makes: Refining, Natural Gas and Coal

OBJECTIVES

- Explain how a refinery separates crude oil into fractions by boiling point and how cracking changed the amount of gasoline a barrel yields.
- List the main products of a 159-liter barrel of crude oil with approximate volumes, and name the chief uses of natural gas and the ranks of coal.
- Compute percentages, fuel-economy distances and energy comparisons from a yield table, and read an energy-use table in the style of a science-reasoning test.

Warm-up. Walk through one room of your house with a notebook and a three-minute timer. Write down everything you can find that is made from petroleum or natural gas, or that runs on them: plastic cups, synthetic carpet, nylon zippers, candles made of paraffin, pens, the asphalt shingles outside the window, the gas stove. Stop at three minutes and count. Most students find more than fifteen.

Video. Coming soon. How an oil refinery works, fractional distillation of crude oil, what products come from a barrel of oil, natural gas uses, ranks of coal; look for U.S. Energy Information Administration Energy Kids, American Chemical Society and chemistry teacher channels, Smithsonian, USGS, Science Max, and Homeschool Pop (Alternate).

KEY TERMS

hydrocarbon
A molecule made of hydrogen and carbon atoms. Crude oil and natural gas are mixtures of hydrocarbons of many sizes, from methane (one carbon) to asphalt (dozens of carbons).

fractional distillation
Separating a mixture by heating it so that its parts boil off at different temperatures. In a refinery tower, the smallest molecules rise highest and the heaviest stay at the bottom.

fraction
One of the groups of molecules collected from a distillation tower, such as gases, gasoline, kerosene and jet fuel, diesel, lubricating oil and residue.

cracking
Breaking large hydrocarbon molecules into smaller ones with heat, pressure or catalysts, so that more gasoline can be made from a barrel.

natural gas
Mostly methane (CH_4), the lightest hydrocarbon. It is found above oil in traps or on its own, is moved by pipeline, and is burned for heat and electricity or turned into fertilizer.

coal rank

The grade of a coal by how much carbon and heat it holds: lignite (lowest), then subbituminous, then bituminous, then anthracite (highest, hardest and shiniest).

CORE IDEAS

The story. In 1908 Henry Ford began selling the Model T, and within a few years America had a new problem: not enough gasoline. A refinery of that day simply heated crude oil and collected what boiled off, and only about one fifth of a barrel came out as gasoline. At the Standard Oil refinery in Whiting, Indiana, a chemist named William M. Burton and his colleague Robert Humphreys tried something refiners thought reckless. They heated the heavy fraction called gas oil in a sealed steel still to about 370 °C under pressure several times that of the air. The big molecules shook apart into smaller ones, and the smaller ones were gasoline. The patent was granted in January 1913, and thermal cracking roughly doubled the gasoline a refinery could wring from a barrel. The gasoline age began with a chemist who understood that a barrel of oil is a crowd of molecules of every size, which chemistry can sort and reshape.

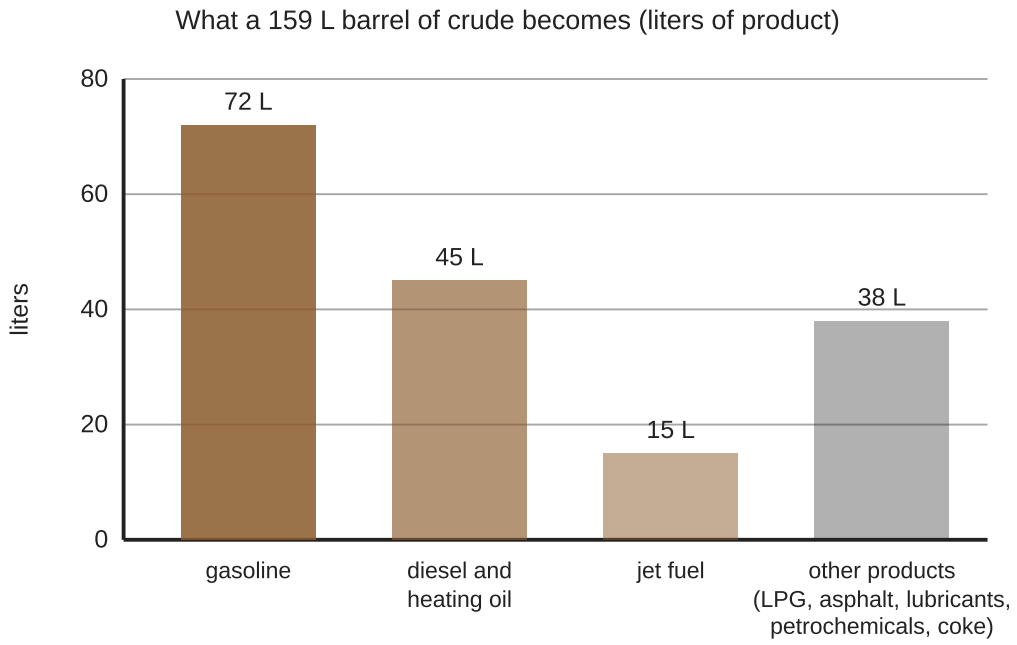
How they figured it out. A hydrocarbon molecule is a chain or ring of carbon atoms with hydrogen atoms attached. Methane, the main part of natural gas, has one carbon. Gasoline molecules have roughly five to twelve. Diesel runs from about twelve to twenty, and the thick residue at the bottom has far more. Small molecules boil at low temperatures and big ones at high temperatures, so a refinery heats the crude to about 350 to 400 °C and feeds the vapor into a tall tower that is hottest at the bottom and coolest at the top. Each fraction condenses on trays where the temperature matches its boiling range. Gases that never condense, propane and butane, come off the top below about 40 °C. Gasoline and naphtha collect from roughly 40 to 200 °C, kerosene and jet fuel from about 150 to 275 °C, diesel and heating oil from about 250 to 350 °C, and lubricating oils and heavy fuel oils below that. The residue that will not boil becomes asphalt or coke. Cracking units then break the heavy fractions into gasoline-sized pieces. A modern refinery is less a kettle than a very large chemistry set run around the clock.

The big idea. From a 159-liter barrel of crude a typical American refinery makes about 72 liters of gasoline, about 45 liters of diesel and heating oil, about 15 liters of jet fuel and about 38 liters of other products: propane and butane, asphalt, lubricants, waxes, petroleum coke and the chemical feedstocks that become plastics, synthetic rubber, nylon, polyester and many medicines. Those volumes add up to about 170 liters, more than went in, because cracking makes lighter, bulkier molecules out of dense heavy ones. At American refineries gasoline is the biggest share, a bit over 40 percent. Energy is the reason these fuels are prized. A liter of gasoline holds about 32 megajoules; a kilogram of good bituminous coal about 27 megajoules; a cubic meter of natural gas about 38 megajoules; a whole barrel of crude about 6,100 megajoules. Hydrocarbons also feed us: most nitrogen fertilizer is made from ammonia whose hydrogen comes mainly from natural gas.

In the world today. Oil is not the whole story of fuels from the earth. **Natural gas**, mostly methane, sits above oil in many traps and alone in others. It moves by pipeline, heats nearly half of American homes and generates more of the nation’s electricity than any other fuel.

Coal is a black sedimentary rock made of compressed plant material; you can often see bark and leaf patterns in a lump of it. Geologists rank coal by its carbon and heat: soft brown lignite, then subbituminous and bituminous coal, which fire most coal power plants, and hard, shiny anthracite, mined in eastern Pennsylvania, which burns hot and nearly smokeless. Baked without air, bituminous coal becomes coke, which turns iron ore into steel. Figures from the U.S. Energy Information Administration for a recent year put petroleum at about 38 percent of the energy Americans use, natural gas about 36 percent, and coal, nuclear power and renewable sources near 9 percent each. Every one of those sources needs people: refinery operators, chemical engineers, pipeline inspectors, mine engineers, geologists, welders and truck drivers.

God’s handiwork. That a single element, carbon, can bond four ways and build chains of every length, and that those chains can be sorted by nothing more than heat and gravity, is a piece of the order that Kepler and Faraday delighted to trace in creation. The Psalmist says, “The earth is the LORD’S, and the fulness thereof” (Psalm 24:1). The fulness includes the oil, the gas and the coal, and the mandate of Genesis 1:28 means using them with skill and without waste: a tight engine, a well-insulated house, a road that lasts. Stewardship is not fear of the gift but care in using it.



What a 159-liter barrel makes, in liters, at a typical U.S. refinery (approximate figures after the U.S. Energy Information Administration). The total is about 170 liters because cracking makes lighter, bulkier molecules.

PICTURE STUDY



Coalbrookdale by Night, Philip James de Loutherbourg, 1801 · Oil on canvas · Science Museum, London

Philip James de Loutherbourg, a painter born in Strasbourg who settled in London and also designed scenery for the theater, painted the ironworking valley of Coalbrookdale in Shropshire, England. There, in 1709, Abraham Darby had learned to smelt iron ore with coke, which is coal baked without air, in place of charcoal from trees. By 1801 the valley was full of furnaces that burned day and night. This painting shows the Madeley Wood (or Bedlam) Furnaces lighting up the sky.

Everything in the scene runs on coal. Coke heated the furnaces, coal-fired steam engines blew air into them, and the iron that came out built bridges, rails and engines. It is one of the first English paintings of industry, and the painter treats the furnaces as dramatically as another artist might treat a storm or a volcano.

Look closely

- Find the brightest part of the picture. What is burning there, and what fuel feeds it?
- Follow the smoke. How does the painter use it to show how much fuel is being burned?
- Find the people and animals. How large are they next to the furnaces?
- Look at the dark edges of the painting. What is the countryside like around the works?

Talk about it

1. Coal had to be turned into coke before it made good iron. From this lesson, what happens to coal when it is baked without air?
2. Why might a painter in 1801 find a furnace as worth painting as a mountain or a storm?

3. Name three things in your home made of iron or steel, and explain how coal helped make them.

> **Safety first.** Rubbing alcohol is flammable: do the evaporation test with a parent, far from any flame or stove, in a well-ventilated room, and keep the bottle capped when not pouring. Do not taste any liquid. Wipe up oil drops at once so no one slips.

EXPERIMENT: SORTING BY EVAPORATION: A KITCHEN MODEL OF THE DISTILLATION TOWER

A refinery sorts molecules by how easily they turn to vapor. You cannot boil crude oil at home, but you can race three common liquids whose molecules differ in size and stickiness and watch the lightest leave first, just as the lightest fractions rise to the top of the tower.

Question: Which liquid evaporates fastest, and does doubling the drop's spread change the time? Prediction: rank water, rubbing alcohol and cooking oil before you start, and give a reason.

You will need

- Rubbing alcohol (isopropyl), water, and cooking oil
- Three identical plates or a smooth tray, marked into three zones with masking tape
- A medicine dropper or three identical straws for making equal drops
- A stopwatch or clock with a second hand, a ruler, and a thermometer to record room temperature
- Lab notebook and pencil; a fan (optional, for a second experiment)

Steps

1. Record the room temperature. Place one drop of each liquid, the same size, in its own zone at the same moment, using the same dropper rinsed and dried between liquids (or three identical straws).
2. Measure the diameter of each drop in millimeters right away and record it.
3. Start the stopwatch. Record the time when each drop has completely disappeared. If a drop has not evaporated after 20 minutes, record "more than 1,200 s" and describe how it looks.
4. Repeat the whole race two more times. Average the three times for each liquid.
5. Second experiment, change one thing only: spread a drop of alcohol with the back of a clean spoon so it covers about twice the area, and race it against an unspread drop of the same size. Record both times.
6. Make a table: Liquid, Drop diameter (mm), Time 1, Time 2, Time 3, Average (s). Add a second small table for spread versus unspread.
7. Write a conclusion in three or four sentences: rank the liquids by evaporation time, explain the result in terms of molecule size and how strongly molecules hold one another, and connect it to which fractions leave the top of a distillation tower first.

Tips

- What we change: the liquid (and, in part two, the spread of the drop). What we keep the same: drop size, surface, room temperature, air movement, start time. What we measure: seconds to disappear.
- Alcohol molecules are small and let go of one another easily; water molecules are small but cling tightly (hydrogen bonding); cooking oil molecules are very large. Expect alcohol first, water second, oil not at all in your lifetime at room temperature, which is why heavy fractions need a hot tower.

Check your work

- I worked with a parent, away from any flame, and kept the alcohol capped.
- I ran three trials and averaged them, and changed only one variable in the second experiment.
- I can explain how my results model a distillation tower and name which real fraction each liquid is most like.

FIELD NOTEBOOK

1. Draw a distillation tower as a tall column, hot at the bottom and cool at the top, and label where gases, gasoline, kerosene and jet fuel, diesel, lubricating oil and residue are drawn off, with approximate temperatures.
2. Copy the barrel bar graph and add a fifth bar showing what a barrel yielded before cracking: about 32 liters of gasoline (one fifth of 159). Write one sentence under it about what Burton changed.
3. Record your warm-up room survey as a tally chart with categories: fuel, plastic, fiber, rubber, wax, asphalt, medicine or other. Total it.

> **From history.** The word kerosene was coined by Abraham Gesner, a physician and geologist from Nova Scotia, who in the 1840s and 1850s worked out how to distill a clear lamp oil from coal and asphalt rock. He built the name from the Greek word for wax, and his North American Kerosene Gas Light Company was selling lamp oil in New York by the mid-1850s, several years before Drake’s well. When cheap Pennsylvania crude arrived, refiners simply switched to it, and “coal oil” became a country name for kerosene that lasted into the twentieth century.

WORKED EXAMPLES

Example 1. A 159-liter barrel of crude yields about 72 L of gasoline, 45 L of diesel and heating oil, 15 L of jet fuel and 38 L of other products. (a) What total volume of products is made? (b) What percent of the products is gasoline? (c) By what percent does the volume grow during refining?

(Use the map or drawing “Read each bar’s height in liters to check the total.” shown earlier in this lesson.)

1. (a) Total: 72 + 45 + 15 + 38 = 170 L.
2. (b) Gasoline share: 72 ÷ 170 = 0.424, about 42 percent.
3. (c) Volume gain: 170 − 159 = 11 L. As a percent of the input: 11 ÷ 159 = 0.069, about 7 percent.
4. Check: the gain is small but real; it comes from cracking heavy, dense molecules into lighter, less dense ones that take up more room for the same mass.

Answer: (a) About 170 L. (b) About 42 percent. (c) About 7 percent more volume than the crude that went in.

Example 2. A family car uses 7.0 liters of gasoline per 100 km. How far can it drive on the 72 L of gasoline from one barrel? A more efficient car uses 5.0 L per 100 km; how far would it go on the same gasoline, and how much farther is that?

1. Distance = fuel ÷ rate × 100 km. First car: 72 ÷ 7.0 = 10.29; × 100 km ≈ 1,029 km.
2. Second car: 72 ÷ 5.0 = 14.4; × 100 km = 1,440 km.
3. Difference: 1,440 − 1,029 = 411 km farther on the same barrel’s gasoline.
4. Sense check: using fewer liters per 100 km must give more kilometers; 5.0 is 5/7 of 7.0, so the distance should be 7/5 = 1.4 times as far, and 1,029 × 1.4 ≈ 1,440. It is.

Answer: About 1,030 km for the 7.0 L/100 km car and 1,440 km for the 5.0 L/100 km car, about 410 km farther.

Example 3. One barrel of crude oil holds about 6,100 MJ of energy. (a) How many kilograms of bituminous coal at 27 MJ/kg hold the same energy? (b) How many cubic meters of natural gas at 38 MJ/m³? (c) A household uses about 30 kWh of electricity a day. If 1 kWh = 3.6 MJ, for how many days would one barrel's energy run the house (ignoring losses in generation)?

1. (a) Coal: 6,100 MJ ÷ 27 MJ/kg ≈ 226 kg, about a quarter of a metric ton.
2. (b) Gas: 6,100 ÷ 38 ≈ 160 m³, about the volume of a large two-car garage.
3. (c) Daily use in MJ: 30 kWh × 3.6 MJ/kWh = 108 MJ per day.
4. Days: 6,100 ÷ 108 ≈ 56 days, close to two months. (A real power plant turns only about a third of fuel energy into electricity, so the practical figure is nearer 19 days.)

Answer: (a) About 226 kg of coal. (b) About 160 m³ of natural gas. (c) About 56 days of household electricity before losses, about 19 days after typical power-plant losses.

PRACTICE

1. EASY What is fractional distillation, and which fraction comes off the top of the tower?
2. EASY Name the four main product groups from a barrel of oil and give their approximate volumes in liters.
3. EASY Put the ranks of coal in order from lowest to highest carbon content.
4. MEDIUM What did William Burton's thermal cracking do, and why did it matter in 1913?
5. MEDIUM A truck uses 12 L of diesel per 100 km. How far can it travel on the 45 L of diesel from one barrel?
6. MEDIUM Data reading. Approximate U.S. refinery yield per 42-gallon barrel, in gallons: gasoline 19, distillate (diesel and heating oil) 12, jet fuel 4, other products 10. (a) What is the total in gallons, and how does it compare with 42? (b) Convert the gasoline figure to liters (1 gallon = 3.785 L). (c) Which statement is supported? (i) Refineries destroy about 3 gallons per barrel. (ii) Refineries produce slightly more volume than they take in. (iii) Jet fuel is the largest product.
7. MEDIUM Data reading. Share of U.S. energy use by source for a recent year, rounded, from the U.S. Energy Information Administration: petroleum 38 percent, natural gas 36 percent, coal 9 percent, nuclear 9 percent, renewable sources 9 percent. (a) What share comes from oil, gas and coal together? (b) The shares add to 101 percent. Which is the best explanation? (i) An error in the data. (ii) Rounding each number to the nearest whole percent. (iii) Some energy is counted twice. (c) If the nation used about 94 quadrillion BTU in total, about how much came from natural gas? Give your answer in quadrillion BTU to the nearest whole number.
8. HARD Experiment design. You want to know whether temperature changes how fast rubbing alcohol evaporates. Describe a safe procedure, name the independent and dependent variables, two variables to control, and the number of trials. State one safety rule.

9. HARD A liter of gasoline holds about 32 MJ and a kilogram of anthracite about 30 MJ. A homeowner burns 500 kg of anthracite in a winter. How many liters of gasoline would hold the same energy, and about how many barrels' worth of gasoline is that (72 L per barrel)?
10. CHALLENGE Written explanation. In four or five sentences, explain why a refinery is better described as a chemistry set than a kettle, and give two examples of things in your own home that began as a fraction of crude oil or as natural gas. End with one sentence on what good stewardship of these resources looks like.

COMMON MISTAKES

- Thinking refineries make only gasoline. Gasoline is the largest product, a bit over 40 percent, but diesel, jet fuel, propane, asphalt, lubricants and the raw materials for plastics, fibers and medicines all come from the same barrel.
- Thinking natural gas is gasoline vapor. Natural gas is mostly methane, a one-carbon molecule found in the ground; gasoline is a liquid mixture of molecules with about five to twelve carbons made at a refinery.
- Calling coal a mineral. Coal is a rock made of compressed plant material; minerals are inorganic crystals with fixed chemical compositions. You can often see plant structures in a lump of coal.

Make it a game · Barrel Bingo. Draw a 4 by 4 grid and write a product category in each square: fuel, plastic, fiber, rubber, wax, asphalt, lubricant, medicine, paint or coating, fertilizer, cosmetic, adhesive, toy, kitchen item, electrical insulation, free space. Set a timer for four minutes and hunt the house. Each real item you can bring back or point to fills one square; you must say which fraction or source it came from (gasoline, kerosene, residue, petrochemical feedstock, natural gas). Four in a row wins; a full card earns a second round where you must name a job connected to each item.

Scripture. "The earth is the LORD'S, and the fulness thereof; the world, and they that dwell therein." (Psalm 24:1, KJV)

Everything that comes out of a barrel, and out of a gas well or a coal seam, belongs first to God. We are stewards, which is a reason both to use these gifts gladly for the good of our neighbors and to use them carefully.

Practice answers

1. Separating crude oil into groups of molecules by boiling point in a tower that is hot at the bottom and cool at the top. The gases (propane and butane) come off the top because the smallest molecules boil at the lowest temperatures.
2. Gasoline about 72 L; diesel and heating oil about 45 L; jet fuel about 15 L; other products (propane, butane, asphalt, lubricants, chemical feedstock and more) about 38 L.
3. Lignite, subbituminous, bituminous, anthracite.
4. It heated heavy gas oil under pressure to break large molecules into smaller gasoline-sized ones, roughly doubling the gasoline from a barrel, just as the Model T made gasoline demand

soar.

5. 45 ÷ 12 = 3.75; × 100 km = 375 km.
6. (a) 19 + 12 + 4 + 10 = 45 gallons, 3 more than the 42 that went in. (b) 19 × 3.785 ≈ 72 L. (c) (ii).
7. (a) 38 + 36 + 9 = 83 percent. (b) (ii). (c) 0.36 × 94 ≈ 34 quadrillion BTU.
8. Place equal drops of alcohol on identical plates in a cool room, a warm room and (with a parent) a sunny windowsill; record each spot’s temperature with a thermometer and time each drop to disappear; three trials at each temperature. Independent: temperature. Dependent: time to evaporate (s). Control: drop size, plate surface, air movement, humidity as far as possible. Safety: no flames or hot stoves anywhere near the alcohol; keep the bottle capped; ventilate the room.
9. Energy: 500 × 30 = 15,000 MJ. Gasoline: 15,000 ÷ 32 ≈ 469 L. Barrels of gasoline: 469 ÷ 72 ≈ 6.5 barrels’ worth.
10. A strong answer: a kettle only heats; a refinery sorts molecules by boiling point, then cracks heavy ones into light ones and rearranges others, so the products are chosen, not merely found. Examples: plastic containers and nylon or polyester clothing from petrochemical feedstocks; paraffin candles; asphalt shingles; fertilizer for the garden made from natural gas. Stewardship: using the gift skillfully and without waste, such as efficient engines, insulated houses and well-built roads, because the earth and its fulness are the Lord’s.

Unit 4 review

Answer each question. Show your work for calculations, label your diagram clearly, and use complete sentences for explanations. Metric units unless the question gives others. The test is worth 60 points.

1. (4 pts) Multiple choice. Which idea made Drake’s well at Titusville succeed where earlier attempts had caved in? (a) A larger steam engine. (b) Driving an iron pipe through the loose gravel to bedrock and drilling inside it. (c) A spinning rotary bit. (d) Pumping heavy mud into the hole.
2. (5 pts) Drake’s pump produced about 20 barrels a day. Convert this to liters per day (1 barrel = 159 L), and explain in one sentence what product people wanted from the oil in 1859 and why.
3. (4 pts) Multiple choice. The Spindletop oil was trapped by (a) an underground lake, (b) a flat stack of layers with no fold, (c) sandy layers tilted up against a salt dome under hard cap rock, (d) a coal seam.
4. (5 pts) The Lucas gusher flowed about 100,000 barrels per day. Convert this to liters per second (1 barrel = 159 L; 1 day = 86,400 s). Show your work.
5. (5 pts) Spindletop produced 17.4 million barrels in 1902 but had fallen to about 10,000 barrels a day by 1904. Explain why, using the words wells and pressure, and describe one thing drilling mud does in a well.
6. (8 pts) Diagram. Draw a cross-section of an anticline trap. Label the source rock, the reservoir rock, the seal, the gas, the oil, the water and a well drilled in the best place. Then write one sentence explaining why the fluids stack in the order you drew.
7. (4 pts) Multiple choice. Shale makes a good seal mainly because of its (a) high porosity, (b) very low permeability, (c) dark color, (d) high density.
8. (6 pts) A 400 cm³ block of sandstone soaks up 72 mL of water. (a) What is its porosity? (b) A reservoir of this sandstone covers 1 km by 1 km, is 10 m thick, and 60 percent of its pore space holds oil. Find the oil in place in cubic meters and in barrels (1 m³ = 6.29 barrels).
9. (5 pts) Suppose a museum sign says, “This oil formed from algae buried 150 million years ago.” In three or four sentences, state what in this claim is observed and what is interpreted, and briefly give the young-earth creation reading of the same evidence.
10. (5 pts) Data reading. Products from one 159 L barrel at a typical U.S. refinery: gasoline 72 L, diesel and heating oil 45 L, jet fuel 15 L, other products 38 L. (a) What is the total product volume? (b) What percent of the products is gasoline? (c) Why is the total more than 159 L?
11. (4 pts) Multiple choice. In a distillation tower, which fraction is collected highest, at the coolest level? (a) Asphalt residue. (b) Diesel. (c) Kerosene. (d) Gases such as propane and butane.
12. (5 pts) Name the three ranks of coal in order of increasing carbon content, and give two uses of natural gas other than heating a house.

UNIT PROJECT: FROM ROCK TO BARREL: MY OIL FIELD MODEL AND PRODUCTS POSTER

Build a clear-sided model of an oil trap (anticline or salt dome) in a jar or small aquarium using gravel, sand and clay, with a straw well and colored water and oil, and photograph or draw it with every part labeled: source rock, reservoir, seal, gas, oil, water, well. Beside it, make a poster titled “What a Barrel Makes” with a bar graph of the four product groups in liters, a drawing of a distillation tower with its fractions and temperatures, and ten household items traced back to their fraction or to natural gas or coal.

Finish with a one-page report that tells the story of either Drake’s well or Spindletop in your own words, with three correct dates and two calculations (such as a flow rate in liters per second or a porosity), and a short paragraph that states fairly what museum signs say about how oil formed, what is actually observed, and how a young-earth Christian reads it.

- **Model and diagram**: The trap model works (oil collects under the seal) and the labeled drawing or photograph names all seven parts correctly.
- **Data and calculations**: The bar graph, tower diagram and two calculations use correct figures, metric units and clear work.
- **History and fairness**: The report gives accurate dates and people, and the paragraph on origins states the mainstream claim, the observations and the creation reading fairly and respectfully.
- **Care and presentation**: The poster and report are neat, well organized and easy to read, with sources named where figures were checked.

Answer key

1. (b).
2. 20 × 159 = 3,180 L per day. They wanted kerosene for lamps, because whale oil was scarce and costly and candles were dim; there were no cars, so gasoline was at first a leftover.
3. (c).
4. 100,000 × 159 = 15,900,000 L/day; ÷ 86,400 ≈ 184 L/s.
5. Hundreds of wells were crowded onto one hill, and each drew down the same reservoir pressure, so the pressure that pushed oil up was drained in a few years, leaving much oil behind. Drilling mud carries chips up, cools the bit, supports the walls of the hole, and its weight holds back oil and gas to prevent a blowout (any one).
6. Layers arched upward; shale seal over a sandstone reservoir; within the reservoir, gas at the crest, oil below it, water below the oil with a level oil-water contact; a dark organic shale source rock beneath; the well drilled at the crest into the oil. The fluids stack by density: gas is lightest, then oil, and salty water is heaviest, so each floats on the one below.
7. (b).
8. (a) 72 ÷ 400 = 0.18 = 18 percent. (b) Bulk volume 1,000 × 1,000 × 10 = 10,000,000 m^3; pore volume × 0.18 = 1,800,000 m^3; oil × 0.60 = 1,080,000 m^3; × 6.29 ≈ 6,800,000 barrels, about 6.8 million.
9. Observed: oil contains molecules from living things such as algae, source rocks are rich in organic carbon, and heat and pressure can turn such material into oil, as laboratory experiments show in hours to weeks. Interpreted: the 150 million years, which is calculated

from assumed slow rates of burial and heating. The young-earth reading agrees on the algae and the chemistry but sees rapid burial in the Flood of Genesis, with the oil forming in the centuries that followed. The date is a conclusion from assumptions, not a measurement.

10. (a) 170 L. (b) 72 ÷ 170 ≈ 42 percent. (c) Cracking breaks dense, heavy molecules into lighter ones that take up more volume for the same mass, so refining adds volume.
11. (d).
12. Lignite, bituminous, anthracite (subbituminous lies between lignite and bituminous; accept it if named). Natural gas: generating electricity; making ammonia for nitrogen fertilizer; also cooking, industrial heat, or fuel for vehicles.

UNIT 5

Maps and GIS

Every earth resource in this course, from soil and well water to coal and building stone, has a place, and the way to know a place is to map it. This unit teaches you to read and make the three kinds of maps a working geologist, driller, miner or forecaster uses every day: the **geologic map** that shows the rock beneath the soil, the **topographic map** that shows the shape of the land in contour lines, and the digital **geographic information system (GIS)** that stacks any number of such maps on shared coordinates and lets you ask questions of them.

You will begin in 1815 with William Smith, the blacksmith's son who read the order of England's strata in canal cuttings and colored the first geological map of a nation. You will learn how the United States Geological Survey mapped a continent in contour lines, and how a London doctor named John Snow used a hand-drawn map in 1854 to find the source of a cholera outbreak, the ancestor of every GIS. You will install the free program QGIS, or build a GIS of tracing paper if you have no computer, and finish by finding the USGS geologic map of your own county, redrawing its legend, measuring its units and checking one line of it against the real rock in a creek bank.

Throughout, you will keep two columns in your notebook: what the map *observes* (order, thickness, dip, fossils, elevation, position) and what later interpretation *adds* (the millions of years printed in a legend). The order of the strata is data that Christians of every view accept; the ages are a claim you will learn to recognize, state fairly, and set beside the young-earth reading.

BEFORE YOU BEGIN

- Can multiply and divide decimals, convert between centimeters, meters and kilometers, and compute a percent
- Can read a simple map with a compass rose, a scale bar and a legend
- Knows that sedimentary rock forms in layers and that fossils are found in it (Grade 7 or earlier)
- Can use a ruler, a protractor and a calculator

MASTERY CHECKLIST

- I can tell how William Smith used the fixed order of strata and their fossils to make the first geological map of a country, and I can correlate layers between two places using fossils.
- I can read a topographic map: find elevation, hilltops, valleys, stream direction and steep or gentle slopes from contour lines, and compute a gradient as rise over run.
- I can convert a map scale such as 1:25,000 into a metric statement and use it to measure real distances and areas.

- I can explain how a GIS stacks vector and raster layers on shared coordinates, how an attribute table works, and how GPS finds a position by timing signals.
- I can find my county's geologic map, read its legend, contacts, faults and strike-and-dip symbols, and compute the percent of the county covered by each unit.
- I can separate what a geologic map observes (order, dip, fossils) from the ages a legend adds, and state both readings fairly.

OPTIONAL BOOKS AND RESOURCES

- **QGIS (free, open-source GIS software)** (https://qgis.org/): Free for Windows, Mac and Linux. Install with a parent's permission (Lesson 5.3). The long-term release is the most stable choice for students. An OpenStreetMap basemap is built in under XYZ Tiles.
- **USGS National Geologic Map Database (MapView)** (https://ngmdb.usgs.gov/): Free. Zoom to your county in MapView and click to open the best available geologic map, from the USGS or your state survey, with its legend (Lesson 5.4 and the Unit 8 capstone).
- **USGS topoView** (https://ngmdb.usgs.gov/topoview/): Free. Browse and download every historical and current USGS topographic map of your area as an image or GeoTIFF for Lesson 5.2, or to open in QGIS.

5.1 William Smith's Geological Map (1815) ★

OBJECTIVES

- Tell how William Smith, a canal surveyor, discovered that rock layers in England lie in a fixed order and dip gently eastward, and how he turned that discovery into the first geological map of a whole country in 1815.
- State the principle of faunal succession and use fossils to correlate rock layers between two or more locations.
- Use a map scale and a dip gradient to compute real distances and depths in metric units, and distinguish what Smith observed (order) from what later textbooks added (ages).

Warm-up. Stack five slices of bread of different kinds (white, wheat, rye, or color the slices with markers on paper) and tilt the whole stack about 10 degrees. Now slice straight down through the stack with a butter knife, as if you were digging a canal. Look at the cut face. Which layer do you meet first on the high side? Which on the low side? Could you predict what is under the top slice on the low side without cutting?

Video. Coming soon. William Smith 1815 geological map, strata and fossils, Somerset Coal Canal; search the British Geological Survey, Geological Society of London, Natural History Museum (London), Oxford University Museum of Natural History, Royal Institution and USGS channels, or a short documentary clip on the map that changed the world.

KEY TERMS

stratum (plural strata)
A single layer of sedimentary rock, usually with a flat top and bottom, stacked with other layers like pages in a book.

outcrop
A place where bedrock shows at the surface, such as a cliff, quarry, road cut or stream bank, with no soil covering it.

dip
The tilt of a rock layer, measured as the angle (or gradient) at which it slopes down from horizontal, and the direction it slopes toward.

geologic map
A map that uses colors and symbols to show which rock units lie just beneath the soil, and where one unit meets the next.

principle of faunal succession
The observation that each rock layer in a sequence contains its own set of fossils, in the same order wherever the layers are found, so fossils can be used to identify a layer.

correlation

Matching a rock layer at one place with the same layer at another place, using its position in the stack, its rock type and its fossils.

CORE IDEAS

The story. In 1791 a young surveyor named William Smith was sent to measure a coal mine at High Littleton, in Somerset, England. He was a village blacksmith's son who had taught himself geometry and learned surveying at eighteen. Two years later he was hired to lay out the Somerset Coal Canal, and for six years he watched workmen dig deep cuttings through the countryside. He noticed something no one had written down. The rock layers always came in the same order: coal at the bottom, then a red marl, then a gray clay full of fossil oysters, then the honey-colored limestone Bath was built from, and so on up to the white chalk of the downs. Every layer tilted gently toward the east, so that walking east he met younger and younger rocks at the surface. He compared the layers to slices of bread and butter laid at a slant on a plate. In June 1799, at a friend's house in Bath, he dictated a table of these strata and colored his first small map of the rocks around the city.

How they figured it out. Smith's great tool was the fossil. Each stratum carried its own kinds of shells, and the same shells turned up in the same layer whether he stood in Somerset or nearly three hundred kilometers away in Yorkshire. A gray clay full of the thick, curled oyster *Gryphaea* was always the same clay. This is the **principle of faunal succession**, and it let him **correlate** layers across the whole country. For fifteen years he traveled England as a drainage engineer, examining quarries, wells, canal cuts and sea cliffs and marking each stratum on maps. Because he also knew each layer's **dip**, he could reason about rocks he could not see: if the coal came to the surface here and dipped east at a known gradient, he could tell a mine owner how deep a shaft must go a few kilometers to the east. On August 1, 1815, the London mapmaker John Cary published Smith's *A Delineation of the Strata of England and Wales, with part of Scotland*: fifteen hand-colored sheets, about 2.6 meters tall and 1.9 meters wide when assembled, at 5 miles to the inch. Each unit had its own color, shaded darker at its base to show where it rested on the layer beneath.

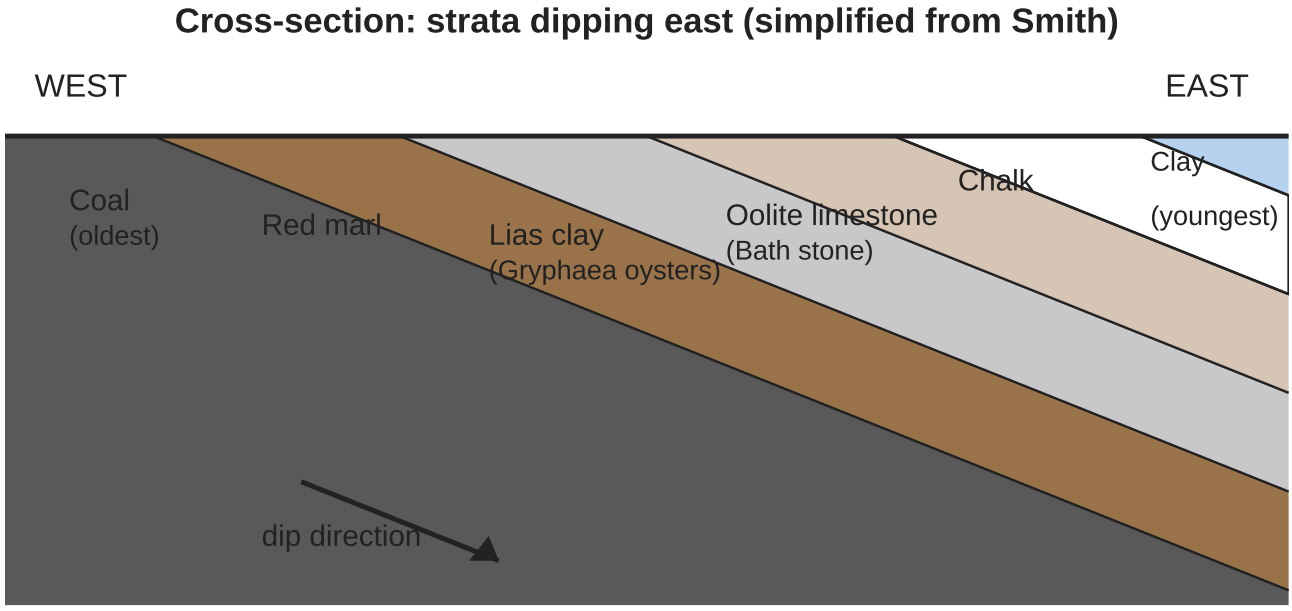
The big idea. A **geologic map** is a prediction machine. It shows the rock that lies just under the soil, and because layers continue underground along their dip, the map tells you what a well or a mine shaft will pass through. Three ideas make it work. First, strata are laid down in order, oldest at the bottom, so position in the stack tells you relative order. Second, each stratum has its own fossils, so a layer can be recognized far from where you first saw it. Third, strata dip, so a layer seen at the surface in one place is buried at a predictable depth in another. Smith used these ideas to find coal, locate water-bearing sandstone and choose building stone. Every geological survey map since, including the USGS maps of Lesson 5.4, follows his method.

Observation and interpretation. Notice what Smith measured and what he did not. He measured the *order* of layers, their *thickness*, their *dip* and their *fossils*. He did not measure how long any layer took to form, and his map has no dates on it. Later geologists attached period names and millions of years to his stack; those are interpretations resting on assumed

rates, not things seen in a canal cut. Keep the two in separate notebook columns: what was observed, and what it is thought to mean. See the ⏳ box below.

In the world today. The map did not make Smith rich. A rival Geological Society map of 1820 borrowed heavily from his work and sold for less, and in 1819 he spent about ten weeks in a London debtors' prison. He left for Yorkshire and worked as a land steward and surveyor. But the truth of the map outlasted the trouble. In 1831 the Geological Society gave him its first Wollaston Medal, and its president, Adam Sedgwick, called him the Father of English Geology. The British Geological Survey still colors its maps by the method of the blacksmith's son who read the rocks in a canal ditch.

God's handiwork. Smith could map England because the strata are orderly: the same layer, with the same fossils, runs for hundreds of kilometers and keeps its place in the stack. Job says of God, "the thing that is hid bringeth he forth to light" (Job 28:11). A geologic map brings hidden things to light; it is patient, honest looking at a world made to be understood.



Smith's slices of bread and butter: strata dipping gently east. Walking east, you cross older to younger layers at the surface, and each layer continues underground along its dip.

⏳ Thinking About Time

What the sign says. Textbooks say that Smith's ordered stack of strata became the geologic column, and that the gray clay with Gryphaea (the Lias) formed in the Jurassic, which museum signs date to about 200 million years ago.

What we observe. What we observe is what Smith observed: layers in a fixed order, each with its own fossils, dipping gently and traceable for hundreds of kilometers. No one has observed how long a layer took to form; the ages come from assumed rates applied to measurements made today.

How Christians read it. Christians who hold the young-earth reading accept Smith's order as real data and understand the great fossil-bearing stacks as laid down rapidly, much of it in the Flood year and the centuries after. Other Christians hold old-earth views and read the same column as long ages. Both agree the order is observed; the millions of years are an interpretation to be labeled as such.

Try it. Shake a jar of mixed sand, gravel and silt in water and let it settle; note the ordered layers form in minutes.

Genesis 7:11

PICTURE STUDY



A Delineation of the Strata of England and Wales, with part of Scotland, William Smith (engraved and published by John Cary), 1815 · Hand-colored engraved map on fifteen sheets, about 2.6 m by 1.9 m when assembled · Copies at the Geological Society of London, Burlington House, and the Natural History Museum, London

This is the first geological map of an entire country. William Smith colored each rock unit by hand, using about twenty colors, and shaded the base of each unit darker so the eye could follow the way layers rest on one another. The colored bands sweep across the country in long curves because the layers dip gently, mostly toward the east and southeast, and come to the surface in strips.

Along the side Smith printed a table of the strata in order, with the kinds of rock and the uses people made of them: coal, building stone, brick clay, water. He meant the map to be useful to miners, farmers, canal builders and landowners, not just to scholars.

Look closely

- Find the long band of white or pale color in the southeast. That is the chalk of the downs. Which direction do the bands run?
- Look at any single colored band. Is its lower edge darker than its upper edge? Why did Smith do this?
- Find the coal fields, printed in dark colors in the north and the west. Why would these be the oldest rocks shown, if layers dip east?
- Look at how the bands bend and curve. What would make a flat layer appear as a curved strip on the ground?

Talk about it

1. Why does a map of what is *under* the soil need colors instead of just lines?
2. If you were a mine owner in 1815, what could this map tell you that no earlier map could?
3. Smith measured order, dip and fossils but never a date. Why is it important to remember what a map does and does not show?

> **Safety first.** Use a table knife or plastic knife for slicing the model, and keep fingers behind the blade. Wash hands after handling colored dough or sand.

EXPERIMENT: STRATA IN A BOX: MAPPING HIDDEN LAYERS

You will build a tilted stack of layers, each with its own “fossil,” cut it the way canal builders cut through England, and test Smith’s claim that fossils and dip let you predict what lies underground where you have not dug.

Question: Can a marker fossil and a measured dip predict the depth of a layer at a new location? Prediction: write what you expect before you cut.

You will need

- A shoebox or small plastic tub
- Five batches of colored play dough, or layers of damp sand, flour, coffee grounds and cornmeal
- Small “fossils” that differ by layer: dried beans, lentils, rice, small pasta shapes, peppercorns
- A table knife, a ruler, a protractor
- Graph paper, colored pencils, your lab notebook

Steps

1. Prop one end of the box up about 3 cm so the floor is tilted. Press in five layers, one at a time, each about 1.5 cm thick. Mix a different “fossil” into each layer and record which fossil goes with which layer, bottom to top.
2. Set the box flat again. The layers now dip toward the low end. Measure the dip: rise over run. For example, if the stack drops 3 cm across a 20 cm box, the dip gradient is 3

÷ 20 = 0.15, or 15 percent.

3. Cut a shallow trench (your “canal”) across the high end of the box, about 2 cm deep. Draw the cut face on graph paper and label each layer by its fossil.
4. Predict: at a point 10 cm toward the low end, how deep must a “well” (a straw pushed straight down) go to reach the layer with the beans? Use depth = gradient × distance, plus the depth at the trench. Write the prediction.
5. Push the straw down at that point, pull it out, and read the layers inside it like a core. Measure where the bean layer actually begins. Record predicted and measured depth.
6. Repeat the prediction at 15 cm. Then cut a second trench at the low end and draw it. Correlate the two drawings: draw lines connecting the same layer in both cuts.
7. Change one variable: build a second box with a steeper tilt (prop it 6 cm). Keep layer thickness and fossils the same. Repeat the prediction test. Does the error grow or shrink?

Tips

- Keep layers the same thickness so the only thing you change between boxes is the dip.
- If your core is too crumbly to read, chill the dough box in the refrigerator for ten minutes first.
- Smith shaded the base of each unit darker. Do the same on your drawings so the stacking order is easy to see.

Check your work

- I can measure the dip of a layer as a gradient.
- I can predict the depth of a layer at a new place and test the prediction with a core.
- I can correlate the same layer between two cuts using its fossil.

FIELD NOTEBOOK

1. Draw a cross-section of your dough box in true proportion, with a scale bar, and label each layer with its fossil. Shade the base of each layer darker, as Smith did.
2. Copy Smith’s simplified order of English strata, chalk at the top and coal at the bottom, as a tall column. Beside each layer write one use people made of it (building stone, water, brick clay, fuel).
3. Make a two-column page titled “Observed” and “Interpreted.” Under Observed, list four things Smith measured. Under Interpreted, list two things later geologists added to his column.

> **From history.** Smith’s map was expensive, about five guineas, and only around four hundred copies were printed. In 1820 the Geological Society of London published a rival map under George Bellas Greenough that drew heavily on Smith’s work and sold more cheaply, and Smith, already in debt from buying a quarry that failed, was sent to the King’s Bench debtors’ prison in 1819 for about ten weeks. He left London and found work in Yorkshire, where he designed the round Rotunda Museum at Scarborough so that

fossils could be displayed in the order of the strata. Recognition came late: the Geological Society awarded him its first Wollaston Medal in 1831, and he received a government pension the next year. He died in 1839.

WORKED EXAMPLES

Example 1. Smith's map is drawn at 5 miles to the inch. Express this as a representative fraction and as a metric scale statement. Then find the real distance between two towns that are 12.5 cm apart on the map. (1 mile = 1.609 km; 1 inch = 2.54 cm.)

1. Representative fraction: 5 miles = 5 × 63,360 inches = 316,800 inches, so the scale is 1:316,800.
2. Metric statement: 1 cm on the map = 316,800 cm on the ground = 3,168 m = 3.17 km.
3. Real distance: 12.5 cm × 3.17 km per cm = 39.6 km.

Answer: Scale 1:316,800, or 1 cm = 3.17 km. The towns are about 39.6 km apart.

Example 2. A coal seam comes to the surface at a canal cut and dips eastward at a gradient of 1 in 25 (it drops 1 m for every 25 m you go east). A landowner wants to sink a shaft 1.5 km east of the cut. How deep must the shaft go to reach the seam?

1. Write the gradient as a decimal: 1 ÷ 25 = 0.04 (a 4 percent dip).
2. Convert the distance to meters: 1.5 km = 1,500 m.
3. Depth = gradient × horizontal distance = 0.04 × 1,500 m = 60 m.

Answer: About 60 m deep. (Smith made exactly this kind of prediction for mine owners.)

Example 3. Three canal cuttings lie in a line from west to east. Cutting 1 (west) shows, top to bottom: red marl, then coal. Cutting 2 shows: gray clay with *Gryphaea* oysters, then red marl. Cutting 3 (east) shows: limestone with fossil sea urchins, then gray clay with *Gryphaea*. Put all four rock units in order from oldest to youngest, and predict what a well at Cutting 3 would reach beneath the gray clay.

1. In each cutting the lower layer is older. Cutting 1: coal is below red marl, so coal is older than red marl.
2. Cutting 2: red marl is below the gray clay, so red marl is older than the gray clay. The red marl in Cuttings 1 and 2 correlates (same rock, same position).
3. Cutting 3: gray clay with *Gryphaea* is below the limestone, so the clay is older than the limestone. The *Gryphaea* fossil correlates the clay in Cuttings 2 and 3.
4. Combine: coal (oldest) → red marl → gray clay with *Gryphaea* → limestone with sea urchins (youngest).
5. If the sequence holds, a well at Cutting 3 drilled below the gray clay should pass next into red marl, and then into coal.

Answer: Oldest to youngest: coal, red marl, gray clay (*Gryphaea*), limestone (sea urchins). Below the gray clay at Cutting 3: red marl, then coal.

PRACTICE

1. EASY What is a stratum? Give one place near your home where you might see strata exposed.
2. EASY In what year was Smith’s map published, and roughly how tall was it when its fifteen sheets were put together?
3. EASY Smith’s strata dip gently toward the east. If you walk from west to east across England, do you meet older or younger rocks at the surface as you go? Why?
4. MEDIUM State the principle of faunal succession in one sentence. Then explain how Smith used it to match a clay layer in Somerset with a clay layer in Yorkshire.
5. MEDIUM On Smith’s map, 1 cm represents 3.17 km. Two quarries are 8.0 cm apart on the map. How far apart are they in reality? If a stratum dips 1 in 50 between them, how much deeper is the layer at the lower quarry?
6. MEDIUM Data reading. Four wells were drilled in a west-to-east line, and the depth to the top of a coal seam was recorded. Well A (0 km east): 20 m. Well B (1 km east): 60 m. Well C (2 km east): 100 m. Well D (3 km east): 140 m. Which statement is best supported by the data? (A) The seam rises toward the east. (B) The seam deepens about 40 m for every kilometer eastward. (C) The seam is horizontal. (D) The seam is thicker in the east. Then predict the depth at a well 4 km east.
7. MEDIUM Data reading. Two quarries list their layers from top to bottom. Quarry North: (1) yellow limestone with sea urchins, (2) gray clay with Gryphaea, (3) red sandstone. Quarry South: (1) gray clay with Gryphaea, (2) red sandstone, (3) coal. Which layers appear in both quarries? Which quarry exposes the oldest rock? What layer would you

expect above the limestone at Quarry North if the regional order continues upward with a white chalk?

8. HARD Experiment design. You want to test whether the dip of a layered model affects how accurately a marker layer's depth can be predicted 10 cm away. Name the independent variable, the dependent variable, two things you would keep the same, and how you would measure the result.
9. HARD Short explanation. A road map and a geologic map of the same county are the same size and show the same towns. Explain in three or four sentences why only the geologic map can help a farmer decide where to drill a water well.
10. CHALLENGE Suppose a museum label beside a Gryphaea fossil reads "Lias, Jurassic, about 200 million years old." In three sentences, separate what Smith actually observed about the Lias from what the label adds, and explain why a careful reader should label the second part as interpretation.

COMMON MISTAKES

- Thinking Smith measured the ages of rocks. He measured order, thickness, dip and fossils; the millions of years on museum labels were added later by others and rest on assumptions.
- Thinking the colors on a geologic map show the color of the soil or the plants. They stand for rock units beneath the soil, and the legend tells you which is which.
- Thinking strata lie flat everywhere. Most layers dip, which is exactly why a layer seen at the surface in one place is buried at a predictable depth a few kilometers away.

> **Make it a game · Canal Cut Challenge.** One player secretly draws a cross-section of five tilted layers on graph paper, labels each with a fossil symbol, and hides it. The other players are given only two "canal cuts": the top-to-bottom order of layers at the far left and at the far right, plus the dip gradient. They must predict the depth of a named layer at three marked points. Reveal the drawing and score a point for each prediction within one grid square. Swap roles. Bonus point for correctly naming the oldest layer.

> **Scripture.** "He cutteth out rivers among the rocks; and his eye seeth every precious thing. He bindeth the floods from overflowing; and the thing that is hid bringeth he forth to light." (Job 28:10–11, KJV)

Job 28 describes miners cutting through rock to find hidden treasure, and then says that God sees every precious thing and brings hidden things to light. Smith's map brought the hidden order of England's rocks to light. Mapping the earth honestly is one way of seeing a little of what God already sees.

Practice answers

1. A stratum is a single layer of sedimentary rock with roughly flat top and bottom, stacked with others. Examples: a road cut, a quarry wall, a creek bank, a cliff.
2. 1815; about 2.6 m tall (and about 1.9 m wide).

3. Younger. Because the layers tilt down toward the east, each younger layer that sits on top comes to the surface farther east, while the older layers beneath it are buried.
4. Each layer in a sequence of strata contains its own set of fossils, in the same order wherever the layers occur. Smith found the same fossils (such as the oyster Gryphaea) in a gray clay in both places and so recognized it as the same layer, even though he could not trace it continuously on the ground.
5. 8.0 × 3.17 = 25.4 km. Gradient 1 ÷ 50 = 0.02; depth change = 0.02 × 25,400 m = 508 m, about 510 m deeper.
6. (B). Each kilometer east adds 40 m of depth (a gradient of 40/1,000 = 0.04). The data say nothing about thickness, so (D) is not supported. At 4 km: 20 + 4 × 40 = 180 m.
7. Gray clay with Gryphaea and red sandstone appear in both. Quarry South exposes the oldest rock (coal, beneath the red sandstone). Above the limestone at Quarry North you would expect the white chalk.
8. Independent variable: the dip (tilt) of the layers. Dependent variable: the error between predicted and measured depth of the marker layer at 10 cm. Keep the same: layer thickness, the marker material, the distance to the test point, the box size. Measure: push a straw core at the test point, measure the depth where the marker layer begins with a ruler, subtract from the predicted depth, and repeat several times to average.
9. A road map shows surface features such as roads and towns but nothing about rock. A geologic map shows which rock units lie beneath the soil and how they dip. Water is stored in porous units such as sandstone, so the geologic map shows where that unit is at the surface and how deep it lies elsewhere along its dip. The farmer can therefore choose a site where the water-bearing unit is reachable at a reasonable depth.
10. Smith observed that the Lias is a gray clay with Gryphaea that always sits above the red marl and below the oolite limestone, dipping gently east. The label adds a period name and an age in years, which no one observed; they come from assumptions about how fast layers form and how fast certain atoms decay. Because the age depends on those assumptions rather than on direct measurement of the layer’s history, it belongs in the interpretation column, while the order and fossils belong in the observation column.

5.2 Topographic Maps: Reading the Shape of the Land

★

OBJECTIVES

- Explain what a contour line is, state the rules contour lines follow, and read elevation, slope, hilltops, valleys and stream direction from a topographic map.
- Convert a map scale such as 1:25,000 into a metric distance statement and use it to measure real distances on a map.
- Compute a gradient (rise over run) from contour elevations and map distance, and explain how closely or widely spaced contours show steep or gentle ground.

Warm-up. Make a fist and rest it on the table, knuckles up. With a washable marker, draw a line around your hand at the level of the table, then another line a finger's width higher, and another, up to the knuckles. Now look straight down at your fist from above. The lines you see are contour lines. Where are they close together? Where are they far apart? Which knuckle is the highest "summit"?

Video. Coming soon. How to read a topographic map, contour lines, map scale and gradient; search USGS, National Park Service, US Forest Service, Ordnance Survey (UK), Natural Resources Canada and REI or Scouting channels for beginner map-reading lessons.

KEY TERMS

topographic map
A map that shows the shape and elevation of the land using contour lines, along with streams, roads, buildings and place names.

contour line
A line on a map joining all points that are at the same elevation above sea level.

contour interval
The difference in elevation between one contour line and the next, such as 10 m or 20 m, printed in the map margin.

index contour
A heavier contour line, usually every fifth one, labeled with its elevation so you can find your place in the pattern quickly.

map scale
The ratio between a distance on the map and the same distance on the ground, written as a fraction such as 1:25,000 (1 cm on the map = 250 m on the ground).

gradient
The steepness of a slope, found by dividing the rise in elevation by the horizontal distance (rise over run), often written as a percent.

CORE IDEAS

The story. On March 3, 1879, Congress created the United States Geological Survey to classify the public lands and examine the geologic structure and mineral resources of the nation. Its second director, John Wesley Powell, was the one-armed Civil War veteran who had led the first recorded boat expedition down the Colorado River through the Grand Canyon in 1869. Powell saw at once that you cannot map rocks, water or minerals until you have mapped the shape of the ground itself. Under him the Survey sent parties of topographers into the field with plane tables, transits and steel tapes to measure the land, quadrangle by quadrangle. The project grew into about 55,000 maps at a scale of 1:24,000, each covering a rectangle 7.5 minutes of latitude by 7.5 minutes of longitude. The last sheet of that first complete series was finished in 1992, more than a century after Powell set the work going.

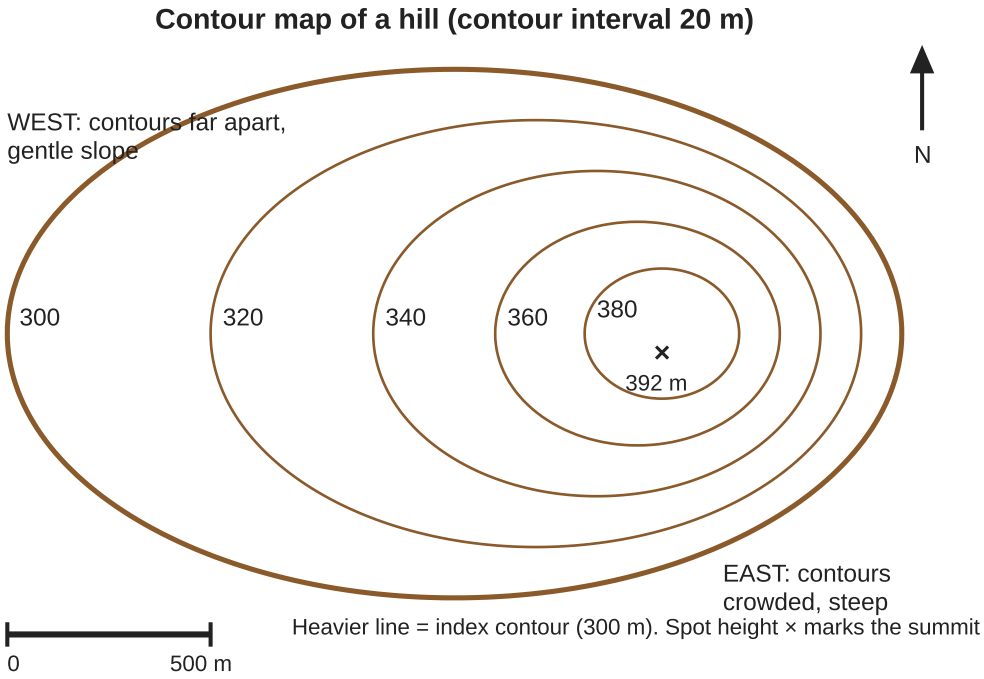
How they figured it out. The problem of a topographic map is to show height on a flat sheet. The answer is the **contour line**: a line joining every point that stands at the same elevation above sea level. Imagine the sea rising 20 meters and tracing a new shoreline around every hill, then rising another 20 meters and tracing another. Those shorelines, drawn on paper and viewed from above, are the contours of a map with a 20 m **contour interval**. The idea is older than the USGS. In the 1770s the English mathematician Charles Hutton, working out the mass of the earth from survey measurements on the Scottish mountain Schiehallion, drew lines through points of equal height and saw the shape of the mountain appear on his page. Surveyors measured elevations by triangulation and leveling and set brass *benchmarks* into rock that still mark known elevations today. Modern maps add aerial photographs and lidar, a laser scanner carried by aircraft that measures the ground to within a few centimeters.

The big idea. Contours obey rules, and the rules let you read the land. Contour lines never cross one another, because a point cannot have two elevations. Every contour closes on itself, even if it runs off your sheet. Where contours are **close together** the ground is steep; where they are **far apart** it is gentle. A hilltop is a small closed loop; a depression is a closed loop with short hachure ticks pointing inward. Where a contour crosses a stream it bends into a V, and the point of the V always points *upstream*, toward higher ground. Every fifth line is an **index contour**, drawn heavier and labeled. You can also measure. A map’s **scale** tells you how much ground one centimeter stands for: at 1:25,000, one centimeter is 25,000 cm, or 250 m. At 1:24,000, the USGS standard, one centimeter is 240 m. Combine scale with the contour interval and you can compute a **gradient**, rise divided by run, the number a road builder or well driller needs.

Try it and see. On a USGS sheet, colors carry meaning: brown for contours, blue for water, green for woods, black for buildings and roads, red for major highways. The margin gives the contour interval, the scale as a fraction and as a bar, the magnetic declination and the date. In the project you will build a model hill, flood it in steps and trace the shorelines to make your own contour map, then test whether contour spacing really predicts slope. In Lesson 5.4 you will lay a geologic map on top of a topographic one, because geologists draw rock contacts on topographic bases.

In the world today. Topographic maps are working tools in every earth-resource career in this course. The driller plotting a well, the soil surveyor walking a field, the mine engineer planning a haul road, the forecaster thinking about where cold air will pool at night in a valley: all begin with the contour map. The USGS now publishes the US Topo series, a 1:24,000 map of every quadrangle rebuilt from digital data every three years, free to download. Metric countries print their standard sheets at 1:25,000 and 1:50,000, which makes the arithmetic easy: 1 cm equals 250 m or 500 m.

God's handiwork. When God answers Job out of the whirlwind, He asks, "Who hath laid the measures thereof, if thou knowest? or who hath stretched the line upon it?" (Job 38:5). The surveyor who stretches a steel tape across a hillside is following, in a small way, a world that was measured before he arrived. The land has a shape that can be measured, drawn and trusted, and a good map is a form of truth-telling about the earth.



Contour map of a hill. Contour interval 20 m. The gentle west slope has widely spaced contours; the steep east slope has crowded contours. The summit is marked with a spot height.

PICTURE STUDY



Topographic Map of Switzerland (the Dufour Map), Guillaume-Henri Dufour and the Swiss Federal Topographic Bureau, 1845–1865 · Copper-engraved map in 25 sheets at 1:100,000, relief shown by hachures · Swiss Federal Office of Topography (swisstopo), Wabern, Switzerland; sheets viewable online

Before contour lines became standard, mapmakers showed mountains with hachures: short strokes drawn down the slope, thick and close on steep ground, thin and sparse on gentle ground. General Guillaume-Henri Dufour, head of the Swiss survey, directed the first complete map of Switzerland on this method. His engravers lit every mountain as if from the northwest, so the eye reads the Alps as solid shapes. The map won a gold medal at the Paris world's fair of 1855, and in 1863 Switzerland named its highest peak the Dufourspitze in his honor.

Hachures show steepness beautifully but cannot give you an exact elevation at any point. Contour lines can. Studying a hachured map helps you see what contour maps are trying to tell you.

Look closely

- Find the steepest-looking slopes. Are the strokes there long and thick, or short and thin?
- Find a valley floor. How did the engraver show flat ground?
- Imagine a light shining from the upper left of the sheet. Which sides of the ridges are darkest?
- Choose one peak and sketch how its contour lines would look if the map used contours instead of hachures.

Talk about it

1. What can a hachured map show well, and what can it not tell you?
2. Why might a contour map be more useful than this one to someone laying out a road or a pipeline?
3. Why do you think making a careful national map took twenty years?

> **Safety first.** Water can make floors slippery; work over a tray or sink and mop spills at once. If you shape the model hill with a knife, use a table knife and keep fingers behind the blade.

EXPERIMENT: FLOODING A HILL: MAKE YOUR OWN CONTOUR MAP

You will make a model hill, raise the water level around it in equal steps, trace each shoreline, and draw a true contour map from above. Then you will test the rule that closely spaced contours mean steep ground.

Question: Does the spacing between contours predict the measured slope of the model? Prediction: write what you expect before you start.

You will need

- A clear plastic box or large food container with straight sides
- Modeling clay, play dough or a potato cut and shaped into a hill with one steep side and one gentle side
- A ruler, a dry-erase or permanent marker, a measuring cup
- A sheet of clear plastic (a page protector or acetate) and a fine marker
- Graph paper and your lab notebook

Steps

1. Build a hill in the box, about 8 cm tall, with one steep side and one gentle side. Press it firmly so water cannot get under it.
2. On the outside of the box, mark the water levels you will use: every 1 cm from the bottom. Your contour interval is 1 cm.
3. Pour water in to the first mark. With the marker, trace the shoreline on the hill itself. Add water to the next mark and trace again. Repeat until the hill is covered.
4. Pour out the water. Lay the clear plastic across the top of the box and look straight down. Trace every shoreline you can see onto the plastic. Copy the result onto graph paper. Label each line with its elevation (1 cm, 2 cm, 3 cm and so on) and make every fifth line heavier as an index contour.
5. Measure slope directly: lay the ruler on the steep side and measure the horizontal run for a 4 cm rise; do the same on the gentle side. Compute each gradient as rise ÷ run.
6. Now measure on your map: the horizontal distance between the 2 cm and 6 cm contours on each side. Divide 4 cm by that distance. Compare with the direct measurement. How close are they?

7. Change one variable: build a second hill the same height but with a different shape (a ridge, or a hill with a saddle). Keep the interval at 1 cm and the water steps the same. Draw its map and note how the pattern changes.

Tips

- Hold the box perfectly level each time you add water, or the shoreline will not be a true contour.
- Use the same marker color for shorelines so you can count them later; use a different color for the index contours on the paper map.
- If the clay floats or leaks, weigh it down with a few coins pressed into its base.

Check your work

- I can trace shorelines to make contour lines and label them with the correct elevations.
- I can tell steep from gentle ground by contour spacing and check it against a direct measurement.
- I can compute a gradient as rise over run from my own map.

FIELD NOTEBOOK

1. Draw your flooded-hill contour map neatly in ink, with a title, a north arrow, a scale bar in centimeters and the contour interval in the margin, as a real map has.
2. Draw a small contour map of an imaginary place that includes a hilltop, a stream valley (with the V pointing upstream) and a depression with hachures. Label each feature.
3. Find your home on a free USGS topo (or a map of your area) and copy the contours within a few hundred meters of your house. Note the contour interval and estimate your home’s elevation.

> **From history.** Contour lines were first used for water, not land. In 1729 the Dutch surveyor Nicolaas Cruquius published a chart of the Merwede River with lines of equal depth, and French and Dutch engineers used such isobaths for harbors through the 1700s. Charles Hutton, computing the mass of the earth from the Schiehallion survey of 1774, drew lines of equal height across his page of surveyed points and saw the mountain take shape. By the mid-1800s the French and British surveys were adopting contours for land, and the USGS made them the standard for American maps from its first sheets in the 1880s.

WORKED EXAMPLES

Example 1. A hiking map is drawn at 1:25,000. A trailhead and a lake are 6.8 cm apart on the map. How far apart are they on the ground, in meters and kilometers?

1. At 1:25,000, 1 cm on the map represents 25,000 cm on the ground.
2. Convert: 25,000 cm = 250 m. So 1 cm = 250 m.
3. Multiply: 6.8 cm × 250 m per cm = 1,700 m = 1.7 km.

Answer: 1,700 m, or 1.7 km (measured in a straight line).

Example 2. On the contour map in the figure (interval 20 m), use the scale bar to measure the ground distance between the 300 m and 380 m contours on the steep east side and on the gentle west side. Then find the gradient of each slope as a decimal and a percent.

(Use the map or drawing "The same 80 m rise is spread over about 1,400 m on the west side and squeezed in" shown earlier in this lesson.)

1. Rise is the same for both sides: 380 m − 300 m = 80 m.
2. Measure with the scale bar (the bar is 500 m long). On the east side the 300 m and 380 m contours are about 400 m apart on the ground. Gradient = 80 ÷ 400 = 0.20, or 20 percent.
3. On the west side the same two contours are about 1,400 m apart. Gradient = 80 ÷ 1,400 = 0.057, or about 5.7 percent.
4. Compare: the east slope is about 3.5 times as steep as the west slope, and its contours are about 3.5 times as close together.

Answer: East side: about 0.20 (20 percent), steep. West side: about 0.057 (5.7 percent), gentle. Contour spacing and gradient are inversely related: closer lines, steeper ground.

Example 3. A map has a 20 m contour interval. (a) A cabin sits halfway between the 340 m and 360 m contours. Estimate its elevation. (b) A hilltop is enclosed by the 380 m contour but has no spot height. What is the range of possible elevations for the summit? (c) A trail climbs from the 300 m contour to the 380 m contour. How many contour lines does it cross, counting both?

1. (a) Halfway between 340 m and 360 m is 340 + 10 = 350 m. (Interpolating assumes the slope is even between the two lines.)
2. (b) The summit is above 380 m, but if it reached 400 m there would be a 400 m contour drawn. So the summit is at least 380 m and less than 400 m.
3. (c) Contours crossed: 300, 320, 340, 360, 380. That is 5 lines, and 4 intervals of 20 m = 80 m of climb.

Answer: (a) About 350 m. (b) Between 380 m and just under 400 m. (c) 5 contour lines, an 80 m climb.

PRACTICE

1. EASY What does a contour line show? What does the contour interval tell you?
2. EASY A map is at 1:50,000. How many meters does 1 cm on the map represent? How about 3.5 cm?
3. EASY Contours on the north side of a hill are crowded close together; on the south side they are far apart. Which side is steeper? Which side would you choose for a gentle trail?
4. MEDIUM A contour crosses a stream and makes a V shape. Which way does the point of the V aim, upstream or downstream? Explain with the rising-sea picture.
5. MEDIUM A road climbs from the 120 m contour to the 200 m contour over a map distance of 2.0 cm on a 1:25,000 map. Find the gradient as a percent.
6. MEDIUM Data reading. A student walked east along a straight line and recorded elevation every 200 m: 0 m: 410 m; 200 m: 418 m; 400 m: 450 m; 600 m: 520 m; 800 m: 528 m; 1,000 m: 530 m. (a) Which 200 m segment is steepest, and what is its gradient? (b) Between which two readings would the contours on a 20 m-interval map be farthest apart? (c) How many 20 m contours would the walker have crossed in total?
7. MEDIUM Data reading. Four maps have these scales and contour intervals: Map W 1:10,000, 5 m; Map X 1:24,000, 10 m; Map Y 1:50,000, 20 m; Map Z 1:250,000, 50 m. (a) On which map does 1 cm cover the most ground? (b) Which map shows the most detail of a small hill 300 m across? (c) A 300 m-wide hill is 60 m high. On which map would its contours be most crowded?
8. HARD Experiment design. You want to test whether the contour interval you choose changes how accurately a contour map predicts a hill’s true slope. Describe the experiment: independent variable, dependent variable, what stays the same, and what you measure.

9. HARD Short explanation. Why can two contour lines never cross on a map of the land? What single landform comes closest to making them touch, and how do mapmakers handle it?
10. CHALLENGE A well driller’s truck can safely climb a gradient of at most 25 percent. On a 1:24,000 map with a 10 m contour interval, what is the smallest spacing (in mm on the map) between neighboring contours that the truck can handle? Show your work.

COMMON MISTAKES

- Thinking that contours close together mean gentle ground. The opposite is true: crowded contours mean elevation changes quickly, so the slope is steep.
- Thinking the V of a contour at a stream points downstream. It points upstream, toward higher ground, because the contour bends uphill into the valley.
- Thinking a 1:250,000 map is a “larger-scale” map than a 1:24,000 map because the number is larger. The fraction 1/250,000 is smaller, so it is a small-scale map showing less detail.

Make it a game · Blind Summit. One player draws a secret contour map of a small landscape with a hill, a valley and a saddle (interval 10 m) on graph paper. The other players may ask only yes-or-no questions about elevations at grid points (“Is point C4 above 50 m?”). After twelve questions they must each draw the map as they imagine it, marking the summit, the valley and the steepest slope. Score three points for the summit square, two for the valley, two for the steepest side, and a bonus point if the stream V points the right way. Rotate the mapmaker.

Scripture. “Where wast thou when I laid the foundations of the earth? declare, if thou hast understanding. Who hath laid the measures thereof, if thou knowest? or who hath stretched the line upon it?” (Job 38:4–5, KJV)

God speaks of the earth as a thing measured and lined out, like a building under a surveyor’s cord. Our maps work because the land has a true shape that can be measured. A surveyor stretching a line is reading a measured world.

Practice answers

1. A contour line joins all points at the same elevation above sea level. The contour interval is the elevation difference between neighboring contour lines.
2. 1 cm = 50,000 cm = 500 m. 3.5 cm = 1,750 m (1.75 km).
3. The north side is steeper (crowded contours). The south side, with widely spaced contours, is gentler and better for a trail.
4. Upstream, toward higher ground. If the sea rose to that contour’s elevation, water would flow up the valley a little way, so the shoreline (the contour) bends uphill along the stream and points upstream.
5. Rise = 80 m. Run = 2.0 cm × 250 m = 500 m. Gradient = 80 ÷ 500 = 0.16 = 16 percent.
6. (a) The 400 m to 600 m segment: rise 70 m over 200 m, gradient 0.35 (35 percent). (b) Between the 800 m and 1,000 m readings: the rise is only 2 m, so the ground is nearly flat

and the contours would be farthest apart (no contour is crossed in that segment). (c) From 410 m to 530 m the walker crosses 420, 440, 460, 480, 500 and 520: six contours.

7. (a) Map Z: 1 cm = 2,500 m. (b) Map W: 1 cm = 100 m, so the hill is 3 cm wide and has twelve 5 m contours. (c) Map Z: the hill would be only 0.12 cm wide with one 50 m contour squeezed inside, so the lines would be most crowded (and least useful).
8. Independent variable: contour interval (for example 0.5 cm, 1 cm and 2 cm of water per step). Dependent variable: the difference between the slope computed from the map and the slope measured directly on the model. Keep the same: the same hill, box, water, viewing position and the same two sides measured. Measure: for each interval, flood and trace, draw the map, compute rise ÷ run between two contours on each side, then compare with the ruler-measured gradient. Repeat each trial at least twice.
9. A contour line marks a single elevation, so a crossing would mean one point had two elevations at once, which is impossible for a land surface. A vertical cliff comes closest: its contours run together and appear to merge. Mapmakers draw them touching or use a cliff symbol; only an overhang would truly let lines cross, and that is shown with a special symbol.
10. A 25 percent gradient means a 10 m rise over a 40 m run (10 ÷ 0.25 = 40 m). At 1:24,000, 1 cm = 240 m, so 40 m = 40 ÷ 240 cm = 0.167 cm, about 1.7 mm. Contours closer than about 1.7 mm apart mark ground too steep for the truck.

5.3 Free GIS: Layers, Coordinates and QGIS

OBJECTIVES

- Explain what a geographic information system (GIS) is, how layers of vector and raster data stack on shared coordinates, and how an attribute table links each map feature to its data.
- Describe how GPS satellites give a receiver its coordinates by timing radio signals, and compute the position error caused by a given timing error.
- Open the free program QGIS (or a paper substitute), add a basemap and a point layer, measure a distance and an area, and name three earth-resource careers that use GIS every day.

Warm-up. Take three sheets of tracing paper or clear page protectors and one printed map of your neighborhood (or a quick sketch). On the first sheet trace only the roads. On the second, mark only the places water is found: creeks, ponds, a well, a water tower. On the third, mark the homes of three people you know. Stack the sheets on the map and line up the corners. Now ask a question that needs two sheets at once: whose home is closest to water? That stack is a GIS made of paper.

Video. Coming soon. What is GIS, map layers, vector and raster data, how GPS works, QGIS beginner tutorial; search the QGIS project channel, Esri, USGS, NASA, NOAA SciJinks, Ordnance Survey and university geography department channels for short introductions.

KEY TERMS

geographic information system (GIS)
Computer software that stores map features together with data about them, so you can display them as layers, ask questions and measure.

layer
One set of map features of the same kind (roads, wells, rock units, elevation) drawn on the same coordinates so it can be stacked with other layers.

vector data
Map features stored as shapes: points (a well), lines (a road or stream) and polygons (a rock unit, a county), each defined by coordinates.

raster data
A map stored as a grid of equal cells, each holding one value such as elevation or land cover; satellite images and elevation models are rasters.

attribute table
The spreadsheet behind a vector layer: one row for each feature and one column for each fact about it, such as a well’s depth or a unit’s rock type.

coordinate reference system (CRS)

The agreed rule for turning a spot on the round earth into numbers on a flat map, such as latitude and longitude on WGS 84, the system GPS uses.

CORE IDEAS

The story. In the last days of August 1854, cholera broke out in the Soho district of London, and more than five hundred people died within about ten days. Most doctors blamed bad air. The physician John Snow believed the disease traveled in water, and he set out to prove it with a map. He learned where each victim had lived and marked every death with a short black bar at its address. The bars piled up around one spot: the public pump on Broad Street. The exceptions fit too. Workers at a nearby brewery drank the brewery's own water and were spared; a widow far away had Broad Street water carried to her because she liked its taste, and she died. On September 8 the parish removed the pump handle. Snow had done with pencil and paper what a geographic information system does today: he laid data on a map, asked a question of the pattern and found an answer that saved lives.

How they figured it out. The computer version began in Canada in the 1960s, when Roger Tomlinson built the Canada Geographic Information System to inventory the nation's land and gave the method its name. The key idea is the **layer**. Each kind of feature is stored separately, on the same coordinates: roads, streams, wells, rock units. Stack them and they line up. **Vector data** are shapes drawn from coordinates: points for wells, lines for streams, polygons for rock units or counties. Behind every vector layer sits an **attribute table**, one row per feature, with columns for whatever you know about it: a well's depth in meters, its yield, the year it was drilled. **Raster data** are grids of equal cells, each holding one number; an elevation model might use cells 30 m on a side. Because everything shares coordinates, you can ask questions a paper map cannot answer quickly: which wells lie within 500 m of a stream? How many hectares of the county are underlain by limestone?

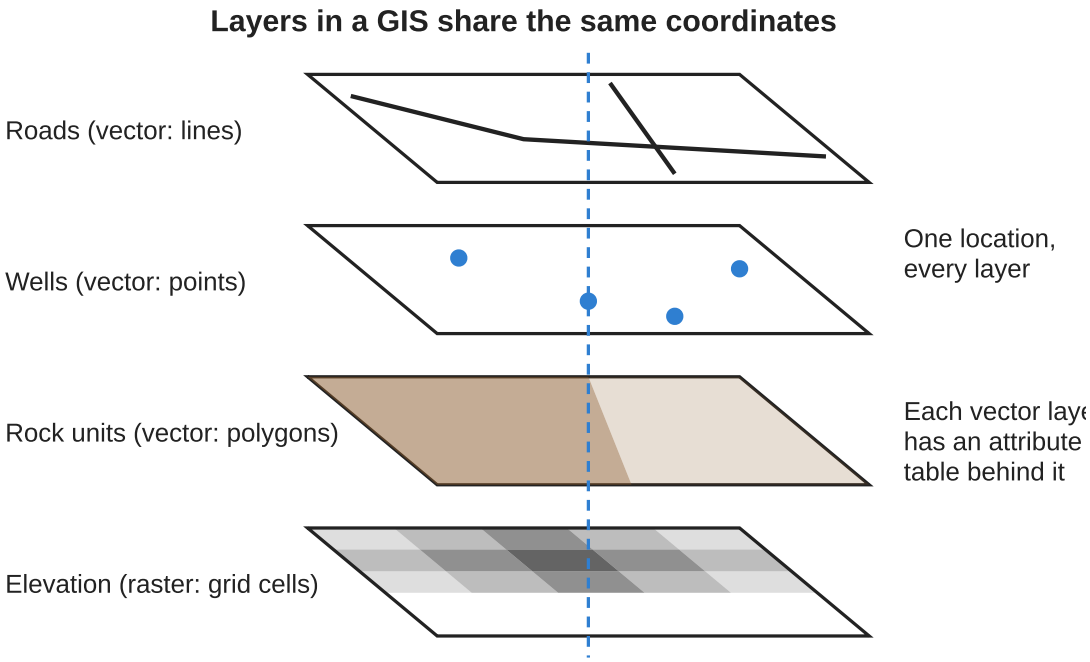
The big idea. A GIS is a map joined to a database, and the glue between them is the **coordinate reference system**. The earth is round and a screen is flat, so every layer must agree on how to flatten it. The most common starting point is latitude and longitude on the WGS 84 system, the same reference GPS receivers use. About two dozen GPS satellites circle the earth at an altitude of roughly 20,200 km, each carrying atomic clocks and broadcasting the exact time. Your receiver notes how late each signal arrives and multiplies that delay by the speed of light, about 300,000 km per second, to find its distance from each satellite. With four or more satellites it solves for its own latitude, longitude and elevation. The arithmetic is unforgiving: a timing error of one millionth of a second puts you 300 m off.

Try it and see. The best GIS for a student costs nothing. **QGIS** is free, open-source software begun in 2002 by Gary Sherman and maintained by volunteers around the world; it runs on Windows, Mac and Linux. After you install it, drag the OpenStreetMap basemap from the Browser panel (under XYZ Tiles) into the map and zoom to your town. Create a point layer, add your house, the nearest creek and a well or water tower, and type a name for each in the attribute table. Use the measuring tool to find a distance in meters and an area in hectares. Free data are everywhere: elevation and streams from the USGS National Map, geologic maps from the USGS National Geologic Map Database, roads and parcels from your county

or state GIS office. If you have no computer, the tracing-paper stack from the warm-up is a true GIS in slow motion, and the project gives a paper version of every step.

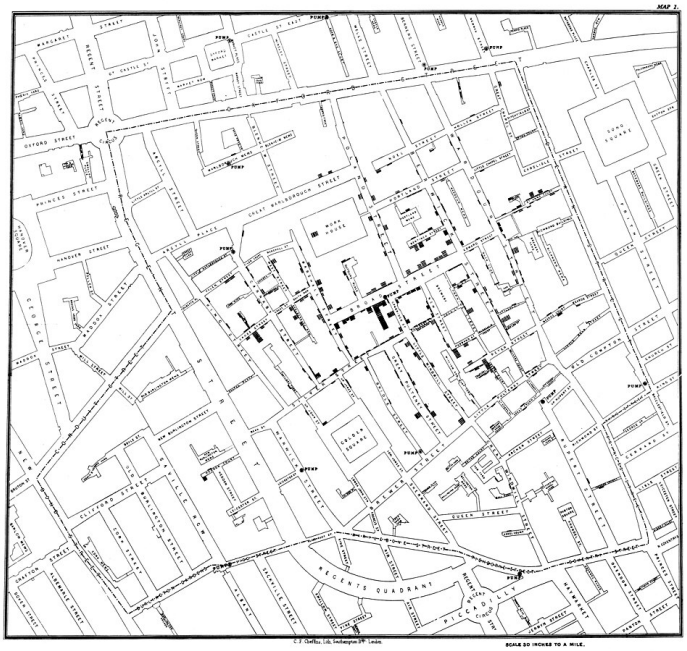
In the world today. Nearly every career in this course runs on GIS. County offices keep parcels, zoning and 911 addresses in it. Oil and gas companies map leases, wells and pipelines; mining engineers plan pits; soil scientists publish soil surveys; the National Weather Service draws its warning polygons in GIS. A GIS technician or analyst spends the day turning field notes, survey data and satellite images into layers other people can trust. The skills are the ones in this lesson: knowing what a coordinate means, keeping layers honest, and asking a map a clear question.

God's handiwork. Isaiah asks, "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?" (Isaiah 40:12). Every layer in a GIS is a small act of measuring what God has already measured completely. Snow's map healed a neighborhood because he counted carefully and told the truth about the pattern.



A GIS stacks layers on shared coordinates. Points, lines and polygons are vector data; the elevation grid is raster data. One location (dashed line) can be looked up in every layer at once.

PICTURE STUDY



Map of Cholera Deaths in Soho, London, 1854 (the Broad Street Pump Map), John Snow (lithographed by Charles F. Cheffins), 1855 · Lithograph, published in the second edition of Snow's *On the Mode of Communication of Cholera* · Copies in the Wellcome Collection, London, and in many libraries; widely reproduced

John Snow marked every cholera death of the 1854 outbreak with a short black bar at the victim's address and marked the public water pumps with small circles. The bars pile up around the pump on Broad Street and thin out toward the other pumps. It is one of the most famous maps ever made, because it used location as evidence.

Notice that Snow did not simply draw a picture. He gathered a table of facts (who died, where they lived, where they drew water) and put each fact at its coordinates. That is exactly what a GIS attribute table does. The map is a paper database.

Look closely

- Find the Broad Street pump. How do the stacks of bars change as you move away from it?
- Find the other pumps on the map. Are there many deaths near them?
- Look for a block with no bars close to the pump. Snow explained the brewery there: its workers drank the brewery's water. Why does an exception like this make the argument stronger?
- Each bar is one person. What does it mean to count carefully when every mark is a life?

Talk about it

1. What question did Snow ask of his map, and what layers of information did he combine to answer it?

2. If you redrew this map in a GIS, what would be a point layer, a line layer and an attribute column?
3. Why is a map sometimes more convincing than a table of the same numbers?

EXPERIMENT: PAPER GIS, THEN REAL GIS: MEASURING A FIELD TWO WAYS

You will build a three-layer paper GIS of a place you know, measure the area of one feature by counting raster cells, and then (if a computer is available) repeat the measurement in QGIS and compare. Without a computer, the paper half stands alone as a complete lab.

Question: How closely does a raster cell count estimate the true area of a field or pond? Prediction: write whether you think a coarse grid or a fine grid will give the closer answer, and why.

You will need

- A printed map or aerial view of your neighborhood, farm or park (a free USGS topo or a printout from an online map), ideally with a scale bar
- Three sheets of tracing paper or clear page protectors, fine markers in three colors, a ruler
- A sheet of 1 cm graph paper printed on transparency, or a grid drawn on tracing paper
- Lab notebook; a calculator
- Optional: a computer with QGIS installed from qgis.org and an internet connection, with a parent’s permission

Steps

1. Tape the map down. On sheet 1 (vector lines) trace roads and streams. On sheet 2 (vector points) mark at least six features: your home, a well or water tower, a bridge, a church, a store, a hilltop. Number them.
2. Make an attribute table in your notebook for sheet 2: columns for number, name, type, and one measurement, such as straight-line distance from home in meters (use the scale bar).
3. On sheet 3 (vector polygon) trace the outline of one field, pond, parking lot or park. This is the feature you will measure.
4. Raster method: lay the 1 cm grid over sheet 3 and count every cell more than half inside the polygon. Use the scale bar to find the ground size of one cell (for example, if 1 cm = 100 m, one cell = 100 m × 100 m = 10,000 m^2, which is 1 hectare). Area ≈ cells × cell area. Record it.
5. Repeat with a finer grid (0.5 cm cells; each is one quarter the area). Record the second estimate. Which do you predict is closer to the truth?
6. Stack all three sheets on the map, corners aligned, and ask two questions that need two layers at once. Write the questions and the answers (for example, “Which point is within 200 m of a stream?”).
7. QGIS (optional): open QGIS, drag the OpenStreetMap basemap from XYZ Tiles into the map, zoom to your area, create a new point layer and add your six points with names in

the attribute table. Then use the measure tool to trace the same field and read its area. Compare with both grid counts. Record the percent difference: (grid − QGIS) ÷ QGIS × 100.

Tips

- Line up the sheets with two registration marks (small crosses) drawn in the same corners of every layer; real GIS does this with coordinates.
- Cells on the edge of the polygon cause most of the error. Count a cell only if more than half is inside, and be consistent.
- If QGIS asks about a coordinate reference system, accept the default (EPSG:4326, WGS 84) for this first project.
- Ask a parent before installing software or searching for data; stick to USGS, state and county sites for downloads.

Check your work

- I can build layers of points, lines and a polygon on shared registration marks and keep an attribute table for them.
- I can estimate an area with a raster grid, in square meters and hectares, and explain why a finer grid changes the answer.
- I can answer a question that needs two layers at once, on paper or in QGIS.

FIELD NOTEBOOK

1. Draw a clean copy of your three-layer paper GIS as an exploded view (layers drawn slightly apart, like the figure) with the attribute table for the point layer beside it.
2. Draw the GPS idea: a receiver on the ground, four satellites, and a line from each labeled with its distance; write the speed of light and show the 300 m error for one microsecond.
3. Copy John Snow’s method as a flowchart: question, data gathered, layer drawn, pattern seen, exceptions explained, action taken.

> **From history.** The phrase “geographic information system” comes from Roger Tomlinson, an English-born geographer working in Canada. In the early 1960s the Canadian government wanted to inventory the land of the entire nation for farming, forestry and wildlife, a job that would have taken clerks years with paper overlays. Tomlinson proposed storing the maps in a computer, and the Canada Geographic Information System, begun in 1963, became the first working GIS. The same decade saw Howard Fisher found the Harvard Laboratory for Computer Graphics (1965), and Jack and Laura Dangermond start a small consulting firm called Esri in 1969 that grew into the largest GIS company in the world. QGIS, the free program in this lesson, was begun by Gary Sherman in 2002 and reached version 1.0 in 2009.

WORKED EXAMPLES

Example 1. A GPS receiver computes its distance from a satellite by timing the radio signal, which travels at about 300,000 km per second. (a) How far does the signal travel in one microsecond (one millionth of a second)? (b) How far in 10 nanoseconds (ten billionths of a second)? What does this tell you about the clocks a GPS satellite needs?

1. Write the speed in meters per second: 300,000 km/s = 300,000,000 m/s.
2. (a) One microsecond = 0.000001 s (one millionth). Distance = 300,000,000 m/s × 0.000001 s = 300 m.
3. (b) Ten nanoseconds = 0.00000001 s (one hundred-millionth). Distance = 300,000,000 m/s × 0.00000001 s = 3 m.
4. A clock error of one microsecond would place you 300 m from where you are. To locate you within a few meters the system needs clocks good to about ten nanoseconds, which is why the satellites carry atomic clocks.

Answer: (a) 300 m. (b) 3 m. Position error grows in direct proportion to timing error, so the satellite clocks must be accurate to a few billionths of a second.

Example 2. A land-cover raster uses square cells 30 m on a side. In one county, 250 cells are classed as a limestone quarry. (a) What is the area of one cell in square meters? (b) What is the quarry’s area in square meters and in hectares (1 ha = 10,000 m²)? (c) If the whole county covers 1,200 km², what percent of the county is the quarry?

1. (a) One cell: 30 m × 30 m = 900 m².
2. (b) 250 cells × 900 m² = 225,000 m². In hectares: 225,000 ÷ 10,000 = 22.5 ha.
3. (c) Convert the county to square meters: 1,200 km² × 1,000,000 m² per km² = 1,200,000,000 m². Percent = 225,000 ÷ 1,200,000,000 × 100 = 0.019 percent, about two hundredths of one percent.

Answer: (a) 900 m². (b) 225,000 m² = 22.5 ha. (c) About 0.02 percent of the county.

Example 3. Two wells are recorded in WGS 84 latitude and longitude. Well 1: 39.05° N, 95.40° W. Well 2: 38.95° N, 95.40° W. One degree of latitude is about 111 km everywhere on earth. (a) How far apart are the wells, in kilometers? (b) Express 39.05° in degrees and minutes. (c) Why could you not use the same 111 km figure for a difference in longitude?

1. (a) The wells share the same longitude, so the distance is purely north-south. Difference in latitude = 39.05° − 38.95° = 0.10°. Distance = 0.10 × 111 km = 11.1 km.
2. (b) 0.05° × 60 minutes per degree = 3 minutes. So 39.05° = 39° 03′.
3. (c) Lines of longitude converge toward the poles, so a degree of longitude shrinks from about 111 km at the equator to zero at the poles; at 39° N it is only about 86 km. Only latitude degrees are nearly constant.

Answer: (a) 11.1 km. (b) 39° 03′ N. (c) A degree of longitude gets shorter toward the poles (about 86 km at 39° N), so the 111 km rule works only for latitude.

PRACTICE

1. EASY In your own words, what two things does a GIS join together that a paper map keeps apart?
2. EASY Classify each as point, line or polygon vector data: a water well, a county boundary, a pipeline, a quarry pit, a weather station.
3. EASY What is the difference between vector data and raster data? Give one example of each.
4. MEDIUM A GPS signal arrives 0.070 seconds after it left the satellite. Using 300,000 km/s, how far away is the satellite? Does this fit the typical GPS orbit altitude of about 20,200 km?
5. MEDIUM An elevation raster has cells 10 m on a side. A pond covers 1,860 cells. Find the pond’s area in square meters and hectares.
6. MEDIUM Data reading. An attribute table for a well layer reads: Well A, depth 45 m, yield 20 L/min, distance to nearest stream 120 m. Well B, depth 110 m, yield 60 L/min, distance 850 m. Well C, depth 38 m, yield 12 L/min, distance 60 m. Well D, depth 95 m, yield 55 L/min, distance 640 m. (a) Which wells lie within 500 m of a stream? (b) Describe the relationship between depth and yield in this table. (c) Which single conclusion is NOT supported by the data: (1) deeper wells here yield more; (2) wells near streams are shallower; (3) the water in Well C is unsafe to drink.
7. MEDIUM Data reading. A county land-cover raster (30 m cells) gives these cell counts: cropland 640,000; forest 410,000; pasture 220,000; water 35,000; built-up 95,000. (a) What is the total number of cells, and the county’s area in km²? (b) What percent of the county is forest? (c) Which class covers about 2.5 percent of the county?
8. HARD Experiment design. You want to find out whether a handheld GPS (or phone) gives a less accurate position under thick tree cover than in an open field. Describe the test:

independent variable, dependent variable, what you keep the same, how you measure accuracy, and how many readings you would take.

9. HARD Short explanation. A student loads a county road layer and a USGS geologic map layer into QGIS, but the roads appear hundreds of kilometers away from the geology. In two or three sentences, explain the most likely cause and the fix.
10. CHALLENGE A GIS buffer tool draws a circle of radius 500 m around each of 12 wells to mark land that must be kept free of septic systems. (a) What is the area of one buffer in hectares (use $A = \pi r^2$, $\pi \approx 3.14$)? (b) If none of the buffers overlap, what total area is protected? (c) Two of the wells are 600 m apart. Will their buffers overlap, and how does that affect your total?

COMMON MISTAKES

- Thinking a GIS is just a program that draws pretty maps. The map is the visible part; the power is the database behind it and the questions it can answer across layers.
- Confusing GPS with GIS. GPS is a system of satellites that tells a receiver where it is; GIS is software that stores and analyzes map data. GPS points are one kind of input to a GIS.
- Thinking any coordinate pair can be dropped onto any map. Coordinates mean nothing without their coordinate reference system, and layers in different systems will not line up until they are reprojected.

> **Make it a game · Layer Detective.** One player is the GIS and holds three hidden layer cards for a made-up county: a roads card, a streams card and a wells card, each drawn on the same 6 by 6 grid. The other players are analysts. Each turn an analyst asks one query that combines two layers, such as “How many wells are within one square of a stream?” or “Which grid row has both a road and a stream?” The GIS answers truthfully. After eight queries the analysts must draw the whole map. Score one point for each feature placed in the correct square. The player who writes the sharpest query, judged by the GIS, earns a bonus point.

> **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)

God knows the earth completely, down to its dust, by measure. Our layers and coordinates are a small, honest copy of a measured creation. Measuring carefully, as John Snow did, is a way of serving our neighbors.

Practice answers

1. A map (the shapes and positions of features) and a database (a table of facts about each feature). In a GIS each feature on the map is linked to a row of data.
2. Well: point. County boundary: polygon (the county is an area). Pipeline: line. Quarry pit: polygon. Weather station: point.

3. Vector data store features as shapes made of coordinates (points, lines, polygons), such as a layer of wells. Raster data store a grid of equal cells each with a value, such as an elevation model or a satellite image.
4. Distance = 300,000 km/s × 0.070 s = 21,000 km. Yes: a satellite overhead would be about 20,200 km away, and one lower in the sky is a little farther, so 21,000 km fits.
5. One cell = 10 × 10 = 100 m². Area = 1,860 × 100 = 186,000 m² = 18.6 ha.
6. (a) Wells A and C. (b) In this table, deeper wells have higher yields: the two deepest (B, D) yield the most and the two shallowest (A, C) the least. (c) Statement (3): the table says nothing about water quality, so no conclusion about safety can be drawn from it.
7. (a) Total = 1,400,000 cells. Each cell is 900 m², so area = 1,400,000 × 900 = 1,260,000,000 m² = 1,260 km². (b) Forest = 410,000 ÷ 1,400,000 × 100 = 29.3 percent. (c) Water: 35,000 ÷ 1,400,000 × 100 = 2.5 percent.
8. Independent variable: the setting (open field versus under tree canopy). Dependent variable: position error, the distance between the GPS reading and the true position. Keep the same: the same receiver, the same time of day, the same length of time waiting for a fix, and a known true position for each spot (for example, a surveyed benchmark, a point measured carefully from a map, or the average of many readings). Measure: record latitude and longitude at least ten times at each spot, convert the differences from the true point to meters (0.00001° of latitude is about 1.1 m), and compare the average error in each setting.
9. The two layers were made in different coordinate reference systems, and one of them is labeled wrongly or not labeled at all, so QGIS cannot line them up. The fix is to find each layer’s true CRS in its documentation, assign it correctly, and let QGIS reproject both to a common system such as WGS 84. Coordinates only mean something when you know the rule that produced them.
10. (a) A = 3.14 × 500² = 3.14 × 250,000 = 785,000 m² = 78.5 ha. (b) 12 × 78.5 = 942 ha. (c) Yes: two circles of radius 500 m whose centers are 600 m apart overlap, since 600 m is less than 500 m + 500 m = 1,000 m. The real protected area is less than 942 ha because the overlapping region must be counted only once; a GIS “dissolve” operation does this automatically.

5.4 Mapping My County's Geology with a USGS Map

OBJECTIVES

- Find the geologic map of your own county from the USGS National Geologic Map Database or your state geological survey, and read its legend: unit symbols, colors, contacts, faults and strike-and-dip symbols.
- Explain how a field geologist makes a geologic map on a topographic base, and use contour elevations to find the thickness of a horizontal rock unit.
- Use map scale and area to compute the size of your county and the percent of it covered by each rock unit, and connect those units to the county's water, stone, fuel and soil.

Warm-up. Pick up a handful of gravel from a driveway or a creek bed and sort it into piles by rock type: light, dark, layered, speckled, holey. Count each pile. Now ask: where did each kind come from? A geologic map answers that question for a whole county. Keep your piles; you will compare them with the map's legend at the end of the lesson.

Video. Coming soon. How to read a geologic map, USGS geologic mapping in the field, strike and dip, National Geologic Map Database; search USGS, state geological survey channels (for example Kentucky, Kansas, Utah or Arizona), the Geological Society of America and university geology departments.

KEY TERMS

map unit
A body of rock or sediment shown as one color on a geologic map, usually a named formation, labeled with a short symbol such as Qal or Ks.

legend (explanation)
The key to a geologic map: a column of colored boxes, youngest at the top and oldest at the bottom, describing each unit, plus the meaning of every line and symbol.

contact
The boundary where one map unit meets another, drawn as a solid line where it is seen, dashed where its position is approximate and dotted where it is hidden under younger cover.

fault
A break in the rock along which one side has moved relative to the other, drawn as a heavier line, often with U and D marking the upthrown and downthrown sides.

strike and dip
The orientation of a tilted layer: strike is the compass direction of a horizontal line on the layer, and dip is the angle and direction it slopes down; shown by a T-shaped symbol with the dip angle beside it.

cross-section

A side view drawn along a line on the map (such as A to A′) showing how the units and faults continue beneath the surface.

CORE IDEAS

The story. In 1894 the United States Geological Survey published the first folio of its Geologic Atlas of the United States, covering the Livingston quadrangle in Montana. Each folio held a topographic sheet, a geologic sheet colored by rock unit, cross-sections and a written description, so that a rancher or a miner could hold the geology of a piece of country in a folder. Over fifty years the Survey published 227 of them. Behind every sheet was a geologist on foot with a hammer, a hand lens, a notebook and a Brunton compass, the pocket instrument patented by the Colorado mining engineer David Brunton in 1894 that measures both compass direction and the tilt of a surface. Walking creek beds and ridgelines, he recorded every outcrop he could find, measured the strike and dip of the beds, and plotted each observation on a topographic base map. Where rock was hidden under soil, he drew what the outcrops on either side required.

How they figured it out. Mapping is reasoning from what you can see to what you cannot. A geologist finds a sandstone in a road cut and the same sandstone in a creek bank two kilometers away and draws it as one **map unit**. The line where that sandstone meets the shale above it is a **contact**: solid where seen, dashed where approximate, dotted where soil or river gravel covers it. The **strike and dip** symbol tells how the beds tilt: a long bar along the strike, a short tick pointing down-dip, and the dip angle in degrees. Because the land has shape, contacts make predictable patterns across the contours. A horizontal bed follows a contour exactly, so its thickness is simply the difference in elevation between its top and bottom contacts. Most beds dip somewhere between, and their contacts make V’s across valleys. Where beds on one side of a line do not match those on the other, the geologist draws a **fault** and marks which side went up.

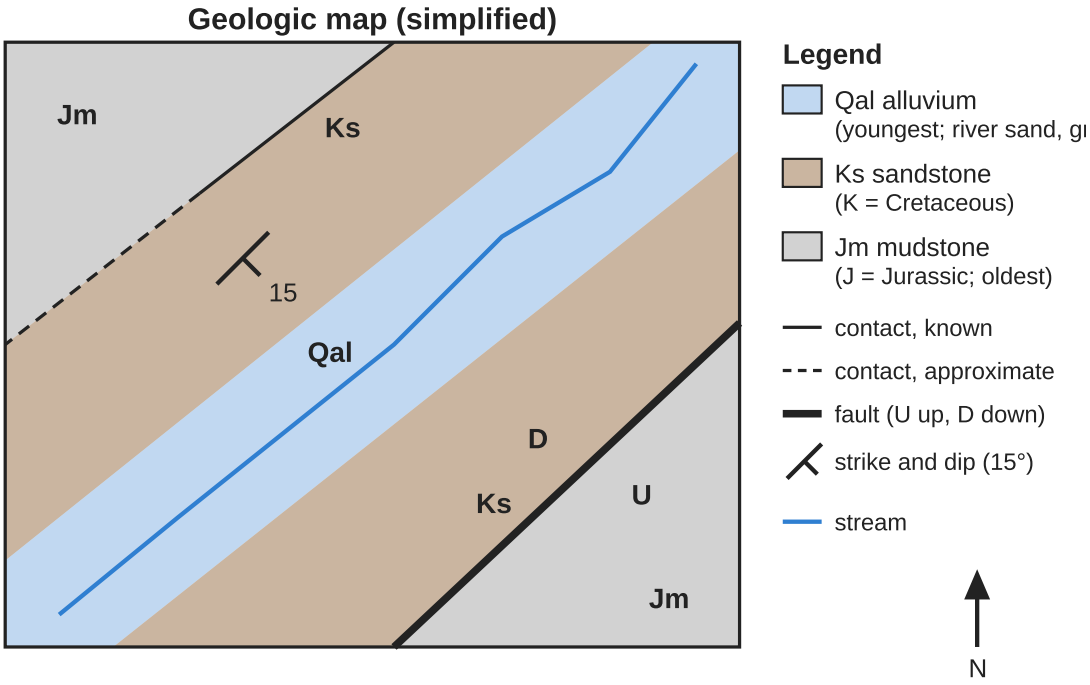
The big idea. Every geologic map comes with an **explanation**, and that is where you start. Colored boxes run down the side, youngest unit on top, oldest at the bottom, each with its symbol and description. The symbols have grammar. A capital letter gives the position in the standard column (Q for Quaternary, K for Cretaceous, J for Jurassic, P for Permian, M for Mississippian, D for Devonian, O for Ordovician), and a small letter or two names the formation: Qal is Quaternary alluvium, the river sand and gravel in valley bottoms; Kd might be the Dakota Sandstone. Colors follow a convention by position too; Quaternary deposits are usually pale yellow. These capital letters are museum words: labels for a unit’s position in the stack and the fossils it carries. Read them as labels for order, and read the millions of years attached to them as the interpretation they are; the ⏳ box sets both readings side by side. Below the legend you will usually find a **correlation of map units** showing which units sit on which, and one or more **cross-sections** showing the beds beneath the line A to A′.

Try it and see. Finding your county’s map is free. The USGS National Geologic Map Database gathers tens of thousands of maps from the USGS and the state surveys. Its MapView tool lets you zoom to your county, click, and open the best available geologic map for that spot, from detailed quadrangles at 1:24,000 to state maps at about 1:500,000. Your

state geological survey will have more, often as GIS layers you can open in QGIS. In the project you will trace the map of your county, redraw its legend in order, measure the county, estimate the share of each unit, and then go find one contact on the ground.

In the world today. Every resource in this course lives in a map unit. The aquifer that feeds your county's wells is a sandstone or limestone with a symbol in the legend. The quarry is a particular limestone bed; the coal or oil field follows particular strata; the best farmland sits on alluvium. A road engineer uses the map to avoid shale that slides, a driller to guess the depth to water before the bit turns, a soil surveyor to explain why the ground changes at the fence line. In Unit 8 you will build your county Earth-resources report on this map.

God's handiwork. When Israel came into the land, Joshua sent men "through the land, and described it by cities into seven parts in a book" (Joshua 18:9). Describing a land in a book is the oldest job of a mapper. Your county is a gift to be known, its stone, water and soil laid down in order beneath your feet, and to map it carefully is to take the gift seriously.



A simplified geologic map and its legend. Youngest unit (Qal) is listed at the top of the legend. The contact between Ks and Jm is solid where seen and dashed where approximate; the fault has lifted the older Jm to the surface on its upthrown (U) side.

⏳ Thinking About Time

What the sign says. A USGS legend lists units by period and attaches ages; a textbook says the Cretaceous spans about 145 to 66 million years ago and the Jurassic about 201 to 145 million years ago, so a unit labeled K is said to be younger than a unit labeled J by tens of millions of years.

What we observe. What we observe on the ground and the map is order and content: the K unit rests on the J unit wherever both are present, each has its own rock type and

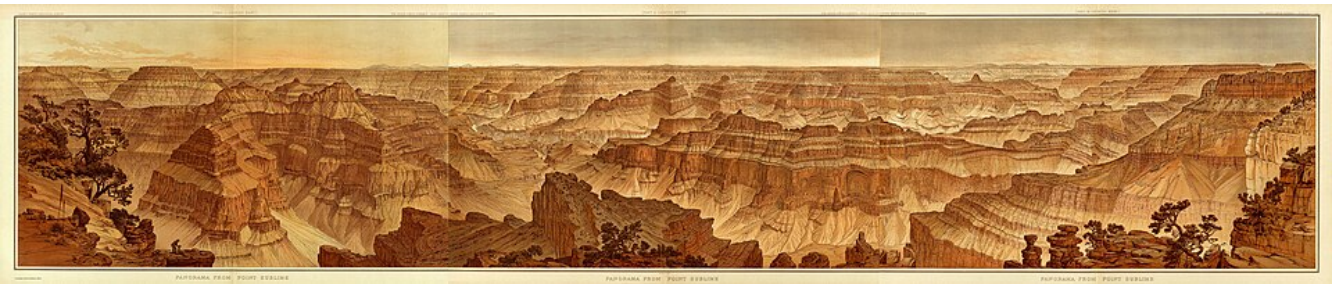
fossils, and the contacts can be walked out and measured. No one has observed the time between them; the ages are calculated from assumed rates and starting conditions.

How Christians read it. Christians who hold the young-earth reading use the same letters and the same order, and understand the thick, fossil-rich sequences as laid down rapidly, mostly during and soon after the Flood year. Some Christians hold old-earth views and accept the long ages. Both groups read the map the same way; they differ about the duration the letters stand for. Say what the sign says, then say what was observed.

Try it. Rewrite your county legend with every unit in order but with the ages left off; everything you need to find water, stone or coal is still there.

Genesis 7:19

PICTURE STUDY



Panorama from Point Sublime (Parts I–III), from the Atlas to Dutton's Tertiary History of the Grand Cañon District, William Henry Holmes, 1882 · Color lithograph by Julius Bien & Co. after drawings by Holmes, published by the U.S. Geological Survey (Monograph 2, Atlas, sheets XV–XVII) · U.S. Geological Survey Library, Reston, Virginia; copies in the Library of Congress and university libraries

William Henry Holmes was an artist who became a geologist by drawing rocks. He traveled with the Hayden Survey in the 1870s and with Clarence Dutton in the Grand Canyon in 1880, and he drew what he saw with such exactness that geologists can follow a single rock layer across kilometers of his panoramas. Where a painter might soften a cliff into mist, Holmes drew every bench, slope and ledge in true proportion.

This is what a geologic map looks like before it is a map. Each cliff-forming limestone and each slope-forming shale that Holmes drew became a colored band on Dutton's maps and a line on his cross-sections. Looking at Holmes teaches you to see a landscape as stacked units.

Look closely

- Find the alternating cliffs and slopes in the canyon wall. Which do you think are hard rock (limestone, sandstone) and which are soft (shale)?
- Follow one ledge with your finger from the foreground into the distance. Does it stay level?

- Notice how Holmes drew the far walls with the same care as the near ones. Why would a geologist want that?
- Find the flat rim surface. What single rock unit must the whole rim be made of, if the layers are nearly horizontal?

Talk about it

1. How is a drawing like this different from a photograph, for a geologist's purposes?
2. If you turned this view into a geologic map seen from above, which units would make the widest bands and which the narrowest? (Think about cliffs and slopes.)
3. Holmes drew the order of the layers exactly. What could he not draw, no matter how careful he was?

> **Safety first.** If you visit a road cut or creek bank to check the map, go with an adult, stay well off the roadway, wear sturdy shoes and safety glasses when breaking rock, and never climb loose slopes or enter fast or deep water.

EXPERIMENT: MY COUNTY ON A GEOLOGIC MAP

You will find the USGS or state geologic map of your county, redraw its legend in order, measure the county with the map scale, estimate the share of each rock unit, and then test one line on the map against the real ground.

Question: Does the map correctly predict the rock exposed at a place I can visit? Prediction: before you go, write the unit you expect to find at your chosen creek bank or road cut and one feature (color, layering, fossils) that will confirm it.

You will need

- Internet access with a parent: the USGS National Geologic Map Database MapView (ngmdb.usgs.gov) or your state geological survey's map site
- A printed geologic map of your county or quadrangle (print the legend too), or a screen and tracing paper
- Tracing paper, colored pencils matching the map's colors, ruler, calculator
- A 1 cm grid on transparency (from Lesson 5.3)
- Lab notebook; for the field check, a hammer, safety glasses, a hand lens and a bag for a sample

Steps

1. Open MapView, zoom to your county, click inside it and open the geologic map offered. Note the map's title, author, year, publisher and scale in your notebook. Print or screenshot the area and the legend.
2. Trace the county boundary and every contact inside it onto tracing paper. Color each unit to match the map. Copy the symbol (such as Qal or Ks) into each area.

3. Redraw the legend as a column: youngest at the top, oldest at the bottom. For each unit write the symbol, the name, the rock type and one practical fact (holds water, quarried for stone, slides when wet, good farmland).
4. Measure the county: using the scale, find its north-south and east-west extent in kilometers and estimate its area. Then lay the grid over your tracing and count cells for each unit. Convert to km² and percent of the county. Make a bar graph.
5. Find three resource points on your tracing: the nearest quarry, well field or public water supply, and the main farmland. Write which unit each sits on and why that makes sense.
6. Choose one contact or outcrop you can reach safely (a creek bank, road cut or quarry overlook). Write your prediction. Visit with an adult, observe the rock, sketch it, take a small sample if allowed, and record whether the map was right.
7. Compare your warm-up gravel piles with the legend. Which units could have supplied each kind of pebble? Which pebbles must have traveled from outside the county?

Tips

- If your county has only a small-scale state map (1:500,000), the units will be broad; that is normal. Note the scale in your report and say what detail is missing.
- Match colors by placing your pencil on the legend box, not the map; printing shifts colors.
- Alluvium (Qal) along rivers hides the bedrock beneath; the geologist drew its edges from the valley shape, so do not expect bedrock outcrops there.

Check your work

- I can find and cite my county's geologic map and read its legend in order.
- I can compute the county's area and the percent covered by each unit, and show it in a bar graph.
- I can predict the rock at a place from the map and check the prediction on the ground.

FIELD NOTEBOOK

1. Draw the legend of your county map as a column in order, colored to match, with the symbol and rock type for each unit and one use beside it.
2. Sketch the outcrop you visited: layers, colors, any fossils, and the contact if you saw one. Label it with the map unit symbol and write whether the map was right.
3. Draw a cross-section across your county along a straight line, using the map's own cross-section as a guide if it has one, showing how the units dip beneath the surface.

> **From history.** The first geologic map of the United States was made before Smith's map of England was published. In 1809 William Maclure, a Scottish-born merchant who had settled in America, published a colored map of the eastern United States showing its rocks in a few broad classes, after crossing and recrossing the Appalachians on horseback. In 1817 he published a revised version. Maclure later served as president of the Academy of Natural Sciences of Philadelphia for more than twenty years. State

surveys followed: North Carolina appointed the first state geologist, Denison Olmsted, in 1823, and by the time the USGS was founded in 1879 many states had already published their own geologic maps.

WORKED EXAMPLES

Example 1. On a geologic map laid over a topographic map, a limestone unit lies horizontally. Its upper contact follows the 420 m contour and its lower contact follows the 365 m contour. (a) How thick is the limestone? (b) On a hillside with a gradient of 0.20 (20 percent), how wide a band of ground, measured horizontally, does the limestone cover?

1. (a) For a horizontal bed, thickness is the elevation difference between top and bottom contacts: 420 m − 365 m = 55 m.
2. (b) Gradient = rise ÷ run, so run = rise ÷ gradient = 55 m ÷ 0.20 = 275 m.
3. On a gentler slope the same bed would make a wider band; on a cliff it would be a thin stripe. Band width on a map depends on slope as well as thickness.

Answer: (a) 55 m thick. (b) About 275 m wide on the ground. (Reminder: outcrop width is not thickness.)

Example 2. A county geologic map is drawn at 1:100,000. The county measures 38 cm east-west and 27 cm north-south on the map. (a) What are the county's real dimensions and area? (b) A 7.5-minute USGS quadrangle near 39° N covers about 11 km east-west by 14 km north-south. About how many quadrangles would you need to cover the county at 1:24,000?

1. (a) At 1:100,000, 1 cm = 100,000 cm = 1,000 m = 1 km. So the county is 38 km by 27 km. Area ≈ 38 × 27 = 1,026 km².
2. (b) One quadrangle covers about 11 × 14 = 154 km². Quadrangles needed ≈ 1,026 ÷ 154 ≈ 6.7.
3. Because the county edges will not line up with quadrangle edges, you would need at least 7; usually 9 to 12 sheets touch a county of this size.

Answer: (a) About 38 km by 27 km, roughly 1,030 km². (b) At least 7 quadrangles, and in practice 9 or more because of partial sheets along the edges.

Example 3. Grid counting on a county tracing gives these areas: limestone 410 km², shale 308 km², sandstone 205 km², alluvium 103 km². The county's total area is 1,026 km². Find the percent of the county covered by each unit and check that the percents add to about 100. Which unit would you expect to hold the county's main aquifer, and which its best farmland?

1. Limestone: 410 ÷ 1,026 × 100 = 40.0 percent.
2. Shale: 308 ÷ 1,026 × 100 = 30.0 percent.
3. Sandstone: 205 ÷ 1,026 × 100 = 20.0 percent.
4. Alluvium: 103 ÷ 1,026 × 100 = 10.0 percent.
5. Check: 40 + 30 + 20 + 10 = 100 percent. Draw four bars of heights 40, 30, 20 and 10.
6. Porous, permeable units store water: the sandstone (and limestone, if it has caves and cracks) would be the aquifer; shale is too tight. Alluvium along the rivers makes deep, level, well-watered soil and is usually the best farmland.

Answer: Limestone 40 percent, shale 30 percent, sandstone 20 percent, alluvium 10 percent (total 100 percent). Likely aquifer: sandstone (or fractured limestone). Best farmland: the alluvium.

PRACTICE

1. EASY In the symbol "Qal," what does the Q stand for and what does "al" stand for? Where in a county would you expect to find this unit?
2. EASY On a geologic map, what is the difference between a solid contact line, a dashed one and a dotted one?
3. EASY In which order are the units listed in a geologic map legend, top to bottom? Why?
4. MEDIUM A strike-and-dip symbol shows a long bar running north-south, a short tick pointing east and the number 12. Describe the layer's orientation in a sentence. If you drilled a well 1 km east of the symbol, would the layer be shallower or deeper than at the symbol?
5. MEDIUM A horizontal sandstone has its base at the 250 m contour and its top at the 290 m contour. How thick is it? On a slope with gradient 0.10, how wide is its outcrop band?
6. MEDIUM Data reading. A legend lists, top to bottom: Qal, alluvium, 0–15 m, sand and gravel; Ks, sandstone, 60 m, porous, yields water; Km, mudstone, 90 m, gray, impermeable; Jl, limestone, 40 m, cavernous, yields water. A well drilled where Qal is at the surface logs: gravel 0–10 m, sandstone 10–70 m, gray mudstone 70–160 m, limestone 160 m to bottom. (a) Does the well log match the legend thicknesses? (b) At what depth would the driller first reach a water-bearing unit, and which one? (c) Why might a driller continue past the first aquifer to 160 m?
7. MEDIUM Data reading. Four stations across a county recorded strike and dip of the same sandstone: Station 1 (west edge): strike N–S, dip 8° E. Station 2: strike N–S, dip 8° E.

Station 3: strike N–S, dip 9° E. Station 4 (east edge): strike N–S, dip 8° E. (a) What simple structure do the data describe? (b) Where in the county is the sandstone deepest underground? (c) Which station's reading would you want to re-measure, and why?

8. HARD Experiment design. You want to test how well the county geologic map predicts the rock at the surface. Describe a fair test: how you would choose sites, what you would record at each, what counts as a correct prediction, and how you would report the result as a number.
9. HARD Short explanation. On a map, the sandstone unit makes a band 2 km wide on the gentle west side of a ridge and only 200 m wide on the steep east side. A student concludes the sandstone is ten times thicker on the west. In three sentences, explain the error.
10. CHALLENGE A coal-bearing unit reaches the surface along a north-south line and dips 5° east. A dip of 5° is a gradient of about 0.087 (the bed drops 8.7 m for every 100 m you go east). A town sits 2.0 km east of the outcrop line, and the ground there is 30 m lower than at the outcrop. How deep below the town's surface is the top of the coal unit?

COMMON MISTAKES

- Thinking the colors on a geologic map show what the rocks actually look like. They follow a convention by position in the column; the legend gives the real rock types and colors.
- Thinking a wide band on the map means a thick bed. Outcrop width depends on slope and dip as well as thickness; a thin bed on flat ground can cover kilometers.
- Thinking every line on a geologic map is a fault. Most lines are ordinary contacts between units that were laid down one on another; faults are drawn heavier and marked separately.

> **Make it a game · Legend Lottery.** Write the symbols of six map units from your county (or the figure) on slips of paper and put them in a cup. Players take turns drawing a slip and, in thirty seconds, must state three things about that unit from memory: its rock type, whether it is above or below one named neighbor, and one resource or hazard tied to it. One point for each correct fact, confirmed from the legend. Draw a blank slip marked "fault" and you must explain which side went up on the figure for two points. First to twelve points wins.

> **Scripture.** "And the men went and passed through the land, and described it by cities into seven parts in a book, and came again to Joshua to the host at Shiloh." (Joshua 18:9, KJV)

Joshua's surveyors walked the land and wrote down what they found before it was divided among the tribes. A geologic map is a land described in a book. Describing your own county faithfully is the first step toward using its gifts well.

Practice answers

1. Q is Quaternary, the top (youngest) position in the standard column; al is alluvium, river-deposited sand, silt and gravel. It is found along stream and river valleys.
2. Solid: the contact was observed and its position is well known. Dashed: the position is approximate. Dotted: the contact is concealed beneath younger deposits such as alluvium or soil.
3. Youngest at the top, oldest at the bottom, matching the order the layers lie in the ground (younger layers rest on older ones).
4. The layer strikes north-south and dips 12 degrees down toward the east. One kilometer east, the layer would be deeper, because it slopes downward in that direction.
5. Thickness = 290 − 250 = 40 m. Band width = 40 ÷ 0.10 = 400 m.
6. (a) Yes: gravel 10 m (within 0–15), sandstone 60 m (10 to 70), mudstone 90 m (70 to 160), then limestone, all as the legend predicts. (b) At 10 m, the top of the Ks sandstone. (c) The Jl limestone below the impermeable mudstone is a second, protected aquifer that may yield more water or cleaner water than the shallow sandstone, which is open to surface contamination.
7. (a) A uniformly tilted sequence: beds strike north-south and dip gently east across the whole county, like Smith's strata. (b) At the east edge, since the beds slope down toward the east. (c) Station 3, because its 9° reading differs slightly from the others; it may be a real local change or a small measurement error, and one repeat would tell.
8. Choose sites before looking at them, for example every road cut or creek bank along one road, so you do not pick only easy ones; aim for at least ten sites spread across several units. At each site write the predicted unit from the map first, then record rock type, color, layering and fossils, and photograph or sketch it. Count a prediction correct if the observed rock matches the legend description of the predicted unit. Report the percent correct (correct sites ÷ total sites × 100) and note any pattern in the misses, such as sites near contacts or under thick soil.
9. Outcrop width depends on both the thickness of the bed and the slope of the ground it crosses. On a gentle slope a bed of fixed thickness spreads over a long horizontal distance, while on a steep slope the same bed is crossed in a short distance. The sandstone is most likely the same thickness on both sides; the band is wider on the west only because the ground there is gentler.
10. Drop of the bed over 2,000 m: 0.087 × 2,000 = 174 m below the outcrop elevation. The town's surface is already 30 m lower than the outcrop, so the depth below the town is 174 − 30 = 144 m, about 145 m.

Unit 5 review

Answer each question. Show your work for calculations, use metric units, and write complete sentences for explanations. For the diagram question, draw neatly and label everything. The test is worth 60 points.

1. (4 pts) Multiple choice. William Smith’s most important discovery for making a geological map was that: (A) all rock layers in England lie perfectly flat; (B) each stratum contains its own fossils in a fixed order, so layers can be matched across the country; (C) coal is always found beneath chalk; (D) the age of each layer can be read from its color.
2. (4 pts) Multiple choice. On a topographic map, contour lines that are very close together show: (A) a flat plain; (B) a lake; (C) a steep slope; (D) a river flowing downhill.
3. (4 pts) Multiple choice. Which of these is raster data in a GIS? (A) a layer of water wells as points; (B) a layer of county roads as lines; (C) a grid of 30 m cells each holding an elevation value; (D) a layer of rock units as polygons.
4. (4 pts) Multiple choice. On a USGS geologic map the symbol Qal means: (A) a quartz layer; (B) Quaternary alluvium, the river sand and gravel in valley bottoms, the youngest unit; (C) a fault zone; (D) the oldest rock in the county.
5. (6 pts) On Smith’s map, 1 cm represents 3.17 km. Two towns are 15 cm apart on the map. (a) How far apart are they in kilometers? (b) A stratum dips 1 in 40 between them (it drops 1 m for every 40 m). How much deeper is the stratum at the second town than at the first? Show your work.
6. (6 pts) A map is drawn at 1:25,000. A trail climbs from the 240 m contour to the 300 m contour over a map distance of 1.6 cm. Find the ground distance and the gradient as a percent. Show your work.
7. (6 pts) (a) A GPS receiver’s clock is off by 2 microseconds (0.000002 s). Using a signal speed of 300,000 km/s, how far off could its computed position be? (b) A land-cover raster uses 30 m cells; 400 cells are classed as gravel pit. What is the pit’s area in hectares?
8. (6 pts) A geologic map shows a strike-and-dip symbol with its long bar running north-south, a short tick pointing west, and the number 20. Explain in two or three sentences what this tells you about the rock layer, and whether a well drilled 500 m west of the symbol would reach the layer at a shallower or a deeper depth than at the symbol.
9. (6 pts) Suppose a geologic map legend lists a sandstone as “Cretaceous, about 100 million years old,” resting on a shale labeled Jurassic. In three or four sentences, separate what a geologist actually observed about these two units from what the legend adds, and explain how a Christian who holds the young-earth reading uses the same map.
10. (6 pts) Data reading. An attribute table for a well layer reads: Well 1, depth 40 m, yield 15 L/min, distance to nearest stream 90 m. Well 2, depth 120 m, yield 70 L/min, distance 700 m. Well 3, depth 55 m, yield 25 L/min, distance 300 m. Well 4, depth 100 m, yield 60 L/min, distance 950 m. (a) Which wells lie within 500 m of a stream? (b)

State the relationship between depth and yield shown in this table. (c) A student concludes that Well 1’s water is contaminated. Is that supported by the table? Explain.

11. (8 pts) Diagram. Draw a contour map of a single hill using a 20 m contour interval. Requirements: (1) at least five labeled contours from 300 m to 380 m; (2) a steep east side and a gentle west side, shown by contour spacing; (3) a small stream valley on the north side, with the contours bending into V’s that point the correct way; (4) a spot height for the summit between 380 m and 400 m; (5) a north arrow, a scale bar in meters and the contour interval written in the margin.

UNIT PROJECT: MY COUNTY IN LAYERS: A GEOLOGIC MAP REPORT

Produce a layered map report of your own county. Layer 1 is your tracing of the USGS or state geologic map with a legend redrawn in order, each unit colored and described (rock type, thickness, one use or hazard). Layer 2 is a topographic tracing of the same area on tracing paper or a QGIS screenshot, showing the main rivers, the highest and lowest points with elevations, and one measured gradient. Layer 3 marks the county’s resources: wells or water supply, quarries, mines or oil and gas fields, and the best farmland, each placed on its map unit.

Include a table and bar graph of the percent of the county covered by each unit, a hand-drawn cross-section along one line, your field check of one outcrop with a sketch and a verdict on whether the map was right, and a one-page essay that keeps observation and interpretation in separate paragraphs: what the map shows was measured, and what the legend’s ages add. This report becomes the base map for your Unit 8 capstone.

- **Map accuracy**: County boundary, contacts, unit symbols and colors match the source map; the source map is cited with title, author, year and scale; the legend is in correct order, youngest at top.
- **Measurement**: County area, percent of each unit, one gradient and the cross-section are computed correctly in metric units with work shown; the bar graph is labeled and matches the table.
- **Field check and reasoning**: A prediction was written before the visit, the outcrop is sketched and described, and the report states plainly whether the map was right and why resources sit on the units they do.
- **Observation and interpretation**: The essay clearly separates what the map observes (order, dip, fossils, elevation) from the ages the legend adds, states the textbook claim fairly, and gives the young-earth reading respectfully.

Answer key

1. (B). Faunal succession let Smith correlate strata far apart. (A) is false since the layers dip; (C) confuses one local order with a rule; (D) is false, Smith measured no ages.
2. (C). Close spacing means elevation changes quickly over a short distance, so the ground is steep.
3. (C). A raster is a grid of equal cells with one value each. The others are vector data (points, lines, polygons).

4. (B). Q marks the top (youngest) position in the column and al stands for alluvium.
5. (a) 15 × 3.17 = 47.6 km, about 48 km. (b) Gradient = 1 ÷ 40 = 0.025. Depth change = 0.025 × 47,600 m = 1,190 m, about 1.2 km deeper.
6. 1 cm = 250 m, so 1.6 cm = 400 m. Rise = 300 − 240 = 60 m. Gradient = 60 ÷ 400 = 0.15 = 15 percent.
7. (a) 300,000,000 m/s × 0.000002 s = 600 m. (b) One cell = 900 m^2; 400 × 900 = 360,000 m^2 = 36 ha.
8. The layer strikes north-south (a horizontal line on the bed runs north-south) and dips 20 degrees down toward the west. The number is the dip angle. Because the layer slopes down to the west, a well 500 m west would reach it deeper than at the symbol.
9. The geologist observed the order (the sandstone rests on the shale), the rock types, their thicknesses and dips, and the fossils each contains. The legend adds period names and an age in years, which were not observed but calculated from assumed rates; those belong in the interpretation column. A Christian holding the young-earth reading accepts the observed order and uses the same symbols, contacts and dips to find water or stone, while understanding the thick fossil-bearing sequence as laid down rapidly, mostly in the Flood year, and labeling the millions of years as the textbook's claim rather than a measurement. Some Christians hold old-earth views; both read the map itself the same way.
10. (a) Wells 1 and 3. (b) Deeper wells have higher yields: the two deepest (2 and 4) yield the most, the two shallowest (1 and 3) the least. (c) No. The table has no column about water quality, so nothing in it supports a conclusion about contamination; a water test would be needed.
11. A correct drawing shows closed, non-crossing contours labeled 300, 320, 340, 360 and 380 m, crowded on the east side and widely spaced on the west; on the north side the contours bend into V's whose points aim upstream, toward the summit; a summit mark with an elevation such as 392 m inside the 380 m contour; a north arrow, a scale bar labeled in meters, and "contour interval 20 m" in the margin. Award 2 points for correct labels and non-crossing contours, 2 for steep/gentle spacing, 2 for the stream V's pointing uphill, 1 for a valid spot height, 1 for arrow, scale bar and interval.

UNIT 6

Weather Careers

Every day, several thousand people in the United States go to work to watch the sky so that the rest of us do not have to. In this unit you will meet them: the observer sergeants who telegraphed the first synoptic weather readings on November 1, 1870; the two Air Force officers who dared to write the first tornado forecast at Tinker Air Force Base in 1948; the Weather Bureau observer at Kitty Hawk whose letter sent the Wright brothers to the beach where they would fly; and the volunteers, from Thomas Jefferson on July 4, 1776 to a Nebraska farmer who read his gauge for 76 years, whose notebooks are the memory of the American climate.

Along the way you will do the work yourself. You will build a barometer and track a pressure fall, measure a storm's speed from the National Weather Service radar and predict when it arrives, decode an airport weather report and calculate a crosswind, and score a week of official forecasts against the simplest forecast of all, "tomorrow like today." Every lesson includes real numbers: ascent rates, lapse rates, flash-to-bang distances, Enhanced Fujita wind speeds, altimeter errors and mean absolute error.

The unit ends with an interview. With a parent's help you will sit down with a forecaster, pilot, observer, farmer or emergency manager and ask what the weather has taught them. "Seest thou a man diligent in his business? he shall stand before kings" (Proverbs 22:29). The sky God made is orderly enough to be measured and surprising enough to keep its watchers humble, and the people who study it for a living are worth knowing.

BEFORE YOU BEGIN

- Can multiply and divide decimals, find a percent and convert between units (m, km, s, min, h)
- Knows that warm air rises, that air has pressure, and what a front is
- Can read a line graph, a bar graph and a data table
- Can use sine and cosine values from a table for 30°, 45°, 60° and 90°

MASTERY CHECKLIST

- I can tell how the national weather service began in 1870 and how observations from stations, balloons, radar and satellites become a forecast, a watch and a warning.
- I can calculate a balloon's ascent time, a lapse rate and a rate of pressure change.
- I can name the four ingredients of severe thunderstorms, label a supercell, and find a storm's speed and arrival time from radar positions.
- I can explain what Doppler radar adds, tell who issues watches and who issues warnings, and tell the story of the first tornado forecast in 1948.
- I can decode a METAR, calculate airspeed, a crosswind component, a cloud base and an altimeter error, and explain why the Wrights chose Kitty Hawk.

- I can describe the main weather careers, conduct and write up an interview with a weather professional, and verify a week of forecasts with mean absolute error.

OPTIONAL BOOKS AND RESOURCES

- **NWS JetStream, an online school for weather** (https://www.weather.gov/jetstream/): Free. The National Weather Service's own weather course, with clear pages on the atmosphere, thunderstorms, radar and how forecasts are made. Use it alongside Lessons 6.1 and 6.2.
- **NWS National Radar** (https://radar.weather.gov/): Free. The live Doppler radar for the whole country. Needed for the storm-speed project in Lesson 6.2; the loop button shows the last hour of motion.
- **NWS Aviation Weather Center** (https://aviationweather.gov/): Free. Current METAR observations and TAF forecasts for every airport, used in Lesson 6.3 to decode a real report for the airport nearest your home.

6.1 The National Weather Service: Telegraphs, Balloons and Radar, 1870 to Today ★

OBJECTIVES

- Tell how the national weather service began in 1870 under the Army Signal Service and how it became today's National Weather Service within NOAA.
- Describe the chain of a modern forecast: surface stations, weather balloons, radar and satellites feeding computer models and the local forecast office that issues watches and warnings.
- Calculate a balloon's ascent time, a lapse rate from a radiosonde profile, and a rate of pressure change from a station's hourly readings.

Warm-up. Before you look at any forecast, step outside for two minutes and be the station. Write down: the sky (clear, partly cloudy, overcast), the wind direction (face into it and use a compass or the sun), a rough wind strength (calm, light, breezy, strong), and the feel of the air (dry, muggy, cold). Then check the National Weather Service page for your town at weather.gov. How many of your four observations agree with the official station? Which one was hardest to judge by eye?

Video. Coming soon. History of the National Weather Service from the 1870 Army Signal Service to NOAA; how a weather balloon and radiosonde are launched; how NEXRAD Doppler radar works (search NOAA, National Weather Service office channels, NOAA SciJinks, Smithsonian, SciShow and university meteorology channels).

KEY TERMS

National Weather Service (NWS)
The United States government agency, part of NOAA, that observes the weather, issues forecasts and warns the public. It began in 1870 under the Army Signal Service and took its present name in 1970.

synoptic observation
A weather reading taken at the same moment at many stations so that a map of the whole region can be drawn. The first American synoptic observations were telegraphed on November 1, 1870.

radiosonde
A small instrument package carried up by a weather balloon that radios back temperature, humidity and pressure while its position is tracked to find the wind.

lapse rate
How fast the air cools with height, in degrees Celsius per kilometer. In the lower atmosphere it averages about 6.5 °C per km.

Doppler radar

A radar that measures not only where rain and hail are but also how fast they move toward or away from the antenna, which reveals wind and rotation inside a storm.

watch and warning
A watch means conditions are favorable for dangerous weather over a large area in the coming hours; a warning means the danger is happening or about to happen in a specific place, so act now.

CORE IDEAS

The story. On February 9, 1870, President Ulysses S. Grant signed a joint resolution of Congress ordering the Secretary of War to take weather observations at military posts and to give notice “of the approach and force of storms” on the Great Lakes and the seacoasts. Behind the law stood a Milwaukee scientist named Increase Lapham, who had counted the ships wrecked by Great Lakes storms and argued that a telegraph could carry a storm warning faster than the storm itself could travel. The job went to the Army Signal Service, whose soldiers already knew telegraphs. At 7:35 in the morning on November 1, 1870, observer sergeants at 24 stations read their thermometers, barometers and wind vanes at the same moment and tapped the numbers to Washington. On November 8, Lapham issued the first storm warning for the Great Lakes. The next year the service hired Cleveland Abbe, an astronomer from Cincinnati who had already been printing daily weather “probabilities,” as its first chief forecaster.

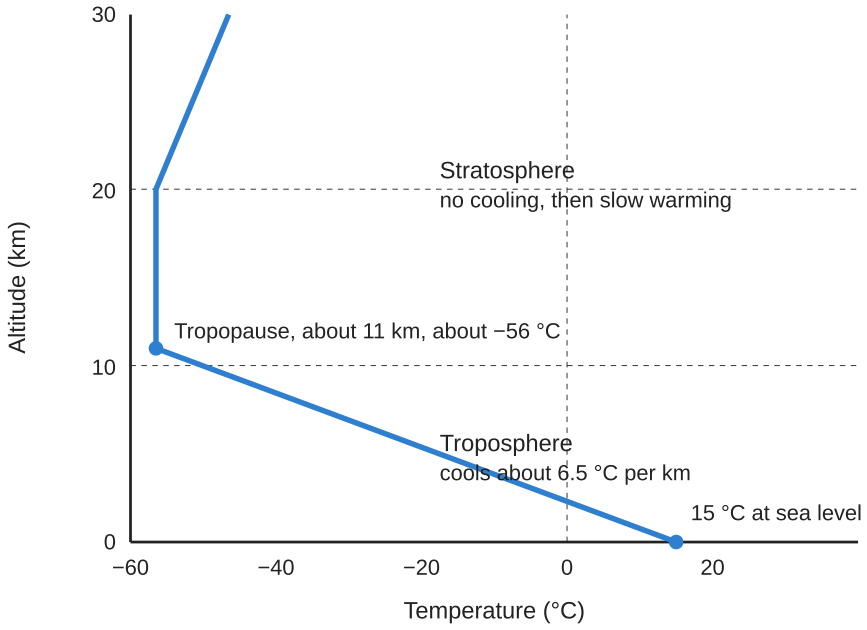
How they figured it out. The secret of the 1870 service was the **synoptic observation**: everyone measuring at the same instant, so that a map could show where the pressure was low, where the wind was blowing, and which way the whole pattern was moving. A forecaster who saw a storm over Chicago in the morning could warn Buffalo by afternoon. In 1890 Congress moved the service out of the Army and made it the civilian U.S. Weather Bureau under the Department of Agriculture, where it also organized the Cooperative Observer Program, a network of volunteers who still read rain gauges and thermometers every day. In 1940 the Bureau moved to the Department of Commerce. In 1970, when the National Oceanic and Atmospheric Administration (NOAA) was created, the Weather Bureau became the **National Weather Service**.

The big idea. A forecast is only as good as the observations that feed it, so the NWS gathers data from the ground, the air and space. About 900 automated surface stations, most at airports, report temperature, pressure, wind, visibility and rain every hour or more often. Twice a day, at 00:00 and 12:00 Universal Time, roughly 90 American sites release a latex weather balloon carrying a **radiosonde**. The balloon climbs about 300 m every minute, swells as the pressure drops, and bursts above 30 km, while the radiosonde radios back a profile of the atmosphere. Those profiles show the **lapse rate**, the steady cooling of air with height that averages about 6.5 °C per kilometer up to the tropopause, about 11 km up, where the cooling stops. About 160 **Doppler radars** sweep the country for rain, hail and rotation, and weather satellites photograph cloud patterns continuously. All of this pours into supercomputer models that solve the equations of moving air. Then the 122 local forecast

offices turn the model output into forecasts, and when danger comes, into **watches and warnings**.

In the world today. The National Weather Service employs several thousand people, and most are not the forecasters you see on television. Meteorologists at forecast offices work rotating shifts around the clock, because weather does not keep office hours. Hydrologists at river forecast centers predict floods. Electronics technicians climb radar towers to keep the antennas turning. Observers launch balloons in blizzards. Incident meteorologists fly to wildfires to forecast the winds for firefighting crews. National centers specialize: the Storm Prediction Center in Norman, Oklahoma watches for tornadoes, the National Hurricane Center in Miami tracks hurricanes, and the Aviation Weather Center in Kansas City serves pilots. Every forecast you read, and every free radar image on your phone, comes from this public service, continued without a break since the sergeants of 1870.

God’s handiwork. When Jesus spoke to the Pharisees, He reminded them that they could read a red sky in the evening and say “It will be fair weather” (Matthew 16:2). Weather lore like that is real observation, and the NWS is the same instinct made exact: measured at the same moment, recorded in numbers, and shared freely. The atmosphere God made is ordered enough that its motions can be written as equations and solved, yet so rich that no forecast is ever perfect. A forecaster learns humility and diligence together: watch carefully, record honestly, warn faithfully, and remember that the Lord “hath his way in the whirlwind and in the storm” (Nahum 1:3).



A standard atmosphere profile of the kind a radiosonde measures. In the troposphere the air cools about 6.5 °C per km; above the tropopause, at about 11 km, the cooling stops.

PICTURE STUDY



Cloud Study, John Constable, 1821 · Oil on paper laid on board · Yale Center for British Art, New Haven, Connecticut

In the summers of 1821 and 1822 the English painter John Constable climbed Hampstead Heath above London and painted the sky, nothing else, dozens of times. He called it “skying.” On the back of many of these oil sketches he wrote the date, the hour, the wind direction and a note on the weather, as if he were a station observer. Constable believed a landscape painter had to understand the sky as “the chief organ of sentiment” in a picture, and that meant watching real clouds change by the minute.

This sketch was made forty-nine years before the sergeants of 1870 took their first synoptic observation. There were no national weather maps yet, but there was patient looking. Constable’s notes are weather records, and his clouds are the same cumulus you will learn to name.

Look closely

- Find the brightest and the darkest parts of the clouds. From which side is the sun shining?
- Are these clouds flat and layered, or heaped and growing? What kind of weather do heaped clouds like these usually bring?
- Look at the brushstrokes. Did Constable paint slowly and carefully or quickly? Why would speed matter when painting clouds?
- Is there any land in the picture? Why do you think the painter gave nearly all of the space to the sky?

Talk about it

1. Constable wrote the wind and the hour on the back of each sketch. Why is a picture without a date and time less useful as a weather record?
2. What could a painter learn from a sky that a thermometer could not? What could a thermometer measure that a painter could not?
3. If you kept a cloud sketchbook for one month, what pattern might you discover about the weather that followed each cloud type?

> **Safety first.** Use scissors with care when cutting the balloon, set the glass jar where it cannot be knocked off a table, and read the outdoor thermometer without looking toward the sun.

EXPERIMENT: A HOME WEATHER STATION AND A THREE-DAY PRESSURE RECORD

In 1870 every station had a barometer, because falling pressure is one of the best signs of a coming storm. You will build a simple barometer from a jar and a balloon, read it beside a thermometer and your own sky observations three times a day for three days, and test whether your homemade instrument tracks the official pressure.

Question: Does a jar barometer rise and fall with the official pressure reported by the nearest National Weather Service station? **What we change:** nothing; we let the weather change. **What we keep the same:** the jar, its spot indoors away from sunlight and heating vents, and the reading times. **What we measure:** the position of the pointer in millimeters, the outdoor temperature in °C, and the official station pressure in hectopascals (hPa).

You will need

- A wide-mouth glass jar
- A large balloon, scissors and a strong rubber band
- A drinking straw, a toothpick and tape
- An index card and a metric ruler
- An outdoor thermometer (°C)
- Your lab notebook and access to the NWS station page for your town at weather.gov

Steps

1. Cut the neck off the balloon and stretch the rest tightly over the jar mouth like a drum skin. Hold it with the rubber band so no air can leak.
2. Tape one end of the straw to the middle of the balloon skin so the straw sticks out past the jar’s edge. Tape the toothpick to the free end as a pointer.
3. Stand the index card beside the pointer and draw a millimeter scale on it with the ruler. Mark the pointer’s starting position as 0 and write the date and time.
4. Write your question and prediction in your notebook. Will the pointer rise or fall when the official pressure rises?
5. Three times a day (morning, midday, evening) for three days, record: the pointer position in mm, the outdoor temperature, the sky and wind by eye, and the official

station pressure in hPa.
6. Rule a table with six columns: Date and time, Pointer (mm), Temperature (°C), Sky and wind, Official pressure (hPa), Notes.
7. Plot two line graphs on the same page, one of pointer position and one of official pressure, with time along the bottom. Do the lines rise and fall together?
8. Calculate the official pressure change between your first and last readings and divide by the hours between them to get a rate in hPa per hour.
9. Write a conclusion: Did your barometer track the station? What weather followed the biggest fall or rise? What is one reason the jar might not match perfectly?

Tips

- When outside pressure rises, it pushes the balloon skin down into the jar and the pointer tip rises. When pressure falls, the skin bulges up and the pointer tip drops.
- Warm air inside the jar also pushes the skin up, so keep the jar away from windows, stoves and vents. That is the main reason jar barometers drift.
- A fall of more than about 3 hPa in three hours is a sign that a storm system is approaching.

Check your work

- I can name what I kept the same and what I measured.
- I can read my barometer and explain which way the pointer moves when pressure rises.
- I can calculate a rate of pressure change in hPa per hour from my table.

FIELD NOTEBOOK

1. Draw a timeline of the national weather service with five dates: 1870 (Signal Service), 1890 (Weather Bureau, Agriculture), 1940 (Commerce), 1970 (NOAA and the National Weather Service), and today. Add one sentence under each.
2. Draw a weather balloon and radiosonde at launch and again just before it bursts above 30 km, roughly to scale, and label what the radiosonde measures (temperature, humidity, pressure, and wind from its track).
3. Make a “Constable page”: sketch today’s sky in pencil and write the date, hour, wind direction and your own one-line forecast on the back, then check it tomorrow.

> **From history.** Cleveland Abbe began publishing daily weather “probabilities” from the Cincinnati Observatory in September 1869, using telegraphed reports from Western Union, more than a year before the government service started. When he joined the Signal Service in 1871 the public nicknamed him “Old Probabilities.” He trained the first generation of American forecasters and argued for decades that weather should be studied with the mathematics of physics, an idea that became the computer models forecasters use today.

WORKED EXAMPLES

Example 1. A weather balloon rises at about 300 m per minute. How long does it take to reach 30 km, and what is that in hours and minutes?

1. Convert the height to meters: 30 km = 30,000 m.
2. Time = distance ÷ rate = 30,000 m ÷ 300 m/min = 100 min.
3. 100 min = 60 min + 40 min = 1 h 40 min.

Answer: About 100 minutes, or 1 hour 40 minutes. The whole flight, including the parachute descent, lasts about two hours.

Example 2. A radiosonde reports 18 °C at the ground and −47 °C at 10 km. What is the average lapse rate, and how does it compare with the standard 6.5 °C per km?

(Use the map or drawing "Lapse rate is the slope of the lower part of this line: 65 °C over 10 km gives 6" shown earlier in this lesson.)

1. Find the temperature change: 18 − (−47) = 65 °C of cooling.
2. Divide by the height: 65 °C ÷ 10 km = 6.5 °C per km.
3. Compare: it equals the standard lapse rate exactly.

Answer: The lapse rate is 6.5 °C per km, the same as the standard atmosphere.

Example 3. A station's barometer reads 1018 hPa at 6:00, 1014 hPa at 9:00, 1009 hPa at 12:00 and 1003 hPa at 15:00. What is the average rate of fall in hPa per hour, and what does it suggest?

1. Total change: 1018 − 1003 = 15 hPa.
2. Total time: 6:00 to 15:00 = 9 h.
3. Rate: 15 hPa ÷ 9 h ≈ 1.7 hPa per hour.
4. Check the last interval alone: 1009 − 1003 = 6 hPa in 3 h = 2 hPa per hour, so the fall is speeding up.

Answer: About 1.7 hPa per hour on average, and faster in the afternoon. A steady, quickening fall like this usually means a low-pressure storm system is approaching.

PRACTICE

1. EASY In what year did the national weather service begin, which president signed the resolution, and which branch of the Army ran it?
2. EASY What does a radiosonde measure directly, and how is the wind found?
3. EASY What is the difference between a tornado watch and a tornado warning?

4. MEDIUM A balloon reaches 24 km in 80 minutes. What is its average rate of climb in meters per minute and in meters per second?
5. MEDIUM If the ground temperature is 22 °C and the lapse rate is 6.5 °C per km, what temperature would a radiosonde report at 5 km?
6. MEDIUM Data reading. Hourly readings at one station:
   10:00: 14 °C, 1012 hPa, wind SW
   11:00: 15 °C, 1010 hPa, wind SW
   12:00: 16 °C, 1007 hPa, wind S
   13:00: 9 °C, 1006 hPa, wind NW
   14:00: 7 °C, 1009 hPa, wind NW
   15:00: 6 °C, 1012 hPa, wind NW
   (a) At what hour did the pressure reach its lowest value? (b) What two other changes happened at about the same time? (c) What passed the station?
7. MEDIUM Data reading. Use the temperature profile graph. (a) About what temperature does the standard atmosphere reach at 11 km? (b) Between 11 km and 20 km, does the temperature fall, rise or stay about the same? (c) A pilot says the air gets colder all the way up. Does the graph support that claim?
   (Use the map or drawing "Read the temperature at 11 km, then follow the line upward." shown earlier in this lesson.)
8. HARD Explain in three or four sentences why the 1870 service insisted that every station read its instruments at the same moment, and what a telegraph added that a careful observer alone could not provide.
9. HARD Experiment design. You want to know whether a jar barometer drifts because of room temperature rather than air pressure. Describe a fair test: what you would change, what you would keep the same, what you would measure, and how you would tell drift from a real pressure change.
10. CHALLENGE In 1870 there were 24 stations; today about 900 automated stations and about 8,700 volunteer observers report. (a) How many times more stations are there today than in 1870 if you count only the automated stations? (b) A forecast office covers about 80,000 km^2 and has roughly 20 automated stations in its area. About how many square kilometers does each station represent, and why do balloons and radar still matter?

COMMON MISTAKES

- Thinking a weather forecast is a guess. It is a calculation from thousands of real measurements, and its errors are measured and tracked every day.
- Thinking a watch and a warning mean the same thing. A watch says "be ready"; a warning says "act now."
- Thinking the air keeps getting colder all the way to space. Cooling stops at the tropopause, about 11 km up, and the stratosphere above it slowly warms.

> **Make it a game · Instrument Relay.** A parent calls out a measurement: "air pressure," "wind speed," "humidity," "temperature at 8 km," "rotation inside a storm," "cloud pattern over the ocean," "rainfall at a farm." You have five seconds to name the

instrument or system that measures it: barometer, anemometer, hygrometer, radiosonde, Doppler radar, satellite, rain gauge and the volunteer observer who reads it. Score a point for each correct answer, a bonus point for naming the year the service began, and play to ten.

Scripture. “He answered and said unto them, When it is evening, ye say, It will be fair weather: for the sky is red. And in the morning, It will be foul weather to day: for the sky is red and lowring. O ye hypocrites, ye can discern the face of the sky; but can ye not discern the signs of the times?” (Matthew 16:2–3, KJV)

Jesus took it for granted that people can read the sky, because the sky is readable: God made the weather orderly. The red-sky rule works because dust in dry western air colors the evening light. The same careful looking that reads a sunset should also read the signs God gives in His Word.

Practice answers

1. 1870; President Ulysses S. Grant; the Army Signal Service.
2. Temperature, humidity and pressure. The wind is found by tracking the balloon’s drift as it climbs.
3. A watch means conditions are favorable for tornadoes over a large area in the next several hours, so stay alert. A warning means a tornado is happening or about to happen in a specific place, so take shelter now.
4. 24,000 m ÷ 80 min = 300 m per min; 300 ÷ 60 = 5 m per second.
5. Cooling = 6.5 × 5 = 32.5 °C; 22 − 32.5 = −10.5 °C.
6. (a) 13:00 (1006 hPa). (b) The temperature dropped 7 °C and the wind shifted from southerly to northwesterly. (c) A cold front, with its low-pressure trough, passed between 12:00 and 13:00.
7. (a) About −56 °C. (b) It stays about the same. (c) No. Cooling stops at the tropopause, about 11 km up, and above about 20 km the air slowly warms.
8. Readings taken at the same instant can be put on one map, showing where pressure is low, where the wind blows and which way the pattern is moving. A single observer sees only one place and cannot tell where a storm is headed. The telegraph carried the readings to Washington in minutes, faster than the storm moved, so a warning could reach a port before the storm arrived.
9. Change: the room temperature of the jar (for example, a cool room and a warm room, or morning and afternoon near a sunny window). Keep the same: the same jar, the same scale and the same reading times. Measure: the pointer position in mm while also recording the official pressure, which should be the same for both jars at the same moment. If the two jars disagree while the official pressure is unchanged, the difference is temperature drift, not pressure. A second identical jar kept in a steady-temperature closet serves as a control.
10. (a) 900 ÷ 24 ≈ 37.5, about 38 times more. (b) 80,000 ÷ 20 = 4,000 km² per station. Surface stations only measure the air at the ground; balloons measure the whole column above, and radar fills in the gaps between stations by showing rain and wind over the whole area every few minutes.

6.2 Storm Chasers and Forecasters: The First Tornado Forecast, Tinker Air Force Base, 1948

OBJECTIVES

- Tell how Ernest Fawbush and Robert Miller issued the first tornado forecast on March 25, 1948, and how the Storm Prediction Center and local forecast offices divide the work of watches and warnings today.
- Name the four ingredients of severe thunderstorms and label the parts of a supercell, and explain what Doppler radar adds to an ordinary radar picture.
- Calculate the distance to lightning from flash-to-bang time, a storm's speed and arrival time from radar positions, and a tornado's EF rating from an estimated wind speed.

Warm-up. Fill a clear glass with cold water and let it sit still. Drop in one drop of food coloring from a spoon held just above the surface and watch where it goes. Now fill a second glass with hot tap water and drop in one drop the same way. Which drop spreads and rises faster? Warm water moves the way warm air does, and a thunderstorm is warm, moist air rising fast. Write one sentence predicting what would happen to a storm if the air above it were even colder than usual.

Video. Coming soon. How tornado forecasts and warnings are made; the Storm Prediction Center and NWS forecast office; supercell structure and Doppler radar hook echo; NSSL storm chasing and VORTEX research (search NOAA, National Severe Storms Laboratory, NWS office channels, NOAA SciJinks, Smithsonian and university meteorology channels).

KEY TERMS

severe thunderstorm
A thunderstorm that produces hail at least 2.5 cm across, wind gusts of at least 93 km/h, or a tornado.

supercell
A long-lived thunderstorm built around one rotating updraft; it produces the strongest tornadoes and the largest hail.

wind shear
A change in wind speed or direction with height. Shear tilts a storm so its updraft and downdraft do not fight each other, and it can start the updraft rotating.

hook echo
A hook-shaped curl of rain on the radar screen on the back side of a supercell, where rotation wraps rain around a possible tornado.

Enhanced Fujita (EF) scale

The six-step scale, EF0 to EF5, used since 2007 to rate a tornado by its damage and the wind speeds that damage implies.

storm spotter
A trained volunteer who watches a storm in person and reports what the radar cannot see, such as a funnel reaching the ground. Spotters are not chasers; they report from a safe place.

CORE IDEAS

The story. On the evening of March 20, 1948, a tornado tore across Tinker Air Force Base near Oklahoma City, wrecking dozens of aircraft and doing more than ten million dollars of damage. The base commander wanted to know whether anyone could have seen it coming. Two Air Force weather officers, Major Ernest Fawbush and Captain Robert Miller, spent the next days pulling the weather maps of March 20 apart: the moist air flowing north from the Gulf, the dry air aloft from the southwest, the sharp change of wind with height. On the morning of March 25 they saw the same pattern taking shape again. The commander asked if they would issue a tornado forecast. No one ever had. The two men knew the odds of a second tornado hitting the same base within a week were tiny, and they wrote the forecast anyway. At about six o'clock that evening a tornado struck Tinker again. Planes had been moved into hangars and people were sheltered, and the first tornado forecast in history had worked.

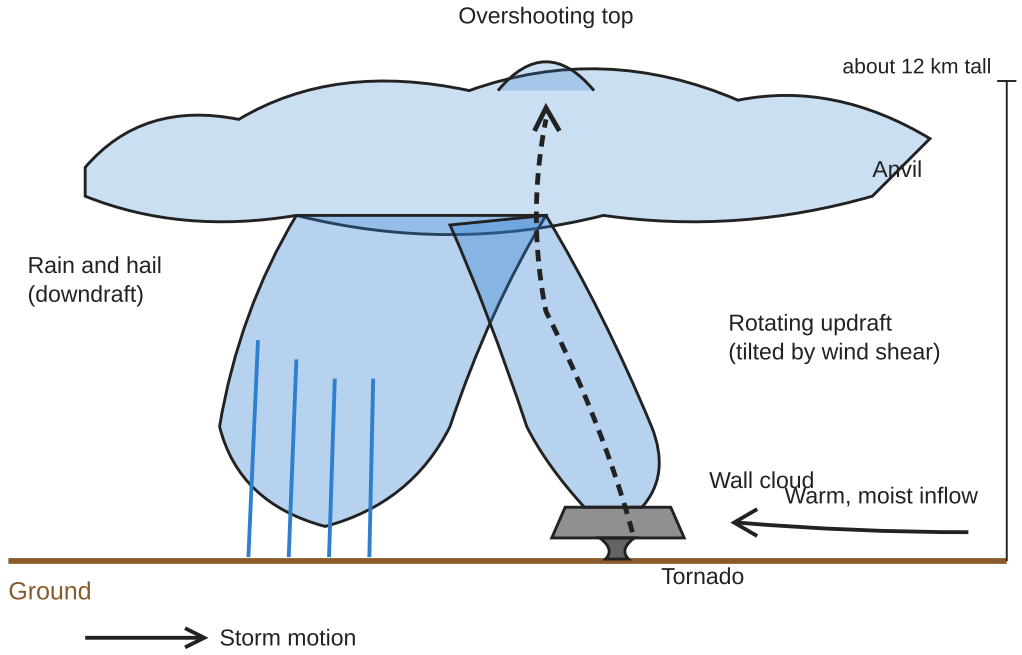
How they figured it out. Fawbush and Miller had found the recipe. A **severe thunderstorm** needs four ingredients: **moisture** near the ground, **instability** (warm air below cold air, so a rising bubble keeps rising, as in your warm-water glass), **lift** to start the air rising (a front, a dry line, or hills), and **wind shear**, a change of wind speed and direction with height. Shear tilts the storm so that its falling rain does not smother its own updraft, and it can set the updraft spinning. A storm built around one rotating updraft is a **supercell**. In 1952 the Weather Bureau began issuing its own tornado forecasts, and the unit that grew from that work is today's Storm Prediction Center in Norman, Oklahoma. In 1971 Tetsuya Fujita of the University of Chicago proposed a scale for rating tornadoes by their damage, and in 2007 it was refined into the **Enhanced Fujita scale**, from EF0 (105 to 137 km/h) to EF5 (over 322 km/h).

The big idea. Tornado forecasting works in two steps by two kinds of forecasters. The Storm Prediction Center studies the whole country and issues outlooks days ahead and **watches** hours ahead, telling a region that the ingredients are in place. Then the local forecast office watches the radar minute by minute and issues **warnings** for specific towns. Ordinary radar shows where rain and hail are. **Doppler radar** also measures whether the drops are moving toward the antenna or away from it, so a forecaster can see rain rushing toward the radar on one side of a storm and away on the other: rotation. On May 24, 1973, scientists from the National Severe Storms Laboratory watched a tornado at Union City, Oklahoma with an experimental Doppler radar while a chase team filmed it from the ground. The radar showed the rotation tightening several minutes before the funnel touched down.

That discovery led to the national network of Doppler radars built in the 1990s, and to warnings that now arrive, on average, about thirteen minutes before a tornado strikes.

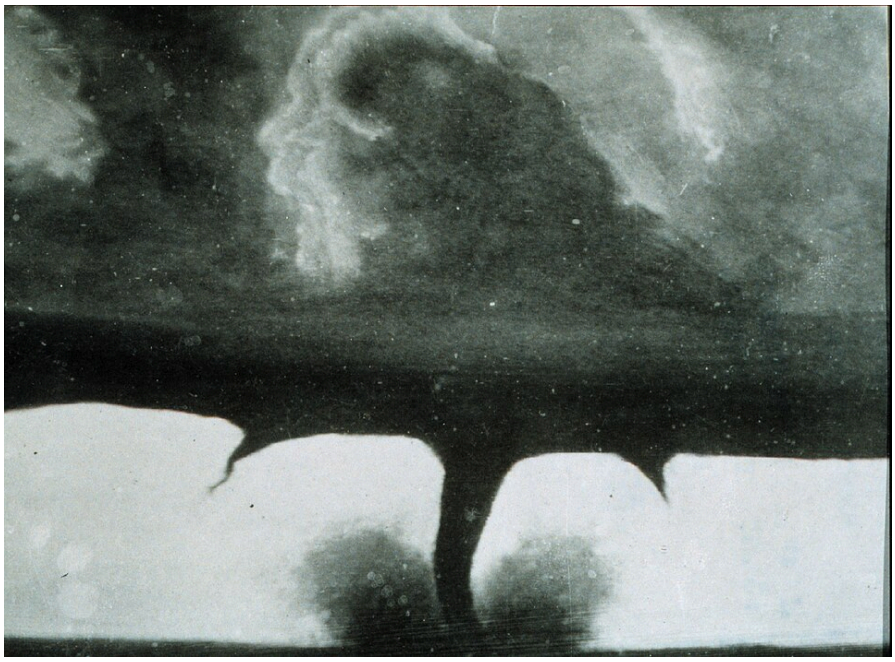
In the world today. Three kinds of people stand between a storm and the public. The warning forecaster sits at the radar in a forecast office and must decide, with the clock running, whether that **hook echo** is a tornado. Trained **storm spotters**, hundreds of thousands of volunteers in the NWS Skywarn program, report from their own driveways what the radar cannot see, because the radar beam passes high above the ground far from the antenna. Research storm chasers from the National Severe Storms Laboratory and universities drive toward storms to place instruments in their path, as in the VORTEX field projects of the 1990s and 2009 to 2010. Chasing is dangerous even for experts. On May 31, 2013, a tornado near El Reno, Oklahoma grew to 4.2 km wide, the widest ever measured, and killed the respected researcher Tim Samaras, his son Paul and his colleague Carl Young. The rule for students is simple: watch the radar, learn the sky, and let the warning, not your curiosity, decide where you stand.

God’s handiwork. “The LORD hath his way in the whirlwind and in the storm, and the clouds are the dust of his feet” (Nahum 1:3). A supercell is one of the most powerful things on earth, a tower of air twelve kilometers tall turning on a single updraft, and yet it obeys rules so exact that two men in 1948 could read the morning map and forecast a tornado for that very evening. Fawbush and Miller risked looking foolish to protect people they would never meet. That is what a forecaster does: he studies the order God built into the air and then speaks plainly, in time, so that others can take shelter.



A supercell seen from the side. Wind shear tilts the storm so the rain falls away from the inflow, and the rotating updraft can lower a wall cloud and a tornado.

PICTURE STUDY



Tornado near Howard, Dakota Territory, F. N. Robinson, August 28, 1884 · Photograph · NOAA Photo Library, Historic National Weather Service Collection

On August 28, 1884, F. N. Robinson photographed a tornado about 22 miles (35 km) southwest of Howard, in Dakota Territory (now South Dakota). It is among the oldest known photographs of a tornado. Cameras of that day needed long exposures, and prints were often touched up by hand, so historians treat early tornado pictures with some care.

In 1884 there was no radar, no warning and no word from the Signal Service, which did not use the word “tornado” in forecasts because it feared causing panic. Sixty-four years later Fawbush and Miller would write the first tornado forecast. This picture shows what forecasters were up against: a thing that appears in minutes and is gone before the plates are developed.

Look closely

- Find the funnel. Where does it meet the cloud and where does it meet the ground? Is it straight or bent?
- Look at the land. How does the flat prairie help a photographer, and why are the Plains where so many tornadoes form?
- How far away do you think the camera stood? What clues give you the distance?
- Why might an 1884 photograph look soft or touched up? What does that tell you about cameras and printing then?

Talk about it

1. What could a photograph like this tell a scientist in 1884 that a written description could not?

2. If Robinson had stood under the cloud to get a sharper picture, what would he have risked? What does that say about the difference between a spotter and a chaser?
3. Today a phone can film a tornado in an instant. What has that changed for forecasters, and what has it not changed?

> **Safety first.** Never go outside to watch a thunderstorm or try to follow one; lightning strikes well ahead of the rain. When thunder roars, go indoors, and stay inside for 30 minutes after the last thunder. Do the lightning-timing activity from inside a house, not a porch or a car window. Use hot tap water, not boiling water, in the warm-up.

EXPERIMENT: MEASURING A STORM'S SPEED FROM RADAR (OR BY COUNTING THUNDER)

A warning forecaster's first question about a storm is "where will it be in twenty minutes?" You will answer it the way the office does, by measuring how far a storm moves between radar scans. If no storm is near your home, use the national radar at radar.weather.gov to pick a storm anywhere in the country.

Question: How fast is this storm moving, and when will it reach the next town in its path? **What we change:** nothing; we take readings at different times. **What we keep the same:** the same radar site, the same zoom level, and the same spot on the storm (its leading edge or its brightest core). **What we measure:** the storm's position in kilometers from a landmark at two or three times at least 10 minutes apart.

You will need

- A computer or tablet showing the NWS radar at radar.weather.gov
- A clear plastic ruler and a dry-erase marker, or a sheet of tracing paper taped to the screen
- A clock
- Your lab notebook

Steps

1. Open the radar, zoom in on an active storm, and find the scale bar on the map. Measure the scale bar with your ruler and write down how many kilometers one centimeter of screen represents.
2. Pick a landmark (a town or a road crossing) ahead of the storm. Mark the storm's leading edge or brightest core on the tracing paper and write the exact time shown on the radar image.
3. Write your question and your prediction of the storm's speed in your notebook before you measure.
4. Wait 10 to 20 minutes without changing the zoom. Mark the new position and time.
5. Measure the distance between your two marks in centimeters and convert to kilometers using the scale. Divide by the time in hours to get speed in km/h.

6. Measure the distance from the storm’s newest position to your landmark and divide by the speed to get the arrival time. Write a one-sentence “warning”: the storm should reach the landmark at about what time?
7. Take a third reading and check whether the storm kept its speed. Record whether your “warning” came true.
8. If a thunderstorm is passing your home, add a second measurement from indoors: each time you see a flash, count the seconds until the thunder and divide by 3 to get the distance in kilometers. Record a distance every two minutes and plot distance against time.
9. Write a conclusion: What was the storm’s speed? How close did your arrival time come? What is one source of error in your method?

Tips

- Storms on the Plains often move 40 to 60 km/h, but some race along at 100 km/h. If your answer is far outside that range, check your scale.
- The radar loop button shows the last hour of scans in a few seconds; it is a quick way to see the direction of motion before you measure.
- Sound travels about 343 m each second, so three seconds of delay is roughly one kilometer.

Check your work

- I can convert a distance measured on a screen to kilometers using the scale bar.
- I can calculate a storm’s speed and predict its arrival time.
- I can explain one reason the real arrival time might differ from my prediction.

FIELD NOTEBOOK

1. Copy the supercell diagram and label the inflow, the rotating updraft, the anvil, the rain and hail, the wall cloud and the tornado. Add an arrow showing which way the storm moves.
2. Draw a radar screen with a hook echo. Beside it draw the same storm on a Doppler velocity screen, with one color for motion toward the radar and another for motion away, and mark where the rotation is.
3. Make a two-column chart of the Enhanced Fujita scale: EF0 through EF5 with the wind speed range in km/h and one example of the damage at each step (EF0: branches broken; EF1: roof shingles torn off; EF2: roofs torn from houses; EF3: walls of well-built houses collapse; EF4: well-built houses leveled; EF5: strong houses swept away).

> **From history.** In October 1743 Benjamin Franklin planned to watch a lunar eclipse from Philadelphia but a northeast storm clouded it out. Later he learned by letter that his brother in Boston, farther to the northeast, had seen the eclipse before the same storm arrived there hours later. The wind blew from the northeast, yet the storm had traveled from the southwest. Franklin concluded that storms are moving systems that can travel

against their own surface wind, the first step toward tracking a storm’s path, the daily business of every forecaster since.

WORKED EXAMPLES

Example 1. You see a lightning flash and count 12 seconds before the thunder. Sound travels about 343 m per second. How far away was the lightning?

1. Distance = speed × time = 343 m/s × 12 s = 4,116 m.
2. Convert to kilometers: 4,116 m ≈ 4.1 km.
3. Quick rule: 12 s ÷ 3 s per km = 4 km. Close to the exact answer.

Answer: About 4.1 km away. Lightning can strike more than 15 km from a storm, so even at this distance you should already be indoors.

Example 2. At 16:00 the radar shows a supercell 30 km southwest of a town. At 16:20 it is 18 km southwest, moving straight toward the town. How fast is the storm moving, and about when will it arrive?

1. Distance moved: 30 − 18 = 12 km in 20 min.
2. Speed: 12 km ÷ 20 min = 0.6 km per min; × 60 = 36 km/h.
3. Remaining distance: 18 km. Time = 18 km ÷ 0.6 km per min = 30 min.
4. Arrival: 16:20 + 30 min = 16:50.

Answer: The storm is moving at 36 km/h and should reach the town at about 16:50. A warning issued at 16:20 would give 30 minutes of lead time, more than double the national average of about 13 minutes.

Example 3. A damage survey after a tornado finds that well-built houses lost their roofs and some exterior walls, which implies winds of about 240 km/h. What EF rating is this, and what is 240 km/h in meters per second?

1. EF scale wind ranges in km/h: EF0 105–137; EF1 138–177; EF2 178–217; EF3 218–266; EF4 267–322; EF5 over 322.
2. 240 km/h falls in the EF3 range (218–266 km/h).
3. Convert: 240 km/h × 1,000 m/km ÷ 3,600 s/h = 66.7 m/s.

Answer: EF3, with winds of about 67 m/s. The rating comes from damage, because almost no tornado passes directly over an anemometer that survives.

PRACTICE

1. EASY Who issued the first tornado forecast, where and on what date?
2. EASY Name the four ingredients of a severe thunderstorm.
3. EASY Which office issues tornado watches, and which office issues tornado warnings?
4. MEDIUM You count 21 seconds between a flash and its thunder. How far away was the lightning? Use 343 m/s.
5. MEDIUM A storm moves 25 km in 30 minutes. What is its speed in km/h, and how long will it take to cross a county 60 km wide?
6. MEDIUM Data reading. A forecaster records flash-to-bang times from the office window:
   18:00: 30 s
   18:04: 24 s
   18:08: 18 s
   18:12: 12 s
   18:16: 6 s
   (a) Convert each time to a distance in km using 3 s per km. (b) How fast is the lightning (and the storm) approaching, in km per minute and km/h? (c) At this rate, when will the storm be overhead?
7. MEDIUM Data reading. One year a forecast office issued 100 tornado warnings. Tornadoes occurred in 70 of the warned areas. Thirty warnings had no tornado. Fifteen tornadoes occurred with no warning at all. (a) How many tornadoes occurred in total? (b) What fraction of tornadoes were warned (the probability of detection)? (c) What fraction of warnings were false alarms? (d) If the office lowered its standard and warned more readily, which of these two fractions would likely rise and which would likely fall?
8. HARD Explain in three or four sentences what Doppler radar shows that an ordinary radar cannot, and why that mattered at Union City, Oklahoma in 1973.
9. HARD Experiment design. You want to test whether warmer water rises faster than cool water when a drop of colored water is released at the bottom of a glass. Describe a fair test: the variable you change, three things you keep the same, what you measure, and how many trials you would run.
10. CHALLENGE The El Reno tornado of May 31, 2013 was 4.2 km wide and moved at about 40 km/h at one stage. (a) How many minutes would its full width take to pass over a single point? (b) A warning gives 13 minutes of lead time and a family needs 3 minutes to reach shelter. If the tornado is moving toward their house at 40 km/h, how far away is it when the warning is issued, and how far away when they are safely in the shelter?

COMMON MISTAKES

- Thinking storm chasers are the ones who warn the public. Warnings come from the forecaster at the local NWS office; chasers and spotters only feed the office information.
- Thinking a tornado’s EF rating is measured with an instrument. It is estimated from damage after the storm, because the winds almost never pass over a working anemometer.

- Thinking you are safe from lightning as long as it is not raining. Lightning can strike 15 km or more from the rain, which is why thunder means go indoors.

Make it a game · Watch, Warning or Wait. A parent reads a situation and you call out the right action in three seconds: “The Storm Prediction Center says ingredients are in place for your state this afternoon” (watch: stay alert, make a plan); “Radar shows a hook echo 15 km from your town, moving toward it” (warning: shelter now); “Clear sky, light wind, no storms within 300 km” (wait: nothing to do); “You hear thunder but see no rain” (go indoors). Add your own situations. Score a point for each right call and a bonus for explaining the reason. Play to ten.

Scripture. “The LORD is slow to anger, and great in power, and will not at all acquit the wicked: the LORD hath his way in the whirlwind and in the storm, and the clouds are the dust of his feet.” (Nahum 1:3, KJV)

The storm that frightens us is small beside the One who made it; to Him the clouds are dust under His feet. Forecasters do not control the whirlwind, but by studying its ways they serve their neighbors, and they do it in humility before the Lord who has His way in the storm.

Practice answers

1. Major Ernest Fawbush and Captain Robert Miller, at Tinker Air Force Base near Oklahoma City, on March 25, 1948.
2. Moisture, instability, lift and wind shear.
3. The Storm Prediction Center in Norman, Oklahoma issues watches; the local NWS forecast office issues warnings.
4. 343 × 21 = 7,203 m, about 7.2 km (the 3-seconds-per-kilometer rule gives 7 km).
5. 25 km ÷ 0.5 h = 50 km/h. 60 km ÷ 50 km/h = 1.2 h, or 1 hour 12 minutes.
6. (a) 10, 8, 6, 4, 2 km. (b) 2 km every 4 min = 0.5 km per min = 30 km/h. (c) From 2 km at 18:16, about 4 more minutes: around 18:20.
7. (a) 70 + 15 = 85 tornadoes. (b) 70 ÷ 85 ≈ 0.82, about 82%. (c) 30 ÷ 100 = 0.30, or 30%. (d) The probability of detection would rise (fewer missed tornadoes) but the false alarm fraction would also rise. Forecasters must balance the two.
8. Ordinary radar shows only where rain and hail are and how heavy they are. Doppler radar also measures whether the drops move toward or away from the antenna, so rain rushing toward the radar beside rain rushing away reveals rotation. At Union City in 1973 the NSSL Doppler radar showed rotation tightening several minutes before the tornado touched down, proving that radar could give warning time. That led to the national Doppler network of the 1990s.
9. Change: the temperature of the water in the glass (for example, 10 °C, 25 °C and 40 °C, measured with a thermometer). Keep the same: the glass size, the amount and temperature of the colored drop, how it is released (same dropper, same depth) and the still, draft-free room. Measure: the time in seconds for the color to reach the surface, using a stopwatch. Run at least three trials at each temperature and average them. Expect the warm glass to show faster rising, because a warm fluid under cooler fluid is unstable, like warm air under cold air in a thunderstorm.

10. (a) 40 km/h = 0.667 km per min; 4.2 ÷ 0.667 ≈ 6.3 min. (b) 13 min × 0.667 km/min ≈ 8.7 km away at the warning; after 3 min it has moved 2 km, so about 6.7 km away when they are in shelter.

6.3 Aviation Weather: The Wrights Choose Kitty Hawk, 1900

OBJECTIVES

- Tell how the Wright brothers used Weather Bureau wind records to choose Kitty Hawk and explain why wind, air density and visibility matter to every flight.
- Decode the main parts of a METAR airport observation and describe what the Aviation Weather Center, airline meteorologists and pilots each do with weather information.
- Calculate airspeed from ground speed and headwind, a crosswind component from a wind angle, a cloud base from the temperature and dew point spread, and an altimeter error from a pressure change.

Warm-up. Fold a simple paper airplane. Throw it gently three times in a still room and mark where it lands each time. Now have someone blow steadily toward you from the far side of the room (or use a fan on low) and throw it three more times into the breeze. Did it go farther, shorter, higher or off to one side? Write down what you saw. The Wright brothers wanted a strong, steady wind for exactly the reason your plane showed.

Video. Coming soon. Why the Wright brothers chose Kitty Hawk; how pilots read METAR and TAF aviation weather reports; the NWS Aviation Weather Center; wind shear and microbursts explained; density altitude (search NOAA, National Weather Service, FAA Safety, NASA, Smithsonian National Air and Space Museum and flight-training channels).

KEY TERMS

airspeed and ground speed
Airspeed is how fast an aircraft moves through the air; ground speed is how fast it moves over the ground. A headwind makes airspeed greater than ground speed; lift depends on airspeed.

METAR
The coded hourly weather observation from an airport: wind, visibility, clouds, temperature, dew point and altimeter setting. A TAF is the matching forecast for the airport.

crosswind component
The part of the wind blowing across the runway rather than along it, found by multiplying the wind speed by the sine of the angle between the wind and the runway.

density altitude
The altitude in the standard atmosphere that has the same air density as the air at the airport right now. Hot, high and humid air has a high density altitude, so wings and engines perform as if they were higher up.

altimeter setting

The current sea-level pressure, which a pilot dials into the altimeter so it reads true altitude. Near sea level, each hectopascal of pressure is worth about 8 m of altitude.

wind shear and microburst
A sudden change of wind speed or direction over a short distance. A microburst is a small, intense downdraft from a thunderstorm that spreads out at the ground and can rob a landing aircraft of airspeed.

CORE IDEAS

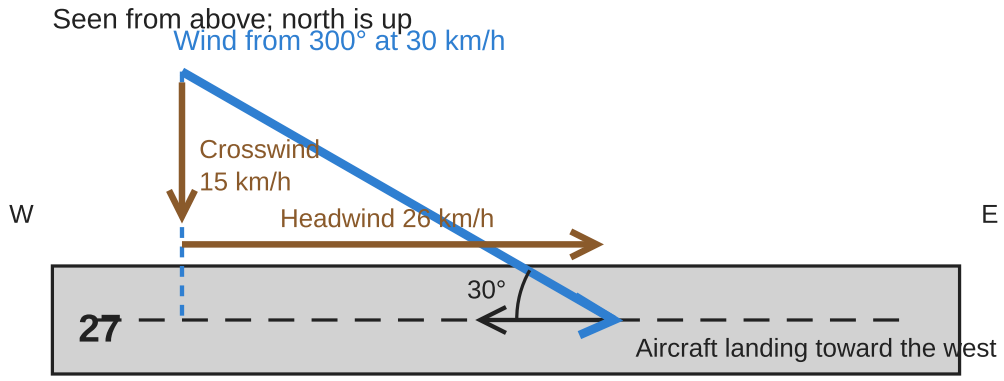
The story. In the summer of 1900 two bicycle makers from Dayton, Ohio, Wilbur and Orville Wright, were ready to test a glider, and they needed a place with steady winds, soft sand for landings and few trees. Wilbur did not guess. He studied the monthly wind tables published by the U.S. Weather Bureau and then wrote to the Bureau's station at Kitty Hawk, North Carolina. The observer there, Joseph Dosher, wrote back on August 16, 1900 that the beach was about a mile wide and clear of trees, and that the wind in September and October blew mostly from the north and northeast. The brothers went. Three autumns later, on December 17, 1903, with a cold wind of about 43 km/h blowing across the sand, Orville flew the powered Flyer for 12 seconds and 36.6 m. The fourth flight that morning, with Wilbur at the controls, lasted 59 seconds and covered 259.7 m. The first airplane flight in history was planned with Weather Bureau data, and aviation and weather have been bound together ever since.

How they figured it out. The Wrights wanted wind because a wing makes lift from the air flowing over it, and what matters is **airspeed**, the speed through the air, not **ground speed**. Flying into a 43 km/h headwind, the Flyer crawled over the sand at about 11 km/h but felt about 54 km/h of air over its wings. That is still the rule: pilots take off and land into the wind, so every airport reports its wind, and runways are numbered by their compass heading. When the wind blows at an angle to the runway, only part of it helps. The **crosswind component** is the wind speed times the sine of the angle: at 30° the crosswind is half the wind, at 60° it is 87 percent, and at 90° the whole wind is pushing the aircraft sideways. Every small aircraft has a maximum crosswind it can safely handle, and the pilot must do this arithmetic before landing.

The big idea. Air is a fluid with weight, and its density changes with pressure, temperature and moisture. The standard atmosphere that engineers use starts at 15 °C and 1013.25 hPa at sea level and cools 6.5 °C per kilometer. On a hot afternoon at a high airport the air is thinner than standard, so the wing makes less lift and the engine less power. Pilots call this high **density altitude**, and it means a longer takeoff roll. Pressure matters a second way. An altimeter is only a barometer with a scale in meters, so the pilot must dial in the current sea-level pressure, the **altimeter setting**, from the nearest station. Near sea level, each hectopascal of pressure equals about 8 m of altitude. A pilot who flies from high pressure into low pressure without resetting will read an altitude higher than the truth: "from high to low, look out below." Clouds matter too. Rising air cools at about 10 °C per kilometer until it reaches its dew point, so the cloud base sits roughly 125 m up for every degree of spread between the temperature and the dew point at the ground.

In the world today. The National Weather Service's Aviation Weather Center in Kansas City, Missouri issues warnings for turbulence, icing, thunderstorms and volcanic ash across the country, and every airport observation is published as a **METAR** in a compact code that pilots learn to read at a glance. A report such as *27015G25KT 10SM FEW040 BKN250 22/12 A2992* means wind from 270° at 15 knots gusting to 25, visibility 10 statute miles, a few clouds at 4,000 ft, a broken layer at 25,000 ft, temperature 22 °C, dew point 12 °C, and an altimeter setting of 29.92 inches of mercury, which is 1013 hPa. Airlines employ their own meteorologists to route flights around storms and into favorable winds. Dispatchers, air traffic controllers and the pilots themselves all read the same data. The hardest lesson came from **wind shear**. After Eastern Air Lines Flight 66 crashed at New York's Kennedy Airport in a thunderstorm on June 24, 1975, Tetsuya Fujita identified the cause as a small, violent downdraft he named a downburst, and after a similar microburst brought down Delta Flight 191 at Dallas–Fort Worth on August 2, 1985, airports were fitted with Doppler wind-shear radars and pilots were trained to escape. Microburst crashes, once a regular tragedy, have become rare.

God's handiwork. "To make the weight for the winds; and he weigheth the waters by measure" (Job 28:25). Long before anyone weighed the air with a barometer, Job spoke of the weight of the winds, and every pilot stakes his life on it. The air has exactly the density that lets a wing lift a family across an ocean, and it obeys rules so steady that a pressure reading at one airport tells a pilot how high he is a hundred kilometers away. The Wrights succeeded because they trusted measurements over hunches and wrote to a weather observer before they packed a single crate. Careful reading of what God has made is not the opposite of faith; it is one of the ways a diligent person honors the Maker.



Runway 27 (heading 270°)

Crosswind = wind × sin(angle) = 30 × 0.50 = 15 km/h

Headwind = wind × cos(angle) = 30 × 0.87 ≈ 26 km/h

A 30 km/h wind at 30° to the runway splits into a 26 km/h headwind along the runway and a 15 km/h crosswind across it. Crosswind = wind × sin(angle).

PICTURE STUDY



First flight of the Wright Flyer, Kitty Hawk, John T. Daniels, December 17, 1903 · Glass-plate photograph · Library of Congress, Washington, D.C.

John T. Daniels was a surfman at the Kill Devil Hills Life-Saving Station, one of a handful of local men who came to help the Wright brothers on the cold, windy morning of December 17, 1903. Orville set up the camera on its tripod, aimed it at the end of the launch rail and told Daniels to squeeze the bulb if anything interesting happened. Daniels had never used a camera. He squeezed it at exactly the right instant, and this became one of the most famous photographs ever made.

Orville lies at the controls on the lower wing. Wilbur, who had steadied the wingtip as the machine rolled down the rail, has just let go and runs beside it. The wind was about 43 km/h out of the north, so cold that the brothers had to warm their hands between attempts. Look closely and you can see the sand and the flatness of the beach that Joseph Dosher had described in his letter three years before.

Look closely

- Find the launch rail under the aircraft. Why did the Wrights need a rail on soft sand?
- Which way is the wind blowing? Use the direction of the flight and what you know about taking off into the wind.
- Look at the land. Where are the trees, hills and buildings? Why did this matter to the Wrights?
- Wilbur is running alongside. About how fast is the Flyer moving over the ground, judging by that?

Talk about it

1. The Flyer’s ground speed was only about 11 km/h, slower than a bicycle, yet it flew. Explain how the wind made that possible.
2. Daniels had never taken a photograph. What would have been lost if he had squeezed the bulb two seconds later?
3. The Wrights wrote to a Weather Bureau observer before choosing a site. What does that tell you about how they worked?

> **Safety first.** Keep fingers, hair and loose clothing away from fan blades, and have a parent position the fan. Throw paper airplanes away from faces and eyes. Never look directly at the sun when observing the sky.

EXPERIMENT: CROSSWIND DRIFT: A PAPER GLIDER WIND TEST

A pilot landing in a crosswind must know how far the wind will push the aircraft sideways. You will measure that push with a paper glider and a fan, changing only the angle between the wind and the flight path, and test whether the sideways drift grows the way the sine rule predicts.

Question: How does the angle between the wind and the flight path change a glider’s sideways drift? **What we change:** the fan angle: 0° (headwind), 30°, 60° and 90° (full crosswind). **What we keep the same:** the same glider, the same fan speed, the same launch point and the same gentle throw. **What we measure:** how far sideways from the center line the glider lands, in centimeters.

You will need

- One sturdy paper glider (a simple dart design)
- A box fan or desk fan with a steady low setting
- Masking tape and a tape measure or meter stick
- A protractor or a printed angle guide
- A large open floor space (a hallway or garage)
- Your lab notebook

Steps

1. Tape a straight center line 4 m long on the floor. Mark the launch point at one end.
2. Write your question and prediction: at which angle will the glider drift farthest sideways, and roughly how much more at 90° than at 30°?
3. Set the fan 2 m from the launch point so its breeze blows straight toward you along the line (0°). Use the protractor to check the angle. Throw the glider gently three times and measure the sideways distance of each landing from the center line. Record all three.
4. Move the fan so the breeze crosses the line at 30°, keeping it 2 m from the line. Throw three times and record.
5. Repeat at 60° and at 90°.

6. Make a table with columns: Angle, Trial 1, Trial 2, Trial 3, Average drift (cm). Add a column with sin(angle): 0, 0.50, 0.87, 1.00.
7. Draw a bar graph of average drift at each angle. Does the drift grow roughly in step with the sine values? For example, is the drift at 30° about half the drift at 90°?
8. Write a conclusion of three sentences: what you found, whether it matched your prediction, and one reason a real airplane might not follow the rule exactly.

Tips

- Throws vary. A gentle, level push from the same spot each time matters more than a strong throw.
- If the glider tumbles in the full crosswind, lower the fan speed for all trials and start over; the fan speed must stay the same throughout.
- The headwind trial (0°) should give the smallest drift and may also give the longest or shortest flight; note both.

Check your work

- I can name the variable I changed, what I kept the same and what I measured.
- I can calculate a crosswind component from a wind speed and an angle.
- I can explain why pilots take off and land into the wind.

FIELD NOTEBOOK

1. Draw a runway from above with its number, a wind arrow at 45°, and the headwind and crosswind components. For a 40 km/h wind, label the crosswind (40 × 0.71 ≈ 28 km/h).
2. Write out a METAR for today’s weather at the nearest airport (find it at aviationweather.gov) and decode each group beneath it in plain words.
3. Sketch the Wright Flyer in flight with two arrows: a short one for ground speed over the sand and a long one for airspeed through the wind. Label the headwind.

> **From history.** The Wrights were not the only ones to lean on the Weather Bureau. The Air Commerce Act of 1926 made the Bureau responsible for weather service to the new airmail and passenger routes, and by the 1930s airports had become the nation’s most important weather stations. That is why so many official records today come from airports: the automated station at the end of the runway serves both the pilot about to land and the forecaster drawing the evening map.

WORKED EXAMPLES

Example 1. On December 17, 1903 the Flyer covered 36.6 m over the ground in 12 s into a headwind of about 43 km/h. What were its ground speed and its approximate airspeed in km/h?

1. Ground speed = 36.6 m ÷ 12 s = 3.05 m/s.
2. Convert: 3.05 m/s × 3.6 = 11.0 km/h.
3. Airspeed = ground speed + headwind = 11 + 43 = 54 km/h.

Answer: Ground speed about 11 km/h; airspeed about 54 km/h. The wing felt 54 km/h of air, which is why the Wrights wanted the wind.

Example 2. A pilot is landing on runway 27 (heading 270°). The wind is from 300° at 30 km/h. Find the angle between wind and runway, the crosswind component and the headwind component. Use sin 30° = 0.50 and cos 30° = 0.87.

(Use the map or drawing "The wind arrow splits into a part along the runway and a part across it." shown earlier in this lesson.)

1. Angle = 300° − 270° = 30°.
2. Crosswind = 30 km/h × sin 30° = 30 × 0.50 = 15 km/h.
3. Headwind = 30 km/h × cos 30° = 30 × 0.87 ≈ 26 km/h.

Answer: A 15 km/h crosswind and a 26 km/h headwind. The headwind helps; the crosswind must be within the aircraft's limit.

Example 3. A pilot sets the altimeter to 1013 hPa at takeoff and flies 300 km to an airport where the pressure is 1001 hPa, forgetting to reset. Near sea level each hectopascal is worth about 8 m. What does the altimeter read when the aircraft is really at 500 m, and is the error dangerous? Also: the ground temperature is 24 °C and the dew point 14 °C; estimate the cloud base.

1. Pressure difference: 1013 − 1001 = 12 hPa.
2. Altitude error: 12 hPa × 8 m per hPa ≈ 96 m, about 100 m.
3. Flying from high pressure to low, the altimeter reads too high: it shows about 600 m when the aircraft is really at 500 m. The aircraft is lower than the pilot thinks: "from high to low, look out below."
4. Cloud base: spread = 24 − 14 = 10 °C; 10 × 125 m ≈ 1,250 m above the ground.

Answer: The altimeter reads about 600 m while the true altitude is 500 m, a 100 m error on the dangerous side. The cloud base is about 1,250 m, which agrees with a METAR report of a few clouds at 4,000 ft (about 1,220 m).

PRACTICE

1. EASY Why did the Wright brothers want a strong, steady wind at Kitty Hawk, and who gave them the information to choose it?
2. EASY What is the difference between airspeed and ground speed? If a plane has an airspeed of 200 km/h and a 50 km/h headwind, what is its ground speed?
3. EASY What does the Aviation Weather Center do, and where is it?
4. MEDIUM The wind is from 240° at 40 km/h and you are landing on runway 18 (heading 180°). What is the crosswind component? Use sin 60° = 0.87.
5. MEDIUM The temperature is 30 °C and the dew point is 18 °C. Estimate the cloud base above the ground. Then convert 15 knots to km/h (1 knot = 1.852 km/h).
6. MEDIUM Data reading. Decode this METAR: *KDEN 151753Z 09012KT 6SM BR OVC008 04/03 A2985*. (a) What are the wind direction and speed? (b) What is the visibility? (c) How high is the overcast cloud layer? (d) The temperature is 04 and the dew point 03. Why does such a small spread fit the low cloud and the mist (BR)?
7. MEDIUM Data reading. A pilot's handbook lists takeoff distance for a small plane at sea level pressure:
   Air temperature 0 °C: 400 m
   10 °C: 440 m
   20 °C: 485 m
   30 °C: 535 m
   40 °C: 590 m
   (a) By about how many meters does the takeoff roll grow for each 10 °C of warming? (b) The runway is 550 m long. At which listed temperature does takeoff become unsafe? (c) Why does hot air lengthen the roll?
8. HARD Explain in three or four sentences what a microburst is, why it is so dangerous to a landing aircraft, and what changed after the crashes of 1975 and 1985.
9. HARD Experiment design. You want to find out whether a paper glider flies farther into a headwind or with a tailwind. Describe a fair test with the variable you change, three things you keep the same, what you measure, and how you would handle the fact that throws vary.
10. CHALLENGE An airliner cruises at an airspeed of 850 km/h. Flying east it has a 150 km/h tailwind from the jet stream; flying west it faces the same wind as a headwind. The route is 4,000 km. (a) Find the ground speed and flight time each way. (b) How much longer is the westbound flight, in minutes? (c) Why do airline meteorologists study the jet stream every day?

COMMON MISTAKES

- Thinking a headwind is bad for a pilot. A headwind lowers the ground speed needed for takeoff and landing, which is why runways point into the common winds.
- Thinking an altimeter measures height directly. It measures air pressure and must be reset to the local sea-level pressure, or it will read wrong by about 8 m for every hectopascal of difference.

- Thinking hot weather is good flying weather. Hot, high and humid air is thin, so takeoffs are longer and climbs are weaker.

Make it a game · METAR Decoder Race. A parent writes a made-up METAR on a card, for example *KABC 121856Z 18020G30KT 3SM RA BKN015 18/16 A2970*, and starts a timer. You decode it aloud group by group: wind from 180° at 20 knots gusting 30, visibility 3 statute miles, rain, broken clouds at 1,500 ft, temperature 18 and dew point 16, altimeter 29.70. Then answer two bonus questions: what is the crosswind on runway 27 (use sin 90° = 1), and how high is the cloud base by the spread rule? Beat your time with a new card; three cards without a mistake wins.

Scripture. “To make the weight for the winds; and he weigheth the waters by measure.” (Job 28:25, KJV)

Air has weight, and God set that weight exactly. A barometer measures it, an altimeter trusts it, and a wing rides on it. The ancient words of Job describe what every pilot depends on each time the wheels leave the ground.

Practice answers

1. Lift depends on airspeed, so a headwind let the glider and Flyer fly at a low ground speed. Wilbur used Weather Bureau wind tables and a letter from Joseph Dosher, the Weather Bureau observer at Kitty Hawk.
2. Airspeed is speed through the air; ground speed is speed over the ground. Ground speed = 200 − 50 = 150 km/h.
3. It is the NWS center in Kansas City, Missouri that issues aviation forecasts and warnings for turbulence, icing, thunderstorms and volcanic ash.
4. Angle = 240 − 180 = 60°; crosswind = 40 × 0.87 ≈ 35 km/h.
5. Spread = 12 °C; base ≈ 12 × 125 = 1,500 m. 15 × 1.852 ≈ 28 km/h.
6. (a) From 090° (east) at 12 knots. (b) 6 statute miles. (c) Overcast at 800 ft, about 240 m. (d) A 1 °C spread means the air is nearly saturated, so clouds form very close to the ground: 1 × 125 m ≈ 125 m, which agrees with a low overcast and mist.
7. (a) About 40 to 55 m per 10 °C, growing a little faster at higher temperatures. (b) At 40 °C the roll (590 m) exceeds the runway; 30 °C (535 m) leaves almost no margin. (c) Hot air is less dense, so the wing makes less lift and the engine less power at a given speed: high density altitude.
8. A microburst is a small, intense downdraft from a thunderstorm that hits the ground and spreads outward. An aircraft landing through it first meets a headwind that boosts airspeed, then a downdraft, then a tailwind that suddenly drops airspeed and lift when the aircraft is low and slow. After Eastern Flight 66 in 1975 Fujita identified the downburst, and after Delta Flight 191 in 1985 airports were equipped with Doppler wind-shear radar and pilots trained in escape maneuvers, so such crashes became rare.
9. Change: the fan direction, blowing toward the launcher (headwind) or away (tailwind), at the same distance and setting. Keep the same: the glider, the fan speed and distance, the launch point and the type of throw. Measure: the straight-line distance from launch to landing in cm. Throw at least five times in each condition and compare averages; discard any throw that hits a wall. Include a no-wind control.

10. (a) East: 850 + 150 = 1,000 km/h; 4,000 ÷ 1,000 = 4.0 h. West: 850 − 150 = 700 km/h; 4,000 ÷ 700 ≈ 5.71 h. (b) 5.71 − 4.0 = 1.71 h ≈ 103 min longer. (c) Routing to ride the jet stream eastbound and avoid it westbound saves hours of flight time and large amounts of fuel.

6.4 Career Interview: Jefferson's Thermometer, July 4, 1776, and the People Who Watch the Weather

OBJECTIVES

- Describe the main weather careers (forecaster, observer, hydrologist, radar technician, broadcast and aviation meteorologist, research scientist, emergency manager) and what training each requires.
- Plan, conduct and write up an interview with a working weather professional, with prepared questions, careful notes and a thank-you letter.
- Convert temperatures between Fahrenheit and Celsius and score a week of forecasts against what actually happened using mean absolute error.

Warm-up. Write down three jobs you can think of that depend on knowing tomorrow's weather. Now add three more that you would not have guessed. (Hints: who decides whether to spray a field, pour concrete, launch a rocket, fly a helicopter, open a ski lift, or send out snowplows?) Circle the one you would most like to ask about. Who in your town might actually do that job?

Video. Coming soon. A day in the life of a National Weather Service meteorologist; NWS Cooperative Observer volunteers; careers in meteorology and atmospheric science; broadcast meteorologist behind the scenes (search NOAA, National Weather Service, NOAA SciJinks, American Meteorological Society, Smithsonian and local TV station channels).

KEY TERMS

Cooperative Observer
A volunteer who reads a thermometer and rain gauge at the same time every day for the National Weather Service. The program began in 1890 and has about 8,700 observers today.

meteorologist
A scientist who studies the atmosphere. Most forecasters hold a bachelor's degree in meteorology or atmospheric science, which requires calculus and physics.

hydrologist
A scientist who forecasts rivers and floods from rain, snowmelt and soil conditions; the NWS runs 13 river forecast centers.

forecast verification
Checking a forecast against what really happened and measuring the error, so that forecasters can learn and improve.

mean absolute error

The average size of the forecast errors, ignoring whether each was too high or too low. A smaller value means a better forecast.

persistence forecast
The simplest forecast: tomorrow will be the same as today. A real forecast must beat persistence to be worth anything.

CORE IDEAS

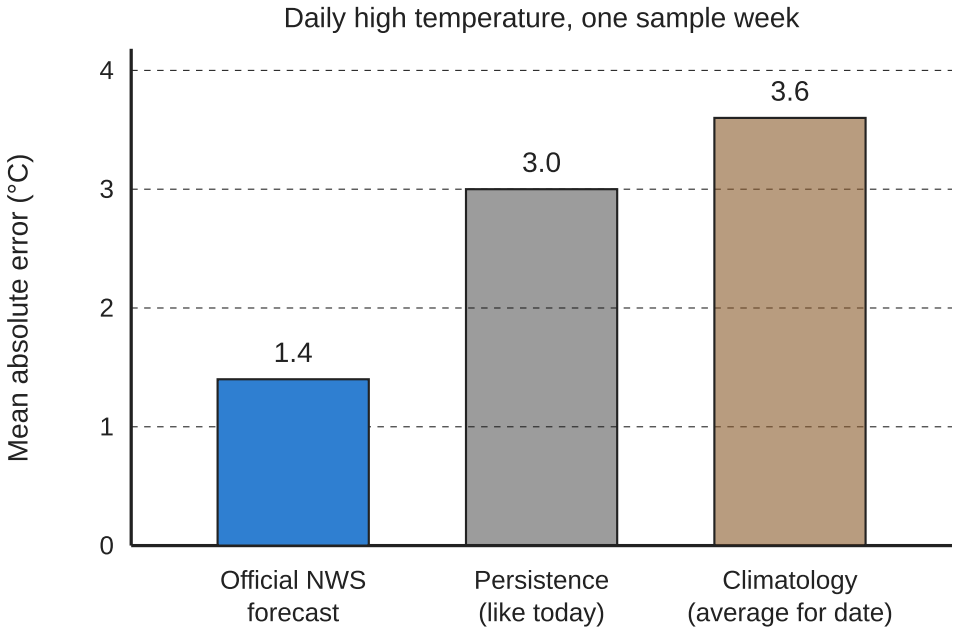
The story. On July 4, 1776, in Philadelphia, Thomas Jefferson had more on his mind than the weather. Yet his account book for that day records that he bought a thermometer from a Philadelphia shopkeeper, and his weather diary records a reading of 76 °F at one o'clock in the afternoon, with cooler readings in the morning and evening. Jefferson went on keeping weather records for nearly fifty years, at Monticello and wherever he traveled, writing down temperature, wind and sky twice a day and trading observations by letter with James Madison. He was never paid for it. He simply believed that a country could not be understood until its climate was measured, and he was right. The National Weather Service still gives a Thomas Jefferson Award to its finest volunteer observers, and the patience Jefferson showed is the first thing you will notice when you interview anyone who works with the weather.

How they figured it out. Jefferson's habit became a national program in 1890, when the Weather Bureau organized the **Cooperative Observer** network. Today about 8,700 volunteers, many of them farmers, ranchers and retired teachers, read a thermometer and rain gauge at the same hour every day and send the numbers in. Some have done it for a lifetime; Edward Stoll of Elwood, Nebraska kept his station for 76 years, from 1905 to 1981, and the NWS award for 50 years of service bears his name. Those daily numbers are how we know the climate of every county: the average first frost, the record rainfall, the drought years. A weather career can begin exactly here, with a notebook and a rain gauge, and it can grow in many directions. The forecasters you met in Lessons 6.1 and 6.2 are **meteorologists**, scientists who finished a four-year degree in atmospheric science built on calculus and physics. Beside them work **hydrologists** forecasting rivers, electronics technicians keeping the radar turning, incident meteorologists on wildfires, and observers who launch the balloons.

The big idea. Weather work reaches far beyond the government. Every television station employs broadcast meteorologists, many holding the American Meteorological Society's certification seal. Airlines, shipping companies, electric utilities, farm cooperatives and insurance firms hire forecasters, because a storm costs money and a good forecast saves it. The Air Force and Navy train their own weather officers and enlisted forecasters. Universities and the National Severe Storms Laboratory employ research scientists who chase storms with instruments and write the computer models everyone else uses. County emergency managers turn warnings into sirens, shelters and road closures. Pilots, farmers, fishermen and construction foremen are not meteorologists, yet they read the sky every morning as part of their trade. When you plan your interview, choose any of these. Each has a different story about the day the weather mattered most.

Try it and see. A good interview is an experiment with a person instead of a rain gauge: you prepare, you observe carefully, you record exactly, and you do not put words in your subject's mouth. Start by writing ten questions, and make most of them open, so they cannot be answered with a yes or no: "What does a normal shift look like?" "What did you study, and what do you wish you had studied?" "Tell me about a forecast that went wrong and what you learned." "How do you know when you were right?" That last question matters, because every honest forecaster practices **forecast verification**. The NWS checks its forecasts every day, and one plain measure is the **mean absolute error**: the average size of the miss, ignoring the sign. A forecast of 25 °C for a day that reached 28 °C is a 3 °C error whether it was high or low. The lowest bar any forecast must clear is the **persistence forecast**, "tomorrow like today," and a forecaster who cannot beat persistence has added nothing. You will score the official forecast this way in your project, and you will then be able to ask your interview subject a question that shows you have done your homework.

God's handiwork. "Seest thou a man diligent in his business? he shall stand before kings" (Proverbs 22:29). Jefferson writing 76 °F on the day of the Declaration, Edward Stoll walking to his rain gauge for 76 years, a forecaster checking yesterday's miss before writing today's forecast: these are pictures of diligence. God made a world regular enough to be recorded and surprising enough to keep us humble, and He made people to work at understanding it. When you sit down with a person who has spent a life watching the sky, listen for both the regularity and the surprise. Then ask what it has taught them about the One who "weigheth the waters by measure."



Forecast verification for one sample week. The official forecast missed the daily high by 1.4 °C on average; "tomorrow like today" missed by 3.0 °C; the long-term average for the date missed by 3.6 °C.

PICTURE STUDY



The Fog Warning, Winslow Homer, 1885 · Oil on canvas · Museum of Fine Arts, Boston

Winslow Homer painted *The Fog Warning* in 1885 in Prouts Neck, Maine, drawing on the halibut fishermen who worked from schooners off New England and on the Grand Banks. A dory fisherman has rowed away from his schooner to catch halibut on a hand line, and he has done well: two great fish lie in the boat. But as he turns for home he sees a bank of fog sliding across the water between him and the ship. If it closes in before he reaches the schooner, he may never find it.

This fisherman is not a meteorologist, yet reading the weather is part of his trade, as it is for pilots, farmers and builders. He has to judge the fog's speed, the distance to the ship, and his own strength, and decide now. Homer leaves the ending unpainted. A forecaster's job is to make sure that no one has to make that judgment alone.

Look closely

- Find the schooner and the fog bank. Which is closer to the fisherman? Which is moving faster?
- Look at the angle of the dory on the wave and the set of the man's shoulders. What is he doing with his body while he looks back?
- How does Homer show the weight of the halibut? Why might the fisherman be tempted not to throw them overboard even if the boat is slow?
- What colors does Homer use for the sea, the sky and the fog? Where is the only warm color?

Talk about it

1. What two measurements would this fisherman most want from a forecaster before he rowed away from the schooner?
2. Name three other jobs where a person must read the weather and decide quickly. What do they have in common?
3. If you interviewed a fisherman, a pilot and an NWS forecaster, what single question would you ask all three?

EXPERIMENT: INTERVIEW A WEATHER PROFESSIONAL, AND SCORE A WEEK OF FORECASTS

This project has two parts. In the first you will keep a week of forecast records and verify them, so that you understand a forecaster's work from the inside. In the second you will interview someone who works with the weather, using what you learned to ask better questions. Start the forecast log on day one, because it needs seven days to finish.

Question: Does the official forecast beat a persistence forecast at predicting tomorrow's high temperature? **What we change:** the method of forecasting (official NWS forecast, persistence, and the long-term average for the date). **What we keep the same:** the same station, the same seven days, and the same measurement of the actual high. **What we measure:** the absolute error of each method each day in °C, and the mean absolute error over the week.

You will need

- Access to the NWS forecast page for your town at weather.gov and its daily climate report (or your own outdoor max-min thermometer)
- Your lab notebook
- A phone, email or a planned visit for the interview, arranged by a parent
- Ten prepared questions on an index card
- Paper and an envelope for a thank-you letter

Steps

1. Each evening for seven days, write down the NWS forecast high for tomorrow, today's actual high (this is the persistence forecast for tomorrow), and the long-term average high for tomorrow's date (listed in the NWS climate report or in an almanac).
2. The next day record the actual high. Compute the absolute error for each of the three methods: ignore the sign and just write the size of the miss.
3. After seven days, average the errors for each method to get its mean absolute error. Draw a bar graph with three bars. Which method won? Did the official forecast beat persistence?
4. With a parent, choose an interview subject: the nearest NWS forecast office (ask for the warning coordination meteorologist, whose job includes public outreach), a television meteorologist, a pilot, a county emergency manager, a Cooperative Observer, a farmer or a fishing boat captain. A parent makes the first contact and explains that you are a student.

5. Write ten questions on an index card. Include at least six open questions, one about training and education, one about a day the weather mattered most, and one about verification: “How do you know when a forecast was good?”
6. During the interview, take notes in your own words and mark any exact words you want to quote with quotation marks. Ask before recording audio. Keep to the time you promised, about twenty minutes.
7. Within one day, write a two-page interview report: who the person is and what they do, their training, their best story, their answer about verification, and two things that surprised you. Add your forecast verification table and graph.
8. Write and mail or email a thank-you letter within three days. Mention one specific thing you learned.

Tips

- NWS offices welcome student contact but are busiest during severe weather; ask for a quiet-weather week.
- If no professional is available, a Cooperative Observer, a pilot or a farmer who reads the sky daily is a fine subject, and so is a retired forecaster.
- If the official forecast loses to persistence in your week, that is a real result. Ask your interview subject why it might happen in some seasons.

Check your work

- I can compute mean absolute error for three forecasting methods and say which won.
- I prepared open questions, took accurate notes and quoted only exact words.
- I wrote a complete report and sent a thank-you letter.

FIELD NOTEBOOK

1. Copy Jefferson’s July 4, 1776 reading into your notebook in both scales: 76 °F = 24.4 °C. Beneath it, record your own readings at the same times of day (morning, 1 p.m., evening) for three days.
2. Draw a “career map” with the National Weather Service in the center and at least eight weather jobs around it, with a line from each to the training it needs (degree, technical school, on-the-job, volunteer).
3. Rule your forecast verification table for the project with columns: Date, NWS forecast, Persistence, Climatology, Actual high, Error NWS, Error persistence, Error climatology.

> **From history.** George Washington kept a weather diary too. On December 12, 1799, he wrote that snow began about one o’clock and turned to hail and then to a settled cold rain; he had ridden over his farms through it, and the next day he had a sore throat. His last entry, on December 13, recorded more snow and then a clearing sky. He died late the next evening. Jefferson, Washington and Madison were all faithful amateur observers, and their notebooks are among the oldest continuous weather records in America.

WORKED EXAMPLES

Example 1. Jefferson recorded 76 °F at 1 p.m. on July 4, 1776 and 68 °F at 6 a.m. Convert both to Celsius, and find the morning-to-afternoon rise in °C.

1. °C = (°F − 32) × 5 ÷ 9.
2. 76 °F: (76 − 32) × 5 ÷ 9 = 44 × 5 ÷ 9 = 220 ÷ 9 ≈ 24.4 °C.
3. 68 °F: (68 − 32) × 5 ÷ 9 = 36 × 5 ÷ 9 = 20.0 °C.
4. Rise: 24.4 − 20.0 = 4.4 °C (check: 8 °F × 5 ÷ 9 ≈ 4.4 °C).

Answer: About 24.4 °C in the afternoon and 20.0 °C in the morning, a rise of 4.4 °C: a mild summer day in Philadelphia.

Example 2. A student scores five days of high-temperature forecasts. Official forecast errors (ignoring sign): 1, 2, 0, 3, 1 °C. Persistence forecast errors: 3, 5, 2, 4, 1 °C. Find the mean absolute error of each and decide which method is better.

(Use the map or drawing “The shorter the bar, the better the method. Climatology, the long-term average f” shown earlier in this lesson.)

1. Official: 1 + 2 + 0 + 3 + 1 = 7; 7 ÷ 5 = 1.4 °C.
2. Persistence: 3 + 5 + 2 + 4 + 1 = 15; 15 ÷ 5 = 3.0 °C.
3. Compare: 1.4 °C is less than 3.0 °C, so the official forecast missed by less than half as much.

Answer: Official mean absolute error 1.4 °C; persistence 3.0 °C. The official forecast is clearly better. It beat the simplest method, which is the first test any forecast must pass.

Example 3. Edward Stoll read his station every day for 76 years. (a) About how many daily observations is that? (b) If each observation took 10 minutes, how many hours did he give, and how many full 24-hour days is that?

1. (a) 76 years × 365 days = 27,740 observations, plus 19 leap days ≈ 27,759. Call it about 27,800.
2. (b) 27,800 × 10 min = 278,000 min; ÷ 60 = about 4,630 hours.
3. 4,630 h ÷ 24 h per day ≈ 193 full days.

Answer: About 27,800 observations and roughly 4,600 hours, more than six months of round-the-clock work, given ten minutes at a time.

PRACTICE

1. EASY What did Thomas Jefferson record on July 4, 1776, and why does the National Weather Service remember him?
2. EASY Name four weather careers, and say which of them usually require a four-year degree in meteorology or atmospheric science.
3. EASY What is a persistence forecast, and why does a forecaster care about it?
4. MEDIUM Convert 50 °F to Celsius and 35 °C to Fahrenheit.
5. MEDIUM A forecaster predicted highs of 20, 23, 25, 22 and 19 °C. The actual highs were 22, 23, 21, 24 and 19 °C. Find the mean absolute error.
6. MEDIUM Data reading. A Cooperative Observer's rain gauge totals for one station (mm):
   Year 1: April 60, May 95, June 110, July 80
   Year 2: April 35, May 50, June 45, July 30
   Year 3: April 70, May 100, June 105, July 90
   (a) What was the April to July total in each year? (b) Which year was the drought year, and what percent of the three-year average did it receive? (c) Why does a county need a volunteer record like this rather than the airport station 80 km away?
7. MEDIUM Data reading. Use the forecast error bar graph. (a) Which method had the smallest mean absolute error, and what was it? (b) How many times larger was the persistence error than the official forecast error? (c) A student claims that climatology is useless because its bar is tallest. Give one reason climatology is still a useful comparison.
   (Use the map or drawing "Compare the heights of the three bars." shown earlier in this lesson.)
8. HARD Rewrite these three closed interview questions as open questions that will draw out a story or an explanation: (a) "Do you like your job?" (b) "Is forecasting hard?" (c) "Did you go to college?"
9. HARD Experiment design. You want to find out whether the official forecast is more accurate one day ahead than three days ahead. Describe a fair test: what you change, what you keep the same, what you measure, how long you would run it, and how you would decide the answer.
10. CHALLENGE An observer reads a max-min thermometer at 7 a.m. daily, so each day's "high" is really the highest temperature in the 24 hours before 7 a.m. A hot afternoon on Monday followed by a cool Tuesday will be recorded under which date, and how might this bias a comparison with a forecast written for "Tuesday"? What simple rule fixes the problem?

COMMON MISTAKES

- Thinking every weather job needs a science degree. Observers, radar technicians, emergency managers and spotters all do essential weather work with other training.
- Averaging forecast errors with their signs. A +3 and a −3 would average to zero and hide two bad misses; mean absolute error uses the sizes only.
- Asking only yes-or-no questions in an interview. Open questions ("Tell me about…", "How do you decide…") are what bring out the stories and the lessons.

Make it a game · Hot Seat Interview. One family member becomes a weather professional (forecaster, pilot, farmer, Cooperative Observer, emergency manager, radar technician) and has two minutes to invent a believable day in that job. You interview them with only open questions. Every closed yes-or-no question costs you a point; every answer that reveals a story or a lesson earns one. Then switch roles. The player with the most points after each person has been interviewed once wins.

Scripture. “Seest thou a man diligent in his business? he shall stand before kings; he shall not stand before mean men.” (Proverbs 22:29, KJV)

Diligence is doing the small, faithful thing every day: reading the gauge, checking yesterday’s forecast, writing the thank-you letter. God honors that kind of work, and the people who do it well are the ones others come to trust when the storm is coming.

Practice answers

1. He bought a thermometer and recorded the temperature, 76 °F at 1 p.m. He kept weather records for nearly fifty years, and the NWS names its top award for volunteer observers after him.
2. Examples: NWS forecaster, hydrologist, broadcast meteorologist, airline or military meteorologist, research scientist, radar electronics technician, Cooperative Observer, emergency manager. Forecasters, hydrologists, broadcast and airline meteorologists and researchers normally need the degree; technicians, observers and many emergency managers do not.
3. “Tomorrow will be like today.” It is the simplest forecast possible, so a real forecast must do better than persistence to be worth anything.
4. (50 − 32) × 5 ÷ 9 = 10 °C. 35 × 9 ÷ 5 + 32 = 95 °F.
5. Errors: 2, 0, 4, 2, 0. Sum 8; 8 ÷ 5 = 1.6 °C.
6. (a) Year 1: 345 mm; Year 2: 160 mm; Year 3: 365 mm. (b) Year 2. Average = (345 + 160 + 365) ÷ 3 = 290 mm; 160 ÷ 290 ≈ 0.55, about 55% of average. (c) Rain varies greatly from place to place, especially from thunderstorms, so a gauge 80 km away may miss a local drought or flood entirely.
7. (a) The official forecast, 1.4 °C. (b) 3.0 ÷ 1.4 ≈ 2.1 times. (c) Climatology shows how much a forecast gains over simply knowing the season; any forecast that cannot beat climatology for a week has added no skill, and in some seasons climatology beats persistence.
8. Examples: (a) “What part of your work do you look forward to, and what part is hardest to get through?” (b) “Tell me about a forecast that went wrong. What did you learn from it?” (c) “What did you study to get here, and what do you wish you had studied more?”
9. Change: the lead time of the forecast, recording both the one-day and the three-day forecast for the same target day. Keep the same: the same station, the same variable (daily high), the same source of the actual high, and the same set of days. Measure: the absolute error of each forecast each day. Run it for at least two weeks, ideally a month, so that a few unusual days do not decide the result. Compute the mean absolute error for each lead time; the smaller value is the more accurate, and the size of the gap shows how much accuracy is lost per day of lead time.
10. Monday afternoon’s high is recorded on Tuesday’s line, because it falls in the 24 hours ending at 7 a.m. Tuesday. A Tuesday forecast of a cool day would then look badly wrong even though

it was right. The fix: compare each forecast with the observation period it was written for, for example by using the reading taken the morning after the forecast day, or by using a station that reports the calendar-day high at midnight.

Unit 6 review

Answer each question. Show your work for calculations and use complete sentences for explanations. For multiple choice, write the letter of the best answer. The test is worth 60 points.

1. (4 pts) The national weather service began in 1870 under (a) the Department of Agriculture (b) the Army Signal Service (c) NOAA (d) the Smithsonian Institution
2. (5 pts) A weather balloon climbs at 300 m per minute and bursts at 33 km. How long is the climb? The radiosonde reports 20 °C at the ground and −45 °C at 10 km; what is the average lapse rate?
3. (5 pts) A station’s pressure reads 1020 hPa at 08:00 and 1008 hPa at 14:00, while the wind shifts from south to northwest and the temperature drops 8 °C. (a) What is the rate of pressure change in hPa per hour? (b) What most likely passed the station?
4. (4 pts) A tornado watch means (a) a tornado has been seen; take shelter now (b) conditions are favorable for tornadoes over a large area in the coming hours (c) a tornado has passed (d) the radar is broken
5. (5 pts) Tell the story of the first tornado forecast: who, where, when, and what pattern the forecasters recognized.
6. (5 pts) At 15:10 a storm is 42 km west of a town; at 15:40 it is 24 km west, moving straight toward the town. Find its speed in km/h and its arrival time. Also: you count 9 seconds from flash to thunder; how far away is the lightning (use 343 m/s)?
7. (8 pts) Diagram. Draw a supercell thunderstorm from the side. Label the warm moist inflow, the rotating updraft, the anvil, the overshooting top, the rain and hail region, the wall cloud and the tornado. Add an arrow for wind shear and a sentence explaining what the shear does for the storm.
8. (4 pts) On a hot afternoon at a high-elevation airport, a small plane needs a longer takeoff roll because (a) the air is denser (b) the air is thinner, so the wing makes less lift and the engine less power (c) the runway is longer (d) the wind is always calm
9. (5 pts) A plane lands on runway 09 (heading 090°) with wind from 150° at 36 km/h. Find the angle, the crosswind component and the headwind component (sin 60° = 0.87, cos 60° = 0.50). Then: the pilot set the altimeter to 1015 hPa and the local pressure is now 1005 hPa; by about how much and in which direction does the altimeter read wrong?
10. (5 pts) Decode this METAR in plain words: *KOKC 231852Z 17018G28KT 7SM SCT035 BKN100 28/19 A2990*. Then estimate the cloud base from the temperature and dew point spread and compare it with the scattered layer.
11. (5 pts) Over five days the official forecast highs missed by 2, 1, 3, 0 and 2 °C, and the persistence forecast missed by 4, 2, 5, 1 and 3 °C. Find the mean absolute error of each and state which is better and why a forecaster compares against persistence at all.
12. (5 pts) Jefferson recorded 76 °F on July 4, 1776. Convert it to Celsius. Then name three weather careers that normally require a degree in meteorology and two that do not, and write one open interview question you would ask a forecaster.

UNIT PROJECT: WEATHER CAREERS NOTEBOOK AND INTERVIEW REPORT

Assemble a lab notebook that shows a forecaster's work from the ground up: your three-day barometer and pressure record with its graph and rate of change, your radar storm-speed measurement with the predicted and actual arrival times, a real METAR from the nearest airport decoded line by line with a crosswind calculation for one of its runways, and your seven-day forecast verification table with a bar graph of mean absolute error for the official forecast, persistence and climatology.

Finish with your two-page interview report on a working weather professional, including their training, their best story, their answer about how they know a forecast was good, and a copy of your thank-you letter. Present the notebook to your family and explain which weather career you found most interesting and why.

- **Accuracy**: Calculations (ascent time, lapse rate, pressure rate, storm speed, crosswind, cloud base, mean absolute error) are correct, in metric units, with work shown.
- **Records**: Each experiment states its question, what was changed, what was kept the same and what was measured, with complete dated tables and labeled graphs.
- **Interview**: Questions are open and prepared, notes are accurate, quotations are exact, the report is complete and a thank-you letter was sent.
- **Care**: The notebook is neat, clearly organized by lesson, and presented aloud with understanding.

Answer key

1. (b) the Army Signal Service. It moved to Agriculture in 1890 as the Weather Bureau, to Commerce in 1940, and became the National Weather Service within NOAA in 1970.
2. 33,000 ÷ 300 = 110 min (1 h 50 min). Lapse rate = (20 − (−45)) ÷ 10 = 65 ÷ 10 = 6.5 °C per km.
3. (a) 12 hPa ÷ 6 h = 2 hPa per hour, falling. (b) A cold front with its low-pressure trough.
4. (b). A warning is the one that means take shelter now.
5. Major Ernest Fawbush and Captain Robert Miller at Tinker Air Force Base near Oklahoma City issued the forecast on March 25, 1948, five days after a tornado had struck the base on March 20. They recognized the same ingredients returning: moist Gulf air at the surface, dry air aloft, a front or dry line for lift, and strong wind shear. A tornado struck the base that evening, and the forecast had protected people and aircraft.
6. 18 km in 30 min = 36 km/h. Remaining 24 km ÷ 0.6 km per min = 40 min, so arrival about 16:20. Lightning: 343 × 9 = 3,087 m, about 3.1 km.
7. Inflow at low level entering the front of the storm; a tilted rotating updraft rising to a flat anvil with a bump (overshooting top) above it; rain and hail falling on the rear side away from the inflow; a lowered wall cloud beneath the updraft with the tornado below it. Shear (wind changing with height) tilts the storm so the rain does not fall into and choke the updraft, and it can set the updraft rotating. Award 1 point for each of the seven labels and 1 point for the shear explanation.
8. (b). This is high density altitude: hot, high and humid air is thin.

9. Angle 60°. Crosswind = 36 × 0.87 ≈ 31 km/h; headwind = 36 × 0.50 = 18 km/h. Altimeter: 10 hPa × 8 m ≈ 80 m too high (the aircraft is lower than it reads).
10. Oklahoma City, observed on the 23rd at 18:52 UTC; wind from 170° at 18 knots gusting to 28; visibility 7 statute miles; scattered clouds at 3,500 ft and a broken layer at 10,000 ft; temperature 28 °C, dew point 19 °C; altimeter 29.90 inches of mercury. Spread = 9 °C; 9 × 125 ≈ 1,125 m, close to the scattered layer at 3,500 ft (about 1,070 m).
11. Official: 8 ÷ 5 = 1.6 °C. Persistence: 15 ÷ 5 = 3.0 °C. The official forecast is better. Persistence is the simplest possible forecast, so a real forecast must beat it to show any skill.
12. (76 − 32) × 5 ÷ 9 ≈ 24.4 °C. Degree: NWS forecaster, hydrologist, broadcast meteorologist, airline or military meteorologist, research scientist. No degree required: Cooperative Observer, radar electronics technician, storm spotter, many emergency managers. Example question: “Tell me about a forecast that went wrong and what you learned from it.”

UNIT 7

Origins Debate Fairly Told

Every museum sign, textbook and park brochure you will ever read about rocks carries two kinds of statements mixed together: what was measured, and what was concluded from the measurement under certain assumptions. This unit teaches you to tell them apart. You will watch Mount St. Helens lay down meters of fine layers in an afternoon in 1980 and cut a canyon in a day in 1982. You will meet Hugh Miller, the Scottish stonemason who loved the Bible and the Old Red Sandstone and read the days of Genesis as ages. You will stand with James Hutton at Siccar Point in 1788 and follow the radiometric clock from Boltwood to Patterson. And you will float with John Wesley Powell into the “Great Unknown” in 1869 to see the one place where all three readings of earth history are laid out on the same walls.

This course holds young-earth creation: God made the heavens and the earth in six days a few thousand years ago, and the Flood of Genesis 6 to 9 is history that shaped the rocks. Many Christians hold other views, and secular geology claims a history of billions of years. You will learn to state each view in words its holders would accept, give its best evidence, pose its hardest question in the form it is answered, and label every number as a measurement or a claim. “He that answereth a matter before he heareth it, it is folly and shame unto him” (Proverbs 18:13).

The work is quantitative throughout: adding the Genesis 5 chronology, computing an avalanche deposit’s thickness, reading rates off a sand-tray channel, building scale models of competing timelines, stepping through half-lives with a penny clock, and turning a thickness into years under three different assumed rates. The unit ends with a blind fairness test, in which readers who do not know your view try to guess it from your three summaries, and fail.

BEFORE YOU BEGIN

- Can multiply and divide large numbers and decimals, use scientific notation, and convert between mm, cm, m and km
- Can compute a rate (amount ÷ time) and read a line graph and a data table
- Knows the rock cycle, sedimentary layers and fossils from earlier grades, and William Smith’s principle of ordering strata (Lesson 5.1)
- Can read Genesis 1 to 11 and find a verse by chapter and verse

MASTERY CHECKLIST

- I can state the young-earth creation view, add the Genesis 5 chronology to the Flood, and explain what Mount St. Helens showed about rapid deposition and erosion.
- I can summarize the gap view and the day-age view fairly, name a verse and a historical Christian for each, and list what all Christian views share.
- I can state what secular geology claims (about 4.5 billion years, the geologic time scale, uniformitarianism) and explain how radiometric dating works, including half-life

steps and its three assumptions.
- I can sort statements into observations, interpretations and assumptions, and label every age in years as a claim.
- I can turn a layer thickness into a time under an assumed rate, build a scale model of a timeline, and show how the assumed rate changes the result.
- I can write three summaries of equal length, free of loaded words, that pass a blind fairness test.

OPTIONAL BOOKS AND RESOURCES

- **USGS Mount St. Helens** (https://www.usgs.gov/volcanoes/mount-st.-helens): Free. The Cascades Volcano Observatory's pages on the 1980 eruption, with the measured volumes, thicknesses and the 1982 mudflow, used in Lesson 7.1. Read the numbers for yourself before the lesson.
- **USGS Geologic Time (general interest publication)** (https://pubs.usgs.gov/gip/geotime/): Free. A short, plain statement of the mainstream claim: relative time, the time scale and radiometric dating. Use it in Lesson 7.3 as the "what the sign says" source, and practice labeling each number as measurement or claim.
- **National Park Service: Grand Canyon National Park** (https://www.nps.gov/grca/): Free. The park's geology pages and layer diagrams give the formation names and the sign's ages used in Lesson 7.4. The formation names are shared by all views; the ages are the claim to be summarized fairly.

7.1 Young-Earth Creation: What Mount St. Helens Showed on May 18, 1980 ★

OBJECTIVES

- State the young-earth creation position in its own terms: creation in six ordinary days, a chronology of a few thousand years drawn from the Genesis genealogies, and a global Flood that laid down much of the fossil-bearing rock record.
- Describe what geologists measured at Mount St. Helens in 1980 to 1982 (thick layered deposits and a canyon formed in hours to days) and explain why creation geologists treat it as a model for rapid deposition and erosion.
- Separate observations (layers, thicknesses, fossils) from assumptions (constant rates, starting conditions) and use the assumed rate to show how the same measurement can yield very different ages.

Warm-up. Fill a clear jar two-thirds with water. Add a handful of mixed material: coarse sand or aquarium gravel, fine sand, and a spoonful of flour or garden soil. Cap it, shake hard for ten seconds, set it down and watch for three minutes. Count the bands that form. Write down how long the layering took. If you came back next week and saw those bands, could you tell from the bands alone that they formed in minutes?

Video. Coming soon. Mount St. Helens May 18, 1980 eruption, debris avalanche, pyroclastic flow deposits and the 1982 mudflow canyon; search USGS Cascades Volcano Observatory, USGS, Smithsonian Global Volcanism Program, Oregon Public Broadcasting and Moody Science classics for footage of the eruption and of layered deposits forming quickly.

KEY TERMS

young-earth creation
The view that God created the heavens and the earth in six ordinary days a few thousand years ago, as the plain reading of Genesis 1 and the genealogies of Genesis 5 and 11 suggest.

Flood geology
The study of the rock record in light of the global Flood of Genesis 6 to 9, which young-earth geologists hold laid down much of the fossil-bearing sedimentary rock rapidly within about a year and the centuries after.

catastrophism
The idea that much of the rock record was formed by sudden, high-energy events (floods, eruptions, landslides) rather than by slow everyday processes.

chronology

A timeline worked out by adding up recorded ages and dates, such as the years from Adam to the Flood in Genesis 5.

assumption
Something taken as true in order to do a calculation but not itself measured, such as a rate staying constant for the whole time being estimated.

debris avalanche
A fast-moving landslide of broken rock, ice and soil; the one at Mount St. Helens in 1980 was the largest in recorded history.

CORE IDEAS

The story. At 8:32 on the morning of Sunday, May 18, 1980, a magnitude 5.1 earthquake shook Mount St. Helens in Washington State. The bulging north face of the volcano let go. A young USGS geologist named David Johnston, watching from a ridge about 10 km away, radioed “Vancouver! Vancouver! This is it!” and was never heard from again. In the next few minutes the mountain lost about 400 m of its summit, dropping from 2,950 m to 2,549 m. A debris avalanche of about 2.5 cubic kilometers of rock and ice roared 22 km down the North Fork Toutle River valley and buried about 60 square kilometers to an average depth of 45 m. A sideways blast flattened forest across some 600 square kilometers. Pyroclastic flows of hot ash and pumice poured out of the crater for hours, and an ash column rose about 24 km into the sky. Fifty-seven people died. The USGS has studied the deposits ever since, and that record is what makes the mountain so important for the question of this unit.

How they figured it out. Geologists mapping the new ground found that the deposits were not shapeless heaps. Pyroclastic flows had laid down beds of ash and pumice with fine, flat laminations, some only millimeters thick, stacked meters deep, all in a single afternoon. Hot mudflows had sorted sand and gravel into graded layers. Then on March 19, 1982, a small eruption melted snow in the crater and sent a mudflow across the pumice plain. In a matter of hours it cut a system of channels tens of meters deep through the 1980 deposits, with steep walls and side branches. A stream now trickles along the bottom. A visitor who did not know the history might reason, “A small stream cut this canyon, so it must have taken a very long time.” The geologists who documented it know otherwise. Creation geologists point to Mount St. Helens as a tested, documented case where thick layered deposits and a canyon formed quickly, and they ask whether the same kind of process, scaled up to a year-long worldwide Flood, could account for much of what we see in the rock record.

The big idea. Young-earth creation starts with the text of Genesis. Genesis 1 counts six days, each with “the evening and the morning,” and Exodus 20:11 says, “in six days the LORD made heaven and earth, the sea, and all that in them is.” Genesis 5 and 11 give the age of each father when his son was born, and when these are added, the Flood falls 1,656 years after creation and Abraham about 2,000 years before Christ. In 1650 James Ussher, Archbishop of Armagh, published a chronology that set creation at 4004 BC, and many English Bibles printed his dates in the margins for two centuries. Genesis 7:11 says that on the day the Flood began “were all the fountains of the great deep broken up,” which young-earth geologists read as a global catastrophe that tore up the old sea floors and land and

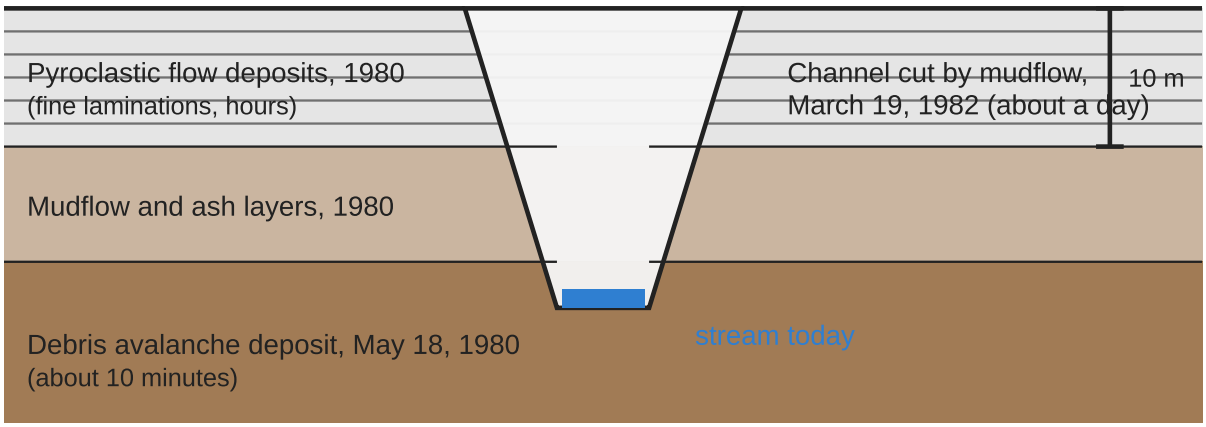
buried plants and animals in fast-moving sediment. On this reading, most of the thick, fossil-bearing layers of the continents, including the layers of the Grand Canyon, are Flood deposits, and the single ice age that followed was a consequence of warm oceans and ash-filled skies in the centuries after the Flood.

Observation and interpretation. Notice that the debate is not mainly about what is observed. Everyone agrees the layers exist, that fossils lie in a general order, and that a stream flows in the bottom of the 1982 canyon. The debate is about **rates** and **starting conditions**, which no one measured in the past. Young-earth geologists point to several observations that they think fit rapid deposition better than slow: sedimentary layers that spread flat across whole continents; sharp, nearly uneroded contacts between layer after layer; thick layer stacks folded without cracking, as if still soft; fish fossils caught in the act of eating or giving birth; trees standing upright through several layers; and, since Mary Schweitzer's 2005 report in *Science*, flexible blood vessels and other soft tissue inside dinosaur bone. Mainstream geologists have answers for each of these, which you will hear in Lesson 7.3. The honest habit is to write each observation in one column, each interpretation in another, and name the assumptions in between.

Try it and see. The warm-up jar is the simplest Flood-geology experiment. A single pour of mixed sediment sorts itself in minutes into graded bands, coarse at the bottom and fine at the top. One pour can make several layers, so counting layers is not the same as counting years unless you already know how each layer formed. Today's project asks a second question about rates: does a channel in sand deepen at a steady pace, or fast at first and then slowly? If the rate is not constant, then measuring today's slow trickle and multiplying backward will give a wrong age. That is the heart of the young-earth case: the present slow rates are not the only key to the past, because the past may have been catastrophic.

God's handiwork. The young-earth reading does not require anyone to ignore the rocks. It takes the rocks as true witnesses and takes Genesis as a true history, and it tries to read both together. Psalm 104:8 describes waters that "go up by the mountains" and "go down by the valleys." Whether or not a reader takes that as a picture of the Flood's retreat, the Bible everywhere treats the earth as a place God shaped on purpose, which is why it rewards careful measuring.

Cross-section of the pumice plain, Mount St. Helens (schematic)



Vertical scale approximate. Thicknesses vary across the plain.

Mount St. Helens: layers laid down in hours in 1980 and a channel cut through them in hours in 1982. A small stream now runs in the bottom of a canyon it did not cut.

⏳ Thinking About Time

What the sign says. Standard textbooks say the sedimentary layers of the continents took hundreds of millions of years to form at slow rates, and that the dinosaurs died out about 66 million years ago.

What we observe. What we observe today are the layers, their fossils, their thicknesses and their contacts, together with measured modern events such as Mount St. Helens, where meters of laminated deposits formed in an afternoon and a canyon tens of meters deep formed in a day. No one measured the rate at which the ancient layers formed.

How Christians read it. Young-earth creation, the view this course holds, reads Genesis as history: six days, a chronology of a few thousand years, and a global Flood that laid down most fossil-bearing rock rapidly. Some Christians read the days as long ages or place a gap before them; Lesson 7.2 states those views fairly. All sides agree the layers are real; they differ on the rates and starting conditions assumed.

Try it. Shake a jar of mixed sand, gravel and soil in water and time how long the bands take to form.

Genesis 7:11

PICTURE STUDY



The Subsiding of the Waters of the Deluge, Thomas Cole, 1829 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C.

Thomas Cole, the founder of the Hudson River School of American landscape painting, painted this scene the year he sailed for Europe. It shows the morning after the Flood: the waters are draining out of a torn rocky landscape, the sky is clearing, and in the foreground lie a skull, a shattered tree and heaps of tumbled stone. Far off, the sea is calm, a soft light has returned, and the ark floats on the water while a dove flies toward land.

Cole was reading the geologists of his day, who argued about how much of the earth's surface had been shaped by water. He gives us a painter's answer: the rocks themselves look torn and newly made, and the quiet light says that judgment has passed and a new world is beginning.

Look closely

- Find the skull and the broken tree in the foreground. What do they tell you happened here?
- Look at the shapes of the rocks. Do they look worn smooth by slow weather, or freshly broken and tumbled?
- Where is the light coming from? What part of the picture is brightest, and why might Cole have chosen that?
- Find the ark on the calm water and the dove flying toward land. What do they suggest about what comes next?

Talk about it

1. Cole shows the earth after a catastrophe. What kinds of rock features would a geologist expect a draining Flood to leave behind?
2. Why do you think a painter in 1829 chose this subject? What were people arguing about then?
3. Which parts of this picture are observation (things anyone could see after a flood) and which are interpretation?

> **Safety first.** The project uses flowing water and several kilograms of damp sand. Work outdoors or over a large tray and towel, keep water away from electrical outlets, and lift the sand tray with help. Wash hands afterward.

EXPERIMENT: DOES A CHANNEL CUT AT A STEADY RATE? A SAND-TRAY TEST OF THE CONSTANT-RATE ASSUMPTION

At Mount St. Helens a canyon formed in hours, yet a small stream now flows in it. In this experiment you will cut a channel in packed sand with flowing water and measure its depth every 30 seconds to find out whether the rate stays the same.

Question: Does channel depth grow at a constant rate? Prediction: write what you expect the depth to be at 30, 60, 90 and 120 seconds before you start.

You will need

- A plastic tray or shallow storage box at least 40 cm long
- About 4 kg of damp play sand, or sand mixed with a little flour so it packs firm
- A 2-liter bottle with a small hole punched near the base and a strip of tape to cover it
- A ruler, a stopwatch or phone timer, a bucket to catch runoff
- A block of wood or a book to tilt the tray
- Lab notebook, graph paper and pencil

Steps

1. Pack the damp sand into the tray in flat layers about 2 cm thick, pressing each firmly. If you have colored sand or a dark soil, make one layer a different color so you can see it in the channel wall later.
2. Tilt the tray about 5 cm at one end (measure and record the tilt). Set the bucket under the low end.
3. Fill the bottle, hold it at the high end with the hole facing the sand and the tape on. Start the timer as you pull the tape so water flows steadily onto the sand.
4. At 30, 60, 90 and 120 seconds, read the depth of the deepest part of the channel with the ruler (measure from the original sand surface to the channel floor). Record each in a table: time, depth, change in depth since last reading.
5. Compute the rate for each 30-second interval in cm per second. Plot depth against time on graph paper. Is the line straight or does it bend?

6. Change one variable: repeat with the tray tilted 10 cm, keeping the same sand, same bottle and same hole size. Record the new table and plot it on the same graph.
7. Pretend you are a visitor who only saw the last 30 seconds. Using only that interval's rate, calculate how long the whole channel "must have" taken. Compare with the true time of 120 seconds.

Tips

- Keep the bottle at the same height for the whole run so the flow does not change on its own.
- If the channel is hard to read, slide a toothpick to the bottom and mark it, then measure the toothpick.
- Look at the channel wall at the end. Can you see the colored layer? Was it cut cleanly or smeared?

Check your work

- I can compute a rate from a depth and a time interval.
- I can tell from my graph whether the rate was constant and explain why that matters for estimating age.
- I can explain why a rate measured now may not be the rate that formed a feature in the past.

FIELD NOTEBOOK

1. Draw your sand-tray channel in cross-section at 120 seconds, with a scale bar, showing the colored layer in the wall and the water at the bottom. Title it with the true time it took.
2. Make a chronology strip: a line with marks for creation (year 0), the birth of Noah (year 1056), the Flood (year 1656) and the death of Methuselah, using the ages in Genesis 5.
3. Draw the summit profile of Mount St. Helens before (2,950 m) and after (2,549 m) May 18, 1980, to the same scale, and shade the part of the mountain that became the debris avalanche.

> **From history.** James Ussher (1581 to 1656) was a careful scholar who read Hebrew, Greek and Latin and collected one of the finest libraries in Ireland. His chronology, published in Latin in 1650 as the *Annales Veteris Testamenti*, used the Genesis genealogies together with dated events in Babylonian and Persian history to tie Scripture to the calendar. Beginning in 1701 his dates were printed in the margins of many English Bibles, which is why generations of readers saw "4004 BC" beside Genesis 1. His arithmetic was sound for the text he used; the debate today is over whether the genealogies are meant as a complete chronology, not over his adding.

WORKED EXAMPLES

Example 1. Genesis 5 gives the age of each father when the next son was born: Adam 130, Seth 105, Enos 90, Cainan 70, Mahalaleel 65, Jared 162, Enoch 65, Methuselah 187, Lamech 182, and Noah was 600 years old when the Flood came (Genesis 7:6). How many years from creation to the Flood does this chronology give?

1. Add the nine ages to find the year of Noah's birth: 130 + 105 = 235; + 90 = 325; + 70 = 395; + 65 = 460; + 162 = 622; + 65 = 687; + 187 = 874; + 182 = 1,056. Noah was born in year 1,056 after creation.
2. Add Noah's age at the Flood: 1,056 + 600 = 1,656.
3. Check one landmark: Methuselah was born in year 687 and lived 969 years (Genesis 5:27), so he died in year 687 + 969 = 1,656, the year of the Flood.

Answer: 1,656 years from creation to the Flood (using the Hebrew text that the KJV follows). Methuselah died in the Flood year.

Example 2. The USGS reports that the 1980 debris avalanche at Mount St. Helens had a volume of about 2.5 cubic kilometers and buried about 60 square kilometers of valley. What was its average thickness? Compare with the USGS figure of about 45 m.

1. Average thickness = volume ÷ area. Convert both to meters: 2.5 km^3 = 2.5 × 10^9 m^3; 60 km^2 = 6.0 × 10^7 m^2.
2. Divide: 2.5 × 10^9 m^3 ÷ 6.0 × 10^7 m^2 = 41.7 m.
3. The USGS average of about 45 m agrees within rounding, since both the volume and the area are round figures. A deposit over 40 m thick was laid down in minutes.

Answer: About 42 m average thickness, consistent with the published figure of about 45 m. The whole deposit formed in a few minutes.

Example 3. Suppose a mudflow cuts a channel 30 m deep through soft volcanic deposits in one day. Years later a visitor measures the small stream at the bottom and finds it lowers its bed by about 1 mm per year. If the visitor assumes that rate has always been the rate, how old will the channel seem? By what factor is that estimate wrong?

1. Assumed age = depth ÷ rate = 30 m ÷ 0.001 m per year = 30,000 years.
2. True time = 1 day. Convert the estimate to days: 30,000 years × 365 days per year = 10,950,000 days.
3. The estimate is too large by a factor of about 11 million. The measurement (30 m) was correct; the assumption (constant 1 mm per year) was wrong.

Answer: About 30,000 years, roughly 11 million times too long. The error comes entirely from assuming today's rate applied in the past.

PRACTICE

1. EASY In one or two sentences, state the young-earth creation position.
2. EASY On what date did Mount St. Helens erupt, and how much height did it lose? (Before: 2,950 m. After: 2,549 m.)
3. EASY Which verse in the Ten Commandments says that God made heaven and earth in six days?
4. MEDIUM Using the Genesis 5 ages in the worked example, find the year (after creation) in which Lamech, Noah's father, was born. Adam died at age 930 (Genesis 5:5). How old was Lamech when Adam died?
5. MEDIUM Data reading. The table lists three events at Mount St. Helens. Event A: debris avalanche, May 18, 1980, lasted about 10 minutes, deposit average 45 m thick. Event B: pyroclastic flows, June 12, 1980, lasted a few hours, deposit about 8 m of fine laminated layers. Event C: mudflow, March 19, 1982, lasted about one day, cut a channel about 30 m deep. Which statement is best supported by the data? (A) Thicker deposits always take longer to form. (B) Deposit thickness alone does not tell how long a deposit took to form. (C) Erosion is always slower than deposition. (D) Fine laminations take longer to form than coarse deposits.
6. MEDIUM Data reading. A student's sand-tray channel had these depths: 0 s, 0.0 cm; 30 s, 2.1 cm; 60 s, 3.4 cm; 90 s, 4.2 cm; 120 s, 4.7 cm. Compute the rate (cm per second) for the first and the last 30-second intervals. Was the rate constant? If a visitor used only the last interval's rate to estimate how long the 4.7 cm channel took, what would the estimate be?
7. HARD Experiment design. You want to test whether the speed of flowing water changes how fast a channel deepens in packed sand. Name the independent variable, the dependent variable, three things to keep the same, and what you would measure and how often.
8. HARD Ash from the 1980 eruption fell 2 cm thick on a town in eastern Washington in a single afternoon. If someone later assumed that dust settles at 0.1 mm per year and

used that rate, how many years would the ash layer seem to represent? What assumption produced the error?

9. HARD Short explanation. Young-earth geologists point out that in many thick stacks of sedimentary rock the contact between one layer and the next is flat and sharp, with no stream channels, soil or roots cut into the lower layer. In three or four sentences, explain why they read this as evidence of little time between the layers, and state one thing a careful reader should still check.
10. CHALLENGE Ussher placed creation at 4004 BC. Using the 1,656 years from the worked example, in what year BC would the Flood fall? How many years ago was that from AD 2026? (There is no year 0: 1 BC is followed by AD 1.)

COMMON MISTAKES

- Thinking young-earth creation means ignoring the rocks. It takes the rocks as true evidence and disputes the assumed rates and starting conditions, not the measurements.
- Thinking the number of layers equals the number of years. One pour in a jar makes several layers in minutes, and Mount St. Helens laid down thousands of laminations in hours.
- Thinking a stream at the bottom of a canyon must have carved the canyon. The 1982 channel at Mount St. Helens was cut by a mudflow in a day; the stream came afterward.

> **Make it a game · Rate Detective.** One player secretly chooses a deposit from a card deck the family makes beforehand: a 2 cm ash fall (one afternoon), a 45 m avalanche deposit (ten minutes), a 30 m mudflow canyon (one day), a 5 cm layer of silt from a river flood (one week), or a 1 mm band of lake mud (one season). The player reads out only the thickness. The others must each state an assumed rate and the age it gives, then vote on whether the deposit was fast or slow. Reveal the true time. Score a point for every correct fast-or-slow call, and a bonus point for naming the assumption that fooled the losers. First to seven wins.

> **Scripture.** “For in six days the LORD made heaven and earth, the sea, and all that in them is, and rested the seventh day: wherefore the LORD blessed the sabbath day, and hallowed it.” (Exodus 20:11, KJV)

This verse, spoken by God at Sinai, ties the week of work and rest to the week of creation. Young-earth Christians read it as confirming six ordinary days. Whatever view a Christian holds, the verse teaches that the pattern of our work comes from the pattern of God’s.

Practice answers

1. God created the heavens and the earth in six ordinary days a few thousand years ago, and the global Flood of Genesis 6 to 9 laid down much of the fossil-bearing rock record rapidly.
2. May 18, 1980; it lost 2,950 − 2,549 = 401 m, about 400 m.

3. Exodus 20:11: “For in six days the LORD made heaven and earth, the sea, and all that in them is.”
4. Lamech was born in year 874 (130 + 105 + 90 + 70 + 65 + 162 + 65 + 187). Adam died in year 930, so Lamech was 930 − 874 = 56 years old. Adam and Noah’s father lived at the same time for 56 years.
5. (B). The thickest deposit (45 m) formed in the shortest time (minutes), and fine laminations formed in hours, so thickness and fineness are not reliable clocks by themselves. (A), (C) and (D) are contradicted by the table.
6. First interval: 2.1 ÷ 30 = 0.070 cm/s. Last interval: (4.7 − 4.2) ÷ 30 = 0.017 cm/s. The rate fell by about four times, so it was not constant. Estimate from the last rate: 4.7 ÷ 0.017 ≈ 280 s, more than double the true 120 s.
7. Independent: water speed (change it by raising the bottle or using a larger hole). Dependent: channel depth after a set time. Keep the same: sand type and packing, tray tilt, total volume of water, starting surface. Measure the deepest point of the channel with a ruler every 30 seconds for 2 minutes, and repeat each run twice to average.
8. 2 cm = 20 mm; 20 mm ÷ 0.1 mm per year = 200 years. The error comes from assuming a slow, constant modern rate when the layer actually formed in one catastrophic event.
9. If a layer sat exposed for thousands of years before the next was laid on it, we would expect its surface to be eroded by streams, weathered into soil, or burrowed by plants and animals. A flat, sharp contact looks like the lower layer was still fresh when the next arrived, which suggests little time. Therefore they read many such contacts as rapid, continuous deposition. A careful reader should still check whether the contact really is unweathered everywhere it is exposed, and should state the slow-rate explanation beside the rapid one before deciding.
10. Flood: 4004 − 1,656 = 2348 BC. Years ago: 2,348 + 2,026 − 1 = 4,373 years ago (subtracting one because there is no year 0).

7.2 Old-Earth Christian Views: Hugh Miller, Thomas Chalmers, and the Day-Age and Gap Readings

OBJECTIVES

- Summarize the gap view and the day-age view accurately, naming the Genesis verses each leans on and one historical Christian who held each.
- List what young-earth and old-earth Christians agree on (God created from nothing, Adam and Eve were real, Scripture is true) and where they differ (the length of the days, the age of the rocks, the extent of the Flood).
- Use time = thickness ÷ rate and a scale model to show how the same rock measurement is read differently under different assumed rates, and label each reading as an interpretation.

Warm-up. Read Genesis 1:1 to 1:5 aloud. Then read Psalm 90:4. Write down, in your own words, what each passage says about a day. Now ask: if you had only these two passages, what is the strongest case for ordinary days, and what is the strongest case for long ages? Write one sentence for each side before anyone discusses.

Video. Coming soon. Hugh Miller stonemason geologist Old Red Sandstone, Cromarty, fossil fish; day-age and gap interpretations of Genesis 1 explained by a pastor or church historian; search National Museums Scotland, Scottish Geology Trust, Christian apologetics ministries with a history focus, and university religion department lecture channels.

KEY TERMS

day-age view
The reading of Genesis 1 in which each of the six “days” is a long age of time, so creation took place over a very long period in the order Genesis gives.

gap view
The reading in which Genesis 1:1 describes an original creation, a long gap of time (holding most of the rock record) falls before Genesis 1:2, and the six days that follow are ordinary days of remaking the earth.

framework view
The reading in which the six days are a literary pattern (days 1 to 3 form realms, days 4 to 6 fill them) rather than a timeline, so Genesis 1 is silent on how long creation took.

concordism
Trying to match the order of events in Genesis 1 to the order claimed by mainstream geology and astronomy, as day-age writers do.

Old Red Sandstone

A thick body of red sandstone and shale in Scotland, Wales and England, famous for fossil fish; a museum word for the Devonian rocks Hugh Miller quarried and wrote about.

extent of the Flood
Whether the Flood of Genesis 6 to 9 covered the whole earth (global) or a large region (local); young-earth Christians hold it was global, and old-earth Christians are divided.

CORE IDEAS

The story. In 1819 a seventeen-year-old apprentice stonemason named Hugh Miller began splitting rock in a quarry on the shore of the Cromarty Firth in the north of Scotland. Inside the red slabs he found the stony shapes of fish, armored and strange, pressed flat in the stone. He kept finding them for twenty years. Miller had no university training, but he read everything, measured everything and wrote with the plain force of a man who had handled the rocks himself. In 1840 he moved to Edinburgh to edit *The Witness*, a newspaper of the evangelical party in the Church of Scotland, and in 1841 he published *The Old Red Sandstone*, which made him famous in Britain and America. He was a committed Christian who stood with Thomas Chalmers in the Disruption of 1843, when hundreds of ministers left the state church to found the Free Church of Scotland. And he was an old-earth geologist. His last book, *The Testimony of the Rocks* (1857), argued that the "days" of Genesis 1 were long ages, each shown to Moses as a vision.

How they figured it out. Miller's friend and leader, Thomas Chalmers, had taken a different road to an old earth. Around 1814, reviewing the French anatomist Georges Cuvier's work on fossils, Chalmers suggested that Genesis 1:1 describes an original creation, that an unmeasured stretch of time falls before verse 2, and that the six days which follow are ordinary days in which God remade a ruined earth. This is the **gap view**. Its readers take "the earth was without form, and void" as "the earth *became* without form," and place the fossil-bearing rocks in the gap. The Oxford clergyman and geologist William Buckland taught a version of it, and the notes of the Scofield Reference Bible (1909) carried it into many American homes. Miller came to think the gap view did not fit the rocks, because the fossils are not all older than the present world; many of the fossil kinds are kinds still living. So he read each day as an age instead. This is the **day-age view**. Its readers point to Psalm 90:4, "a thousand years in thy sight are but as yesterday," to 2 Peter 3:8, and to Genesis 2:4, which calls the whole creation week "the day that the LORD God made the earth and the heavens." They note that Genesis 1 moves from light, to seas and sky, to dry land and plants, to sea creatures and birds, to land animals and man, and they argue that this order broadly matches what the rocks show. This matching is called **concordism**.

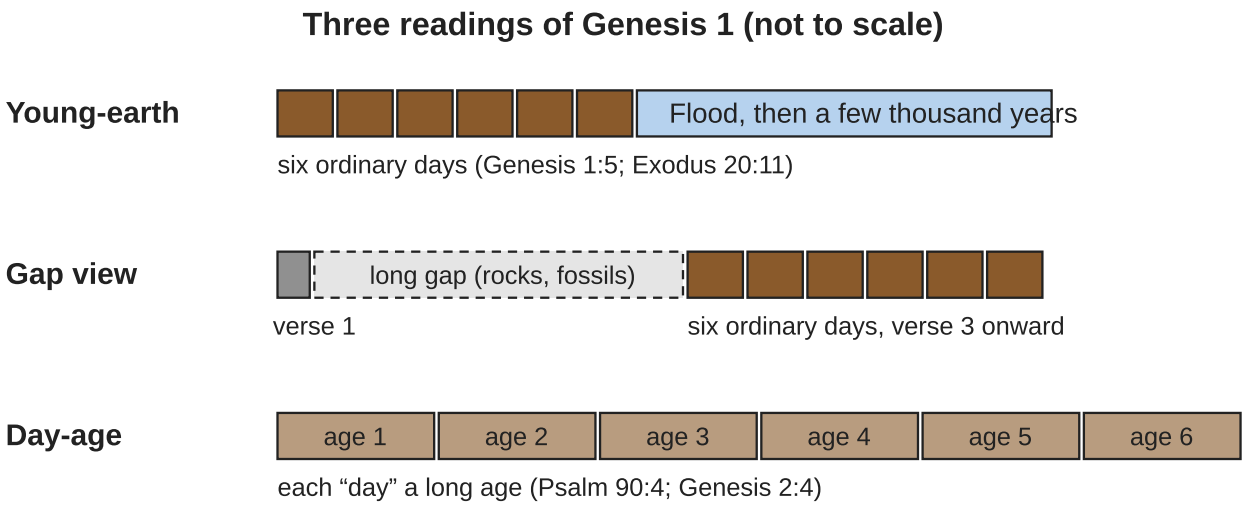
The big idea. A fair summary gives each view its best case and its hardest question. The gap view keeps the days ordinary and keeps Exodus 20:11, but its critics ask whether Hebrew grammar allows "became" in Genesis 1:2 and whether there could be death and fossils before Adam's sin. The day-age view keeps the order of Genesis 1 and reads "day" with its wider biblical range, but its critics point to "the evening and the morning" repeated six times, to plants made on day three before the sun on day four, and to birds on day five before land animals on day six, which is not the order textbooks give. A third reading, the

framework view, holds that the six days are a literary pattern, three days of forming realms and three days of filling them, so that Genesis 1 does not say how long creation took. Young-earth creation, which this course holds, answers that the plain words, the repeated “evening and morning,” Exodus 20:11 and the genealogies all point to ordinary days a few thousand years ago, and that the hardest questions for the old-earth views are death before sin and a Flood that must then be made local or quiet. Each side has answers to the other’s questions. You are learning them, not to win, but to state them without distortion.

Observation and interpretation. Every one of these Christians believed that God created everything out of nothing, that Adam and Eve were real people made in His image, that sin and death entered through Adam, and that the Bible is true. They did not disagree about any rock. Miller measured the same Old Red Sandstone a young-earth geologist measures. The disagreement is in two places: how to read certain Hebrew words and sentences, and what rates and starting conditions to assume when turning rock thicknesses into years. A 300 m sandstone is 300 m thick for everyone. At an assumed 0.1 mm per year it reads as 3 million years; at 1 m per day it reads as 300 days. Neither number was measured. One is a day-age or secular interpretation; the other is a Flood interpretation. Write both in the interpretation column and the 300 m in the observation column.

Try it and see. Today’s project asks a question every view must face: does one pour of mixed sediment make one layer or many? If a single flow can lay down several graded bands in minutes, then “count the layers and multiply by years” is a method that depends on an assumption. Old-earth and young-earth Christians both accept this result; they differ on how often, in the past, deposition was fast.

God’s handiwork. Hugh Miller learned to see with a stonemason’s hammer in one hand and a Bible in the other. He died sadly, worn down by illness and overwork, in December 1856, before his last book was printed. His widow, Lydia, saw *The Testimony of the Rocks* through the press. Christians who disagreed with his reading of Genesis still honored his honesty, his labor and his faith, and that is the model for this unit.



Brown = creation days. Dashed = time the view places before the days. Blue = time after creation.
All three readings agree: God created all things; Adam was real; Scripture is true.

Three readings of the same chapter. The bars are not to scale: on the gap and day-age readings the long stretches would be millions of times longer than the days.

⏳ Thinking About Time

What the sign says. Textbooks and museum signs say the Old Red Sandstone that Hugh Miller quarried formed in the Devonian, about 360 to 420 million years ago, and that the earth is about 4.5 billion years old.

What we observe. What we observe is a thick stack of red sandstone and shale with beautifully preserved fossil fish, often whole, with fins and scales in place. We can measure its thickness and study its grains. We cannot observe how fast it was laid down.

How Christians read it. Young-earth Christians read the sandstone as a rapid deposit, most likely from the Flood, and the whole fish as animals buried before they could rot or be scattered. Old-earth Christians such as Miller read it as a long age of slow deposition with occasional rapid burials. Both agree the fossils are real fish and the layers are real; the years are interpretation on either reading.

Try it. Bury a leaf in a jar of wet sand for a week and another in open air; see which keeps its shape.

Genesis 1:5

PICTURE STUDY



Hugh Miller, David Octavius Hill and Robert Adamson, 1843 · Calotype photograph (salted paper print from a paper negative) · National Galleries of Scotland, Edinburgh

Hill and Adamson were the first great photographers of Scotland, working in Edinburgh only a few years after photography was invented. Their calotype process used paper negatives and needed sittings of a minute or more in bright sun, so every picture is still and deliberate. Hugh Miller was one of the first to sit for them, and they photographed him more than once, sometimes posed as the stonemason he had been.

The portrait shows a man who was at once a laborer, a scholar and a church leader. Hill and Adamson photographed many of the ministers who left the Church of Scotland in 1843, and Miller, who edited their newspaper, belongs to that company.

Look closely

- Look at his clothes. Is he dressed as a gentleman or as a working man? Why might a famous writer choose that?
- Look at the background. Was this picture taken indoors or outside, and how can you tell?
- Early photographs needed long, still sittings. How can you tell from his posture and face?
- Look at the light and shadow on his face and hands. Where was the sun?

Talk about it

1. Miller learned geology by cutting stone, not in a classroom. What can a person learn from handling rocks that cannot be learned from a book?

2. He was an old-earth Christian who loved the Bible. How should a young-earth student describe a man like that?
3. What would you want to ask him if you could sit beside him at the quarry?

> **Safety first.** The project uses glass jars and water. Use a plastic jar if one is available, wipe spills at once, and do not shake a glass jar near a hard floor.

EXPERIMENT: ONE POUR, HOW MANY LAYERS? TESTING WHETHER LAYER COUNT EQUALS EVENT COUNT

Every view of earth history must decide what a layer means. In this experiment you will pour mixed sediment into water a known number of times and have a partner count the layers without knowing how many pours you made.

Question: Does one pour produce one layer? Prediction: write how many bands you expect from one pour, from two pours and from three.

You will need

- A tall clear jar or 1-liter bottle with the top cut off, three-quarters full of water
- Three kinds of sediment: coarse sand or aquarium gravel, fine sand, and a fine powder such as flour, garden soil or crushed chalk
- Three small cups, a spoon, a ruler, a flashlight
- A partner who leaves the room during the pours
- Lab notebook and colored pencils

Steps

1. Mix one spoon of each sediment in a cup. With your partner out of the room, pour the whole cup into the water in one motion. Wait two minutes for the water to clear.
2. Call your partner in. Shine the flashlight through the jar and ask them to count the distinct bands and write the number down without talking to you. Record their count beside your true pour count (1).
3. Partner leaves. Pour two more mixed cups, one right after the other, ten seconds apart. Wait, call the partner, and record their count beside the true count (3).
4. Measure the total thickness of sediment with the ruler and the thickness of each band your partner identified. Draw the jar in cross-section to scale and color the bands.
5. Change one variable: repeat the single-pour test with the jar tilted 20 degrees against a book. Keep the same sediment mix and amount. Does the tilted bottom change the number or shape of the bands?
6. Compare your partner’s counts with the true pour counts in a table. Compute the ratio bands ÷ pours for each test.
7. Write a conclusion: can a person who did not see the pours tell how many events made the layers? What else would they need to know?

Tips

- Coarse grains settle first; a single pour usually makes a graded band (coarse at the bottom, fine at the top) that the eye can split into two or three bands.
- If the water stays cloudy, wait longer; the finest powder settles last and makes the thin cap on each band.
- Keep each pour the same size so the only thing you change is the number of pours.

Check your work

- I can explain why the number of layers is not automatically the number of events or years.
- I can keep variables the same and change only one.
- I can state what a geologist must assume to turn a layer count into a time.

FIELD NOTEBOOK

1. Draw the three timelines from the figure in your own hand and, under each, write the one verse that view leans on most.
2. Draw a fossil fish from the Old Red Sandstone as Miller would have seen it, flattened in red stone, with its armored head plates and tail, and write two observations and one interpretation beside it.
3. Make a two-column page: “All these Christians agree” and “They differ on,” with at least four items in the first column and three in the second.

> **From history.** The Scofield Reference Bible, published by Oxford University Press in 1909 and revised in 1917, printed C. I. Scofield’s notes on the same page as the KJV text. His note on Genesis 1:2 presented the gap view, and because the Bible sold in the millions, many American Christians of the twentieth century first met the old-earth question there. Earlier, in the 1820s and 1830s, Oxford’s William Buckland and Cambridge’s Adam Sedgwick, both ordained clergymen, taught geology as a science fully compatible with Scripture while holding that the rocks required long ages. The young-earth position was argued in the same years by writers such as George Fairholme and Granville Penn, and it returned to wide attention in 1961 with *The Genesis Flood* by John Whitcomb and Henry Morris.

WORKED EXAMPLES

Example 1. A textbook says the earth is about 4.54 billion years old. If a day-age reader spread that whole time evenly across the six creation days, how long would each "day" be? Compare with the "thousand years" of Psalm 90:4 taken as an exact length of a day.

1. Divide the textbook age by six: 4,540,000,000 years ÷ 6 = 757,000,000 years, about 760 million years per day.
2. If instead each day were exactly 1,000 years, six days would be 6,000 years, which is close to the young-earth total, not the textbook total.
3. So the day-age view does not take Psalm 90:4 as a formula; it uses the verse only to show that "day" can mean a stretch of time of unstated length. The 760-million-year figure is an interpretation built on the textbook number, not a measurement.

Answer: About 760 million years per "day" if the textbook age is spread evenly. Six literal thousand-year days would total only 6,000 years, so day-age readers use the psalm as an example of flexible meaning, not as a measurement.

Example 2. Make a scale model of the textbook timeline. Let 4.54 billion years be a straight walk of 1,000 m. How far along the walk is (a) 6,000 years, (b) the museum sign's 66 million years for the end of the dinosaurs, and (c) the chart's 540 million years for the start of the Cambrian?

1. Scale: 1,000 m ÷ 4,540,000,000 years = 2.20×10^{-7} m per year.
2. (a) 6,000 years × 2.20×10^{-7} m/yr = 0.00132 m, about 1.3 mm, less than the thickness of a coin, at the very end of the walk.
3. (b) 66,000,000 × 2.20×10^{-7} = 14.5 m from the end of the walk.
4. (c) 540,000,000 × 2.20×10^{-7} = 119 m from the end of the walk, so 881 m of the walk would come before the first Cambrian fossils.

Answer: (a) About 1.3 mm; (b) about 14.5 m; (c) about 119 m from the end of a 1,000 m walk. The model shows how the textbook timeline is laid out; it does not test whether the timeline is right.

Example 3. A red sandstone is measured at 300 m thick. Read it three ways: (a) at an assumed slow rate of 0.1 mm per year, (b) at an assumed 1 cm per year, and (c) at an assumed Flood rate of 1 m per day. Which of the four numbers is an observation?

1. Time = thickness ÷ rate. Convert 300 m to the units of each rate.
2. (a) 300 m = 300,000 mm; 300,000 ÷ 0.1 mm/yr = 3,000,000 years.
3. (b) 300 m = 30,000 cm; 30,000 ÷ 1 cm/yr = 30,000 years.
4. (c) 300 m ÷ 1 m/day = 300 days, within a Flood year.
5. Only the 300 m was measured. The three times depend on the assumed rate, which differs by a factor of millions between (a) and (c).

Answer: (a) 3 million years; (b) 30,000 years; (c) 300 days. The observation is the thickness, 300 m. Every time is an interpretation that stands or falls with its rate.

PRACTICE

1. EASY In one sentence each, state the gap view and the day-age view.
2. EASY Who was Hugh Miller, and what rock did he become famous for?
3. EASY Name one verse day-age readers use, and one verse gap readers use.
4. MEDIUM List three things young-earth, gap and day-age Christians all affirm, and two things they disagree about.
5. MEDIUM Data reading. The table compares orders. Genesis 1: day 3 plants; day 4 sun, moon, stars; day 5 sea creatures and birds; day 6 land animals and man. Textbook order of first appearance: sun before any life; sea creatures before land plants; land animals (reptiles) before birds; man last. Which Genesis-to-textbook pairs match in order and which do not? Which view, day-age or young-earth, needs the orders to match, and why?
6. MEDIUM Data reading. In the layer-count experiment, four families reported: Family A, 1 pour, partner counted 3 bands; Family B, 1 pour, 2 bands; Family C, 3 pours, 7 bands; Family D, 3 pours, 9 bands. Compute bands ÷ pours for each family. What is the average ratio? Which conclusion do the data support? (A) Each pour makes exactly one band. (B) Each pour makes about two to three bands. (C) Band count cannot be measured. (D) More pours make fewer bands.
7. HARD Experiment design. You want to test whether the speed of a pour changes the number of bands a single pour makes. Name the independent and dependent variables, two things to keep the same, and how you would make the count fair.
8. HARD A shale 50 m thick is read by one geologist at 0.05 mm per year and by another as a deposit of 50 days. What age does each get? What single word describes what each number is?
9. HARD Short explanation. In three or four sentences, give the strongest case for the day-age view and then the strongest question a young-earth reader puts to it. Write both so that a day-age Christian would say you were fair.

10. CHALLENGE Thomas Chalmers and Hugh Miller were close allies in the Free Church of Scotland (1843) yet held different old-earth views, and both differed from young-earth Christians of their day. In four or five sentences, explain how Christians can hold different readings of Genesis 1 and still share the same faith, and name what must not be given up by any of them.

COMMON MISTAKES

- Thinking that old-earth Christians do not believe in creation. Chalmers, Buckland and Miller all held that God created everything; they differed on the length of the days.
- Mixing up the gap view and the day-age view. The gap view keeps six ordinary days but adds time before them; the day-age view makes the days themselves long.
- Thinking the thickness of a layer tells its age. Thickness is observed; age comes from an assumed rate, and the assumed rate is the whole debate.

> **Make it a game · Which View Said It?.** Write twelve statements on cards, four for each of young-earth, gap and day-age: for example, “The six days are ordinary days and the rocks formed mostly in the Flood,” “A long age of time lies between verse 1 and verse 2,” “Each day is a long age in the order Genesis gives.” Shuffle. A reader draws a card and reads it aloud; players hold up one, two or three fingers for young-earth, gap or day-age. One point for each correct call. Bonus round: the reader states a view and a player must give its best verse in ten seconds. Play to fifteen.

> **Scripture.** “But, beloved, be not ignorant of this one thing, that one day is with the Lord as a thousand years, and a thousand years as one day.” (2 Peter 3:8, KJV)

Day-age readers lean on this verse; young-earth readers answer that Peter is speaking of God’s patience, not defining the days of Genesis. Both agree on what the verse plainly teaches: God is not bound by our clocks, and His promises are not late.

Practice answers

1. Gap view: Genesis 1:1 is the original creation, a long gap of time falls before verse 2, and the six days that follow are ordinary days of remaking the earth. Day-age view: each of the six days is a long age, and creation took place over a very long time in the order Genesis gives.
2. A Scottish stonemason who became a geologist, writer and newspaper editor (1802 to 1856); he was famous for the fossil fish of the Old Red Sandstone.
3. Day-age: Psalm 90:4 or 2 Peter 3:8 (a thousand years as a day) or Genesis 2:4 (“in the day that the LORD God made”). Gap: Genesis 1:2 (“the earth was without form, and void,” read as “became”).
4. All affirm: God created everything from nothing; Adam and Eve were real people made in God’s image; the Bible is true (also: sin and death came through Adam; Christ is Creator and Redeemer). They disagree about the length of the creation days, the age of the rocks, and whether the Flood was global or local.
5. Match: man last in both; sea creatures before land animals in both. Do not match: Genesis has plants (day 3) before the sun (day 4), the textbook has the sun first; Genesis has birds (day 5)

before land animals (day 6), the textbook has reptiles before birds. The day-age view needs the orders to match because it reads Genesis 1 as the same sequence spread over ages (concordism); the young-earth view does not depend on the textbook order, since it reads the fossil order as mainly the order of burial in the Flood.

6. Ratios: A 3.0, B 2.0, C 2.33, D 3.0; average (3.0 + 2.0 + 2.33 + 3.0) ÷ 4 = 2.58, about 2.6 bands per pour. (B) is supported; (A) and (D) are contradicted; (C) is false since bands were counted.
7. Independent: pour speed (dump in one second versus trickle over twenty seconds). Dependent: number of bands counted. Keep the same: the amount and mix of sediment, the jar and water depth. Fairness: have a partner who did not see the pour count the bands, use the same flashlight and distance, and repeat each speed three times and average.
8. First: 50 m = 50,000 mm; 50,000 ÷ 0.05 = 1,000,000 years. Second: 50 days (a rate of 1 m per day). Each number is an interpretation; the 50 m is the observation.
9. Strongest case: the Hebrew word for day can mean a long period, as Genesis 2:4 and Psalm 90:4 show, and the broad movement of Genesis 1 from light to seas and land to living things to man resembles the order geologists describe, so the two can be read together. Strongest question: Genesis 1 says “the evening and the morning” after each day and numbers them, and Exodus 20:11 builds the human week on them, which is how ordinary days are described; also plants come before the sun and birds before land animals, which does not fit the textbook order. (Any answer that states both sides accurately and without ridicule is acceptable.)
10. They shared the heart of the faith: that God created all things from nothing by His word, that man was made in His image, that Adam’s sin brought death and that Christ saves. Their disagreement was about how to read the word “day” and the first two verses, and about the rates assumed in geology, not about whether God created. A Christian can therefore differ on the days while fully trusting the Bible. What must not be given up is the truth of Scripture, creation by God, a real Adam, and the Flood as a real judgment. (Accept any thoughtful answer that keeps these essentials and treats the other views respectfully.)

7.3 What Secular Geology Claims: Hutton at Siccar Point (1788) and the Radiometric Clock

OBJECTIVES

- State accurately what mainstream geology claims: an earth about 4.5 billion years old, a geologic time scale of eons, eras and periods, and slow processes acting over long ages (uniformitarianism), and name the people and dates behind those claims.
- Explain how radiometric dating works, step through half-life calculations, and name the three assumptions every radiometric date depends on (starting amounts, a closed system, a constant rate).
- Read a geologic time scale and a decay graph as a museum visitor would, distinguish the measurement from the interpretation, and state the young-earth response without misrepresenting either side.

Warm-up. Put 32 pennies heads-up on the table. Each “shake” is one round: flip every penny by hand, and remove all that land tails. Count what is left after each round and write it down. How many rounds until about half are gone? Until a quarter? If I handed you a pile of 4 pennies and said it came from this game, could you tell me how many rounds it had been through? What would you have to assume?

Video. Coming soon. James Hutton Siccar Point unconformity, Charles Lyell uniformitarianism, how radiometric dating and half-life work, the geologic time scale; search USGS, British Geological Survey, Smithsonian National Museum of Natural History, Royal Society of Edinburgh, NASA and university geology department channels, and watch as a reporter learning the claim accurately.

KEY TERMS

uniformitarianism
The principle, pressed by Hutton and Lyell, that the slow processes we see today (erosion, deposition, uplift) acting over very long times explain the rock record; often summed up as “the present is the key to the past.”

unconformity
A surface in the rocks where one set of layers rests on an older set that was tilted or eroded first, which geologists read as a break in deposition.

geologic time scale
The chart that divides the textbook’s 4.5 billion years into eons, eras and periods (such as Cambrian, Jurassic, Cretaceous), with ages in millions of years; the period names are museum words you will meet on signs.

radiometric dating

Estimating the age of a rock or fossil from the amounts of a radioactive parent isotope and its daughter product, using the known half-life.

half-life

The time it takes for half of the atoms of a radioactive isotope to decay. For carbon-14 it is 5,730 years; for potassium-40 about 1.3 billion years; for uranium-238 about 4.5 billion years.

closed system

A sample that has gained or lost no parent or daughter atoms since it formed; radiometric dates assume this, and it cannot be checked by looking at the rock alone.

CORE IDEAS

The story. In June 1788 three men took a small boat along the coast of Berwickshire, Scotland, looking for a particular kind of rock contact. One was James Hutton, an Edinburgh physician turned farmer and chemist. The others were his friends John Playfair, a mathematician and minister, and the young geologist James Hall. At a headland called Siccar Point they found it: gray layers of rock standing almost on end, with red sandstone lying flat across their broken tops. Hutton reasoned that the gray layers had been laid down flat under the sea, hardened, tilted upright, lifted, worn down to a level surface, and then buried under new sand, which also hardened and was raised to become a cliff. Each step, he argued, happens today at a creeping pace, so the whole sequence must have taken an immense time. Playfair wrote afterward that the mind seemed to grow giddy by looking so far into the abyss of time. Hutton had already presented his *Theory of the Earth* to the Royal Society of Edinburgh in 1785, and the printed version (1788) ends with words every geology student learns: we find “no vestige of a beginning” and “no prospect of an end.”

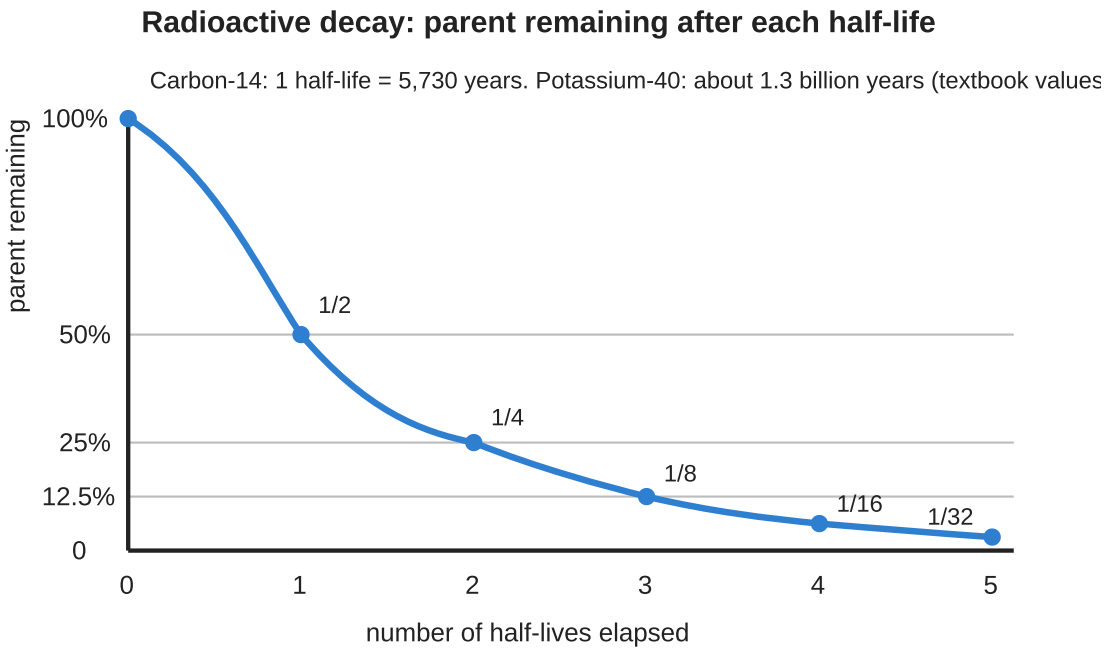
How they figured it out. Hutton’s idea was taken up by Charles Lyell, whose *Principles of Geology* (three volumes, 1830 to 1833) argued that geologists should explain the past only by causes now in operation, acting at about their present rates. Charles Darwin carried the first volume aboard HMS *Beagle* in December 1831. Lyell’s method is **uniformitarianism**. Using it, geologists built the **geologic time scale**, naming the layers William Smith had ordered (Lesson 5.1) with words like Cambrian, Devonian, Jurassic and Cretaceous and estimating their lengths from thicknesses divided by assumed slow rates. In 1862 the physicist William Thomson, later Lord Kelvin, a devout Christian, calculated from the cooling of a once-molten earth that it was probably no more than about 100 million years old, and later he narrowed the figure to 20 to 40 million years, far less than Lyell wanted. The discovery of radioactivity in 1896 changed the argument. Radioactive atoms give off heat, which weakened Kelvin’s cooling calculation, and they decay at a fixed rate, which gave geologists a clock. In 1907 Bertram Boltwood at Yale used uranium and lead to assign ages of hundreds of millions to a couple of billion years to certain minerals. Arthur Holmes published *The Age of the Earth* in 1913. In 1956 Clair Patterson at Caltech measured lead isotopes in meteorites and announced an age of about 4.55 billion years for the earth and the solar system together. The USGS today states the figure as about 4.5 billion years.

The big idea. Here is the claim stated fairly, as a textbook would. The earth formed about 4.5 billion years ago. The earliest fossils of simple cells are claimed to be over 3 billion years old; abundant animal fossils appear at the start of the Cambrian, about 540 million years ago; dinosaurs appear in the Triassic and vanish at the end of the Cretaceous, about 66 million years ago; and the Ice Age of the Pleistocene ended about 12,000 years ago. The main evidence offered is radiometric dating, cross-checked by several isotope pairs on the same rocks, together with the order of fossils, the thickness of sediments, counts of annual-looking layers in lakes and ice, and the slow rates of plate motion measured today. **Radiometric dating** works like the penny game. A parent isotope such as potassium-40 decays into a daughter such as argon-40 with a fixed **half-life**. Measure the ratio of daughter to parent in a mineral, assume the daughter was absent at the start, and the ratio tells you how many half-lives have passed. Two half-lives leave one quarter of the parent; three leave one eighth. For carbon-14, with a 5,730-year half-life, the method is used on wood, bone and cloth; for potassium and uranium, on volcanic minerals.

Observation and interpretation. What is measured in the laboratory is real and precise: the ratio of atoms today, and the decay rate today. What is assumed is threefold. First, the starting amounts: how much daughter was already present when the rock formed. Second, a **closed system**: no atoms leaked in or out through heat, water or pressure since then. Third, a constant rate through the whole time being measured. Mainstream geologists know these are assumptions and design checks for them, such as isochron plots and comparing methods. Young-earth geologists accept the measured ratios and decay rates and question the assumptions, pointing to rocks of known recent age (such as dacite from the Mount St. Helens lava dome, formed in the 1980s) that gave old potassium-argon dates because of inherited argon, to disagreements between methods on the same rock, and to measurable carbon-14 reported in coal and diamond samples that, on the textbook timeline, should contain none. Mainstream geologists answer that those cases are explained by known contamination or excess argon, and that most dates agree well. A fair reader states both answers and labels the age as an interpretation of a measurement.

Try it and see. Today’s project is the penny clock. You will shake coins, remove the “decayed” ones, and plot the curve. Then you will try to date a bag of coins someone else prepared, and find that your answer depends on knowing how many coins the bag started with. That single discovery is the heart of the dating debate, and you can hold it in your hand.

God’s handiwork. Lord Kelvin, who gave the world the absolute temperature scale and fought Lyell over the age of the earth, said in a talk at University College, London, in 1903 that science positively affirms creative power. The decay of an atom is as regular as a pendulum, and the regularity is part of the order God built into matter. Learning what secular geology claims, and why, is not a danger to faith; it is part of loving God with all your mind and treating your neighbor’s argument honestly.



The decay curve. Each half-life cuts the remaining parent in half. Reading the age from the curve requires knowing where the sample started.

⏳ Thinking About Time

What the sign says. Textbooks and the USGS say the earth is about 4.5 billion years old, dated chiefly by uranium-lead measurements on meteorites and ancient zircon crystals, and that the geologic periods on museum signs (Cambrian, Jurassic, Cretaceous) are hundreds of millions of years old.

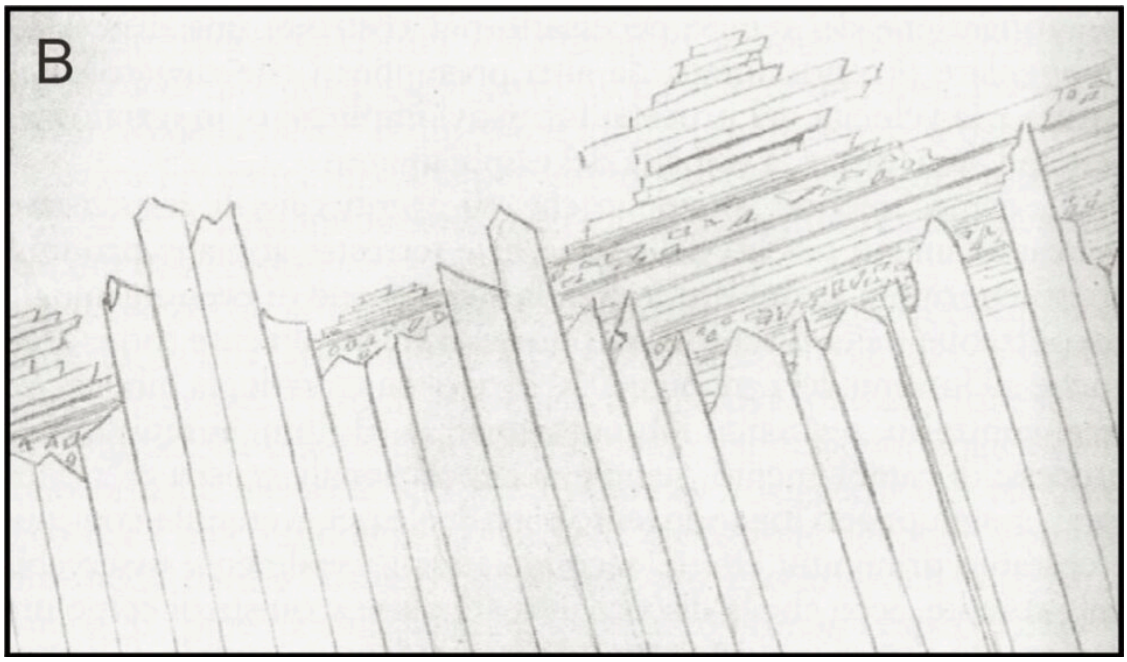
What we observe. What we observe is the ratio of parent to daughter atoms in a sample today and the decay rate today, both measured precisely in laboratories; also the order of layers and fossils. No one measured the starting amounts, watched the system stay closed, or measured the rate through the whole claimed age.

How Christians read it. Young-earth Christians accept the measurements and hold that one or more of the three assumptions fails: inherited daughter atoms, open systems during the Flood, or rates that were not always constant. They read the rock record as a few thousand years old. Some Christians accept the mainstream dates and read Genesis as long ages or a gap. Both the claim and the response should be stated in their own terms.

Try it. After three rounds of the penny game, hand the remaining coins to someone and ask them to tell you the number of rounds without knowing the starting count.

Job 38:4

PICTURE STUDY



Field Sketch of the Unconformity at Siccar Point, Sir James Hall, June 1788 · Drawing (field sketch) · Drawn on the spot during the Siccar Point visit; the Commons image is a photographic reproduction of the original sketch

James Hall was the youngest of the three men in the boat in June 1788, a twenty-seven-year-old who would later become one of the first geologists to test rocks by experiment. While Hutton talked and Playfair listened, Hall drew. This quick field sketch is the earliest picture of Siccar Point, made on the very day the three men found it.

A field sketch is not a painting. Hall left out color, sky and sea and drew only what mattered to the argument: the steep lower beds, the flat upper beds, and the line where they meet. It is a record of observation made on the spot, the same kind of record you keep in your own lab notebook.

Look closely

- Find the line where the steep lower layers stop and the flat upper layers begin. Is it drawn as sharp or ragged?
- Which way do the lower layers lean? Count as many as you can.
- What did Hall leave out of the sketch? Why might a geologist leave those things out?
- Compare this sketch with a modern photograph of Siccar Point. What did Hall get right?

Talk about it

1. Hutton read this outcrop as: deposit, harden, tilt, erode, deposit again. Which of those steps can you actually see in the sketch, and which are reasoning?

2. A young-earth geologist reads the same outcrop and says the tilting and planing-off could happen quickly in a catastrophe. What would you need to measure to decide between slow and fast?
3. Why is it useful that both sides agree on what the sketch shows before they argue about how long it took?

EXPERIMENT: THE PENNY CLOCK: HALF-LIVES, AND DATING A BAG OF UNKNOWN COINS

Radioactive atoms decay by chance, each with a fixed probability per unit time, so a large pile behaves predictably even though each atom is unpredictable. Coins do the same: each flip has a one-half chance of "decaying."

Question: Can you find the number of rounds (the age) of a coin sample from the number of coins remaining? Prediction: write what you think you need to know besides the final count.

You will need

- 100 pennies or other identical coins (or 100 dried beans marked on one side)
- A box or jar with a lid to shake them in
- Graph paper, pencil, lab notebook
- A second person to prepare the "unknown" bags
- Three paper bags

Steps

1. Put all 100 coins in the box, shake, and pour them out. Remove every coin showing tails; these have "decayed." Count the survivors and record: round 1, survivors.
2. Return only the survivors to the box and repeat for rounds 2 through 7, or until none are left. Record each count.
3. Plot survivors against round number. Draw the smooth curve. Mark the expected values 50, 25, 12.5, 6.25 beside your real points. How close is your pile to the ideal halving?
4. Compute the ratio of decayed coins (daughter) to surviving coins (parent) after each round. After 1 round it should be near 1:1; after 2 rounds near 3:1; after 3 rounds near 7:1.
5. Now the dating test. Your partner, out of your sight, starts with a number of coins they choose (40, 64 or 100), runs some number of rounds, and hands you a bag containing the survivors and, separately, the decayed coins. Using both counts, estimate the number of rounds. Check your answer with your partner.
6. Repeat, but this time the partner secretly adds 20 extra decayed coins to the bag before handing it over (an inherited daughter). Estimate the rounds again. How far off were you, and why?
7. Write a conclusion naming the three assumptions your dating method needed (starting count, no coins added or removed, the same flip rule every round) and which one the partner broke.

Tips

- Small piles wander far from the ideal; 100 coins behaves better than 20. Real samples hold trillions of atoms, so their curves are very smooth.
- If you count both survivors and decayed coins, you can recover the starting number, which is what geologists try to do with daughter atoms. The trap is when daughter atoms were present at the start.
- Keep a clean table: round, survivors, decayed, ratio.

Check your work

- I can plot a decay curve and read half-lives from it.
- I can estimate an age from a daughter-to-parent ratio.
- I can name the three assumptions and show how breaking one changes the estimated age.

FIELD NOTEBOOK

1. Copy the decay curve from your own data onto a clean graph with labeled axes, and mark where 1, 2 and 3 half-lives fall.
2. Draw Siccar Point or the Jedburgh unconformity as a labeled cross-section: tilted lower layers, the flat contact, horizontal upper layers. Under it write Hutton's five steps and circle the ones that are inferred rather than seen.
3. Make a simplified geologic time scale as a vertical bar with the textbook ages (museum words) on the left and, on the right, a column headed "assumptions behind the number."

> **From history.** Clair Patterson's 1956 measurement had a side effect that changed daily life. To measure the tiny traces of lead in meteorites, he had to build one of the first ultra-clean laboratories, because lead from gasoline, paint and solder contaminated everything. He found that the lead in modern air, water and even Arctic snow was hundreds of times higher than natural levels, and he spent the rest of his life arguing for its removal from gasoline, which the United States completed in the 1990s. The same careful measuring that produced the famous age also cleaned the air children breathe.

WORKED EXAMPLES

Example 1. A piece of wood from an old beam is measured to have one eighth of the carbon-14 ratio of living wood. Carbon-14 has a half-life of 5,730 years. What age does the carbon-14 method give, and what must be assumed?

1. Count halvings: 1 → 1/2 → 1/4 → 1/8 is three halvings, so three half-lives have passed.
2. Age = 3 × 5,730 years = 17,190 years.
3. Assumptions: the wood started with the same carbon-14 ratio as living wood today (starting amount); no carbon was added or removed since (closed system); the decay rate and the atmosphere's carbon-14 level stayed constant. Young-earth researchers question the atmospheric starting level, especially before and just after the Flood, which would make the oldest carbon-14 ages too large.

Answer: About 17,200 years by the method; the measurement is the ratio, and the age depends on the three assumptions, especially the starting level of carbon-14 in the air.

Example 2. Read the time scale. The textbook gives these ages: earth formed 4,540 million years ago; Cambrian began 540 million; Cretaceous ended 66 million. (a) What fraction of the textbook timeline comes before the Cambrian? (b) What fraction comes after the dinosaurs? Express both as percentages.

1. (a) Time before the Cambrian = 4,540 − 540 = 4,000 million years. Fraction = 4,000 ÷ 4,540 = 0.881, or 88.1 percent.
2. (b) Time after the end of the Cretaceous = 66 million years. Fraction = 66 ÷ 4,540 = 0.0145, or about 1.5 percent.
3. So, on the textbook chart, almost nine tenths of earth history is claimed to come before abundant animal fossils, and the whole time since the dinosaurs is about one seventieth of the chart. These are chart facts, not measurements.

Answer: (a) About 88 percent of the chart is before the Cambrian; (b) about 1.5 percent is after the Cretaceous. Both describe the textbook claim.

Example 3. Charles Lyell visited Niagara Falls in 1841. The gorge below the falls is about 11 km long. Lyell assumed the falls had retreated at about 0.3 m per year. (a) What age did that give the gorge? (b) Surveys in the 1800s measured a retreat of about 1 m per year. What age does that rate give? (c) What does the comparison show about rate assumptions?

1. (a) Time = distance ÷ rate = 11,000 m ÷ 0.3 m/yr = 36,700 years, which Lyell rounded to about 35,000 years.
2. (b) 11,000 m ÷ 1 m/yr = 11,000 years.
3. (c) Changing the rate by a factor of about three changed the age by the same factor. Neither calculation measured the past; both assumed the rate stayed constant over the whole length of the gorge. A faster rate in the past (for example, during meltwater floods) would shorten the time further, which is the young-earth point.

Answer: (a) About 37,000 years (Lyell said about 35,000); (b) about 11,000 years; (c) the age is only as good as the assumed rate, and the observed rate alone cannot tell you what the rate was earlier.

PRACTICE

1. EASY What did Hutton, Playfair and Hall find at Siccar Point in 1788, and what did Hutton conclude from it?
2. EASY Define uniformitarianism in one sentence and name the book that spread it.
3. EASY After two half-lives, what fraction of a parent isotope remains? After four?
4. MEDIUM Name the three assumptions behind every radiometric date, and for each give one way it could fail.
5. MEDIUM Data reading. A student’s penny clock gave: round 0, 100 coins; round 1, 52; round 2, 24; round 3, 13; round 4, 7; round 5, 3. Which statement is best supported? (A) The number removed each round is constant. (B) About half the remaining coins are removed each round. (C) The coins decay faster in later rounds. (D) The curve is a straight line. Then: if a bag held 6 survivors and 94 decayed coins, about how many rounds had it been through?
6. MEDIUM Data reading. The textbook time scale lists: Paleozoic era, 540 to 252 million years ago; Mesozoic era, 252 to 66 million; Cenozoic era, 66 million to the present. Which era is claimed to be longest? How many times longer than the Cenozoic is the Mesozoic? What single phrase should a careful student write beside each number?
7. HARD Experiment design. You want to test whether the starting number of coins changes the half-life of the penny clock (the number of rounds needed to lose half). Name the independent and dependent variables, two things to keep the same, and how many trials you would run and why.
8. HARD A volcanic mineral is measured with three daughter argon-40 atoms for every one parent potassium-40 atom. Textbook half-life of potassium-40: 1.3 billion years. What

age does the method give if no argon was present at the start? If in fact one third of the argon was trapped in the mineral when it formed, what age should it have given?

9. HARD Short explanation. In three or four sentences, state the mainstream case for an old earth so that a geologist would say you stated it correctly. Do not add your own objections in this answer.
10. CHALLENGE Lord Kelvin, using heat flow, argued from the 1860s to the 1890s that the earth was at most about 100 million years old, and later only 20 to 40 million, far too young for Lyell and Darwin; after 1896 radioactivity gave a source of heat that weakened his argument. In four or five sentences, explain what this episode shows about how assumptions enter age calculations, and why a young-earth student should still learn Kelvin's and Patterson's arguments accurately.

COMMON MISTAKES

- Thinking radiometric dating measures age directly. It measures a ratio of atoms today; the age is calculated from that ratio under three assumptions.
- Thinking half-life means all the atoms are gone after two half-lives. Half remains after one, a quarter after two, an eighth after three; it never reaches zero by halving.
- Thinking Hutton, Lyell and Kelvin were enemies of religion. Hutton believed in a designing Creator, Lyell attended church, and Kelvin was an outspoken Christian; they argued about rates and heat, not about whether God exists.

> **Make it a game · Half-Life Hustle.** Deal each player 16 beans. On each round, everyone flips a coin for each bean they still hold; heads keep the bean, tails put it in the center. Before the round, each player predicts their count after the flip. Closest prediction scores a point. After three rounds, the dealer secretly builds a "mystery bag" of survivors and decayed beans and announces only the two counts; the first player to name the correct number of rounds scores three points. Then the dealer plays a trick round with extra decayed beans slipped in, and the first to say "inherited daughter" and explain why the date is too old scores five. Play to fifteen.

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

God asks Job a question no scientist can answer: no one was there at the beginning. Every age calculation, old or young, is reasoning backward from what we see now under assumptions about what we did not see. The verse is a call to humility for everyone who dates the earth, and a reminder that the One who laid its foundations has told us about it.

Practice answers

1. An unconformity: near-vertical gray layers with flat red sandstone lying across their eroded tops. Hutton concluded that the lower rocks had been deposited, hardened, tilted, eroded and then buried by new sediment, which by slow present-day rates would take an immense time.
2. The principle that the slow processes we see today, acting over long times, explain the rock record ("the present is the key to the past"); Charles Lyell's Principles of Geology (1830 to

1833).

3. After two: 1/4 (25 percent). After four: 1/16 (6.25 percent).
4. Starting amounts (daughter atoms may have been present at the start, as argon trapped in fresh lava); closed system (heat or groundwater may have added or removed atoms); constant rate (the rate is assumed never to have differed through the whole time measured).
5. (B). Each count is roughly half the one before (100, 52, 24, 13, 7, 3), so the number removed falls each round and the curve bends; (A), (C) and (D) are contradicted. Six survivors out of 100 is near 6.25, which is four half-lives, so about 4 rounds.
6. Paleozoic: 540 − 252 = 288 million years; Mesozoic: 252 − 66 = 186 million; Cenozoic: 66 million. The Paleozoic is claimed longest. Mesozoic ÷ Cenozoic = 186 ÷ 66 = 2.8 times longer. Beside each number write “textbook claim” or “interpretation,” since the numbers come from assumed rates and radiometric assumptions, not from observation of the time.
7. Independent: starting number of coins (for example 20, 50, 100). Dependent: rounds needed to fall to half (or the fraction remaining after a fixed number of rounds). Keep the same: the coins, the shaking method, the rule for which side decays. Run at least three trials at each starting number and average, because small piles vary a lot by chance; the expected result is that the half-life (one round) does not depend on starting number, only the smoothness of the curve does.
8. Daughter:parent of 3:1 means 1/4 of the parent remains, so two half-lives: 2 × 1.3 = 2.6 billion years by the method. If one third of the argon (1 of the 3 atoms per parent) was inherited, the true daughter:parent ratio is 2:1, meaning 1/3 of the parent remains, which is between one and two half-lives (about 1.58 half-lives), roughly 2.1 billion years. The inherited daughter made the date about half a billion years too old; the measured ratio was correct, the starting-amount assumption was not.
9. Mainstream geologists hold that the earth is about 4.5 billion years old, based chiefly on uranium-lead dates from meteorites and the oldest minerals, which agree with each other and with other isotope methods. They point to thick sequences of sediment, unconformities like Siccar Point, the consistent order of fossils, counts of annual-looking layers in lakes and ice, and today’s slow rates of plate motion and erosion as fitting a long history. They argue that cross-checks between methods on the same rocks make the assumptions reasonable. (Any accurate, fair statement in the geologist’s own terms is acceptable.)
10. Kelvin’s calculation was sound mathematics built on an assumption: that the earth had no internal heat source and had simply cooled from molten. When radioactivity was discovered, the assumption failed and the age changed enormously, which shows that an age estimate is only as good as its starting assumptions. Patterson’s 4.55 billion years likewise rests on assumptions about starting lead ratios in meteorites and closed systems. A young-earth student should learn both arguments accurately in order to read any textbook or museum sign truthfully, to state the claim in its own terms before answering it, and to recognize that the young-earth response is itself about assumptions, not about denying measurements.

7.4 Writing a Respectful Summary of Each: Powell's Grand Canyon (1869) and the Three-Column Method

OBJECTIVES

- Write a summary of the young-earth, old-earth Christian and secular readings of the Grand Canyon that a holder of each view would accept as accurate, using the five rules of a fair summary.
- Sort statements about a rock record into observations, interpretations and assumptions, and label every number as a measurement or a claim.
- Compute scale drawings and implied deposition rates from layer thicknesses and textbook ages, and explain why the same thickness yields different times under different readings.

Warm-up. Ask a parent or sibling to tell you, in two sentences, why they like a food you dislike. Now repeat their reasons back to them in your own words, without any hint that you disagree, until they say, "Yes, that is exactly it." Count how many tries it took. Write down one word you had to remove because it gave away your opinion. That skill, saying the other side so well they nod, is today's lesson.

Video. Coming soon. John Wesley Powell 1869 Colorado River expedition, Grand Canyon rock layers from rim to river, Great Unconformity, Coconino Sandstone cross-bedding; search National Park Service, USGS, Smithsonian National Museum of Natural History, Arizona PBS, and Moody Science classics; watch as a reporter learning how each side describes the same walls.

KEY TERMS

fair summary
A restatement of someone else's view, in its own terms and with its best evidence, that the holder of the view would accept as accurate; sometimes called a steel-man.

loaded word
A word that signals the writer's opinion instead of describing, such as "merely," "so-called," "obviously" or "blindly"; a fair summary removes them.

claim
A statement someone asserts is true; in this unit, every age in years is a claim that rests on a measurement plus assumptions, and should be labeled as such.

Great Unconformity
The surface in the Grand Canyon where flat-lying Tapeats Sandstone rests on tilted or crystalline rocks below; named by John Wesley Powell, and read by every view as a break in the record.

cross-bedding

Sloping layers inside a bed of sandstone, left by sand grains rolling down the face of a moving dune or sand wave; the Coconino Sandstone is full of it.

formation
A named body of rock that can be mapped as a unit, such as the Kaibab Limestone or Redwall Limestone; the names are shared by all geologists whatever ages they hold.

CORE IDEAS

The story. On August 13, 1869, at the mouth of the Little Colorado River in Arizona, Major John Wesley Powell wrote, in the account of the voyage he later published, “We are now ready to start on our way down the Great Unknown.” Powell had lost his right arm at the Battle of Shiloh in 1862. He and nine men in four wooden boats had pushed off from Green River, Wyoming, on May 24. By August the party was down to three boats, the flour was moldy, and the walls of the canyon rose higher every day. For the next seventeen days they ran rapids no one had charted, portaging when they could and praying when they could not. On August 28 three men left the party at a rapid Powell named Separation Rapid, climbed out, and were never seen again; they are believed to have been killed on the plateau. On August 30 the remaining six floated out of the Grand Canyon at the mouth of the Virgin River. Powell went on to lead a second voyage in 1871, to name the **Great Unconformity**, and in 1881 to become the second director of the United States Geological Survey. The canyon he mapped is about 446 km long, up to 29 km wide and about 1,600 m deep, and its walls are the one place where every reading in this unit is laid out in public, on the same rocks, for anyone to compare.

How they figured it out. Start with the three-column method you have used all unit. In the first column, *observations*: the canyon exposes a stack of flat-lying sedimentary **formations**, from the Kaibab Limestone at the rim, down through the cross-bedded Coconino Sandstone, the red Hermit Shale and Supai Group, the cliff-forming Redwall Limestone, the Muav Limestone and Bright Angel Shale, to the Tapeats Sandstone, which rests on the Great Unconformity above dark Vishnu Schist in the inner gorge. The layers run flat for hundreds of kilometers. The Coconino holds animal trackways; the Redwall holds marine shells and corals. The Colorado River flows through the bottom carrying sand and silt. In the second column, *claims*: the park sign says the Kaibab is about 270 million years old, the Tapeats about 525 million, the schist over 1,700 million, and that the river cut the canyon within roughly the last six million years. Young-earth geologists claim the sedimentary stack was laid down mostly within the Flood year and carved soon after, as the waters drained or, as some propose, when large lakes left behind by the Flood broke through. Old-earth Christians accept the sign’s ages and read Genesis 1 as day-age or gap. In the third column, *assumptions*: rates, starting conditions, closed systems, and how Hebrew words are read. Notice that the first column is the same for all three views. That is why a fair summary is possible at all.

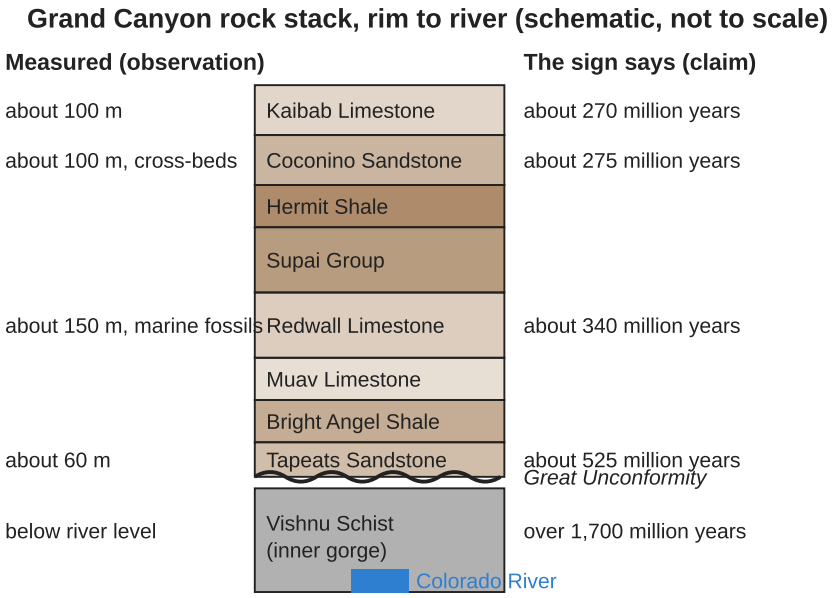
The big idea. Five rules make a summary fair. First, **say it so they would nod**: write each view in the words its holders use, and test it on someone who holds it if you can. Second, **give its best evidence**, not its weakest: for the secular view, agreement between isotope

methods and the fossil order; for the young-earth view, continent-wide flat layers, sharp contacts and rapid deposition observed at Mount St. Helens; for the old-earth Christian view, the wider meaning of “day” in Scripture together with the same rock evidence. Third, **state its hardest question in the form its holders answer it**, because every view has one and every view has an answer. Fourth, **label every number**: a thickness is a measurement, an age in years is a claim. Fifth, **give equal space and remove loaded words**. The Bible gives the reason: “He that answereth a matter before he heareth it, it is folly and shame unto him” (Proverbs 18:13). A reader who meets a museum sign, a textbook or a classmate should be able to hear the whole matter before answering.

Try it and see. Today’s project tests your fairness the way a scientist tests anything, with a blind trial. You will write three summaries of the Grand Canyon, one per view, each the same length, and hand them unlabeled to readers who do not know which view you hold. If readers guess your own view no better than chance, your summaries are fair. If they spot you at once, the loaded words are still there. You will also count those words before and after editing, so that fairness becomes a number you can improve.

In the world today. This skill is a working tool, not just a classroom exercise. A Christian geologist at a drilling company uses the names Kaibab, Redwall and Tapeats every day, because formations are shared labels on shared maps whatever ages a person holds, and she must read her colleagues’ reports accurately. A museum docent must describe the sign truthfully. A pastor must summarize his neighbor’s view before he disagrees with it. Peter told believers to “be ready always to give an answer to every man that asketh you a reason of the hope that is in you with meekness and fear” (1 Peter 3:15). Meekness does not mean having no position. This course holds young-earth creation. Meekness means stating your neighbor’s view so well that the disagreement, when it comes, is about the real question: the rates and starting conditions no one measured, and the reading of a text everyone can open.

God’s handiwork. Powell called the Grand Canyon the most sublime spectacle on earth. The same walls stand there for the secular geologist, the day-age Christian and the Flood geologist, and the sun rises on all three alike. The rock does not change its testimony depending on who is looking, and a summary that respects the rock will respect the people who read it.



Flat layers, sharp contacts, about 1,200 m of sediment above the Great Unconformity; full depth about 1,600 m. Young-earth reading: the stack laid down mostly in the Flood year; the ages on the right are the sign's claims.

One wall, three columns. Thicknesses are measurements; the ages on the right are what the park sign says, and are labeled as claims. Every view in this unit begins from the same stack.

⏳ Thinking About Time

What the sign says. The National Park Service and standard textbooks say the Kaibab Limestone at the rim is about 270 million years old, the Tapeats Sandstone about 525 million, the Vishnu Schist in the inner gorge over 1,700 million, and that the Colorado River carved the canyon within about the last six million years.

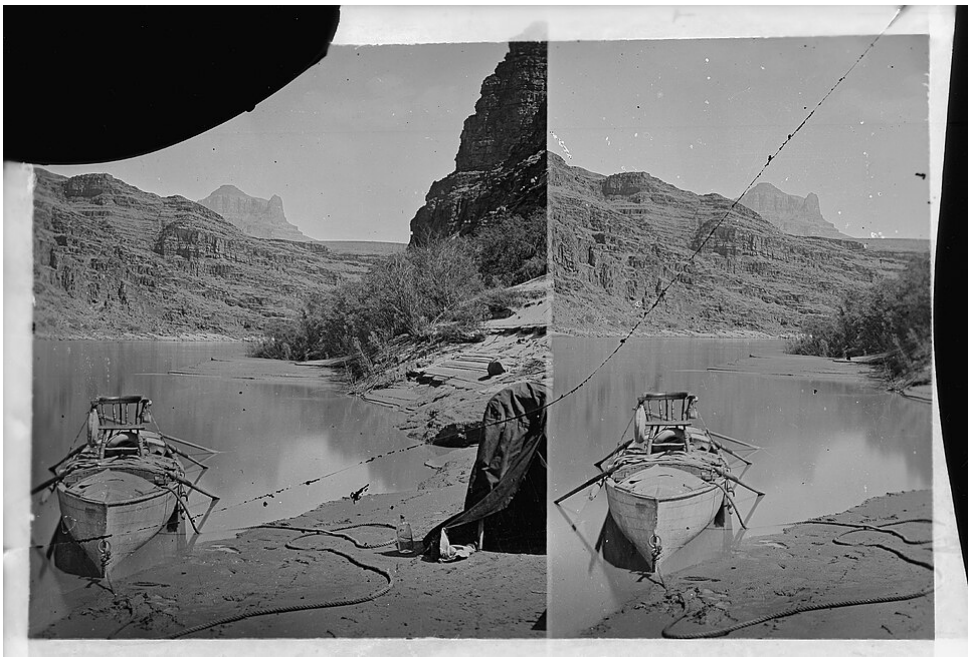
What we observe. What we observe is a stack of flat-lying sedimentary formations about 1,200 m thick resting on the Great Unconformity, layers that stay flat and sharp-edged for hundreds of kilometers, cross-beds and trackways in the Coconino Sandstone, marine fossils in the Redwall, and a river carrying sediment today. No one measured the rate at which any layer formed or the rate at which the canyon was first cut.

How Christians read it. Young-earth Christians read the stack as mostly Flood deposits laid down within a year and the canyon as cut soon afterward by draining or dammed water. Some Christians accept the sign's ages and read Genesis as long ages or a gap. All three readings agree on the first column; they differ on rates, starting conditions and the reading of Genesis.

Try it. Write the sign's sentence and the young-earth sentence for the Kaibab Limestone side by side, then underline every word that is a measurement.

Genesis 8:3

PICTURE STUDY



Colorado River, Grand Canyon: Major Powell's Boat with Chair Facing the Camera, Photographers of the second Powell expedition (E. O. Beaman, James Fennemore and John K. Hillers), 1871 to 1872 · Photograph from a glass-plate negative · National Archives and Records Administration, College Park, Maryland (Records of the U.S. Geological Survey)

In 1871 and 1872 Powell went down the Green and Colorado rivers a second time, now with photographers, so that the canyon could be recorded and not only described. Because he had only one arm, Powell rode in an ordinary armchair lashed to the deck of his boat, the Emma Dean, where he could sit high, scan the rapids ahead and signal the other boats.

The photographers hauled heavy cameras and glass plates through the canyon and had to coat, expose and develop each plate on the spot. This picture of the Major's empty chair at the river's edge is a record of fieldwork itself: the boat, the river and the walls that every reading of the canyon begins from.

Look closely

- Find the chair. Why would a one-armed leader want to sit high above the water?
- Look at the canyon walls behind the boat. Can you see layers or bands in the rock?
- Compare the size of the boat with the rock around it. What does that tell you about the scale of the canyon?
- What in the picture tells you the photographer had to work quickly and simply?

Talk about it

1. A photograph is a record of what was in front of the camera. List three observations a geologist of any view could make from it.

2. Powell’s team made photographs so others could check their descriptions. How is that like labeling every number in a fair summary?
3. Why does an empty chair at the river’s edge make a stronger picture than a posed group of men?

EXPERIMENT: THE BLIND FAIRNESS TEST: THREE SUMMARIES OF ONE CANYON

A fair summary can be tested the way any claim is tested. You will write three summaries of the Grand Canyon rock record, one for each view, edit out loaded words, and give them unlabeled to readers who do not know which view you hold. If they cannot tell, you passed.

Question: Can readers detect my own view from my summaries of all three? Prediction: write how many of your readers you think will guess your view correctly from the first draft, and from the edited draft. By chance alone, guessing among three views, about one in three would.

You will need

- Lab notebook and pencil, or a word processor with a word counter
- Three index cards or three sheets of paper, labeled only A, B and C on the back
- A list of loaded words to hunt for: merely, so-called, obviously, blindly, just, supposedly, claims (used as a sneer), real, true (used of only one side), and any exclamation point
- At least four readers: family members, friends or a co-op class, who do not know which view you hold
- A ruler and a 40 cm strip of paper for the scale column

Steps

1. Build the first column. On the 40 cm strip draw the Grand Canyon stack to scale (1 cm = 40 m), using the thicknesses in the figure, and label each formation. This is the observation column every summary must start from.
2. Write draft 1: three summaries of 100 to 120 words each, in this order: young-earth creation, old-earth Christian (day-age or gap), secular geology. Each must state the view in its own terms, give its best evidence for the canyon, and state the hardest question it faces in the form its holders answer it. Write them in random order on cards A, B and C with no labels.
3. Count. In a table record for each summary: word count, number of loaded words from the list, and number of ages in years that are not labeled as a claim. Total the loaded words for draft 1.
4. Run the blind test on draft 1. Give the cards to at least two readers. Ask each: “Which of these three views does the writer hold?” Record each answer as correct or incorrect.
5. Edit. Remove every loaded word, label every age as a claim (“the sign says,” “creation geologists hold”), and trim or lengthen so that no summary is more than 10 percent longer than the shortest. Record the new counts as draft 2.
6. Run the blind test on draft 2 with at least two new readers who did not see draft 1. Record their answers.

7. Analyze and conclude. Compute the fraction of readers who guessed correctly for each draft and compare both with the chance level of one in three. State what you changed (the loaded-word count), what you kept the same (the facts, the order of the three views, the question asked), and what you measured (correct guesses). Write whether your prediction held and what single edit made the biggest difference.

Tips

- The hardest summary to write fairly is usually the one you disagree with most. Write that one first, while you are fresh.
- A good test of a hard question: would a holder of that view say, “Yes, that is the question people ask me, and here is what I answer”? If you leave out their answer, the summary is not fair yet.
- If every reader guesses correctly even after editing, look at length and order rather than words; the view you give the most space is often the one you hold.

Check your work

- I can write a summary of each view that its holders would accept.
- I can count and remove loaded words and label every age as a claim.
- I can run a blind test, compare the result with chance, and explain what I changed, kept the same and measured.

FIELD NOTEBOOK

1. Draw the Grand Canyon stack from the figure as a scale column, 1 cm = 40 m, with each formation labeled and the Great Unconformity marked with a wavy line. Leave a blank column on the right headed “the sign says” and a second headed “young-earth reading,” and fill in one line each for the Kaibab, Coconino and Tapeats.
2. Make a three-column page headed Observation, Claim, Assumption. Enter at least six lines from this unit, drawing on Mount St. Helens, the Old Red Sandstone, the penny clock and the Grand Canyon.
3. Draw Powell’s boat in a rapid, with the canyon walls rising on both sides, and copy his August 13, 1869 sentence beneath it.

> **From history.** Powell’s 1869 voyage was the last great blank on the map of the United States to be filled in. He published his account in 1875 as *Exploration of the Colorado River of the West*, and in 1881 he became the second director of the USGS, where he pushed for careful topographic mapping of the whole country, the mapping you used in Unit 5. The painter Thomas Moran joined Powell’s survey at the North Rim in 1873, and Congress bought the resulting *Chasm of the Colorado* in 1874 for the Capitol. The park signs that visitors read today descend from the work of Powell’s survey and of the USGS geologists who followed him, so a student who reads the sign accurately is reading a line of careful measurement that began with six exhausted men in two boats.

WORKED EXAMPLES

Example 1. You want to draw the Grand Canyon stack on a 40 cm strip of paper so that the full 1,600 m from rim to river fits exactly. What is the scale? How tall on the strip are the Coconino Sandstone (about 100 m), the Redwall Limestone (about 150 m) and the Tapeats Sandstone (about 60 m)?

1. Scale = real depth ÷ drawing length = 1,600 m ÷ 40 cm = 40 m per cm. So 1 cm on the strip stands for 40 m of rock.
2. Coconino: 100 m ÷ 40 m/cm = 2.5 cm.
3. Redwall: 150 m ÷ 40 m/cm = 3.75 cm, about 3.8 cm.
4. Tapeats: 60 m ÷ 40 m/cm = 1.5 cm. Check: the three together are 7.75 cm, well under 40 cm, leaving room for the other formations and the inner gorge.

Answer: Scale 1 cm = 40 m. Coconino 2.5 cm, Redwall about 3.8 cm, Tapeats 1.5 cm.

Example 2. The park sign gives the Tapeats Sandstone an age of about 525 million years and the Kaibab Limestone about 270 million years. The sedimentary stack between the base of the Tapeats and the top of the Kaibab is about 1,200 m thick. (a) What average deposition rate does the sign’s timeline imply, in millimeters per year? (b) A young-earth reading lays the same 1,200 m down within about 150 days of the Flood year. What average rate is that, in meters per day? (c) By what factor do the two implied rates differ? Which numbers in this problem are measurements?

1. (a) Time on the sign = 525 − 270 = 255 million years. Rate = 1,200 m ÷ 255,000,000 yr = 4.7×10^{-6} m per year = 0.0047 mm per year, less than a hundredth of a millimeter per year on average.
2. (b) Rate = 1,200 m ÷ 150 days = 8 m per day.
3. (c) Convert to the same units: 8 m per day × 365 days = 2,920 m per year. Factor = 2,920 ÷ 0.0000047 ≈ 6.2×10^{8}, about 600 million times.
4. Only the 1,200 m thickness is a measurement. Both the 255 million years and the 150 days are claims from each reading; the rates follow from the claims.

Answer: (a) About 0.0047 mm per year; (b) about 8 m per day; (c) the rates differ by a factor of roughly 600 million. The thickness is measured; the times, and therefore the rates, are interpretations.

Example 3. Make a scale strip comparing the two ages claimed for the Kaibab Limestone: the young-earth reading places it in the Flood about 4,500 years ago, and the sign says about 270 million years. If the young-earth age is drawn as 1 mm, how long must the sign's age be drawn? Express the answer in meters.

1. Ratio of the ages = 270,000,000 ÷ 4,500 = 60,000.
2. If 4,500 years = 1 mm, then 270 million years = 60,000 mm.
3. Convert: 60,000 mm ÷ 1,000 = 60 m, about the length of a 25 m swimming pool laid end to end twice, plus a little.

Answer: 60 m. The two readings differ by a factor of 60,000 for the same rock, which is why a fair summary must label each age as a claim rather than present one as a measurement.

PRACTICE

1. EASY State each of the three views in this unit in one sentence, in words its holders would accept.
2. EASY Who was John Wesley Powell, when did he first run the Grand Canyon, and what feature in the canyon did he name?
3. EASY Find the loaded words in this sentence and rewrite it fairly: "Secular geologists merely assume the so-called ages, which obviously no one measured."
4. MEDIUM Label each statement O (observation), I (interpretation) or A (assumption). (1) The Redwall Limestone contains marine shells. (2) The Redwall formed about 340 million years ago. (3) The decay rate of potassium-40 has been constant for the whole time measured. (4) The Coconino Sandstone has cross-beds. (5) The Coconino's cross-beds were made by desert dunes. (6) The Flood laid down the Coconino as underwater sand waves.
5. MEDIUM Data reading. The table gives three Grand Canyon formations, their approximate thicknesses and the sign's ages for the base and top of the stack they belong to. Coconino Sandstone: 100 m thick, sign age about 275 million years. Redwall Limestone: 150 m thick, sign age about 340 million years. Tapeats Sandstone: 60 m thick, sign age about 525 million years. Which statement is supported by the table alone? (A) Thicker formations are older. (B) The thickness of a formation does not predict the sign's age for it. (C) The Tapeats took the longest to form. (D) The sign's ages were measured directly from the thicknesses.
6. MEDIUM Data reading. In a blind fairness test, readers were asked which of three views the writer holds. Draft 1: 8 readers, 7 guessed correctly. Draft 2 (loaded words removed): 9 readers, 3 guessed correctly. With three views, chance guessing gives about 1 correct in 3. Compute the fraction correct for each draft. Which conclusion do the data best support? (A) Draft 2 is less fair than draft 1. (B) Draft 2 is about as hard to read through as chance, so it is fairer. (C) Readers cannot judge fairness. (D) Both drafts are equally fair.

7. HARD Experiment design. The Coconino Sandstone holds trackways of four-footed animals. In 1979 Leonard Brand of Loma Linda University published experiments in which salamanders walked on dry sand, damp sand and sand under water, to see which made tracks most like the fossils. Design your own version with a small toy animal or your fingertips. Name the independent variable, the dependent variable, three things to keep the same, and what you would measure.
8. HARD A student's three summaries are 118, 121 and 64 words long. The fairness rule says no summary may be more than 10 percent longer than the shortest. By what percent is the longest summary longer than the shortest? Does the set pass? What is the maximum allowed length if the shortest stays at 64 words?
9. HARD Short explanation. Write a three- or four-sentence fair summary of the secular reading of the Grand Canyon: its claim, its best evidence, and the hardest question young-earth geologists put to it, in the form a secular geologist answers it.
10. CHALLENGE Write the full three-column entry for the Coconino Sandstone: at least three observations; the secular claim with its sign age; the young-earth claim; and one assumption behind each claim. Then write one sentence a day-age Christian would add.

COMMON MISTAKES

- Thinking a fair summary means having no view. This course holds young-earth creation; fairness is stating the other views so well their holders would nod, and then disagreeing on the real question.
- Thinking that because all three views agree on the observations, the differences are small. The claimed ages differ by a factor of tens of thousands; the agreement on the first column is what makes honest comparison possible, not what makes it unnecessary.
- Treating formation names and textbook period names as if using them concedes the ages. Kaibab, Redwall, Permian and Cambrian are shared labels on shared maps; a geologist of any view can use them as names without accepting a number.

> **Make it a game · Steel Man.** Players pair off. Each pair secretly draws one of the three views. Player one states that view in thirty seconds as if it were their own, using its best evidence and no loaded words. Player two, acting as a holder of that view, may say only "Yes, that is it" or "Not yet, because…" and name what was missing or slanted. Player one tries again until they hear "Yes, that is it." Count the tries; fewest tries wins the round. For a bonus, a third player listens blind and must guess which view the speaker actually holds; if they cannot, the speaker scores double. Play all three views and total the tries.

> **Scripture.** "He that is first in his own cause seemeth just; but his neighbour cometh and searcheth him." (Proverbs 18:17, KJV)

Any view sounds right until the other side has been heard in full. God's wisdom requires us to hear our neighbor's case before we judge it, and a fair summary is simply obedience to this proverb put on paper.

Practice answers

1. Young-earth creation: God created in six ordinary days a few thousand years ago, and the global Flood laid down most of the fossil-bearing rock rapidly. Old-earth Christian views: God created everything and Genesis is true, but the days are long ages (day-age) or a long time falls before them (gap), so the rocks are very old. Secular geology: the earth is about 4.5 billion years old, dated by radiometric methods, and the rock record formed mainly by slow processes over long ages.
2. A one-armed Civil War veteran, geologist and explorer who led the first boat voyage through the Grand Canyon in the summer of 1869 (May 24 to August 30) and later directed the USGS. He named the Great Unconformity.
3. Loaded: merely, so-called, obviously. Fair rewrite: “Secular geologists calculate the ages from measured isotope ratios under assumptions about starting amounts, closed systems and constant rates.”
4. (1) O; (2) I; (3) A; (4) O; (5) I; (6) I. Statements 5 and 6 are both interpretations of the same observation, 4.
5. (B). The thickest formation (Redwall, 150 m) is neither the oldest nor the youngest on the sign; the thinnest (Tapeats, 60 m) carries the oldest sign age. (A) is contradicted; (C) and (D) cannot be read from the table, since no rates or methods are given.
6. Draft 1: 7 ÷ 8 = 0.875 (87.5 percent). Draft 2: 3 ÷ 9 = 0.333 (33 percent), which equals the chance level of one in three. (B). Draft 1 revealed the writer’s view to nearly everyone; draft 2 revealed nothing beyond chance.
7. Independent: the condition of the sand (dry, damp, under shallow water). Dependent: the shape and clarity of the tracks (for example, whether toe marks are sharp, whether the track walls slump, whether a push-up ridge forms behind each print). Keep the same: the sand type and grain size, the slope of the sand, the weight and gait of the walker, the number of steps. Measure: depth of each print with a ruler, width of the print, and a score for clarity of toe marks, averaged over at least five prints per condition, then compare with photographs of real Coconino tracks.
8. (121 − 64) ÷ 64 = 0.89, so the longest is 89 percent longer than the shortest. The set fails. Maximum allowed = 64 × 1.10 = 70.4, so 70 words; the student should either lengthen the 64-word summary to about 110 words or shorten the other two.
9. Example: Secular geologists hold that the canyon’s layers were deposited over roughly 250 million years, from the Tapeats about 525 million years ago to the Kaibab about 270 million, and that the Colorado River cut the canyon within about the last six million years. Their best evidence is radiometric dates on volcanic rocks in and near the stack that agree between methods, together with the fossil order and features such as cross-bedding read as ancient dunes. Young-earth geologists ask how layers could stay flat and sharp-edged across hundreds of kilometers through millions of years of exposure between them; secular geologists answer that many contacts show slight erosion and soil features when examined closely, and that long gaps need not leave deep valleys on a flat sea floor. (Accept any accurate summary without loaded words that includes claim, evidence and the answered question.)
10. Observations: a fine, well-sorted quartz sandstone about 100 m thick; large sloping cross-beds; trackways of four-footed animals; flat contacts above and below; it can be traced across much of northern Arizona. Secular claim: wind-blown desert dunes, about 275 million years old on the sign; assumption: cross-beds of that form and scale require dry dunes, and the radiometric framework for the surrounding layers holds. Young-earth claim: sand waves moving under fast water during the Flood, with the tracks made by animals walking in shallow water; assumption: underwater sand waves can produce cross-beds of this size and tracks of this form, and the layer formed within the Flood year. Day-age Christian sentence: “I

accept the sign’s age for the Coconino and read the days of Genesis 1 as long ages, so the dunes fit within God’s creation week.”

Unit 7 review

Answer each question. Show your work for calculations and use complete sentences for explanations. For multiple choice, write the letter of the best answer. Where you are asked to summarize a view, write it so that a holder of that view would accept it. The test is worth 60 points.

1. (4 pts) On May 18, 1980, Mount St. Helens (a) erupted slowly over several years (b) lost about 400 m of its summit in minutes and buried a valley under a debris avalanche averaging about 45 m thick (c) produced no layered deposits (d) was cut by a canyon that took centuries to form
2. (5 pts) Using the Genesis 5 ages (Adam 130, Seth 105, Enos 90, Cainan 70, Mahalaleel 65, Jared 162, Enoch 65, Methuselah 187, Lamech 182) and Noah’s age of 600 at the Flood, find the year of the Flood counted from creation. Show the addition.
3. (5 pts) A mudflow cuts a channel 30 m deep in one day. Years later the small stream in it lowers its bed about 1 mm per year. If a visitor assumes that rate has always applied, how old does the channel seem? Name the assumption that produced the error and state the young-earth point this illustrates.
4. (4 pts) The gap view holds that (a) each creation day is a long age (b) Genesis 1 is a literary pattern with no timeline (c) a long stretch of time falls between Genesis 1:1 and 1:2, followed by six ordinary days (d) the Flood was local
5. (5 pts) Write a fair two- or three-sentence summary of the day-age view: what it holds, one verse it leans on, and one Christian who held it. Then name three things day-age, gap and young-earth Christians all affirm.
6. (5 pts) A sandstone is 300 m thick. Find the time it represents at (a) an assumed 0.1 mm per year and (b) an assumed 1 m per day. Which of the three numbers is the observation?
7. (4 pts) Uniformitarianism, as pressed by Hutton and Lyell, is the principle that (a) all rocks formed in the Flood (b) the slow processes seen today, acting over long ages, explain the rock record (c) radioactive decay is not constant (d) the earth is a few thousand years old
8. (5 pts) A sample contains one sixteenth of its original parent isotope. How many half-lives have passed? If the isotope were carbon-14 (half-life 5,730 years), what age would the method give? Name the three assumptions the age depends on.
9. (5 pts) Data reading. A penny clock gave: round 0, 100 coins; round 1, 48; round 2, 26; round 3, 12; round 4, 6. (a) Which statement fits the data: (A) a constant number is removed each round, (B) about half of the remaining coins are removed each round, (C) the decay speeds up. (b) A bag holds 12 survivors and 88 decayed coins; estimate the number of rounds. (c) If 20 of the 88 “decayed” coins had secretly been added at the start, is your estimate too high or too low?
10. (8 pts) Diagram. Draw a cross-section of the Grand Canyon rock stack from rim to river. Label the Kaibab Limestone, Coconino Sandstone, Redwall Limestone, Tapeats Sandstone, the Great Unconformity, the Vishnu Schist and the Colorado River. Add a column on the right headed “the sign says” with the textbook age for the Kaibab and

the Tapeats, and a column headed “young-earth reading” with one sentence. Mark the cross-beds in the Coconino.

11. (5 pts) Label each as O (observation), I (interpretation) or A (assumption), and then rewrite this sentence without loaded words: “Flood geologists just ignore the obviously ancient layers.” (1) The Coconino Sandstone has cross-beds. (2) The cross-beds were formed by desert dunes. (3) No argon was present in the mineral when it formed. (4) The Redwall contains marine shells. (5) The Redwall was deposited in the Flood.
12. (5 pts) The sign says the Kaibab Limestone is about 270 million years old; the young-earth reading places it about 4,500 years ago. (a) By what factor do the ages differ? (b) If the young-earth age is drawn as 1 mm on a strip, how long is the sign’s age in meters? (c) In one sentence, explain why a fair summary labels both numbers as claims.

UNIT PROJECT: THREE READINGS OF ONE CANYON: A FAIR-SUMMARY PORTFOLIO

Assemble a portfolio built on the Grand Canyon rock stack. Include your 40 cm scale column of the formations (1 cm = 40 m) with the Great Unconformity marked, a three-column page (Observation, Claim, Assumption) with at least ten lines drawn from Mount St. Helens, the Old Red Sandstone, the radiometric clock and the canyon, and your worked calculations: the Genesis 5 chronology, the sand-tray channel rates with graph, the 300 m sandstone under three assumed rates, your penny-clock decay curve, and the 60 m scale strip.

Finish with your three summaries of the young-earth, old-earth Christian and secular readings, each of equal length and free of loaded words, together with the blind fairness test results for draft 1 and draft 2 compared with chance. Close with a one-page statement of the view this course holds and you hold, written with the same care you gave the others, and present the portfolio aloud to your family.

- **Accuracy**: Calculations (chronology, rates, half-lives, scale models, thickness-to-time) are correct, in metric units, with work shown, and every age in years is labeled as a claim.
- **Fairness**: Each of the three summaries states the view in its own terms with its best evidence and its hardest question answered; readers in the blind test guessed the writer’s view at about chance.
- **Records**: Each experiment states its question, prediction, what was changed, what was kept the same and what was measured, with dated tables and labeled graphs.
- **Care**: The scale column and three-column page are neat and correctly labeled, and the portfolio is presented aloud with understanding and without mocking any view.

Answer key

1. (b). The USGS measured a debris avalanche of about 2.5 cubic kilometers covering about 60 square kilometers, and the summit fell from 2,950 m to 2,549 m.
2. 130 + 105 + 90 + 70 + 65 + 162 + 65 + 187 + 182 = 1,056 (Noah’s birth); 1,056 + 600 = 1,656 years from creation to the Flood.

3. 30 m = 30,000 mm; 30,000 ÷ 1 mm/yr = 30,000 years. The assumption is that today's slow rate was the rate in the past (constant rate). The young-earth point: present slow rates are not the only key to the past, because the past may have been catastrophic, so a measured rate times a thickness does not by itself give an age.
4. (c). Thomas Chalmers proposed it around 1814, and the Scofield Reference Bible (1909) spread it. (a) is the day-age view; (b) is the framework view.
5. Day-age: each of the six days of Genesis 1 is a long age, so creation took a very long time in the order Genesis gives; readers point to Psalm 90:4 or 2 Peter 3:8 or Genesis 2:4; Hugh Miller held it (Testimony of the Rocks, 1857). All affirm: God created everything from nothing; Adam and Eve were real people made in God's image; the Bible is true (also acceptable: sin and death came through Adam; Christ is Creator and Redeemer).
6. (a) 300 m = 300,000 mm; 300,000 ÷ 0.1 = 3,000,000 years. (b) 300 ÷ 1 = 300 days. The observation is the 300 m thickness; both times are interpretations that depend on the assumed rate.
7. (b). Often summed up as "the present is the key to the past"; Lyell's Principles of Geology (1830 to 1833) spread it.
8. 1 → 1/2 → 1/4 → 1/8 → 1/16 is four half-lives. Age = 4 × 5,730 = 22,920 years, about 22,900 years. Assumptions: the starting amount of parent and daughter (for carbon-14, the atmosphere's starting carbon-14 level); a closed system with no atoms added or lost; a constant decay rate (and constant atmospheric level) over the whole time.
9. (a) (B): each count is roughly half the previous one. (b) 12 of 100 is close to 12.5, three half-lives, so about 3 rounds. (c) Too high: the true start was 80 coins with 12 survivors, 12/80 = 0.15, between two and three rounds (closer to 3, but less than the first estimate suggests). Inherited daughter atoms make a date too old.
10. A stack of flat layers with the Kaibab at the top, Coconino (drawn with sloping internal lines for cross-beds) near the top, Redwall as a thick middle cliff, Tapeats at the base of the sediment resting on a wavy line labeled Great Unconformity, dark Vishnu Schist below in a narrow inner gorge, and the river at the bottom. Right column: sign says Kaibab about 270 million years, Tapeats about 525 million years; young-earth reading: the layers were laid down mostly within the Flood year and the canyon cut soon after. Award 1 point for each of the seven labels and 1 point for the two columns correctly labeled as claims.
11. (1) O; (2) I; (3) A; (4) O; (5) I. Rewrite: "Flood geologists read the layers as deposits of the Flood year and dispute the assumed rates, not the measurements." (Any rewrite that removes just, ignore and obviously and states the view in its own terms is acceptable.)
12. (a) 270,000,000 ÷ 4,500 = 60,000. (b) 60,000 mm = 60 m. (c) Neither age was measured; each is calculated from measurements (thickness, isotope ratios) under assumptions about rates and starting conditions, or read from a text, so both must be labeled as claims rather than presented as observations.

Unit 8: Capstone

Every unit of this course has pointed at one piece of ground: the county you live in. You have learned to read its soil horizons, find its aquifers, name its minerals and fuels, open its maps in a GIS, follow its weather, and read a museum sign about its rocks with care. Now you will put it all together. In this capstone you will choose a county, gather its topographic, geologic and soil maps, go out with a hammer and a notebook to collect and test samples, interview a person who drills, mines, surveys or forecasts there, and write and present a County Earth-Resources Report.

You will follow the people who did this before you: the surveyors of the United States Geological Survey, founded in 1879, who mapped the country one quadrangle at a time; Florence Bascom, who walked the creeks of the Piedmont with a hammer and a hand lens; the writers of the 1930s who sat on porches and wrote down working people's lives; and John Wesley Powell, whose plain, well-evidenced 1878 report on the arid West outlasted the Congress that shelved it. Your report will be smaller, but it will be built the same way: maps, samples, testimony, and claims that carry their evidence with them.

The unit ends where the course began. God made the heaven and the earth and put man in the garden to dress it and to keep it. A report that tells truly what your county has been given, how it is used and how it can be kept well is an act of stewardship, and the skills behind it, reading maps, testing samples, asking good questions and writing plainly, are the same skills that high-school Earth Science and every earth-resource career will ask of you.

BEFORE YOU BEGIN

- Can read a USGS topographic map and a geologic map legend, and use a map scale (Unit 5)
- Can run the home rock tests (hardness, streak, acid fizz) and the soil jar test (Units 1 and 3)
- Can describe an aquifer, a well log and a pump test (Unit 2)
- Can convert feet, gallons, tons, inches and degrees Fahrenheit to metric units

MASTERY CHECKLIST

- I can choose a county, find its topographic, geologic and soil maps from USGS and USDA sources, and record a source for each.
- I can use map scale to convert map distances to meters and kilometers and compute a county's relief.
- I can collect rock, soil and sediment samples safely and lawfully, label them at the site, and test them at home with results in a data table.
- I can write open questions, conduct a respectful interview with a working geologist, driller, miner or forecaster, and record numbers exactly with their units.
- I can convert a worker's figures to metric and check them with a calculation.

- I can write and present a county earth-resources report in which every claim has evidence and a citation and observation is kept separate from interpretation.

OPTIONAL BOOKS AND RESOURCES

- **USGS topoView** (https://ngmdb.usgs.gov/topoview/): Free. Type your county seat, turn on the quadrangle outlines and download current and historic 1:24,000 topographic maps. Historic sheets often mark old quarries, wells and mines.
- **USDA Web Soil Survey** (https://websoilsurvey.nrcs.usda.gov/): Free. Draw an Area of Interest around part of your county, open the Soil Map tab and print the map and its legend of soil map units for Lessons 8.1 and 8.2.
- **Occupational Outlook Handbook (Bureau of Labor Statistics)** (https://www.bls.gov/ooh/): Free. Read the entries for geoscientists, mining and geological engineers, atmospheric scientists, and drilling and service-unit operators before your Lesson 8.3 interview.

8.1 Choosing My County and Gathering Maps

OBJECTIVES

- Choose a county (or parish or borough) for the capstone, locate it on state and national maps, and record its county seat, area in square kilometers, neighbors and main rivers.
- Find and save the three base maps for the county, a USGS topographic quadrangle, a geologic map and a USDA soil map, and explain what question each map answers.
- Use map scale to convert map distances to ground distances in meters and kilometers, convert elevations from feet to meters, and compute the county’s relief.

Warm-up. Without looking at any map, draw the outline of your county from memory on a sheet of paper. Mark your home, the county seat, the nearest creek or river and one high place. Then open a map on a phone or in an atlas and compare. What did you get right? What surprised you? Keep the sketch; you will paste it into the front of your capstone folder.

Video. Coming soon. How to find and download USGS topographic maps (topoView and The National Map), how to use the USDA Web Soil Survey, history of the U.S. Geological Survey and John Wesley Powell; search USGS, USDA NRCS, state geological survey channels and Library of Congress map talks.

KEY TERMS

county seat
The town where a county’s courthouse and government offices are; the usual home of the county’s land records and engineer’s office.

quadrangle
A rectangular map area bounded by lines of latitude and longitude; the standard USGS topographic quadrangle is 7.5 minutes on a side at a scale of 1:24,000.

map scale
The ratio of a distance on the map to the same distance on the ground, written 1:24,000; one centimeter on such a map is 24,000 cm, or 240 m, in the field.

base map
A map that other information is drawn on or compared with; for the capstone the topographic, geologic and soil maps are the three base maps.

soil map unit
An area on a soil map labeled with a short symbol that stands for a named soil series and its slope, such as a silt loam on 2 to 6 percent slopes.

relief
The difference in elevation between the highest and lowest points of an area, in meters.

CORE IDEAS

The story. On March 3, 1879, Congress created the United States Geological Survey and gave it a plain job: to classify the public lands and to examine the geological structure, mineral resources and products of the national domain. Its first director, Clarence King, had already spent years surveying the mountains and mines along the fortieth parallel. The second, John Wesley Powell, took over in 1881 and decided that the Survey could not describe the nation's resources until it had mapped the nation's ground. So the USGS began drawing the country one rectangle at a time. Each rectangle, called a **quadrangle**, was bounded by lines of latitude and longitude, surveyed with chain, transit and level, and printed with brown contour lines for the hills, blue for the water and black for the works of man. The job took a century. Today more than 50,000 of these 7.5-minute quadrangles cover the lower forty-eight states, and every one of them is free to download. Your capstone begins where the Survey began: with a piece of ground and the maps that describe it.

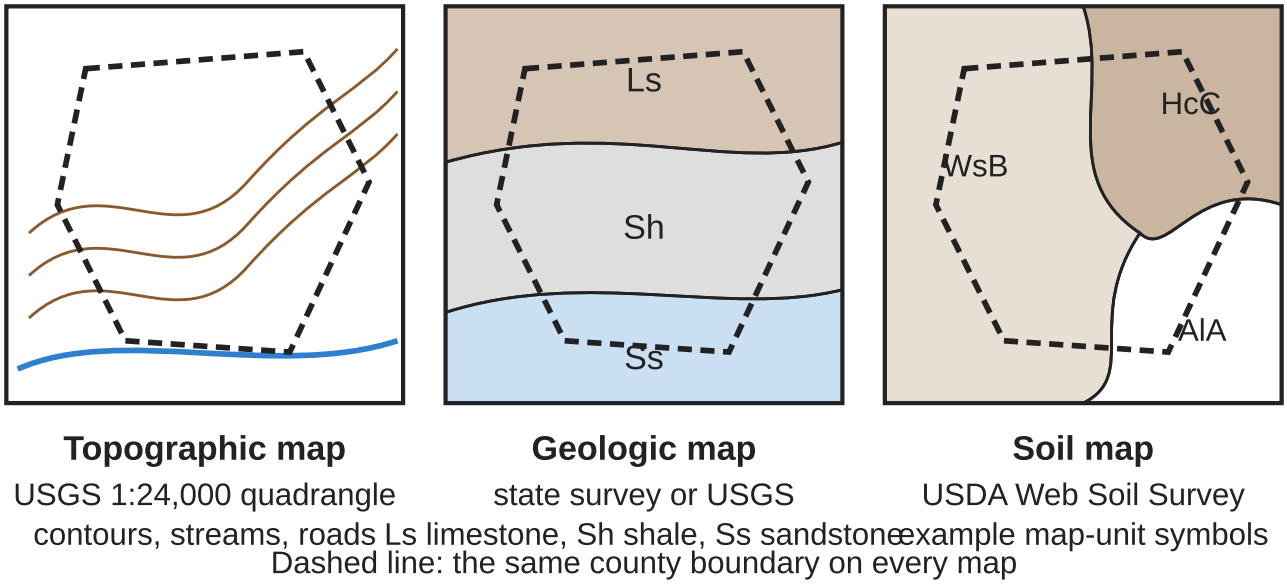
How they figured it out. A quadrangle is 7.5 minutes of latitude tall and 7.5 minutes of longitude wide, drawn at a **scale** of 1:24,000. That ratio means one unit on the paper stands for 24,000 of the same units on the ground, so 1 cm on the map is 24,000 cm, which is 240 m, in the field. Because lines of longitude pinch together toward the pole, a quadrangle in Texas is wider than one in Minnesota; most cover roughly 130 to 180 square kilometers. Counties do not follow quadrangle lines, so your county will be a patchwork of several quads, with some only partly inside the line. Geologic maps and soil maps are built on the same latitude and longitude grid, which is what lets you lay one on top of another and see that the limestone belt on the geologic map matches the ridge on the topographic map and the thin, stony soil on the soil map. Elevations on older USGS sheets are in feet; you will convert them to meters by multiplying by 0.3048.

The big idea. Your report rests on three **base maps**, and each answers a different question. The **topographic map** answers "What shape is the land?" It shows hills by contour lines, streams and lakes in blue, and roads, towns and boundaries in black. The **geologic map**, which you learned to read in Lesson 5.4, answers "What rock lies under the soil?" Each color is a map unit, a body of rock such as a limestone or a sandstone that a geologist can trace across the country, and the legend lists the units in the order they lie on one another. The **soil map** answers "What is the ground like in the top meter or two?" Its units carry short symbols, each standing for a named soil series with a known texture, depth and drainage, the kind of information a farmer, a builder or a well driller needs before the first shovel goes in. One county, three maps, three layers of the same handiwork.

Try it and see. Gathering the maps is a real research task, so do it like a researcher. First choose your county: usually the one you live in, though a county where your family has land or history works too. Louisiana calls them parishes and Alaska calls them boroughs; the United States has about 3,100 of these units, and all have been mapped. Second, find the topographic quads at the USGS topoView site, which lets you type a place name, see the quad outlines and download current or historic sheets. Third, find the geologic map: start at your state geological survey's website, since most states have published county or state maps, and use the USGS National Geologic Map Database to search by place. Fourth, open

the USDA Web Soil Survey, draw an Area of Interest around part of your county and print the soil map and its legend. Save everything in one folder named for the county, and write down the title, publisher, year and scale of each map, because your report must cite its sources.

God's handiwork. Proverbs 25:2 says that it is the glory of God to conceal a thing, but the honour of kings is to search out a matter. A map is a record of searching out. Someone walked those hills with a notebook, broke rock from those creek banks and dug those soil pits so that you could open a file and see, in an afternoon, what took them a season. When you lay the three maps over your county and the pieces fit, you are seeing an order that was there before any surveyor arrived, laid down by the One who made the heaven and the earth.



The same county on its three base maps. The dashed county line is identical on all three, so the maps can be laid over one another. Left: USGS topographic quadrangle (contours and streams). Center: geologic map with limestone (Ls), shale (Sh) and sandstone (Ss) units. Right: USDA soil map with example map-unit symbols.

⏳ Thinking About Time

What the sign says. The legend of your county geologic map lists its units by the textbook time scale, with names such as Pennsylvanian, Cretaceous or Quaternary, and the textbook attaches ages to those names, for example about 300 million years for Pennsylvanian rocks.

What we observe. What the map actually records is where each unit crops out, what it is made of (limestone, shale, sandstone, granite) and which units lie above or below others. Those are field observations that you can check yourself in Lesson 8.2 with a hammer and a hand lens.

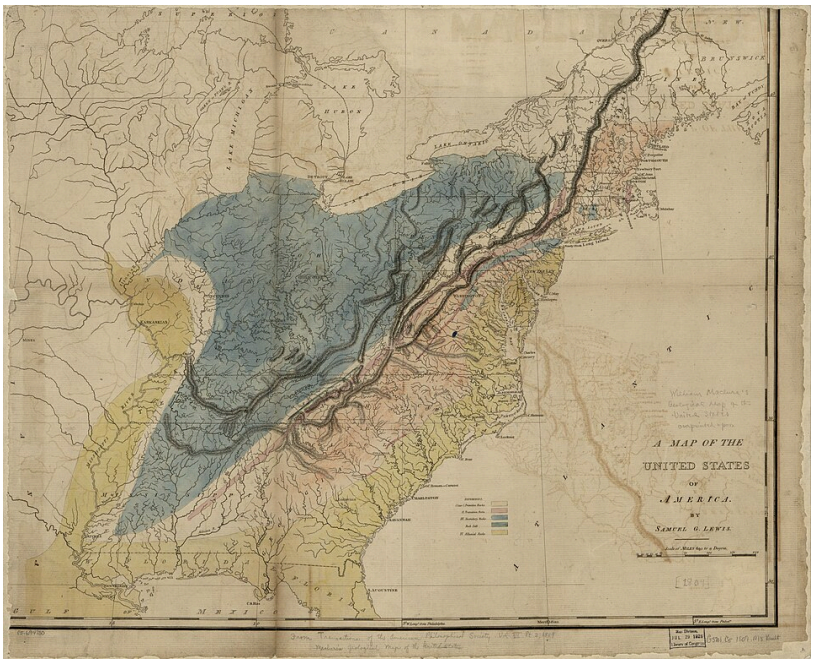
How Christians read it. Young-earth creation geologists read most of the layered rock as laid down rapidly during and soon after the Flood of Genesis 6 to 9, and they use the period names only as labels for layers in order, not as ages. Some Christians hold old-

earth views (Unit 7). Either way, your report should separate the observation (which unit, where) from the interpretation (how old) and say which is which.

Try it. On a copy of your geologic map legend, list the unit names in order and write beside each the rock it is made of, leaving the age column blank; everything the report needs is still there.

Genesis 7:19

PICTURE STUDY



Geological Map of the United States, from Observations on the Geology of the United States, William Maclure, 1809 · Hand-colored engraved map, published in the Transactions of the American Philosophical Society · Library of Congress, Geography and Map Division, Washington, D.C.; copies at the American Philosophical Society, Philadelphia

William Maclure was a Scottish-born merchant who made a fortune, retired young and spent it walking across the United States with a hammer. He said he crossed the Appalachian Mountains some fifty times, and in 1809 he read a paper to the American Philosophical Society in Philadelphia with this colored map attached: the first geological map of the United States, published six years before William Smith’s famous map of England that you studied in Lesson 5.1. He revised it in 1817.

Maclure used the four rock classes of his day, primitive, transition, secondary and alluvial, and colored them as broad bands. The bands follow the grain of the mountains. He had no quadrangles, no contour lines and no state surveys to lean on, only what he saw on foot. His map is a reminder that every county map you download began with someone walking.

Look closely

- Find the long colored bands. Which direction do they run? Compare with the direction of the Appalachian Mountains on a modern map.
- Find the Atlantic coastal plain. How is it colored, and why might the newest, loosest deposits lie nearest the sea?
- Look at the western edge of the map. Where does Maclure's knowledge run out?
- Count the colors. How many rock classes did Maclure use, compared with the dozens of units on a modern county map?

Talk about it

1. What could Maclure know from walking that he could not know from any book in 1809?
2. Find your own state or region on the map. Would Maclure's band for it match the main rock type on your county geologic map?
3. Why is a map with only four classes still useful? What is lost when a map is that simple?

EXPERIMENT: THE COUNTY MAP FOLDER: DO THREE MAPS AGREE?

You will choose your county, gather its three base maps, trace the county outline at one scale and lay the maps over one another to test whether they agree about where the valleys, rock belts and soils are.

Question: Do the topographic, geologic and soil maps of my county agree about where the main valley and the main ridge are? Prediction: write which rock unit and which soil symbol you expect to find along the biggest river before you check. What we change: the map we look at. What we keep the same: the county outline, the scale and the three places we check. What we measure: whether each map places the river valley, the ridge and the flattest farmland in the same spots.

You will need

- Internet access with a parent: USGS topoView (ngmdb.usgs.gov/topoview), the USGS National Geologic Map Database (ngmdb.usgs.gov) or your state geological survey, and the USDA Web Soil Survey (websoilsurvey.nrcs.usda.gov)
- A printer, or a screen and tracing paper
- Tracing paper, ruler with millimeters, calculator, colored pencils
- A folder or binder labeled with the county name
- Lab notebook

Steps

1. Choose your county and write a fact sheet in your notebook: name, state, county seat, area in km² (convert from square miles by multiplying by 2.59), population, neighboring counties, and the main rivers. Note where each fact came from.
2. In topoView, type the county seat, turn on the quad outlines and list every 7.5-minute quadrangle that touches your county. Download or print the one that contains the

county seat, with its collar (the margin, where the scale and contour interval are printed).

3. Find the county's geologic map (your Lesson 5.4 map will do). Record its title, author, year, publisher and scale.
4. In Web Soil Survey, draw an Area of Interest around the county seat and about 10 km of country beside it, open the Soil Map tab and print the map and its legend. Record the symbols of the three largest map units and what soils they stand for.
5. On tracing paper, trace the county outline from a state map and mark three test points: the biggest river at the county line, the highest ridge or hill, and the flattest farmland. Lay the tracing over each base map in turn (scale them to match on screen, or redraw at one scale) and record what each map shows at each point.
6. Fill a table with three rows (river, ridge, farmland) and three columns (topographic, geologic, soil). Then write: Did the maps agree? Was my prediction right? Where they disagree, which map is more detailed (larger scale)?
7. File the fact sheet, the three maps, the tracing and the table in the county folder. This folder is the foundation of Lesson 8.4.

Tips

- Web Soil Survey limits the size of an Area of Interest, so for a large county you may be able to map only part of it; that is fine. Choose the part where you will collect samples in Lesson 8.2.
- Historic topographic sheets in topoView often show mines, quarries, springs and old wells that newer sheets leave off. Download one old sheet and one new one.
- Write the source of every map on the back of its printout at once. You will not remember later.

Check your work

- I have a county fact sheet with sources for each fact.
- I have a topographic quad, a geologic map and a soil map of my county, each with its title, year, publisher and scale recorded.
- I can lay the county outline over all three maps and say where they agree and where they differ.

FIELD NOTEBOOK

1. Draw the outline of your county with north at the top and a scale bar in kilometers. Mark the county seat, the main river and the highest point, with its elevation in meters.
2. Copy the collar of your topographic quad: the quad name, the scale, the contour interval (convert to meters) and the year surveyed.
3. Make a three-column chart titled "What each map answers" with one sentence and one small sketch for the topographic, geologic and soil maps.

From history. Powell's plan to map the whole country had to survive Congress. In the 1880s and 1890s some senators asked why the government should pay to map ground that would never be farmed. Powell answered that no one can manage water, timber, minerals or roads without knowing where they are, and the topographic program went on. In 1992 Congress passed the National Geologic Mapping Act, which set up the National Geologic Map Database and a cost-sharing program with the state surveys, and that database is where you will find your county's geologic map today.

WORKED EXAMPLES

Example 1. On a USGS 1:24,000 quadrangle you measure 3.5 cm from the county courthouse to the river bridge. How far apart are they on the ground, in meters?

1. A scale of 1:24,000 means 1 cm on the map is 24,000 cm on the ground.
2. Multiply: 3.5 cm × 24,000 = 84,000 cm.
3. Convert to meters: 84,000 cm ÷ 100 = 840 m.

Answer: 840 m, or 0.84 km.

Example 2. Your county covers 1,500 km². At your latitude a 7.5-minute quadrangle covers about 150 km². What is the smallest number of quadrangles that could cover the county, and why will you probably need more?

1. Divide the county area by the area of one quad: 1,500 ÷ 150 = 10.
2. Ten is the minimum, and it would only be enough if the county were a neat block of whole quads.
3. County lines do not follow quad lines, so quads along the edge are only partly inside the county. Each partial quad still has to be downloaded. Expect 12 to 16 sheets.

Answer: At least 10 quadrangles; in practice about 12 to 16, because edge quads are only partly inside the county.

Example 3. The topographic map gives the county's highest hill as 1,352 feet and the river at the county line as 617 feet. The two points are 38 km apart. Find the relief in meters and the average slope from hill to river in meters per kilometer.

1. Convert feet to meters (1 ft = 0.3048 m): 1,352 × 0.3048 = 412 m; 617 × 0.3048 = 188 m.
2. Relief is the difference: 412 m − 188 m = 224 m.
3. Average slope: 224 m ÷ 38 km = 5.9 m per km, a gentle slope of about 0.6 percent.

Answer: Relief 224 m; average slope about 5.9 m per km (about 0.6 percent).

PRACTICE

1. EASY Name the three base maps for the capstone and the question each one answers.
2. EASY A state geologic map has a scale of 1:500,000. How many meters on the ground does 1 cm on the map represent? How many kilometers?
3. EASY Which map shows more detail, 1:24,000 or 1:250,000? Explain using the fraction.
4. MEDIUM On a 1:24,000 quad, a straight road from a quarry to the county seat measures 5.2 cm. How long is the road in meters and in kilometers?
5. MEDIUM The table shows ground distance per centimeter for common map scales. Scale 1:24,000: 240 m per cm. Scale 1:100,000: 1 km per cm. Scale 1:250,000: 2.5 km per cm. Scale 1:500,000: 5 km per cm. A county is 60 km from east to west, and your report page is 30 cm wide. Which of these scales would let the whole county fit on one page? Show the width of the map at each scale.
6. MEDIUM A student lists the quads that touch her county and estimates the fraction of each quad that lies inside the county line. Quad A: 100%. Quad B: 60%. Quad C: 100%. Quad D: 25%. Quad E: 100%. Quad F: 40%. Each quad covers 150 km². Estimate the county's area, and state which quad adds the least.
7. MEDIUM Your geologic map shows limestone under your house, but when you dig in the garden you find only brown clay loam. Explain why both can be true and which map describes the garden.
8. HARD A 7.5-minute quad in southern Texas covers about 170 km², while one in northern Minnesota covers about 130 km². Both are 7.5 minutes of latitude by 7.5 minutes of longitude. Explain the difference.
9. HARD Experiment design. You suspect that your county's streams follow the boundaries between rock units. Design a test using only your maps. State what you will compare, how you will measure agreement, how many places you will check, and what result would count against your idea.
10. CHALLENGE Write a six-line county fact sheet for your county, with a source for every line. Then write two sentences explaining why a report needs a source for each fact.

COMMON MISTAKES

- Thinking a bigger number means a more detailed map. 1:24,000 is a larger scale than 1:250,000 because the fraction 1/24,000 is larger, and it shows far more detail.
- Expecting the geologic map to show what you dig in the garden. It shows bedrock; the soil on top is a different map.
- Copying a map without its collar. The scale, contour interval, year and publisher are in the margin, and a map without them cannot be cited or measured.

> **Make it a game · Quad Hunt.** Spread the topographic quad on the table. A parent names a feature on the map (a church, a bridge, a hilltop, a spring) and starts a 30-second timer. Find it, then measure with the ruler how far it is from the courthouse and convert to meters using the scale. One point for finding it, one point for a correct distance within 50 m. Switch roles. First to ten points wins; a wrong conversion loses a point.

> **Scripture.** “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter.” (Proverbs 25:2, KJV)

God has hidden the rock, water and soil of your county beneath its surface. Searching it out with maps, samples and questions is honorable work, and the maps you gather today are the record of others who searched before you.

Practice answers

1. Topographic map: what shape is the land (hills, streams, roads)? Geologic map: what rock lies under the soil? Soil map: what is the ground like in the top meter or two?
2. 500,000 cm = 5,000 m = 5 km per centimeter.
3. 1:24,000. The fraction 1/24,000 is larger than 1/250,000, so each centimeter of map covers less ground (240 m instead of 2,500 m) and can show smaller features.
4. 5.2 × 24,000 = 124,800 cm = 1,248 m, about 1.25 km.
5. At 1:24,000 the map would be 60,000 ÷ 240 = 250 cm wide; at 1:100,000, 60 cm; at 1:250,000, 24 cm; at 1:500,000, 12 cm. Only 1:250,000 and 1:500,000 fit on a 30-cm page; 1:250,000 fits with the most detail.
6. Fractions add to 1 + 0.6 + 1 + 0.25 + 1 + 0.4 = 4.25 quads; 4.25 × 150 km² = 637.5 km², about 640 km². Quad D adds the least (0.25 × 150 = 37.5 km²).
7. The geologic map shows bedrock, which may be a meter or more down; the soil formed on top of it by weathering and is shown on the soil map. The soil map describes the garden.
8. Lines of longitude converge toward the poles, so 7.5 minutes of longitude is a shorter east-west distance in Minnesota than in Texas. The north-south height (7.5 minutes of latitude, about 13.9 km) is nearly the same in both, so the northern quad is narrower and has less area.
9. Lay the traced stream network from the topographic map over the geologic map at the same scale. Choose at least 10 evenly spaced points along the main streams. At each, measure the distance (in cm, converted to m with the scale) from the stream to the nearest contact. Record the rock unit the stream runs on. If most streams run down the middle of a single unit, or the distances to contacts are no smaller than for 10 random points, the idea is not supported. Control: use the same scale, the same tracing and the same person measuring.
10. Sample: name and state (state map); county seat (county website); area in km² (Census figure converted from square miles); highest point and elevation in m (USGS topographic quad); main rivers (quad); population (Census). A reader can check a sourced fact and judge how reliable it is; a fact without a source cannot be checked or corrected, so it is only an opinion to the reader.

8.2 Collecting Samples

OBJECTIVES

- Plan a safe and lawful sampling trip: choose sites from the three base maps, get permission, and pack the right tools.
- Collect, label and record rock, soil and stream-sediment samples with a site number, date, location, and a field description in the notebook.
- Test the samples at home (hardness, streak, acid fizz, density by water displacement, soil jar test) and record the results in a data table.

Warm-up. Put three small rocks from the yard or driveway in a row. Without any tools, write three observations about each: color, whether it has layers or crystals or grains, and how heavy it feels for its size. Now try to tell someone which rock is which using only your notes. If they cannot, your description is not yet good enough for a field notebook.

Video. Coming soon. How geologists collect and label rock samples in the field, field notebook basics, rock and mineral identification tests at home (hardness, streak, acid test), soil jar texture test; search USGS, state geological surveys, Smithsonian National Museum of Natural History, USDA NRCS soil health and university geology field-camp channels.

KEY TERMS

outcrop
A place where bedrock is exposed at the surface and still attached to the ground beneath it, such as a creek bank, cliff or road cut.

float
A loose rock lying on the ground or in a stream that has been moved from its original outcrop by water, ice or gravity; useful, but it does not prove what rock is underneath.

field notebook
The bound notebook in which a geologist writes the date, location, sketch and description of every site and sample at the site, in pencil, before leaving.

sample label
A tag that travels with a sample giving its site number, date, location and collector; a sample without one is only a rock.

density
Mass divided by volume, in grams per cubic centimeter; found for a rock by weighing it and measuring the water it displaces.

soil texture
The proportions of sand, silt and clay in a soil, estimated from the layers that settle in a jar of shaken soil and water.

CORE IDEAS

The story. In 1896 the United States Geological Survey hired a new assistant geologist, Florence Bascom, and sent her into the Piedmont of Pennsylvania, Maryland and Delaware, the belt of hard, worn crystalline rock that lies between the coastal plain and the Appalachian ridges. She had earned her doctorate at Johns Hopkins in 1893, and she was one of the first American geologists to argue from thin sections, slices of rock ground so thin that light passes through them under a microscope. Her field method was simple and strict. Walk the creeks, where running water keeps the rock bare. Break a fresh face with the hammer. Look with the hand lens. Write the location, the rock, the direction its layers tilt and a sketch in the notebook. Number the sample, bag it, and carry it home to cut and study. Over the next thirty years she mapped quadrangle after quadrangle of that country, and the USGS published the results as folios. A map is only as good as the samples behind it.

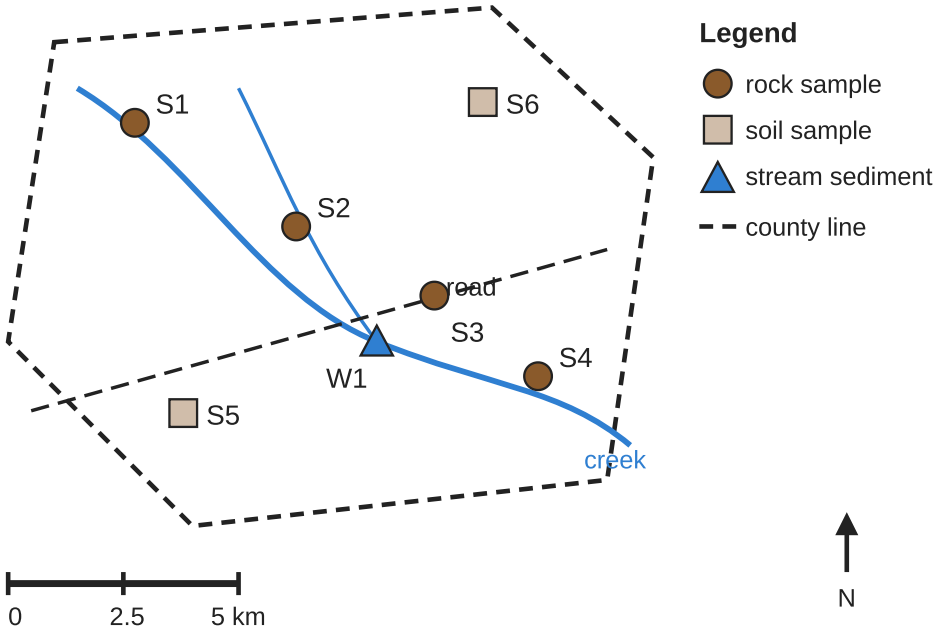
How they figured it out. Good sampling follows a few rules that every field geologist learns. First, know the difference between an **outcrop**, rock still attached to the ground, and **float**, a loose rock that water or gravity has carried from somewhere else. A pebble in a creek may have come from fifty kilometers upstream. Second, take a fresh surface. Weather, roots and lichen change the outside of a rock, so break a piece and describe the inside. Third, take enough: a fist-sized piece for rock, about 500 g for soil, and a trowel-full of sand from a stream bar. Fourth, label at the site, never later. The label gives the site number (S1, S2), the date, the location (from a phone’s coordinates or a mark on the map), and your name. The notebook entry says what the site looks like, what the rock or soil is like, which way layers tilt if you can tell, and a quick sketch with a scale, such as a coin or the hammer in the photo. Fifth, bag each sample by itself.

The big idea. Your maps tell you where to go. Aim for one rock sample from each geologic map unit you can reach, one soil sample from each of the two or three soil map units nearest home, and one pan of sediment from a stream, because a stream carries a mixed sample of everything upstream. Creek banks, road cuts, quarry overlooks, field edges and construction sites are the usual outcrops. Then come the rules of the land. Private land needs the owner’s permission, asked for in person or in writing. National parks forbid collecting entirely, and most state parks do too. Many national forests allow a small amount of hobby collecting, but check that forest’s rules first. Road cuts belong to the highway department, and a student stays well back from traffic and off the loose face. The law and good manners say the same thing: ask, take little, leave the place as you found it, and thank the owner.

Try it and see. At home the samples become data. For a rock, record color on a fresh surface, grain or crystal size, layering, and whether it is made of visible grains (sandstone), fine mud (shale), interlocking crystals (granite) or fizzes with vinegar (limestone and other calcite-bearing rocks). Test hardness against your Mohs tools from Unit 3: a fingernail is about 2.5, a copper coin about 3, a steel nail and window glass about 5.5. Streak it on an unglazed tile. Find its **density**: weigh it, drop it in a measuring cup of water, and divide the mass by the milliliters of water it pushed up. For soil, run the jar test from Lesson 1.4: fill a jar one third with soil, add water and a drop of dish soap, shake hard for two minutes and let it settle. Sand lands in about a minute, silt within a couple of hours, and clay over a day or

two. Measure the layers with a ruler and turn them into percent sand, silt and clay. Enter everything in one table with a row for each sample and a column for each test.

God’s handiwork. Proverbs 24:27 says to prepare thy work without and make it fit for thyself in the field, and afterwards to build thine house. Field first, then house; samples first, then the report. The rocks of your county were there long before you, laid down in order, and the only way to read them honestly is to go and look. A limestone that fizzes under a drop of vinegar in your kitchen is the same stone the county quarry crushes for roads and the same stone that holds the water in some of its wells. To hold it in your hand, labeled and measured, is to know your county in a way no download can give.



A sampling plan drawn on the county outline. Rock sites (circles) are placed one in each map unit along creek banks and road cuts; soil sites (squares) are in two different soil map units; the sediment site (triangle) is on a stream bar. The scale bar lets you measure the spacing between sites.

PICTURE STUDY



Sand Dunes, Carson Desert, Nevada, Timothy H. O'Sullivan, 1867 · Albumen silver print from a glass-plate negative · Library of Congress, Prints and Photographs Division, Washington, D.C. (Geological Exploration of the Fortieth Parallel)

Timothy O'Sullivan had photographed the Civil War before he joined Clarence King's Geological Exploration of the Fortieth Parallel in 1867. The survey crossed Nevada and Utah along the route of the new railroad, mapping the rock and measuring the mines, and O'Sullivan hauled a darkroom wagon and glass plates across the desert to record what the geologists saw.

This photograph shows the survey's wagon at the foot of a dune in the Carson Desert, with the photographer's own footprints leading back to the camera. It is a picture of fieldwork itself: equipment, distance, heat, and the plain fact that to describe a place you must go there.

Look closely

- Find the wagon and the mules. How big is the dune compared with them?
- Follow the footprints. What do they tell you about where the photographer walked and why?
- Look at the surface of the sand. Can you see ripples? What made them?
- Notice how little is in the picture: sand, sky, wagon. Why might O'Sullivan have left it so bare?

Talk about it

1. A geologist in 1867 could carry only so much rock home in that wagon. How would that change what he chose to sample?

2. The footprints are the only record of where the photographer stood. What is the field notebook's job in a sampling trip?
3. What would a sand sample from this dune tell you about the rock upwind of it?

> **Safety first.** Collect only with an adult and with the landowner's permission. Wear safety glasses and gloves when hammering rock, because chips fly, and strike away from your body and from other people. At road cuts stay well off the roadway and never climb a loose face. Near creeks watch for slippery rocks, deep or fast water, unstable banks, snakes and poison ivy. Never enter a quarry, pit or mine without an escort from the operator. Wash hands after handling soil and water, do not drink stream water, and keep vinegar away from eyes.

EXPERIMENT: SIX-SITE SAMPLING TRIP: DOES THE GROUND MATCH THE MAP?

You will plan a route from your county map folder, visit about six sites with an adult, collect and label rock, soil and sediment samples, and test them at home to see whether the maps predicted what you found.

Question: At each site, does the rock or soil on the ground match what the geologic map and soil map predict? Prediction: before you go, write beside each planned site the map unit and one feature you expect (fizzes, gritty, splits in sheets, red clay). What we change: the site. What we keep the same: the way we collect (fresh surface, same size sample), the tests we run and the person running them. What we measure: hardness, fizz, streak, density, grain size and soil texture. Record: a data table with one row per sample.

You will need

- The county map folder from Lesson 8.1 (topographic, geologic and soil maps)
- Rock hammer or a sturdy masonry hammer, safety glasses, work gloves
- Garden trowel, hand lens, ruler, a coin for scale in photos
- Zip bags, a permanent marker, masking tape for labels, a backpack
- Field notebook and pencil; a phone for coordinates and photos
- At home: kitchen scale, measuring cup with milliliter marks, white vinegar, unglazed tile, steel nail, copper coin, glass jar with lid, dish soap

Steps

1. On the geologic map, mark one reachable site in each map unit (creek bank, road cut, quarry overlook, field edge). On the soil map, mark two sites in different soil units. Mark one stream bar for sediment. Number them S1 to S6 (and W1 for the stream) and write your predictions.
2. Get permission for each site on private land. Write the owner's name and the date permission was given in the notebook.
3. At each site, before touching anything, write the site number, date, time, location and a two-line description of the place. Sketch the outcrop with a scale and take a photo with the coin or hammer in it.

4. Rock: break a fresh fist-sized piece from the outcrop, not from float (if float is all there is, write “float”). Soil: scrape away leaves and grass, dig to about 15 cm and take about 500 g. Sediment: scoop a trowel of sand from the stream bar. Bag each sample alone and label the bag at once: site number, date, location, your name.
5. At home, lay the samples out in order. For each rock record fresh color, grain or crystal type, layering, hardness (fingernail, coin, nail, glass), streak and vinegar fizz. Weigh it and find its volume by water displacement; compute density.
6. For each soil, run the jar test: one third soil, water, a drop of soap, shake two minutes, measure the sand layer after 1 minute, the silt layer after 2 hours and the clay layer after 2 days. Compute percent of each and name the texture with the triangle from Lesson 1.4.
7. Fill the data table and add a last column: Did the map predict this? Write yes, no or partly, with a reason. Then write three sentences about the site where map and ground disagreed most, and what you think explains it.

Tips

- Pencil does not run when the notebook gets wet; ink does.
- If a limestone will not fizz, scratch a little powder from it first; the powder reacts faster than a smooth face.
- A sample that fizzes and has visible fossil pieces is still a limestone; note the fossils in the description as an observation.

Check your work

- Every sample has a label and a notebook entry written at the site.
- I have a data table with hardness, streak, fizz, density and grain size for each rock and the texture of each soil.
- I can say which sites matched the maps and which did not, with reasons.

FIELD NOTEBOOK

1. Draw your best outcrop as you saw it, with a scale bar, the layers, and an arrow showing which way the layers tilt. Label the sample point.
2. Draw one rock sample at twice its real size on a fresh surface, with its site number, and list its five test results beside it.
3. Draw your soil jar after two days with the three layers measured in centimeters and the percent of each written beside it.

> **From history.** Soil sampling became a national program in 1899, when the United States Department of Agriculture began its first soil surveys, county-sized studies with colored maps of soil types. More than a century later the National Cooperative Soil Survey, run by the USDA Natural Resources Conservation Service with the states, has mapped nearly the whole country, and every map unit on your Web Soil Survey printout stands on pits dug and samples tested by soil scientists walking the land the way you did.

WORKED EXAMPLES

Example 1. Sample S2 has a mass of 156 g. When dropped into a measuring cup holding 50 mL of water, the level rises to 108 mL. Find its density and say which common rocks it is consistent with.

1. Volume of the rock = water displaced = 108 mL − 50 mL = 58 mL = 58 cm³.
2. Density = mass ÷ volume = 156 g ÷ 58 cm³ = 2.69 g/cm³.
3. Granite and limestone are both about 2.7 g/cm³; porous sandstone is usually lower, about 2.2 to 2.6; basalt is about 3.0. Density alone cannot separate granite from limestone, so run the vinegar test: limestone fizzes, granite does not.

Answer: About 2.7 g/cm³, consistent with granite or limestone; the fizz test decides between them.

Example 2. After two days the soil jar from site S5 shows layers of sand 3.0 cm, silt 1.5 cm and clay 0.5 cm. Find the percent of each and name the texture.

1. Total height = 3.0 + 1.5 + 0.5 = 5.0 cm.
2. Sand: 3.0 ÷ 5.0 = 60%. Silt: 1.5 ÷ 5.0 = 30%. Clay: 0.5 ÷ 5.0 = 10%.
3. On the texture triangle, 60% sand, 30% silt and 10% clay falls in the sandy loam field.

Answer: 60% sand, 30% silt, 10% clay: a sandy loam.

Example 3. You want six evenly spaced rock sites along a 12 km stretch of creek, with a site at each end. How far apart are the sites, and how far apart will they be on a 1:24,000 map?

1. Six sites with one at each end make five gaps, not six.
2. Spacing = 12 km ÷ 5 = 2.4 km = 2,400 m.
3. On a 1:24,000 map, 1 cm = 240 m, so 2,400 m ÷ 240 m per cm = 10 cm between sites.

Answer: 2.4 km apart on the ground, 10 cm apart on the map.

PRACTICE

1. EASY What is the difference between an outcrop and float? Which one tells you for certain what rock lies under that spot?
2. EASY List the four things every sample label must carry.
3. EASY Why do you break a fresh surface before describing a rock?

4. MEDIUM A rock sample has a mass of 240 g and displaces 92 mL of water. Find its density to two decimal places.
5. MEDIUM Four samples were tested. Sample A: scratched by a steel nail, fizzes strongly with vinegar, white streak. Sample B: scratches glass, no fizz, visible interlocking pink, white and black crystals. Sample C: scratched by a fingernail, no fizz, dull gray, splits into thin sheets. Sample D: scratches glass, no fizz, visible rounded sand grains that rub off, gritty. Identify each rock, and state which one would most likely make a good aquifer.
6. MEDIUM Two soils were jar-tested. Soil 1: sand 4.0 cm, silt 1.0 cm, clay 1.0 cm. Soil 2: sand 1.0 cm, silt 2.0 cm, clay 3.0 cm. Find the percent clay in each, and state which soil will drain faster and why.
7. MEDIUM Name two kinds of places where collecting is not allowed, and one thing you must do before collecting on a farm.
8. HARD Experiment design. Your creek sediment seems rounder downstream than upstream. Design an experiment to test whether pebbles become rounder with distance traveled. State the sites, the sample size, how you will measure roundness, what you will keep the same, and what result would support the idea.
9. HARD A pan of wet stream sediment had a mass of 1.2 kg. After drying for two days it had a mass of 0.9 kg. What percent of the wet sample was water? If you want 500 g of dry sediment for a sieve test, how much wet sediment should you collect?
10. CHALLENGE In three or four sentences, explain why one sample from a map unit is not enough to describe that unit, and what you would do with an extra afternoon of collecting.

COMMON MISTAKES

- Treating a creek pebble as proof of the rock beneath the creek. It is float, and it may have traveled far; only outcrop proves the bedrock.
- Testing a weathered surface. A fresh break shows the true color, grains and hardness; the outside has been changed by water, air and lichen.
- Confusing hardness with toughness. Hardness is resistance to scratching; a rock can be hard but break easily, like glassy quartz, or soft but tough, like clay.

Make it a game · Sample Detective. Lay out five labeled samples and your data table. A parent hides the labels and hands you one sample at a time with your eyes closed. Using only touch (grain, weight, layering) you make a guess; then you may open your eyes and use one test of your choice to confirm. Two points for a correct guess by touch, one point for a correct answer after the test. Then switch: you hand the samples to the parent, who must use your notebook descriptions alone to identify them. If the notebook fails, rewrite that description.

Scripture. “Prepare thy work without, and make it fit for thyself in the field; and afterwards build thine house.” (Proverbs 24:27, KJV)

The field comes first, the house afterward. Samples, labels and notebook pages are the work “without”; the report you build in Lesson 8.4 will stand only as firmly as this fieldwork.

Practice answers

1. An outcrop is bedrock still attached to the ground; float is a loose rock moved from somewhere else. Only the outcrop proves what is beneath that spot.
2. Site number, date, location (coordinates or map mark) and the collector’s name.
3. Weathering, lichen and soil stain change the outside; the inside shows the rock’s true color, grains and crystals.
4. 240 ÷ 92 = 2.61 g/cm³.
5. A limestone, B granite, C shale, D sandstone. The sandstone (D) is the most likely aquifer because the spaces between its grains hold and pass water; a fractured limestone can also be an aquifer, but shale and unfractured granite are poor.
6. Soil 1: 1.0 ÷ 6.0 = 17% clay (67% sand, 17% silt). Soil 2: 3.0 ÷ 6.0 = 50% clay (17% sand, 33% silt). Soil 1 drains faster because sand grains leave large pores; Soil 2 is half clay, whose tiny particles pack tightly and hold water.
7. National parks and most state parks (and any posted land). On a farm you must ask the owner’s permission first and record who gave it and when.
8. Choose four stream-bar sites spaced evenly along the creek, for example 0, 4, 8 and 12 km downstream of the first outcrop. At each site collect 20 pebbles of one rock type (say sandstone) chosen without looking. Score each pebble on a 1 (sharp angular) to 5 (well rounded) chart and average the scores. Keep the rock type, pebble size range (2 to 4 cm) and the scorer the same. If average roundness rises steadily with distance, the idea is supported; if it stays flat or falls, it is not.
9. Water lost = 1.2 − 0.9 = 0.3 kg; 0.3 ÷ 1.2 = 25% water. Dry mass is 75% of wet mass, so wet mass needed = 500 ÷ 0.75 = 667 g, about 670 g.
10. A map unit may be tens of meters thick and stretch across the county, and it can change from place to place (a limestone with shale layers, a sandstone that grades to siltstone). One sample shows only one spot. With more time I would collect from the same unit at two or three more sites and at different levels in a thick outcrop, test them the same way, and report the range of results rather than a single value.

8.3 Interviewing a Working Geologist, Driller, Miner or Forecaster

OBJECTIVES

- Identify the earth-resource jobs that exist in or near your county and choose one working person to interview.
- Write ten good interview questions, most of them open questions, run a respectful 20-minute interview, and record the answers accurately.
- Convert the units a worker uses (feet, gallons per minute, tons, inches, degrees Fahrenheit) to metric and check the numbers for your report.

Warm-up. Ask a parent or older relative this one question and write down the answer word for word: “What is the first thing you do when you get to work?” Then ask, “Why that first?” Read your notes back to them. Did you get it right? Interviewing is mostly listening and writing exactly what was said.

Video. Coming soon. A day in the life of a water well driller, a quarry geologist, a mine engineer and a National Weather Service forecaster; how to conduct an oral history interview; search USGS, NOAA National Weather Service, state geological surveys, the Library of Congress American Folklife Center, the Bureau of Labor Statistics career videos and company or trade-association channels for drilling and aggregates.

KEY TERMS

open question
A question that invites a story or an explanation, usually starting with how, why, what or tell me about; it cannot be answered with yes or no.

closed question
A question with a short fixed answer, such as yes, no, a number or a name; useful for facts, poor for stories.

follow-up question
A question asked in reply to an answer, to get more detail or an example; the mark of a listener.

primary source
A first-hand record, such as an interview, a field notebook, a driller’s log or a photograph, as opposed to a book written about the subject later.

well log
The driller’s record of a well: the depth and kind of each layer passed through, the depth of the hole, where water was found, and the well’s yield.

gallons per minute (gpm)

The unit American drillers use for a well's yield; one gallon is 3.785 liters, so 10 gpm is about 38 liters per minute.

CORE IDEAS

The story. Between 1936 and 1940 the Federal Writers' Project sent writers across the United States with a notebook and a single instruction: find ordinary working people and write down their lives in their own words. The writers sat in kitchens and on porches, in coal towns, oil-field camps and farm country, and asked how a person had come to the work, what a day was like, and what the work had taught. They recorded about 2,900 of these life histories, and the Library of Congress keeps them today in a collection called American Life Histories. For many a county they are the only record of how a driller, a miner or a farmer actually did the job. The lesson for your capstone is the same one those writers learned: the maps tell you what lies under your county, but only a person who works it can tell you what it is like to drill it, dig it, test it or forecast its weather.

How they figured it out. Every county has someone to interview; the trick is knowing where to look. Nearly every county has a sand and gravel pit or a crushed-stone quarry, because crushed stone is the most-mined material in the United States, roughly 1.5 billion tonnes a year, and it is too heavy to haul far. The quarry has a foreman, a blaster or a geologist. Every state licenses or registers water well drillers, and the state list will show you the contractor who drills in your county. The county has an engineer's office that deals with road cuts, gravel and drainage, and a soil and water conservation district; there are nearly 3,000 such districts nationwide. The state geological survey employs geologists who may have mapped your county. The National Weather Service runs 122 forecast offices, and a forecaster will often talk with a student by phone or email. In oil, gas or coal counties there are pumpers, drillers and mine engineers. In Lesson 6.4 you interviewed someone about weather; this time choose the job that fits the resource your county depends on most.

The big idea. A good interview is a good set of questions plus a good listener. A **closed question** ("Do you like your job?") gets a yes. An **open question** ("Tell me about the hardest well you ever drilled") gets a story. Write ten questions in advance, mostly open: how you got into this work, what a typical day looks like, which tools matter most, what the ground under this county is like from where you stand, one number from your work (a depth, a yield, a tonnage, a forecast error), the hardest problem you have solved, a safety rule you never break, what a fourteen-year-old should study to do this work, what you wish people understood about it, and what you would show a visitor first. Then listen for the **follow-up question**: when the driller says the well "came in at 180 feet," ask what was at 180 feet and how he knew. Be on time, ask permission before recording, take notes even if you record, and send a thank-you note within a week.

In the world today. Workers speak in the units of their trade, and your report is in metric, so you will convert. Feet to meters: multiply by 0.3048. Gallons per minute to liters per minute: multiply by 3.785. Short tons to tonnes: multiply by 0.907. Inches of rain to millimeters: multiply by 25.4. Degrees Fahrenheit to Celsius: subtract 32 and multiply by 5/9. Write the worker's number first, exactly as said, and your metric figure beside it, so the

reader can see both. A driller may also hand you a copy of a **well log**, the layer-by-layer record of a hole; it is a **primary source**, and your report should cite it as one: “Well log, Smith Drilling, 2019.” The interview itself is cited the same way, with the person’s name, job, and the date. Quote exactly only what you wrote down exactly, and ask permission before using a name.

God’s handiwork. Proverbs 20:5 says that counsel in the heart of a man is like deep water, but a man of understanding will draw it out. A driller knows things about your county that are in no book: where the sandstone is thick, where the water turns hard, which hillside slumps after rain. That knowledge is deep water, and a good question is the bucket. Remember too that the people you interview serve their neighbors with their hands and minds every day. Paul wrote that whatever we do we should do heartily, as to the Lord (Colossians 3:23). Drilling a sound well, mining stone safely, or forecasting a storm in time to warn a town is work God honors, and your report should honor it too.

PICTURE STUDY



Power House Mechanic Working on Steam Pump, Lewis W. Hine, 1920 · Gelatin silver print photograph · National Archives and Records Administration, College Park, Maryland

Lewis Hine had spent a decade photographing child laborers in mines and mills, pictures that helped change the law. After the First World War he turned to what he called work portraits: photographs that showed the skill and dignity of men and women at their trades. This mechanic, bent to the curve of a steam pump with a wrench longer than his forearm, became one of the most famous pictures of American work.

Hine did not snap this in passing. He talked with his subjects, learned what they did, and posed them so the picture told the truth about the job. That is what a good interview does with words.

Look closely

- Follow the curve of the man’s back and the curve of the pump. How do they fit together?
- Look at the wrench and the bolt. What is he actually doing, and what would happen if the bolt were loose?
- Find the light on his arms and shoulders. What does Hine want you to notice about the worker?
- Is anything in the picture unnecessary? What did Hine leave out?

Talk about it

1. If you could ask this mechanic three questions, what would they be? Make at least two of them open questions.
2. Hine posed the picture to show the job truly. How can an interviewer shape a conversation and still record the truth?
3. What jobs in your county today require this kind of strength and skill with heavy equipment?

> **Safety first.** Visit a worksite (quarry, drilling rig, pumping station, mine office or weather office) only with a parent and only by invitation, wearing the hard hat, safety glasses and boots the host requires. Stay where your host tells you, away from moving equipment, open holes and blasting areas. Phone or video interviews are a good choice when a site visit is not possible.

EXPERIMENT: THE CAPSTONE INTERVIEW: DEEP WATER DRAWN OUT

You will find one person who works with your county’s earth resources, prepare ten questions, conduct a 20-minute interview, and turn the answers into a one-page interview record with every number converted to metric.

Question: Which earth resource does my county depend on most, and what is it like to work with it? Prediction: write the resource you expect the worker to name and one number you expect to hear. What we change: nothing; this is an observation, not an experiment, so our job is to record accurately. What we keep the same: the question list and the way we take notes. What we measure: the answers, the numbers, and how well our notes match the recording.

You will need

- The county map folder and sample data table (Lessons 8.1 and 8.2)
- Notebook, two pencils, a printed question list with space for answers
- A phone or recorder, used only with permission
- A calculator and the unit-conversion table from this lesson
- A note card and envelope, or email, for the thank-you

Steps

1. With a parent, list three possible people to interview (for example a well driller from the state license list, a quarry foreman, a county engineer, a conservation district technician, a state survey geologist or an NWS forecaster). Choose the one whose work matches your county's main resource. Have your parent make the first contact and set a time.
2. Write ten questions, at least seven of them open. Put the easy ones first and the one about a number in the middle. Read them aloud and cut any that can be answered yes or no.
3. Before the interview, write the person's name, job, employer and the date at the top of your page. At the start, thank them, say what your report is about, and ask permission to record.
4. Ask your questions, but listen more than you read. Write key phrases and every number exactly as spoken, with its unit. When you hear a number or a surprising claim, ask a follow-up: how do you know, how was it measured, how often.
5. At the end ask, "Is there anything I should have asked?" and whether you may use their name. Thank them. Send a written thank-you note within a week.
6. The same day, write up the interview while it is fresh: a one-page record with the date, the person's job, the main points in order, three exact quotations you are sure of, and a table of every number with the worker's unit in one column and metric in the next.
7. Check your prediction. Did the worker name the resource you expected? Was the number near your guess? Write two sentences on what surprised you most.

Tips

- If the person says a number in feet or gallons, do not convert in your head during the interview; write it exactly and convert later.
- Silence is fine. If you wait three seconds after an answer, people often add the best part.
- If a site visit is offered, accept it with your parent, and bring your samples; workers enjoy telling you what you found.

Check your work

- I have ten questions, at least seven of them open, and I asked at least two follow-up questions.
- My interview record has the date, the person's job, three exact quotations and a table of numbers in the worker's units and in metric.
- I sent a thank-you note and recorded whether I may use the person's name in my report.

FIELD NOTEBOOK

1. Draw the tool the worker said matters most (drill bit, rock hammer, haul truck, radar screen) with labels for its parts and a sentence on what it does.

2. Make a two-column chart: the worker’s numbers with their units on the left, the metric conversions with your arithmetic on the right.
3. Draw a simple well log or a cross-section of the quarry or county as the worker described it, with depths in meters.

From history. In 1949 the Bureau of Labor Statistics published the first Occupational Outlook Handbook, a book describing hundreds of jobs, what workers do, what training they need and what the future looks like for each. It is still published, now free online, and it has entries for geoscientists, mining and geological engineers, atmospheric scientists, and the derrick, rotary-drill and service-unit operators who sink wells. Reading the entry for your interviewee’s job before the interview will give you better questions.

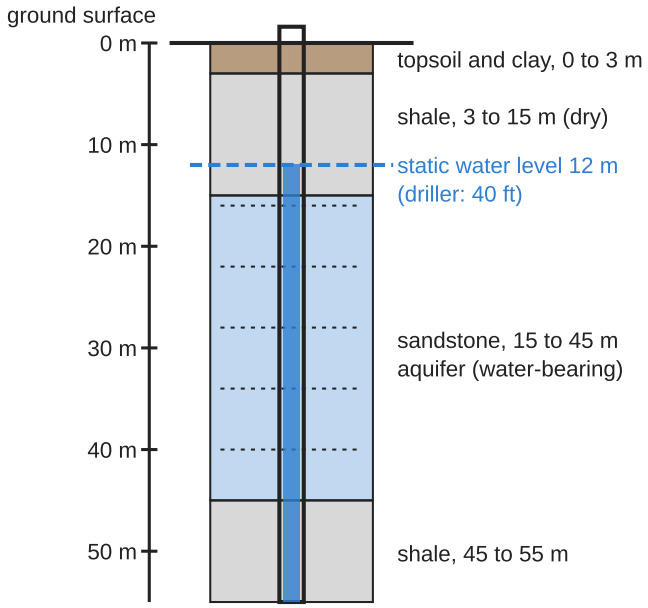
WORKED EXAMPLES

Example 1. Your interview is 20 minutes long. You plan 2 minutes to introduce yourself and 3 minutes at the end for thanks and a photo. If you have ten questions, how long is there for each? If the driller tells long stories and you can only ask six, how long per question?

1. Time for questions = $20 - 2 - 3 = 15$ minutes.
2. Ten questions: $15 \div 10 = 1.5$ minutes each, which is tight for a story.
3. Six questions: $15 \div 6 = 2.5$ minutes each. Mark your six most important questions with a star so you know which to keep if time runs short.

Answer: 1.5 minutes per question for ten; 2.5 minutes each for six. Star the six that matter most.

Example 2. A driller tells you a well in your county is 180 feet deep, the water stands 40 feet below the surface, and it yields 15 gallons per minute. Convert each number to metric and find how many meters of water stand in the well.



The driller's well log, redrawn in meters. The driller said 180 ft deep, water at 40 ft and 15 gpm; converted, that is 55 m, 12 m and 57 L/min. Water rose from the top of the sandstone at 15 m to 12 m, which shows the sandstone here is a confined aquifer (Lesson 2.2).

1. Depth: 180 ft × 0.3048 = 54.9 m, about 55 m.
2. Static water level: 40 ft × 0.3048 = 12.2 m, about 12 m below the surface.
3. Yield: 15 gal/min × 3.785 = 56.8 L/min, about 57 L/min.
4. Water column in the well: 54.9 − 12.2 = 42.7 m, about 43 m of water standing in the casing.

Answer: Depth about 55 m, water level about 12 m down, yield about 57 L/min, and about 43 m of water standing in the well.

Example 3. The same driller says the 180-foot well took two 8-hour days to drill. Find the drilling rate in meters per hour and in feet per hour.

1. Total drilling time = 2 × 8 = 16 hours.
2. Rate in meters: 54.9 m ÷ 16 h = 3.4 m per hour.
3. Rate in feet: 180 ft ÷ 16 h = 11.25 ft per hour. Check: 11.25 × 0.3048 = 3.4 m per hour, the same.

Answer: About 3.4 m per hour (11.25 ft per hour).

PRACTICE

1. EASY Rewrite the closed question “Do you like your job?” as an open question that invites a story.
2. EASY Name four earth-resource jobs that exist in or near a typical county, and where you would find each person.
3. EASY A driller says a well is 250 feet deep. How deep is it in meters?
4. MEDIUM A well yields 20 gallons per minute. Convert to liters per minute. If the pump runs 6 hours a day, how many liters does it deliver each day?
5. MEDIUM A driller shows you records for three wells. Well W1: bottom in sandstone, depth 180 ft, static water level 40 ft, yield 15 gpm. Well W2: bottom in shale, depth 220 ft, static level 60 ft, yield 2 gpm. Well W3: bottom in limestone, depth 150 ft, static level 35 ft, yield 40 gpm. Convert the depth of W3 to meters. Which rock gave the best yield, and what pattern do the data suggest about where to drill in this county?
6. MEDIUM A forecaster gives you average monthly rainfall for the county station in inches: January 2.1, April 3.5, July 4.2, October 2.8. Convert July to millimeters, state which month is wettest, and find the range between the wettest and driest of these months in millimeters.
7. MEDIUM Explain in two or three sentences why you write down exactly what the worker said, including the original units, and only convert and check later.
8. HARD Experiment design. The driller claims that wells finished in sandstone yield more water than wells finished in shale in your county. Design a test using the state’s online well records. State what you will compare, how many wells you will use, what you will keep the same, and what result would support or weaken the claim.
9. HARD A quarry foreman says the quarry ships 500,000 short tons of crushed stone a year. Convert to tonnes. If the quarry works 250 days a year and a truck carries 20 tonnes, how many truckloads leave each working day?
10. CHALLENGE Write a four-sentence thank-you note to the person you interviewed, and list three follow-up questions you would ask in a second interview, each one building on something a worker in that job would likely have said.

COMMON MISTAKES

- Asking only closed questions and getting a list of yes and no answers. Open questions draw out the stories and reasons a report needs.
- Writing what you thought the person meant and later presenting it as a quotation. Quote only words you wrote down exactly; otherwise paraphrase without quotation marks.
- Mixing units in one table, with some wells in feet and others in meters. Keep the worker’s unit in one column and metric in the next, and convert every row.

> **Make it a game · Hot Seat.** One player is the worker (driller, quarry geologist or forecaster) and must answer only in the way that job would, using feet, gallons per minute, tons or inches. The interviewer asks five questions in three minutes; each open

question that gets a full sentence scores one point, each closed question that gets a yes or no costs one point, and a follow-up question that uncovers a new fact scores two. Every number the worker gives must be converted to metric aloud by the interviewer before the next question, or the point is lost. Switch roles and play three rounds.

> **Scripture.** “Counsel in the heart of man is like deep water; but a man of understanding will draw it out.” (Proverbs 20:5, KJV)

A worker’s knowledge of the ground is deep water. The interviewer who asks good questions and listens patiently is the one who draws it out.

Practice answers

1. Sample: “Tell me about a day at work you still remember, and what made it good or bad.” Any question beginning with how, why, what or tell me about that cannot be answered yes or no.
2. A water well driller (state licensing list), a quarry or gravel-pit foreman or geologist (the local quarry), a conservation district or NRCS technician (county USDA office), an NWS forecaster (the regional forecast office). Also a county engineer, a state survey geologist, or an oil, gas or coal worker where those exist.
3. 250 × 0.3048 = 76.2 m.
4. 20 × 3.785 = 75.7 L/min. 75.7 × 60 × 6 = 27,252 L, about 27,000 L per day (27 m^3).
5. W3: 150 × 0.3048 = 45.7 m. The limestone well (W3) gave the best yield, 40 gpm (151 L/min); the shale well was deepest and worst. The data suggest drilling into limestone or sandstone and avoiding shale, though three wells are a small sample and the limestone may be cavernous only in places.
6. July: 4.2 × 25.4 = 106.7 mm, about 107 mm. July is wettest. Range: (4.2 − 2.1) × 25.4 = 53.3 mm, about 53 mm.
7. The exact words and units are the primary source; if you convert in your head you may make an arithmetic slip and lose the original figure. Writing it exactly lets you check the conversion later, quote the person truthfully, and go back to ask if something does not add up.
8. From the state well-record database, select 20 wells finished in sandstone and 20 finished in shale within the county, choosing them by a rule (for example every third well on the list) rather than by eye. Record each well’s yield in L/min and its depth. Compare the median yield of each group. Keep the same county, similar depth range and the same yield definition (the driller’s test yield). If the sandstone median is clearly higher and most sandstone wells beat most shale wells, the claim is supported; if the medians are close or overlap heavily, it is weakened.
9. 500,000 × 0.907 = 453,500 tonnes, about 454,000 t. Per day: 453,500 ÷ 250 = 1,814 t. Trucks: 1,814 ÷ 20 = 90.7, about 91 truckloads a day.
10. Sample note: thanks for the time and the visit; one specific thing learned (for example the well log); how it will be used in the county report; an offer to share the finished report. Sample follow-ups: “You said the water turns hard east of the river; what do you think changes in the rock there?” “How did the dry year change your work?” “What would you do differently if you were starting a well on my family’s land?”

8.4 Writing and Presenting the County Earth-Resources Report ★

OBJECTIVES

- Organize the maps, sample data and interview notes into a written county earth-resources report with a title, abstract, map, data table, figures with captions, conclusion and sources.
- Check every number and claim in the report against a source, give it in metric units, show the calculation, and separate observation from interpretation.
- Give a 6 to 8 minute presentation of the report with a map, a table and a sample tray, and answer questions from the audience.

Warm-up. Take any one page from your county folder (a map, the sample table, the interview record) and explain it aloud to a family member in exactly one minute, timed. Then ask them to tell you what they learned. Whatever they could not repeat back, you did not explain clearly. Write down the one sentence they did remember; that is how to begin your report.

Video. Coming soon. How to write a scientific report with figures, tables and citations; how to give a short science presentation; John Wesley Powell and the 1878 Report on the Lands of the Arid Region; search USGS, the Library of Congress, National Park Service history talks, Smithsonian and university writing-center channels.

KEY TERMS

abstract
A short paragraph at the front of a report, about 100 words, that tells what was studied, how, what was found and what it means.

citation
A note telling the reader exactly where a fact came from: a map's title, publisher, year and scale; an interview's name, job and date; a website's name and the date it was read.

figure caption
The sentence or two under a map, graph or photo that says what it shows, in what units, and where it came from.

evidence
A measurement, observation, map, record or quotation that supports a claim; in this report every claim needs a piece of evidence and a citation.

revision
Reading a draft again to cut, correct and reorder, especially checking every number, unit and source.

visual aid

A map, graph, table or object a speaker shows so the audience can see the evidence while hearing the claim.

CORE IDEAS

The story. In April 1878 John Wesley Powell, who had lost his right arm at Shiloh and run the Colorado River through the Grand Canyon in 1869, handed the Secretary of the Interior a report of about two hundred pages titled *Report on the Lands of the Arid Region of the United States*. West of roughly the hundredth meridian, he wrote, rainfall drops below about 500 mm (20 inches) a year, too little for ordinary farming, so the land should be divided by water rather than by the square-mile survey grid: irrigation farms along the streams, large pasture farms on the dry range, and settlement organized by watershed. He backed every claim with rainfall tables, maps and the records of his own surveys, and he ended with clear recommendations. Congress did little with it at the time. But the report was so well written and so well supported that it set the terms of every western water debate for a century, and you met its results in Lesson 2.4. A report that is clear, honest and backed by evidence can outlast the people who ignored it.

How they figured it out. Your report will follow the shape of Powell's. Say where: a map of the county with scale and north arrow. Say what you measured: tables of your samples and the numbers from your maps. Say what others told you: the interview, cited as a primary source. Say what it means: a conclusion. Say where it all came from: a list of sources. Your outline has nine parts. 1. Title page and **abstract**. 2. Where my county is: the fact sheet and map from Lesson 8.1. 3. The land and its soil (Units 1 and 5): relief, soil map units, your jar-test results. 4. Water (Unit 2): the aquifers, your interview's well numbers, where the county gets its drinking water. 5. Rocks, minerals and energy (Units 3 and 4): the map units, your rock samples, the quarry or mine or oil field if there is one. 6. Weather and climate (Unit 6): rainfall and temperature normals from the National Weather Service station nearest you. 7. The people who work it (Lesson 8.3). 8. Conclusion: the county's chief earth resources and how they can be used and kept well. 9. Sources.

The big idea. Every statement of fact in the report needs three things: a **claim**, the **evidence** for it, and a **citation**. "The county's best aquifers are the sandstone and the limestone" is a claim. "The driller's wells in sandstone and limestone yielded 57 and 151 L/min while the shale well yielded 8 L/min" is evidence. "Interview with J. Smith, well driller, March 4, 2027; well logs on file with the state" is the citation. Every number carries a unit, in metric, with the original unit in parentheses if a worker gave it. Every figure has a **caption**. Every table has a header row with units. And every claim is sorted into observation or interpretation, the habit you built in Unit 7. Where your geologic map legend gives textbook ages for its units, report what the legend says, attributed to the map, and keep it separate from what you observed in the field. A reader should always be able to tell what you saw, what you were told, and what you concluded.

Try it and see. Write the draft fast and revise it slowly. First draft: fill the nine parts from your folder without stopping to polish. **Revision** one: circle every number and find its source; if there is none, cut it or find one. Revision two: read the whole report aloud and

shorten any sentence that made you run out of breath. Revision three: check that the abstract matches the conclusion. Then the presentation. Plan 6 to 8 minutes, with one **visual aid** per part: the county map, the sample tray with labels, the data table, the well log or interview quotation, and a single slide or poster for the conclusion. Practice twice with a timer. Speak to the back of the room, hold up samples, and point to the map. Prepare for three questions you expect, including “How do you know?” The honest answer is always the same: here is the map, here is the sample, here is the person who told me.

God’s handiwork. The prophet Habakkuk was told to write the vision and make it plain upon tables, that he may run that readeth it (Habakkuk 2:2). A report is a vision made plain: a county’s stone, soil, water and weather set down so clearly that anyone can run with it. Your conclusion should end where the course began, with Genesis 2:15: the Lord put man in the garden to dress it and to keep it. Say what your county has been given, say how it is being used, and say how it can be kept well for the children who will dig, drill and forecast there after you.

PICTURE STUDY



Grand Canyon of the Yellowstone, Thomas Moran, 1872 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C. (lent by the U.S. Department of the Interior)

Thomas Moran went west in 1871 with Ferdinand Hayden’s government survey of the Yellowstone country, sketching while the geologists measured. Back in his studio he painted this canvas, more than two meters tall and nearly four meters wide, from his sketches and from William Henry Jackson’s photographs. In 1872 Congress bought it for ten thousand dollars and hung it in the Capitol.

The painting grew out of a report. Hayden’s written survey, Jackson’s photographs and Moran’s field watercolors together helped persuade Congress to set Yellowstone apart as the first national park on March 1, 1872, and this great canvas, finished that spring, became the

survey’s public picture. The two tiny figures on the rocky point stand for the survey party, small against the rock, which was Moran’s way of saying how large the subject was and how small the observers.

Look closely

- Find the two small figures. Why do you think Moran made them so small?
- Look at the canyon walls. What colors are the rocks, and what in the rock could give them those colors?
- Find the waterfall. How did Moran make the eye travel from the foreground to it?
- Compare the cliffs and slopes. Which look like hard rock and which like loose or soft material?

Talk about it

1. This painting grew out of a government survey report. What can a picture show that a table of numbers cannot? What can a table show that a picture cannot?
2. Which one visual aid in your own report would you choose if you could show only one, and why?
3. Hayden’s report was a written document, but the painting and the photographs changed minds. What does that tell you about presenting your report?

EXPERIMENT: THE COUNTY EARTH-RESOURCES REPORT AND PRESENTATION

You will assemble everything from Lessons 8.1 to 8.3 into a written report of about 1,200 to 2,000 words with a map, a data table, at least two captioned figures and a source list, then present it to your family or co-op in 6 to 8 minutes with your samples on the table.

Question: What are my county’s chief earth resources, and how are they being used and kept? Prediction: before you write, state in one sentence which resource you expect to come out on top. What we change: nothing; the report reports. What we keep the same: units (metric), the claim-evidence-citation rule for every fact, and the nine-part outline. What we measure: whether every number has a source and whether listeners can repeat the main finding.

You will need

- The county folder: fact sheet, three base maps, tracing, sample data table, interview record and well log if you have one
- A computer with a word processor, or lined paper and a ruler
- Graph paper for a bar graph; colored pencils
- The sample tray with labeled samples; a poster board or a few slides
- A timer, and an audience of at least three people

Steps

1. Make a one-page outline with the nine parts and, under each, the pieces from your folder that belong there. Mark any part that has no evidence yet and decide how to fill it (a NWS climate table, a second look at the soil map, a phone call to the driller).
2. Write the first draft straight through. Put the county map in part 2 with scale bar, north arrow and caption. Put the sample table in part 5 with a header row and units. Add at least one graph (for example percent of the county in each rock unit, or rainfall by month in millimeters) with a caption.
3. Write the conclusion: the county's chief resource, the evidence that it is chief, how it is used now, and one way it can be kept well. Then write the abstract last, in about 100 words, so it matches what you actually found.
4. Revise. Circle every number: check the arithmetic, the unit and the source. Mark each claim O (observed), T (told by the interview or map) or C (concluded by me). Read aloud and cut.
5. Write the source list: every map (title, publisher, year, scale), the interview (name or role, date), the well log, each website (name and date read). Have a parent check that every citation in the text appears in the list.
6. Build the presentation: five visual aids, one per main part, and a final slide or card with the conclusion in one sentence. Practice twice with a timer, standing, holding up samples. Adjust until you finish between 6 and 8 minutes.
7. Present. Afterward ask the audience to tell you the main finding in their own words and write down what they said. Answer their questions with evidence. File the report, the audience notes and your prediction in the folder; this is your capstone portfolio.

Tips

- A short report with every number sourced is worth more than a long one with guesses.
- Number your figures (Figure 1, Figure 2) and refer to them in the text by number.
- If a question stumps you, say, "I don't know; here is how I would find out." That is a scientist's answer.

Check your work

- My report has all nine parts, a map with scale, a table with units, at least two captioned figures and a source list.
- Every number is metric, sourced and checked, and every claim is marked observed, told or concluded.
- I presented in 6 to 8 minutes with visual aids and the audience could repeat my main finding.

FIELD NOTEBOOK

1. Draw the final county map for part 2 of your report: outline, county seat, main rivers, the sample sites, the interviewee's workplace, a scale bar and a north arrow.
2. Draw a bar graph for the report (percent of county in each rock unit, or monthly rainfall in millimeters) with labeled axes and a caption with the source.

3. Draw the layout of your presentation table: where each sample, map and card will sit so you can reach them in order while speaking.

From history. Ferdinand Hayden’s 1871 survey of the Yellowstone country produced a written report, William Henry Jackson’s photographs and Thomas Moran’s sketches and watercolors. Hayden sent the pictures to Congress along with his report, and on March 1, 1872, President Grant signed the act that made Yellowstone the first national park. Congress then bought Moran’s big painting of the canyon for ten thousand dollars. It is one of the clearest cases in American history of a report with good evidence and good pictures changing what a nation did with its land.

WORKED EXAMPLES

Example 1. Your county is 50 km from east to west and 35 km from north to south. The map on your report page can be 20 cm wide. What scale should the map be, and how tall will it be?

1. Convert the county width to centimeters: 50 km = 5,000,000 cm.
2. Scale = ground distance ÷ map distance = 5,000,000 ÷ 20 = 250,000, so the map is 1:250,000, where 1 cm = 2.5 km.
3. Height on the page: 35 km ÷ 2.5 km per cm = 14 cm. It fits.

Answer: 1:250,000 (1 cm = 2.5 km); the map will be 20 cm wide and 14 cm tall.

Example 2. The quarry foreman said the quarry sells about 500,000 tonnes of crushed limestone a year, and the working face is 20 m high. Limestone has a density of about 2.7 tonnes per cubic meter. How much land area does the quarry remove each year?

1. Volume removed = mass ÷ density = 500,000 t ÷ 2.7 t/m³ = 185,000 m³ (rounded).
2. Area = volume ÷ face height = 185,000 m³ ÷ 20 m = 9,260 m².
3. Convert: 9,260 m² ÷ 10,000 m² per hectare = 0.93 ha, a square about 96 m on a side, each year.

Answer: About 185,000 m³ of rock, which is about 9,300 m² or 0.93 hectare of land per year at a 20 m face.

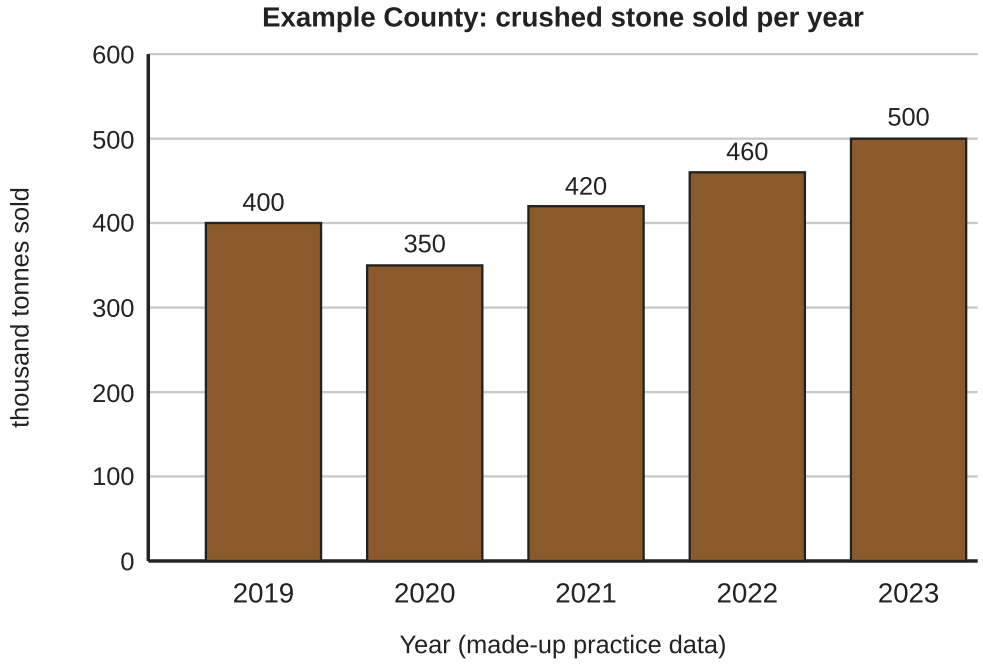
Example 3. Your county has 25,000 people, and the water utility says each person uses about 300 L a day. If 60 percent of the county's water comes from wells, how many cubic meters of groundwater are pumped each day? A well like the one in Lesson 8.3 yields 57 L/min; how many such wells running all day would be needed?

1. Total use = 25,000 × 300 L = 7,500,000 L per day = 7,500 m³ per day.
2. Groundwater share = 0.60 × 7,500 m³ = 4,500 m³ per day.
3. One well all day: 57 L/min × 60 min × 24 h = 82,080 L, about 82 m³ per day.
4. Wells needed = 4,500 ÷ 82 = 55 wells, running without pause; in practice more, since pumps rest.

Answer: About 4,500 m³ of groundwater a day, which would take about 55 wells of 57 L/min running all day.

PRACTICE

1. EASY List the nine parts of the county report in order.
2. EASY Write a claim, a piece of evidence and a citation for the statement that your county's farmland lies on river alluvium.
3. EASY Your presentation is 8 minutes and has six parts with visual aids. How many seconds can you spend on each part if they are equal?
4. MEDIUM The bar graph shows crushed stone sold by an example county's quarry, in thousand tonnes, for 2019 to 2023 (made-up practice data). By what percent did sales rise from 2020 to 2023? What was the total for the five years?



Example County crushed stone sold per year, in thousand tonnes (made-up data for practice). A graph like this, with a caption and a source, belongs in part 5 of the report.

5. MEDIUM A climate table for an example station gives: January mean high 3 °C, mean low −6 °C, precipitation 60 mm. April 17 °C, 5 °C, 90 mm. July 30 °C, 18 °C, 100 mm. October 18 °C, 6 °C, 75 mm. Which month is wettest? What is the difference between the July and January mean highs? Which of these months would be best for fieldwork, and why?
6. MEDIUM A county is 80 km across. What scale would fit it on a 20 cm wide map, and how many kilometers would 1 cm stand for?
7. MEDIUM Your geologic map legend gives an age in millions of years for the sandstone unit, and your sample from that unit fizzed slightly and had visible grains. In two or three sentences, show how you would write this in the report so that the reader can tell observation from interpretation.
8. HARD Experiment design. For an appendix, you want to know whether soils from your county's two main soil map units hold water differently. Design the experiment: what you change, what you keep the same, what you measure, how many trials, and what result would answer the question.
9. HARD A sand and gravel pit sells 300,000 tonnes a year. Gravel in place has a density of about 2.0 tonnes per cubic meter and the pit is dug 15 m deep. How many square meters and hectares does the pit grow each year?
10. CHALLENGE Write the abstract for your report in about 100 words: what you studied, how, what you found and what it means. Then underline the one sentence you would say if you had only ten seconds.

COMMON MISTAKES

- Thinking a longer report is a better report. A short report in which every number has a unit and a source beats a long one with guesses.
- Giving a number without a unit or a source. "The well is 180 deep" tells the reader nothing he can check; "55 m (180 ft), driller's log, 2019" does.
- Blending what the map says, what the worker said and what you concluded into one voice. Mark each claim observed, told or concluded so the reader can weigh it.

> **Make it a game · Three-Minute Pitch.** Each player gets three minutes to present one part of the county report using a single visual aid (a map, a sample, a table). The audience then asks three questions, one of which must be "How do you know?" The speaker scores one point for finishing within 2.5 to 3 minutes, one for every answer backed by a map, sample or interview, and loses a point for any number given without a unit. Rotate until every part of the report has been pitched. Highest score presents first on report day.

> **Scripture.** "And the LORD answered me, and said, Write the vision, and make it plain upon tables, that he may run that readeth it." (Habakkuk 2:2, KJV)

A report exists to be read and acted on. Write it plainly, with maps and tables, so that whoever reads it can run with it.

Practice answers

1. 1 Title and abstract; 2 Where my county is; 3 Land and soil; 4 Water; 5 Rocks, minerals and energy; 6 Weather and climate; 7 The people who work it; 8 Conclusion; 9 Sources.
2. Claim: the county's best farmland lies on the river alluvium. Evidence: on the soil map the deep silt loam units follow the river valley, and my jar test from site S5 in the valley gave 55% silt. Citation: USDA Web Soil Survey, read on the date given, and my sample table, site S5.
3. 8 × 60 = 480 seconds; 480 ÷ 6 = 80 seconds each.
4. 2020: 350; 2023: 500. Rise = 150; 150 ÷ 350 = 0.429, about 43%. Total = 400 + 350 + 420 + 460 + 500 = 2,130 thousand tonnes, about 2.1 million tonnes.
5. July is wettest (100 mm). July high minus January high = 30 − 3 = 27 °C. April or October: mild temperatures, and October is drier than July, so creeks are lower and banks are exposed; either answer with a reason from the table is acceptable.
6. 8,000,000 cm ÷ 20 cm = 400,000, so 1:400,000; 1 cm = 4 km.
7. Sample: "Sample S3, from the unit the state map labels as a sandstone, is a fine-grained, gritty rock that fizzed slightly with vinegar, showing some calcite cement (observed). The map legend assigns this unit an age in millions of years (interpretation reported from the map, not measured by me). Christians read that age differently, as Unit 7 explained; this report records the rock as it was found."
8. Change: the soil (unit 1 versus unit 2). Keep the same: dry soil mass (200 g each, oven- or air-dried), the same funnel and filter, the same 200 mL of water poured at the same rate, the same 10-minute drain time, the same room. Measure: the water that drains through in mL; water held = 200 mL minus drained. Run three trials per soil and average. If one soil holds clearly more water on average and its trials do not overlap the other's, the soils differ; if the averages are close and the trials overlap, no difference is shown.
9. Volume = 300,000 ÷ 2.0 = 150,000 m^3. Area = 150,000 ÷ 15 = 10,000 m^2 = 1.0 hectare per year.
10. Sample: "This report describes the earth resources of (county), using USGS topographic and geologic maps, the USDA soil map, seven field samples tested for hardness, fizz, density and texture, and an interview with a local well driller. The county's bedrock is mostly limestone and shale, with sandstone and limestone aquifers; wells in sandstone and limestone yielded 57 and 151 L/min while shale yielded 8 L/min. Crushed limestone from the county quarry is the chief mined product. The county's most valuable resource is its groundwater, and keeping it clean and recharged is the main stewardship task." The ten-second sentence is the one naming the chief resource.

Unit 8 review

Answer each question. Show your work for calculations with units, and use complete sentences for explanations. Use metric units unless a question asks otherwise. The test is worth 60 points.

1. (5 pts) Multiple choice. Which map scale shows the most detail? (a) 1:24,000 (b) 1:100,000 (c) 1:250,000 (d) 1:500,000
2. (5 pts) On a 1:24,000 topographic map, the distance from a spring to the county courthouse measures 4.0 cm. How far is that on the ground, in meters?
3. (5 pts) Name the three base maps for the county report and the question each one answers.
4. (6 pts) A county geologic map legend lists a limestone unit with a textbook period name and an age of millions of years. In two or three sentences, state what about that unit is observed and what is interpreted, and how your report should handle each.
5. (5 pts) Multiple choice. A rounded pebble picked up from a creek bed is best called (a) an outcrop (b) float (c) a soil map unit (d) a well log. Explain in one sentence why it cannot prove what rock lies under the creek.
6. (6 pts) A rock sample has a mass of 270 g and displaces 100 mL of water. Find its density. Name two common rocks it is consistent with and the test that would tell them apart.
7. (5 pts) After two days a soil jar shows sand 2.5 cm, silt 2.0 cm and clay 0.5 cm. Find the percent of each.
8. (6 pts) A driller tells you a well is 220 feet deep and yields 10 gallons per minute. Convert both to metric. Then find how many liters the well delivers in one hour.
9. (5 pts) Rewrite the closed question “Is drilling dangerous?” as an open question. Then write one follow-up question you could ask if the driller answered, “The well came in at 180 feet.”
10. (6 pts) Diagram. A driller’s log reads: soil 0 to 2 m, clay 2 to 10 m, sandstone (water-bearing) 10 to 40 m, total depth 40 m, static water level 6 m below the surface. Draw and label a well log diagram in meters with a depth scale, the three layers, the casing, the aquifer and the static water level. Then state whether the water level shows the sandstone is confined, and why.
11. (6 pts) Name the three things every statement of fact in the county report needs, and show all three in one example about any county resource.

Unit project: my county earth-resources report

Assemble and present the capstone of the whole year: a written County Earth-Resources Report of about 1,200 to 2,000 words with a scaled county map, a sample data table, at least two captioned figures, an interview record with every number converted to metric, a conclusion on the county’s chief resource and how it can be kept well, and a complete source list. Present it in 6 to 8 minutes to family or co-op with your labeled sample tray and visual aids, and file the audience’s notes with the report.

The report should draw on every unit of the course: soil (Unit 1), water (Unit 2), minerals and mining (Unit 3), oil, gas and coal (Unit 4), maps (Unit 5), weather (Unit 6), and the habit of separating observation from interpretation (Unit 7).

- **Evidence and sources**: Every number has a metric unit and a source; every claim has evidence and a citation; maps, interview and samples are cited correctly in a source list.
- **Fieldwork and data**: Samples were collected safely and lawfully, labeled at the site, tested at home, and reported in a clear table; the sampling plan is shown on the county map.
- **Interview**: The interview used mostly open questions and follow-ups, records exact quotations and the worker's numbers with conversions, and is cited as a primary source.
- **Clarity and presentation**: The report follows the nine-part outline, keeps observation separate from interpretation, has captioned figures and a matching abstract and conclusion, and the presentation ran 6 to 8 minutes with visual aids and clear answers to questions.

Answer key

1. (a) 1:24,000. The fraction 1/24,000 is the largest, so each centimeter covers the least ground (240 m) and the map can show the smallest features.
2. 4.0 × 24,000 = 96,000 cm = 960 m.
3. Topographic map: what shape is the land (hills, streams, roads)? Geologic map: what rock lies under the soil? Soil map: what is the ground like in the top meter or two?
4. Observed: the unit is limestone, where it crops out, and which units lie above and below it; these can be checked in the field. Interpreted: the age in millions of years, which is calculated from assumed rates and starting conditions, not measured directly. The report should record the rock and its position as observation, report the age as what the map says, attributed to the map, and note that Christians read the age differently.
5. (b) float. It is loose and may have been carried from far upstream, so only attached bedrock (an outcrop) proves what lies beneath that spot.
6. 270 ÷ 100 = 2.7 g/cm³. Consistent with limestone or granite (both about 2.7). The vinegar fizz test tells them apart: limestone fizzes, granite does not.
7. Total 5.0 cm. Sand 2.5 ÷ 5.0 = 50%; silt 2.0 ÷ 5.0 = 40%; clay 0.5 ÷ 5.0 = 10% (a loam).
8. 220 × 0.3048 = 67.1 m. 10 × 3.785 = 37.9 L/min, about 38 L/min. In one hour: 37.9 × 60 = 2,271 L, about 2,300 L.
9. Open: "Tell me about the most dangerous moment you have had on a rig and what rule came out of it." Follow-up: "What was the rock at 180 feet, and how did you know you had reached water?" Any open question (how, why, tell me about) and any follow-up asking for detail or how the driller knew are acceptable.
10. The diagram should show a vertical column with a depth scale from 0 to 40 m, soil 0 to 2 m, clay 2 to 10 m, sandstone 10 to 40 m labeled aquifer, a narrow cased well down the middle, and a dashed line at 6 m labeled static water level. The water level (6 m) stands above the top of the sandstone (10 m), so the aquifer is confined: the clay above it holds pressure and water rose 4 m above the aquifer top in the well.

11. A claim, evidence and a citation. Example: Claim: the county’s main mined product is crushed limestone. Evidence: the quarry foreman reported about 454,000 tonnes (500,000 short tons) sold per year, and my sample S2 from the quarry unit fizzed strongly. Citation: interview with the quarry foreman, with the date; my sample table, site S2; county geologic map (title, publisher, year, scale).

UNIT 9 · OPTIONAL

Bonus: Field Lab

The Field Lab is the outdoor part of Grade 8. In the main course you learned how soil surveyors, well drillers, geologists and forecasters do their work. In these four short lessons you go outside and do it: lay a soil transect across your own ground and map it, visit a real well and measure what it can give, walk a line on the county geologic map and check it against the rocks, and interview three earth-resource workers where they stand. Each lesson is a single field session with a short write-up, so the unit can be spread across a season and fitted around good weather.

Everything here is observation first. You will dig to the same depth at every site, time a bucket three times and average, pace a distance and convert it with the map scale, and write down a worker's exact words. Moses described the land God gave Israel as "a land whose stones are iron, and out of whose hills thou mayest dig brass" (Deuteronomy 8:9), and Job 28 honors the people who take iron out of the earth and melt brass out of the stone. The Field Lab is a chance to see those gifts in your own county with your own eyes, and to record what you find the way a careful naturalist would.

BEFORE YOU BEGIN

- Completed Unit 1 (soil horizons and soil testing) and Unit 2 (aquifers and wells)
- Has a printed county geologic map and the USDA Web Soil Survey map of the home property from Unit 5
- Can compute a percentage, an average and a map-scale conversion
- A parent available to arrange visits and go along on every field session

MASTERY CHECKLIST

- I can lay out a sampling transect, collect soil the same way at every site, and name each site's texture from a ribbon test and a jar test.
- I can sketch and label a real well, compute its water column, and measure a flow rate in liters per minute with a bucket and a watch.
- I can pace a distance, convert it with the map scale, and locate outcrops on a strip map.
- I can describe an outcrop (color, grain, layering, fizz, hardness) before deciding whether it matches the geologic map.
- I can run a field interview with open questions, record exact quotations, and turn the answers into a tally, a mean and a bar graph.
- I can write a short, honest field report that says what I measured, how big my sample was, and where the map or my prediction disagreed with the ground.

OPTIONAL BOOKS AND RESOURCES

- **USDA Web Soil Survey** (https://websoilsurvey.nrcs.usda.gov/): Free. Draw a box around your property to see the soil map units and their descriptions. Use it to check your own soil transect map in Lesson 9.1.
- **USGS Water Data for the Nation** (https://waterdata.usgs.gov/): Free. Search for a USGS groundwater monitoring well near you and read its depth-to-water record. A good substitute data source for Lesson 9.2 if no well visit is possible.
- **USGS National Geologic Map Database** (https://ngmdb.usgs.gov/): Free. Download the geologic map that covers your county for the map walk in Lesson 9.3; the legend tells you what rock to expect in each map unit.

9.1 Soil Sample Survey

OBJECTIVES

- Lay out a sampling transect across a yard, field or park and collect soil samples the same way at every site.
- Use the ribbon test and the jar settling test to name the texture of each sample (sand, silt and clay percentages).
- Draw a simple soil map of the property and compare it with the USDA Web Soil Survey map for the same ground.

Warm-up. Take a pinch of soil from a garden bed and another from a bare, trampled path. Wet each one and rub it between your thumb and finger. Gritty means sand, smooth and floury means silt, sticky and shiny means clay. Write a one-word guess for each pinch. You will test your guesses today.

Video. Coming soon. Soil texture jar test and ribbon test, and how a USDA soil survey is made with an auger; search USDA NRCS, university extension (agriculture) channels, Smithsonian, and homeschool science channels.

KEY TERMS

soil survey
A careful, systematic study that samples soil at many points and draws a map showing where each kind of soil lies.

transect
A straight line laid across the ground along which samples are taken at set spacing, so the sampling is fair and repeatable.

soil texture
The mix of sand, silt and clay in a soil, named with a texture class such as loam, sandy loam or clay.

jar test
A settling test: soil is shaken in water, and sand settles first, then silt, then clay, so the layer thicknesses give the percentages.

ribbon test
Pressing moist soil between thumb and finger to push out a ribbon; the longer the ribbon, the more clay the soil holds.

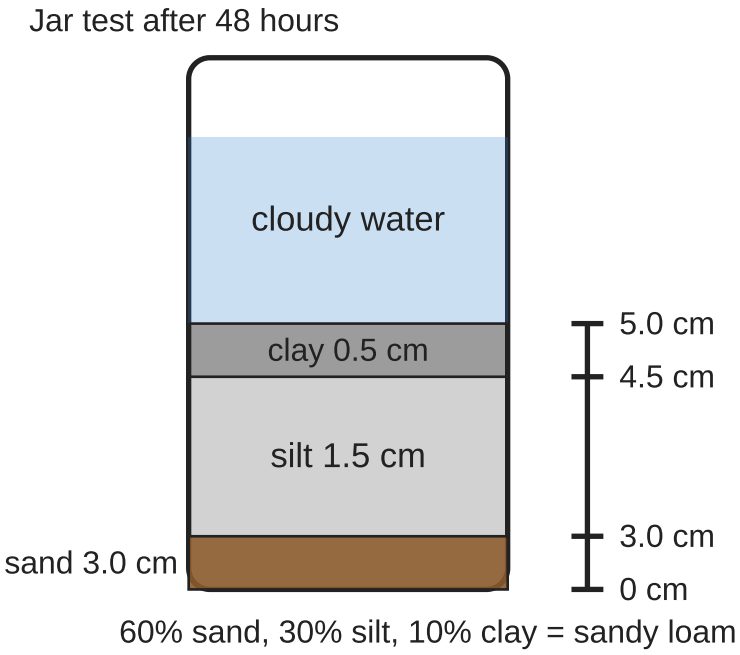
map unit
One colored or lettered area on a soil map, where the soil is alike enough to be described together.

CORE IDEAS

The story. In 1899 the United States Department of Agriculture sent its first soil surveyors into the field. Their chief was Milton Whitney, and one of the first areas they mapped was Cecil County, Maryland. The surveyors walked the county with a hand auger, a notebook and a base map. Every few hundred meters they bored a hole, pulled up the soil, rubbed it between their fingers, wrote down its color and texture, and marked the spot on the map. When the walking was done, they drew lines around the places where the soil was alike and gave each area a name. That is still how a soil survey works. Today nearly every county in the country has been surveyed, and the maps are free on the USDA Web Soil Survey. In this field lab you will make a survey of your own ground, the same way those first surveyors did, and then check your work against theirs.

The big idea. A survey is not a random poke in the dirt. It is *systematic*: you decide the line and the spacing before you start, you dig to the same depth at every site, and you test every sample the same way. That is what makes one site fair to compare with another. The main thing you will test is **texture**, the mix of sand, silt and clay. Sand grains are the largest (0.05 to 2 mm), silt is finer, and clay particles are so small you cannot see one. Because big particles sink faster in water than small ones, a shaken jar of soil sorts itself: sand settles to the bottom in about a minute, silt settles over the next couple of hours, and clay can stay cloudy for a day or more. Measure the layers, divide each by the total, and you have the percentages. The quick field version is the **ribbon test**: moist soil that will not ribbon at all is sandy; a ribbon under 2.5 cm means a loam; a ribbon longer than 5 cm means a clay.

God’s handiwork. Job says of the earth, “out of it cometh bread” (Job 28:5). Soil is the thin, living skin God put between the rock below and the plants above, and no two patches are quite alike. A single back yard can hold a sandy slope that drains in an hour and a clay hollow that stays wet for a week. The surveyor’s job is to notice those differences, record them honestly, and draw them so a farmer, a builder or a gardener can act wisely. When your own map matches the county map, you have learned to see what the surveyors saw. When it does not, you may have found something true that their map, drawn at a coarser scale, could not show. Either way, write down what you actually measured.



Jar test. Sand settles first and lies at the bottom; silt settles next; clay settles last and lies on top. Each layer's thickness divided by the total gives its percentage.

PICTURE STUDY



The Angelus, Jean-François Millet, 1857–1859 · Oil on canvas · Musée d'Orsay, Paris

Millet grew up on a farm in Normandy and painted the people who worked the soil. Here a man and a woman have stopped digging potatoes to pray as the evening church bell rings across the plain of Chailly, near the forest of Fontainebleau. The ground is the real subject: dug, lumpy, flecked with light, stretching to the horizon.

A soil surveyor would read this field at once. The clods are large and hold together, so the soil has some clay. The field is flat and open, so it was probably drained and plowed for generations. Millet painted what he knew by handling it.

Look closely

- Look at the dug ground in the front. Are the clods crumbly or lumpy? What does that tell you about the texture?
- Find the fork, the basket and the wheelbarrow. What tools would a surveyor carry that these farmers do not?
- Follow the field to the horizon. Is the land flat or rolling? Where would water collect after a rain?
- Notice the light. Which way is the sun, and what time of day is it?

Talk about it

1. Why would a farmer who digs the same field every year still benefit from a soil map?
2. The two figures stop their work to pray. How does Job 28:5 connect bread, work and the earth?
3. If you dug a jar test sample from this field, which layer do you predict would be thickest?

> **Safety first.** Dig only where a parent has given permission and away from buried utility lines (call 811 before digging deeper than a trowel if you are unsure). Wear gloves and wash hands afterward. Watch for glass, nails and stinging insects in old soil. Do not sample near septic fields or treated lawns.

EXPERIMENT: FIVE-SITE SOIL TRANSECT

You will lay a straight transect across your yard, a field or a park, dig five small sample holes at even spacing, test each sample two ways, and draw a soil map of the ground you walked. Then you will compare your map with the USDA Web Soil Survey map of the same spot.

Question: Does the soil texture change along a line across our property? Prediction: write where you think the sandiest and the most clay-rich sites will be, and why. What we change: the location of each site. What we keep the same: the sampling depth (15 cm), the amount of soil in each jar and the amount of water. What we measure: ribbon length and jar-test layer thicknesses.

You will need

- Trowel or hand auger, and a ruler marked in centimeters
- Five clear jars with tight lids (all the same size), a spoonful of dish soap, and water
- Five zip bags and a marker for labeling
- A long string or tape measure (20 to 50 m), and five stakes or flags
- Notebook, pencil, clipboard and a simple sketch map of the property

- A phone or computer to open the USDA Web Soil Survey afterward

Steps

1. Choose a transect that crosses different ground: a slope and a hollow, lawn and garden, near a stream and away from it. Stretch the string and mark five sites at equal spacing (for example every 8 m on a 32 m line). Number them 1 to 5 and mark them on your sketch map.
2. At each site, scrape away grass and litter, dig to 15 cm, and take about two handfuls from the bottom of the hole. Bag and label it. Write the site number, the slope, the plants growing there and the soil color in your notebook.
3. Ribbon test at each site: moisten a walnut-sized ball until it is like putty. Squeeze it up between thumb and finger into a ribbon until it breaks. Measure the ribbon in centimeters. No ribbon: sand or loamy sand. Under 2.5 cm: loam. 2.5 to 5 cm: clay loam. Over 5 cm: clay.
4. Jar test at home: fill each jar one-third with soil (pick out roots and stones), add water to three-quarters, add a few drops of dish soap, cap and shake hard for 3 minutes. Set the five jars in a row where they will not be bumped.
5. After 1 minute, mark the top of the settled layer on the glass: that is sand. After 2 hours, mark again: the new layer is silt. After 24 hours (48 is better), mark the top: that is clay. Measure each layer with the ruler.
6. Calculate the percentages: each layer divided by the total, times 100. Write a texture name for each site using the percentages (for example, 60% sand, 30% silt, 10% clay is a sandy loam).
7. Draw your soil map: on the sketch map, draw a boundary line between sites where the texture changed, and color each area. Give each area a name and a one-line description.
8. Open the USDA Web Soil Survey, find your property, and read the map unit name for each of your five sites. In your notebook, write where your map agrees with the survey and where it does not, and a sentence on why.

Tips

- Do not jiggle the jars while they settle. A bumped jar mixes the silt back into the water and ruins the reading.
- If a jar stays cloudy after two days, that cloudiness is still clay in the water. Measure the clay layer anyway and note that your clay number is a little low.
- If your property is small, walk the transect into a nearby park with permission, or use a shorter spacing such as 4 m.

Check your work

- I sampled five sites at the same depth and spacing along a measured line.
- I can name each site’s texture from both the ribbon test and the jar test, and the two tests roughly agree.

- My soil map shows boundaries, and I compared it with the county survey and explained one agreement and one difference.

FIELD NOTEBOOK

1. Draw your transect as a strip map: a straight line with five numbered dots, the slope shown with little arrows, and the texture name written under each dot.
2. Draw one settled jar to scale (1 cm on paper = 1 cm in the jar) and label the sand, silt and clay layers with their thicknesses and percentages.
3. Make a table with columns Site, Color, Ribbon length (cm), % sand, % silt, % clay, Texture name, and fill it in for all five sites.

> **From history.** The hand auger the early surveyors carried has hardly changed. Modern USDA soil scientists still walk their map units, bore holes, and describe each layer by hand, though they now mark the spots with GPS and check their lines against aerial photographs. A finished county soil survey includes a map and a book describing every map unit, how well it drains, how well it holds water, and what it is suited for, from corn to septic systems to house foundations.

WORKED EXAMPLES

Example 1. A jar test from Site 3 settled into layers 3.0 cm of sand, 1.5 cm of silt and 0.5 cm of clay. Find the percentage of each and name the texture.

(Use the map or drawing "The Site 3 jar: 3.0 cm sand, 1.5 cm silt, 0.5 cm clay, total 5.0 cm." shown earlier in this lesson.)

1. Add the layers to get the total: 3.0 + 1.5 + 0.5 = 5.0 cm.
2. Sand: 3.0 ÷ 5.0 × 100 = 60%.
3. Silt: 1.5 ÷ 5.0 × 100 = 30%.
4. Clay: 0.5 ÷ 5.0 × 100 = 10%. Check: 60 + 30 + 10 = 100.
5. On the USDA texture triangle, a soil with about 60% sand and only 10% clay falls in the sandy loam class. A ribbon test on this soil should give a short ribbon of under 2.5 cm, which agrees.

Answer: 60% sand, 30% silt, 10% clay: a sandy loam.

PRACTICE

1. EASY In a jar test, which settles to the bottom first, and why?
2. EASY Why does a surveyor dig every sample to the same depth, 15 cm, instead of just scooping whatever is on top?
3. MEDIUM Data reading. A student's transect gave these jar-test results. Site 1: 1.0 cm sand, 2.0 cm silt, 2.0 cm clay. Site 2: 2.4 cm sand, 2.4 cm silt, 1.2 cm clay. Site 3: 4.5 cm sand, 1.0 cm silt, 0.5 cm clay. (a) Which site has the highest percentage of clay? (b)

What is the percentage of sand at Site 3? (c) Which site would you expect to give the longest ribbon?

4. MEDIUM Experiment design. A student wants to know whether the soil at the bottom of a slope holds more clay than the soil at the top. Name the independent variable, the dependent variable, and two things that must be kept the same.
5. HARD Your soil map shows a sharp change from sandy loam to clay loam between Sites 2 and 3, but the county Web Soil Survey shows one map unit covering all five sites. Give two reasonable explanations, and say what you would do next.

COMMON MISTAKES

- Reading the jar after one minute and calling the whole settled layer “soil.” Only the first layer is sand; silt and clay keep settling for hours and days.
- Thinking dark soil is always rich clay. Color comes mostly from organic matter and iron, not from texture; a dark soil can be sandy, and a pale soil can be clay.
- Sampling only the easy spots, like the garden bed. A survey must follow the planned line and spacing, including the awkward sites, or it is not a survey.

> **Make it a game · Texture by Touch.** A parent puts a damp pinch of soil from each of your five sites into five cups and mixes up the order. Blindfolded, you rub each one and call out a texture class and which site you think it came from. One point for the right texture class, two more if you name the site. Then switch and let your parent try with your notebook closed.

> **Scripture.** “As for the earth, out of it cometh bread: and under it is turned up as it were fire.” (Job 28:5, KJV)

Job marvels that the same earth gives bread from its surface and treasures from beneath. The soil survey studies the top of that gift, the few centimeters God made to grow our food.

Practice answers

1. Sand, because its particles are the largest and heaviest and sink fastest through water. Silt settles next, and the tiny clay particles settle last.
2. So the samples are fair to compare. The top few centimeters are full of roots and litter and vary from spot to spot; sampling at one fixed depth means any difference you find is a difference between sites, not between depths.
3. (a) Site 1: 2.0 ÷ 5.0 = 40% clay. (b) Site 3: 4.5 ÷ 6.0 = 75% sand. (c) Site 1, because ribbon length rises with clay content.
4. Independent variable: position on the slope (top versus bottom). Dependent variable: percentage of clay (from the jar test or ribbon length). Keep the same: sampling depth, amount of soil and water in each jar, shaking time and settling time, and the same person doing the ribbon test. Several samples from each position would make the test stronger.
5. Explanations: (1) The county map is drawn at a coarse scale, and a small area of different soil inside a map unit is too small to be shown; soil surveys note that small patches of other soils lie inside many map units. (2) The ground may have been changed since the survey, for

example by fill, grading or a garden that was amended for years. Next: sample two more sites between 2 and 3 to find where the change really is, check for signs of fill or grading, and record both maps side by side with a note explaining the difference.

9.2 Visiting a Well

OBJECTIVES

- Identify the visible parts of a real water well (casing, cap, pitless adapter or well house, pressure tank, pump control) and sketch them.
- Measure or read the depth to water and compute the water column from the well's total depth.
- Do a bucket test to measure a pump's flow rate in liters per minute and compare it with a family's daily water use.

Warm-up. Fill a measuring cup from the kitchen tap and time it with a watch: how many seconds does one liter take? Divide 60 by that number to get liters per minute. Write the answer down. Today you will measure a well the same way, only bigger.

Video. Coming soon. How a residential water well works (casing, submersible pump, pressure tank), measuring depth to water with a tape, and well drilling footage; search USGS Water Science School, state geological survey and extension channels, and well-drilling company footage.

KEY TERMS

casing
The steel or plastic pipe lining a well that keeps the hole open and keeps surface water and dirt out.

static water level
The depth from the ground surface down to the water in a well when the pump has been off long enough for the water to settle.

water column
The height of water standing in the well: total depth minus depth to water.

artesian well
A well in which water rises above the aquifer on its own because it is under pressure; if it rises above the ground it flows without a pump.

flow rate
How much water moves per unit of time, measured here in liters per minute (L/min).

well log
The driller's record of a well: its depth, the layers passed through, where water was found and how much it yielded.

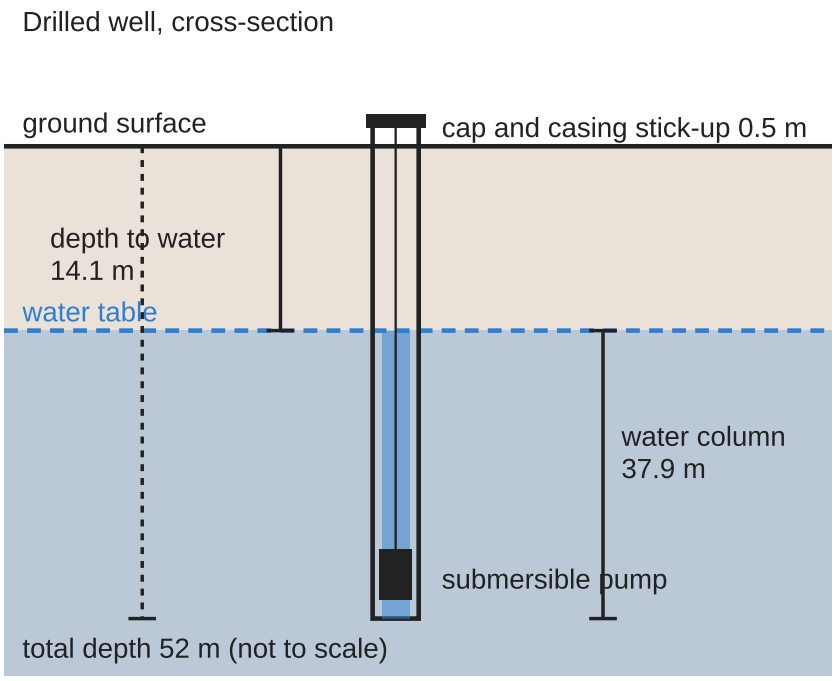
CORE IDEAS

The story. In the year 1126, in the town of Lillers in the old French province of Artois, a well was bored that did something astonishing: water rose up the hole by itself and poured out at

the surface, with no bucket and no pump. The water had entered a sloping layer of rock far away, up in the hills, and was pressed up the well by the weight of water behind it. Wells like it are still called **artesian**, after Artois. Most wells are not so obliging. In most of America a well is a steel or plastic pipe, 10 to 20 cm across, that goes down 20 to 150 meters to a water-bearing layer, with an electric pump hung near the bottom that pushes the water up to a pressure tank in the house. Today you will go and look at one. It may be a neighbor's farm well, your own, a hand pump at a park or campground, or an old stone-lined dug well at a historic site. Every one of them is a window into the aquifer under your feet.

How they figured it out. A well is measured with three numbers. The first is **total depth**, which comes from the driller's log; many states post these logs online, and the owner may have a copy. The second is the **static water level**, the depth from the ground down to the top of the water when the pump has rested. Well professionals measure it with a weighted steel tape or an electric tape that beeps when its tip touches water; the owner may know it, or a USGS monitoring well near you may publish it daily. Subtracting the two gives the **water column**, the height of water the pump has to work with. The third number is **flow rate**, and you can measure that yourself with a bucket and a watch: open a hose bib, fill a bucket of known size, time it, and divide. A pump that fills a 20-liter bucket in 40 seconds is giving 30 liters per minute. Compare that with what a family uses, roughly 300 liters per person per day in American homes, and you can judge whether the well is generous or tight.

God's handiwork. Moses told Israel they were going to "a land of brooks of water, of fountains and depths that spring out of valleys and hills" (Deuteronomy 8:7). The water in a well is not a puddle somebody dug into; it is part of a slow river moving through sand, gravel or cracked rock, fed by rain that fell months or years ago on ground that may be kilometers away. A well is a careful hole into that hidden river, and a good well owner guards it: the cap stays sealed so insects and surface water stay out, the ground slopes away so rain does not pool at the casing, and nothing is dumped nearby. When you visit, look for those signs of care, and ask the owner how the well has behaved in dry years. That answer is a record of the aquifer that no instrument gives.



A drilled well in cross-section. Depth to water is measured from the ground surface; the water column is total depth minus depth to water.

PICTURE STUDY



Eliezer and Rebecca, Nicolas Poussin, 1648 · Oil on canvas · Musée du Louvre, Paris

Nicolas Poussin, a French painter who spent most of his life in Rome, loved orderly scenes from Scripture and the ancient world. Here he paints the moment from Genesis 24 when Abraham's servant Eliezer, sent to find a wife for Isaac, meets Rebecca at the well outside the city of Nahor and gives her a gold earring and bracelets after she has drawn water for him and his camels.

Look past the people to the well itself. It is the center of the town's life: everyone comes here, every evening, with a jar. Before pumps and pipes, a well was a public place, and a town could only be as large as its wells allowed.

Look closely

- Find the well. How is it built? Is there a wall, a lip, a bucket, a rope?
- Count the water jars. How many trips to the well would a family need each day?
- Where is the water being poured, and where is it being carried?
- Look at the hills and buildings behind. Where would the water in this well have come from?

Talk about it

1. A hand-dug well like this one reaches only a little below the water table. What happens to it in a dry year, and why does a drilled well do better?
2. Rebecca watered ten camels by hand. If each camel drank 100 liters, how many 10-liter jars did she lift?
3. Why was a well a good place for a stranger to meet the people of a town?

> **Safety first.** Never lean over, open, or climb on a well. Only the owner or a licensed well professional removes a well cap. Keep away from open dug wells and cisterns, which can be deep and unguarded. Do not drink from a well unless the owner says it is tested and safe. A parent goes with you on every visit, and you stay clear of pumps, wiring and moving machinery.

EXPERIMENT: WELL VISIT RECORD AND BUCKET TEST

You will visit a real well with a parent, sketch and label what you can see, gather its three numbers (total depth, depth to water, flow rate) from the owner, the driller's log or your own bucket test, and write a one-page well record like the ones kept by state geological surveys.

Question: How much water can this well deliver, and is it enough for a family? Prediction: guess the flow rate in liters per minute before you test. What we change: nothing; this is a measurement, repeated three times. What we keep the same: the same tap, fully open, the same bucket. What we measure: seconds to fill the bucket.

You will need

- A well to visit, arranged ahead by a parent (a neighbor or relative, a farm, a park hand pump, or a historic dug well)
- A bucket of known volume (a 10 L or 20 L bucket; check the volume with a measuring jug first)
- A stopwatch or phone timer, notebook, pencil and clipboard
- A tape measure for the casing height and the distance to buildings or septic system
- A copy of the driller's log if the owner has one, or your state's online well-log search

Steps

1. Before the visit, write five questions for the owner: When was the well drilled? How deep is it? Does the water level drop in late summer? Has the water been tested? What does the pump sound like when something is wrong?
2. At the well, stand back and sketch everything you can see: the casing sticking out of the ground, its cap, any electrical conduit, the slope of the ground around it, and the distance to the house, barn, road and septic field. Measure the casing stick-up height in centimeters.
3. Ask to see the pressure tank and pump switch in the house or well house. Sketch them and note the pressure gauge reading. Listen for the pump to turn on and off and time one run.
4. Record the three numbers. Total depth and depth to water come from the owner or the log. If an electric tape reading is offered by a professional, note it exactly as read and note the casing stick-up so you can convert to depth below ground.
5. Bucket test: with the owner’s permission, open an outside hose bib all the way. Fill your bucket and time it. Repeat three times and average. Flow rate in L/min = bucket liters × 60 ÷ average seconds.
6. Compute the water column (total depth minus depth to water) and the liters per day the well could supply at that flow rate if the pump ran one hour a day.
7. Write your well record: location, date, owner’s answers, the sketch, the three numbers and your calculations, and one paragraph on how well cared for the well appears to be.
8. At a hand pump or historic dug well, do the same record but measure flow by counting strokes per bucket, and estimate depth by the owner’s or park sign’s information.

Tips

- A hose bib is partly limited by the pipe and pressure tank, so your bucket test measures the household flow, not the pump’s full yield. Say so in your record.
- If the well is far from the house, the pressure gauge is the best clue to the system’s health: most home systems cycle between about 40 and 60 pounds per square inch (about 275 to 415 kilopascals).
- If you cannot visit any well, use a USGS groundwater monitoring well near you online and record its daily water level for a week instead.

Check your work

- My sketch shows and labels the casing, cap, ground slope and distance to the house and septic field.
- I recorded total depth, depth to water and flow rate, and I computed the water column.
- My bucket test was repeated three times and averaged, and I compared the flow to a family’s daily use.

FIELD NOTEBOOK

1. Draw the well in cross-section from the ground down, to scale (for example 1 cm = 5 m), with the depth to water and total depth labeled from the owner's log.
2. Make a table of your three bucket-test trials: bucket liters, seconds, L/min, and the average.
3. Draw the pressure tank and gauge, and write what the needle read when the pump started and when it stopped.

> **From history.** The United States Geological Survey has measured water levels in thousands of wells for more than a century, some by hand with a steel tape once a month, many now with a pressure sensor that reports every fifteen minutes. Those records are public. The USGS Water Data for the Nation site lets anyone look up the nearest monitoring well and watch the water table rise after a wet winter and fall through a dry summer, the same breathing of the aquifer you will hear in an owner's memory of dry years. Many states also post every driller's log filed since well-reporting laws began, so a well's birth record can often be found with its address.

WORKED EXAMPLES

Example 1. At a farm well, the driller's log says total depth 52 m. A professional's electric tape reads 14.6 m to water, measured from the top of the casing, and the casing sticks up 0.5 m above the ground. A 20 L bucket fills from the hose bib in 40, 42 and 38 seconds. Find (a) the depth to water below ground, (b) the water column, and (c) the flow rate in L/min.

(Use the map or drawing "The farm well: 0.5 m stick-up, 14.1 m to water, 52 m total depth, 37.9 m water c" shown earlier in this lesson.)

1. (a) The tape was read from the top of the casing, which is 0.5 m above ground. Depth to water below ground = 14.6 − 0.5 = 14.1 m.
2. (b) Water column = total depth − depth to water = 52 − 14.1 = 37.9 m.
3. (c) Average fill time = (40 + 42 + 38) ÷ 3 = 40 s.
4. Flow rate = 20 L ÷ 40 s = 0.5 L/s. Multiply by 60 to get liters per minute: 0.5 × 60 = 30 L/min.
5. Check against need: a family of four at about 300 L per person per day uses 1,200 L. At 30 L/min, that takes 1,200 ÷ 30 = 40 minutes of pumping per day. The well is ample.

Answer: (a) 14.1 m below ground; (b) 37.9 m of water column; (c) 30 L/min, enough to supply a family of four in about 40 minutes of pumping a day.

PRACTICE

1. EASY What is the difference between an ordinary drilled well and an artesian well?

2. EASY A well is 60 m deep and the static water level is 18 m below ground. What is the water column?
3. MEDIUM Data reading. A USGS monitoring well posted these depths to water (meters below ground): May 1, 6.2; June 1, 6.5; July 1, 7.1; August 1, 7.9; September 1, 8.3; October 1, 8.0. (a) In which month was the water level lowest? (b) By how much did the depth to water change from May 1 to September 1? (c) Give one reason the level would drop over the summer.
4. MEDIUM A 10 L bucket fills in 25 seconds. What is the flow rate in L/min, and how many liters would that tap give in one hour?
5. HARD Experiment design. You want to find out whether the flow rate from the hose bib changes when another tap in the house is running. Describe the test: what you change, what you keep the same, what you measure, and how many trials you would do.

COMMON MISTAKES

- Reading an electric tape from the top of the casing and forgetting to subtract the stick-up. Depth to water is always reported below the ground surface (or clearly labeled otherwise).
- Thinking a deep well means a lot of water. What matters is the water column and the yield of the layer the well is finished in; a shallow well in good gravel can out-produce a deep well in tight rock.
- Believing a well sits over an underground lake or river. Groundwater fills the tiny pores and cracks in sand, gravel and rock, and moves slowly through them.

> **Make it a game · Pump or Flow?.** A parent reads out a well: its total depth, depth to water, and whether the water rises above the aquifer or above the ground. You answer in five seconds: water column in meters, and whether it is an ordinary well, an artesian well, or a flowing artesian well. One point for each right answer. After ten wells, trade roles and make up wells for your parent, but keep the numbers possible: depth to water can never be more than total depth.

> **Scripture.** “For the LORD thy God bringeth thee into a good land, a land of brooks of water, of fountains and depths that spring out of valleys and hills;” (Deuteronomy 8:7, KJV)

Moses describes a land blessed with water on the surface and below it. A well draws from those hidden depths, and a careful owner treats it as the gift it is.

Practice answers

1. In an ordinary well the water stands at the water table and a pump must lift it. In an artesian well the aquifer is confined and under pressure, so water rises in the well above the aquifer by itself; if it rises above ground, it flows without a pump.
2. $60 - 18 = 42$ m.

3. (a) September 1 (depth to water 8.3 m, the deepest). (b) 8.3 − 6.2 = 2.1 m lower. (c) Less rain soaks in during hot months while plants draw up water and people pump more for lawns and crops, so the aquifer is not refilled as fast as it is drained.
4. 10 ÷ 25 = 0.4 L/s; 0.4 × 60 = 24 L/min; 24 × 60 = 1,440 L in an hour.
5. Change: whether a second tap (say, the kitchen sink) is fully on or off. Keep the same: the same hose bib fully open, the same bucket, the same person timing, and let the pressure tank cycle to the same reading before each trial. Measure: seconds to fill the bucket, converted to L/min. Do at least three trials in each condition and compare averages. Expect the flow at the hose bib to drop when the other tap is running, because the two share the same pump and pressure tank.

9.3 County Rock Map Walk

OBJECTIVES

- Plan a walking route from the county geologic map that crosses at least two map units and find real outcrops along it (road cuts, stream banks, quarries, building stone).
- Use a pace count and the map scale to locate outcrops and measure distances between them.
- Record each outcrop's rock type, color, layering and hardness, and judge whether the ground agrees with the map.

Warm-up. Mark a 30 m line on a sidewalk or driveway with a tape. Walk it naturally three times, counting every time your right foot lands (a double pace). Average the counts. Write: "My double pace = 30 ÷ ___ = ___ m." You will use this number to measure the earth today.

Video. Coming soon. Reading a geologic map in the field, identifying rock outcrops at road cuts, and pace counting for field mapping; search USGS, state geological surveys, university geology field-camp channels, and Smithsonian.

KEY TERMS

outcrop
A place where bedrock shows at the surface, not covered by soil, such as a road cut, stream bank, cliff or quarry wall.

map unit
A colored area on a geologic map standing for one rock formation or deposit, labeled with a short letter code.

contact
The line on a map, and the surface in the ground, where one rock unit ends and the next begins.

pace count
Measuring distance by counting your steps, using your own measured length per double pace.

map scale
The ratio between a distance on the map and the same distance on the ground, such as 1:24,000 (1 cm on the map = 240 m on the ground).

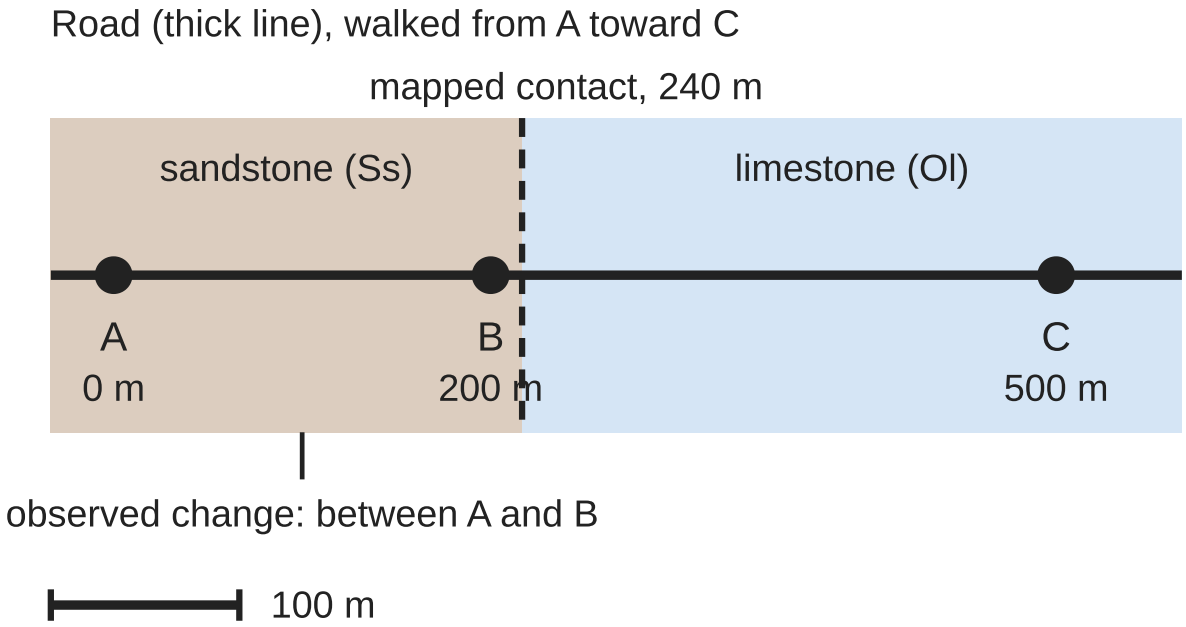
float
Loose pieces of rock lying on the ground that have moved from where they formed, which must not be mistaken for bedrock.

CORE IDEAS

The story. In 1830 the legislature of Massachusetts hired Edward Hitchcock, a Congregational minister and professor at Amherst College, to make a geological survey of the whole state. It was among the earliest state geological surveys in the country, and his report, published in 1833, became a model for the states that followed. Hitchcock had no helicopter and no satellite. He walked, rode and rowed, from the Berkshire hills to the Cape, stopping at every quarry, river bank and road cut, chipping off a sample, writing down what he saw, and marking the spot on his map. Within a few years he was also describing the three-toed footprints that farmers were turning up in the red sandstone of the Connecticut Valley, tracks we now know were made by dinosaurs. Hitchcock saw the handiwork of God in every ledge, and he kept honest notes. A map walk is Hitchcock's method made small: you take the county geologic map you studied in Unit 5, choose a route that crosses a line on it, and go see whether the rocks agree.

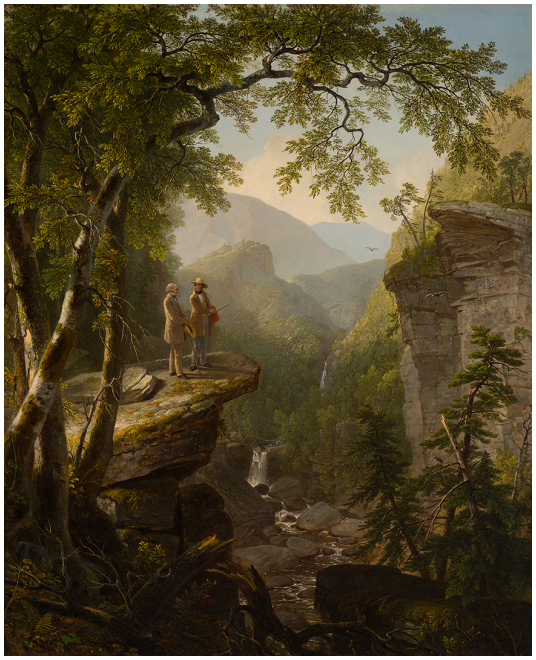
How they figured it out. Three skills make a map walk work. First, **find real outcrops**. Soil hides most bedrock, so the mapper looks where something has cut through it: road cuts, railroad cuts, stream beds and banks, quarries and gravel pits, excavations, and old stone foundations and walls built from the nearest ledge. Loose stones on the ground, called **float**, are clues but not proof; a boulder can travel far by ice, flood or dump truck. Second, **know where you are**. A phone map helps, but mappers also use a pace count because it works when the signal does not. If your double pace is 1.6 m, then 186 double paces is about 300 m, and on a 1:24,000 map that is 1.25 cm. Third, **describe before you decide**. At each outcrop write the color, the grain size, whether it is layered and which way the layers tilt, whether it fizzes with vinegar (limestone does), and how hard it is against a steel nail. Only then compare your notes with the map's description of that unit.

God's handiwork. Moses promised Israel "a land whose stones are iron, and out of whose hills thou mayest dig brass" (Deuteronomy 8:9), and Genesis says of the land of Havilah, "the gold of that land is good" (Genesis 2:12). Scripture treats rocks and ores as gifts placed in particular lands, waiting for people to find and use them. A geologic map is a record of where those gifts lie in your county: the limestone that makes cement and road gravel, the sandstone that built the courthouse, the shale that holds water back or the gravel that lets it through. When you stand at a road cut and match the ledge to the color on the map, you are reading that record with your own eyes. And when the ledge does not match, write that down too. Maps are made by people, and the ground is always the final authority.



Strip map of a map walk. Outcrops A, B and C are located by pace count along the road; the contact between units lies somewhere between A and B.

PICTURE STUDY



Kindred Spirits, Asher B. Durand, 1849 · Oil on canvas · Crystal Bridges Museum of American Art, Bentonville, Arkansas

Asher Durand painted this as a memorial to his friend the painter Thomas Cole, who had died the year before. Cole stands on the ledge with the poet William Cullen Bryant, pointing into a gorge of the Catskill Mountains in New York. The rock they stand on is real: layered sandstone and shale that weather into flat ledges and sheer walls.

Durand believed a painter should study rocks and trees as closely as a scientist does, and he drew outcrops for hours before painting them. Notice how the ledge under the two men shows its layers, and how the cliff across the gorge repeats them. Those are the same beds, seen on both sides of the valley the stream has cut.

Look closely

- Find the layers in the ledge under the men’s feet. Are they tilted or level?
- Look at the cliff across the gorge. Can you match its layers to the ones in the front?
- Where has the stream cut through the rock? What kind of outcrop does that make?
- Find loose rocks in the stream bed. Are they bedrock, or float?

Talk about it

1. Why do streams and gorges make the best outcrops for a mapper?
2. If the beds are level on both sides of the gorge, what does that tell you about what happened here: were the layers bent, or was the valley simply cut down through them?
3. Cole is pointing. If he were a mapper, what three things should he write down about the cliff before he names the rock?

> **Safety first.** Road cuts are beside traffic: park well off the road, wear bright clothing, stay on the far side of the guardrail or ditch, and never stand under a loose or overhanging face. Do not hammer rock near others or without safety glasses. Stay out of active quarries and pits, which are private and dangerous. Do not enter streams in high water. A parent goes with you, and you tell someone your route and return time.

EXPERIMENT: CROSSING THE LINE: A TWO-UNIT MAP WALK

You will use your county geologic map to plan a short walk or drive-and-walk that crosses the contact between two map units, find at least three outcrops along the way, describe them, locate them by pace count, and decide whether the ground matches the map.

Question: Does the rock at the surface change where the map says it should? Prediction: write what rock the map says you will find on each side of the contact and about where you expect to see the change. What we change: our position along the route. What we keep the same: the tests we do at every outcrop (color, grain, layering, vinegar fizz, nail scratch). What we measure: pace count between outcrops and the position of the contact.

You will need

- A printed county geologic map (from the USGS National Geologic Map Database or your state survey) with its legend, and a road map or phone map of the same area
- Notebook, pencil, clipboard and a marker to label samples
- A steel nail, a small bottle of white vinegar, a hand lens if you have one, and a few zip bags for samples

- Bright vest or shirt, sturdy shoes, water, and safety glasses if a parent allows a rock hammer
- Your double-pace length from the warm-up, written on the first page of the notebook

Steps

1. On the map, find a road or trail that crosses a contact line between two units, ideally near a stream, hill or road cut. Trace the route on a photocopy. Write the two unit names, their codes and their legend descriptions in your notebook.
2. Read the legend description of each unit twice and list the field marks that would tell them apart: color, layering, grain size, whether it should fizz with vinegar, how hard it should be.
3. Walk the route with a parent. At the first outcrop, stop, label it A, and describe it before guessing: color (wet and dry), grain size (can you see grains? are they sand-sized or finer?), layering and its tilt, fizz test, nail-scratch test, and any fossils or shells. Sketch the face. Take a fist-sized sample if permitted.
4. Pace to the next outcrop and record the count. Convert to meters with your double-pace length. Mark B on your map copy at that distance along the route. Describe B the same way.
5. Continue to a third outcrop, C. Try to make sure your three outcrops include at least one on each side of the mapped contact.
6. Between outcrops, note float and soil color. A change in the stones in a plowed field or the color of a ditch bank often marks a contact hidden under soil.
7. At home, line up your three descriptions beside the map legend. Decide: does A match the unit the map shows at A? Does C match its unit? Where, between which outcrops, did the rock change? Draw the contact on your strip map where your evidence puts it.
8. Write a half-page field report: route, outcrops with pace distances, descriptions, your contact position, and whether the map and the ground agree. If they disagree, say what you saw, not what you expected.

Tips

- If your county is deep in glacial deposits or flat coastal sand, your map units may be loose sediments rather than hard rock. Describe them the same way: grain size, sorting, color, and whether they are layered in a bank or pit face.
- Vinegar fizzes weakly on limestone. If you see no bubbles, scratch a little rock powder off with the nail and drop vinegar on the powder; the powder fizzes more easily.
- Pace counts drift uphill and in brush. Pace each leg twice if you can, and average.

Check your work

- I planned a route that crosses a mapped contact and listed the field marks of both units before I left.
- I described three outcrops the same way and located them by pace count and map scale.

- I drew where my evidence puts the contact and wrote whether the map and the ground agree.

FIELD NOTEBOOK

1. Draw a strip map of your route: a line for the road or trail, outcrops A, B and C with pace distances, the map’s contact line, and your own contact line if it differs.
2. Sketch the best outcrop face you saw, with the layers drawn and labeled with thickness, color and tilt direction.
3. Make a two-column table: Map legend says / I observed, for each of the two units.

> **From history.** Hitchcock’s 1833 Massachusetts report was followed within a decade by state surveys in New York, Pennsylvania, Virginia and others, and the mappers who walked those states, James Hall, Henry Darwin Rogers and their crews, worked out the layered rock sequence of the Appalachians by exactly the method you used today: find the outcrops, describe them, pace the distances, and draw the contacts where the evidence puts them. The county maps you downloaded descend from theirs, revised by every generation of geologists who went back to look again.

WORKED EXAMPLES

Example 1. A student's double pace is 1.6 m. From outcrop A to outcrop B she counts 125 double paces, and from B to C she counts 186. The county map is at a scale of 1:24,000. (a) How far is it from A to B, and from B to C, in meters? (b) How long should each leg be on the map in centimeters? (c) The map's contact line falls 1.0 cm past A along the road. At B she found limestone that fizzed; at A she found sandstone that did not. Is the mapped contact consistent with what she found?

(Use the map or drawing "The worked example drawn as a strip map: A at 0 m (sandstone), B at 200 m (limes" shown earlier in this lesson.)

1. (a) A to B: 125 × 1.6 = 200 m. B to C: 186 × 1.6 = 297.6, about 300 m.
2. (b) At 1:24,000, 1 cm on the map is 24,000 cm on the ground, which is 240 m. A to B: 200 ÷ 240 = 0.83 cm. B to C: 300 ÷ 240 = 1.25 cm.
3. (c) The contact drawn 1.0 cm past A is 1.0 × 240 = 240 m from A along the road. That is beyond B, which is only 200 m from A.
4. But B already shows limestone, while A shows sandstone. So the real change happened somewhere between A (0 m) and B (200 m), not at 240 m.
5. The mapped contact is at least 40 m too far along the road, which is small at this map scale (less than 2 mm on paper). The ground agrees with the map in kind (sandstone, then limestone) and nearly in place.

Answer: (a) 200 m and about 300 m. (b) 0.83 cm and 1.25 cm. (c) Nearly: the rock types match the map, but the contact lies between A and B (within 200 m of A), a little short of the 240 m the map shows. Draw it where the evidence puts it and note the difference.

PRACTICE

1. EASY Name three kinds of places where bedrock is likely to be exposed in a county covered mostly by soil and fields.
2. EASY On a 1:24,000 map, how many meters does 3.5 cm represent?
3. MEDIUM Data reading. A field notebook lists four outcrops along a road. A: gray, fizzes, no visible grains, hard. B: gray, fizzes, no visible grains, hard. C: red-brown, no fizz, sand-sized grains, nail scratches it. D: red-brown, no fizz, sand-sized grains, nail scratches it. The map shows limestone (unit Ol) for the first 350 m of the road and sandstone (unit Ss) after that. Pace distances from the start: A 60 m, B 280 m, C 330 m, D 520 m. Where does the evidence put the contact, and does the map agree?
4. MEDIUM Why is a boulder in a plowed field weaker evidence than a ledge in a stream bank?
5. HARD Experiment design. You suspect that the hardness test is being done inconsistently by different family members, which could change which unit an outcrop is assigned to. Design a short check to find out, and say what you would do if you were right.

COMMON MISTAKES

- Deciding what rock an outcrop is before describing it, because the map already says. Describe first; the map is a claim to be checked.
- Treating a loose boulder or a gravel driveway as an outcrop. Only rock in place counts as bedrock evidence; float and fill are clues at best.
- Thinking a map scale of 1:24,000 means 1 cm equals 24,000 m. It means 24,000 centimeters, which is 240 m.

Make it a game · Pace Race. A parent picks a landmark 50 to 200 m away. Each player estimates the distance by eye and writes it down, then paces it and converts with their double-pace length. The player whose eye estimate is closest to the paced distance wins the round. For a bonus, convert the distance to centimeters on a 1:24,000 map before anyone else does.

Scripture. “A land wherein thou shalt eat bread without scarceness, thou shalt not lack any thing in it; a land whose stones are iron, and out of whose hills thou mayest dig brass.” (Deuteronomy 8:9, KJV)

God describes a land by its rocks and ores as well as its bread. A geologic map is an inventory of such gifts in your own county, and a map walk is the way to see them.

Practice answers

1. Road cuts and railroad cuts, stream beds and banks, quarries and gravel pits; also cliffs, excavations and old stone foundations or walls built from local ledge.
2. 3.5 × 240 = 840 m.
3. The rock changes from limestone (A, B) to sandstone (C, D), so the contact lies between B at 280 m and C at 330 m. The map puts it at 350 m, which is 20 m or more beyond C. The rock types agree with the map; the contact is slightly closer to the start than mapped.
4. A boulder is float: it may have been carried from somewhere else by ice, floodwater or a farmer clearing a field, so it may not be the bedrock under that spot. A ledge in a stream bank is in place, so it tells you what rock is actually there.
5. Have each person test the same three labeled samples (known soft, medium and hard rock) with the same nail, without knowing the others’ results, and record scratch or no scratch. Compare answers. If the results differ, agree on one method (same nail, same pressure, look for a real groove, not a metal streak) and have one person do all hardness tests on the walk, or test every outcrop twice with two people and record both.

9.4 Interview Field Day

OBJECTIVES

- Visit an earth-resource workplace (quarry office, gravel pit, drilling company, farm co-op, soil and water conservation district, county extension office, or weather office) and interview a worker on site.
- Use a field interview card to record facts in the worker's own words, with the tools, materials and measurements they use every day.
- Tally and compare answers from at least three people and present the results in a simple bar graph.

Warm-up. Ask a parent to describe their job in exactly three sentences while you write it down word for word. Read it back. Did you get it exactly? Where did you fall behind? Today you will practice taking fast, honest notes from a stranger.

Video. Coming soon. A day in the life of a quarry worker, well driller, soil conservationist or meteorologist, and how to conduct an oral history interview; search Library of Congress, USGS, NOAA, USDA NRCS, state geological surveys and career-exploration channels.

KEY TERMS

field interview
An interview done at the place where a person works, so you can see the tools and the ground they talk about.

open question
A question that cannot be answered yes or no, such as "What does a hard day look like?"

direct quotation
A person's exact words, written down and marked with quotation marks; anything else is a paraphrase.

tally
A count of how many people gave each kind of answer, kept with tick marks.

mean
The average: add the values and divide by how many there are.

oral history
A record of the past made by interviewing people who lived it and preserving their words.

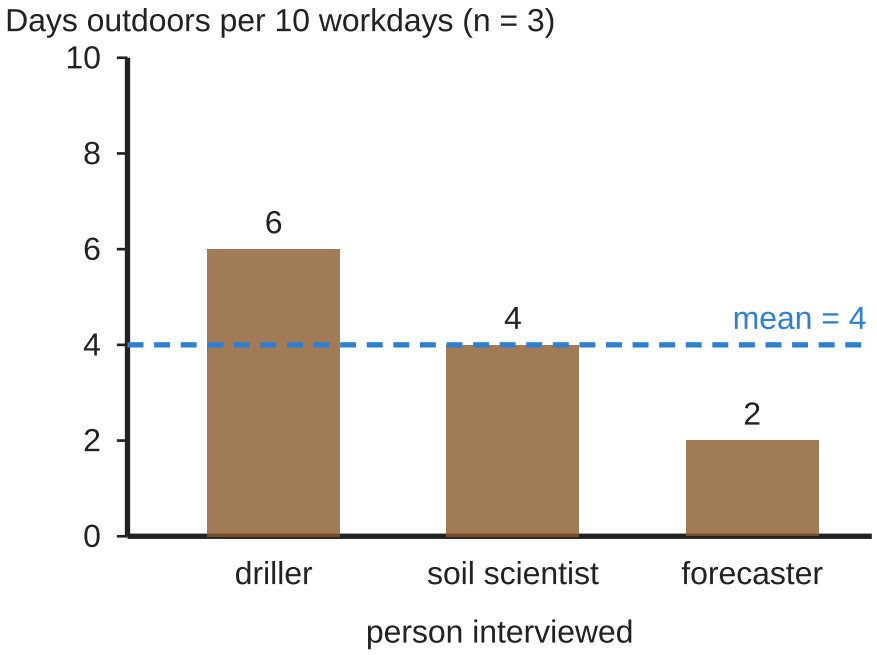
CORE IDEAS

The story. Between 1936 and 1940 the Federal Writers' Project, a government work program during the Depression, sent writers out across the country with notebooks to interview ordinary Americans about their lives and work: tenant farmers in North Carolina,

granite cutters in Vermont, miners, cooks and fishermen. The interviewers were told to let people talk and to write down what they actually said. Thousands of those life histories are preserved today at the Library of Congress, and they are some of the best records we have of what work felt like in that decade. The method was simple: go where the person is, ask open questions, listen more than you talk, and write it down straight. In Unit 8 you interviewed one professional for your county report. Today you take the notebook out to the workplace itself and interview three people where they stand.

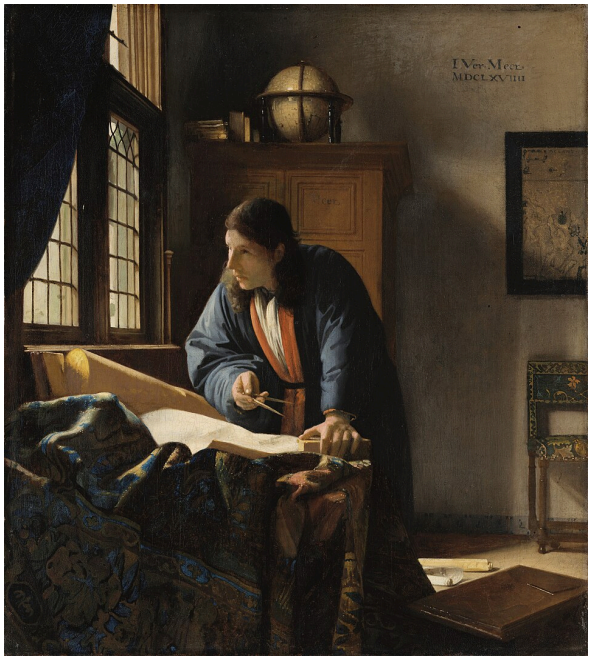
How they figured it out. A field interview is better than a phone call because the place answers questions too. At a gravel pit you can see the face being dug, the screens that sort the stone by size, and the scale house where trucks are weighed. At a drilling company yard you can see the rig, the bits and the racks of casing. At a soil and water conservation district or extension office you can see the soil maps on the wall and the probes in the truck. The **field interview card** keeps you honest: the person’s name and job, three open questions, space for exact quotations, a list of every tool and measurement they mention, and a sketch. Afterward you turn the words into data. If you ask every person the same measurable question, such as how many days out of ten they work outdoors, you can tally the answers, find the **mean**, and draw a bar graph. Three interviews are a small sample, so say so. But three honest answers are worth more than a hundred guesses.

God’s handiwork. Job describes the miner at work: “Surely there is a vein for the silver, and a place for gold where they fine it. Iron is taken out of the earth, and brass is molten out of the stone” (Job 28:1–2). The whole chapter honors the skill of people who go where no bird has looked and bring out what God placed in the earth. The people you interview today are the heirs of that skill, whether they move gravel, find water, read soil or watch the sky, and most of them like being asked about it. Treat their words with care. Quote exactly, do not improve what they said, and send a thank-you note. A good interviewer, like a good scientist, records what is there.



Interview tally from three field interviews: days outdoors in a ten-day work stretch. The dashed line is the mean, 4 days.

PICTURE STUDY



The Geographer, Johannes Vermeer, about 1669 · Oil on canvas · Städel Museum, Frankfurt

Vermeer painted a working man at the moment of thought. The geographer has stopped, dividers in hand, looking toward the window as if an idea has just come to him. Around him are the tools of his trade: a chart on the table, a globe on the cupboard, a map on the wall, rolled papers on the floor. Some scholars have suggested the model may have been Vermeer's neighbor in Delft, the lens-maker Antonie van Leeuwenhoek.

This is what you are looking for in an interview: not only what a person says, but the tools on the table and the map on the wall. A good field interviewer sketches the room.

Look closely

- List every tool and object you can find in the picture. Which ones would a mapper still use today?
- Look at the man's face and hands. Is he measuring, or thinking? How can you tell?
- Where does the light come from, and why would a geographer want his table by that window?
- Find the globe. Why would someone who draws flat maps keep a globe nearby?

Talk about it

1. If you could ask this geographer three open questions about his work, what would they be?
2. What would you sketch on your field interview card from this room?
3. Vermeer shows the man pausing. Why might a worker's pauses and habits tell you as much as their answers?

> **Safety first.** Workplaces have moving trucks, heavy equipment, open pits and loud machinery. Go only with a parent, by appointment, and stay exactly where your host tells you. Wear closed shoes and any safety gear the site requires (hard hat, vest, glasses). Do not approach machinery, pit edges or stockpiles, and do not touch tools without permission.

EXPERIMENT: THREE FIELD INTERVIEW CARDS AND A TALLY

You will prepare interview cards, visit one or more earth-resource workplaces with a parent, interview three people on site, and turn their answers into a short report with a bar graph.

Question: How much of an earth-resource worker's time is spent outdoors, and what tools do they use most? Prediction: write your guess for each job before you go. What we change: the person and job interviewed. What we keep the same: the same three open questions and the same measurable question asked of everyone. What we measure: days outdoors per ten workdays, and a count of tools named.

You will need

- Three index cards or notebook pages ruled as field interview cards: name, job, workplace, date; three open questions; a measurable question; a box for exact quotations; a box for tools and measurements; a space for a sketch
- Pencil, clipboard, and a watch
- A parent-arranged appointment at a quarry or gravel pit office, drilling company, farm co-op, soil and water conservation district, extension office, surveyor's office or weather office

- Thank-you cards and stamps for afterward

Steps

1. Write three open questions that work for any earth-resource job, for example: What did you do yesterday from start to finish? What measurement do you take most often, and what tool do you use? What does a good day look like, and a bad one? Add one measurable question for everyone: Out of ten workdays, how many are mostly outdoors?
2. Practice on a family member with a watch: can you take notes fast enough to keep up? Mark exact words with quotation marks and everything else as paraphrase.
3. At the site, introduce yourself, say what the project is, and ask permission to take notes. Ask your open questions in order, but follow interesting answers with “Can you show me?” Sketch any tool or place they show you.
4. Fill the tools box as you go: every instrument, machine, map or measurement they mention. Ask what units each measurement uses.
5. Ask the measurable question last and write the number down exactly as they say it.
6. Repeat for two more people, at the same site or another. Try to get different jobs: an operator, an office person, a technician.
7. At home, within a day, copy each card cleanly while you still remember the voices. Tally the tools named across all three. Compute the mean days outdoors and draw a bar graph with one bar per person and the mean as a dashed line.
8. Write a one-page report: who you met, what each one does, two exact quotations, the tool tally, the bar graph, and one sentence on what surprised you. Mail the thank-you cards.

Tips

- Three interviews is a small sample. Say so in your report; do not write “drillers spend 60% of their time outdoors” from one driller.
- If a person says a number you did not expect, write it exactly and ask a follow-up; do not round it toward your guess.
- If no visit is possible, two phone interviews plus one in-person interview with a county extension agent still make a fair field day; note which were by phone.

Check your work

- I have three completed field interview cards with names, jobs, exact quotations and a sketch each.
- I tallied the tools named and computed the mean days outdoors correctly.
- My report has a labeled bar graph, two exact quotations and a note on sample size, and the thank-you cards are sent.

FIELD NOTEBOOK

1. Draw one tool or machine you were shown, labeled with its name, what it measures and the units.
2. Make a tally table of every tool and measurement mentioned across the three interviews, with tick marks for how many people named each.
3. Draw your bar graph of days outdoors per ten workdays, one bar per person, with the mean as a dashed line and a title.

> **From history.** The Federal Writers' Project life histories were gathered under the direction of folklorist Benjamin Botkin and others, and the Library of Congress has placed thousands of them online as "American Life Histories: Manuscripts from the Federal Writers' Project, 1936 to 1940." Reading one about a quarryman, a driller or a farmer from your own state is a fine way to prepare for an interview: you will notice how the best interviewers let the worker's own words carry the story.

WORKED EXAMPLES

Example 1. Three people were asked, "Out of ten workdays, how many are mostly outdoors?" A well driller said 6, a soil scientist said 4, and a weather forecaster said 2. (a) Find the mean. (b) Express the driller's answer as a percentage of workdays. (c) If the driller works 50 hours in those ten days and the outdoor days are full days, about how many hours are outdoors?

(Use the map or drawing "The three answers as a bar graph with the mean marked." shown earlier in this lesson.)

1. (a) Mean = (6 + 4 + 2) ÷ 3 = 12 ÷ 3 = 4 days out of 10.
2. (b) 6 ÷ 10 × 100 = 60% of workdays outdoors.
3. (c) 50 hours ÷ 10 days = 5 hours per day on average. 6 outdoor days × 5 hours = 30 hours outdoors, or 60% of 50 hours = 30 hours. Both ways agree.
4. Note the sample: three people, one per job. The mean describes these three, not every driller, soil scientist and forecaster.

Answer: (a) Mean 4 days out of 10. (b) 60%. (c) About 30 of 50 hours.

PRACTICE

1. EASY Rewrite this closed question as an open one: "Do you like your job?"
2. EASY What is the difference between a direct quotation and a paraphrase on your interview card, and how do you mark each?
3. MEDIUM Data reading. Five interviewed workers named these tools: tape measure (4 people), GPS unit (3), soil probe (2), rain gauge (1), rock hammer (2), truck scale (1).

(a) Which tool was named by the most people? (b) What percentage of the workers named a GPS unit? (c) How many tool mentions were there in all?

4. MEDIUM Four people answered the days-outdoors question: 8, 7, 1 and 4. Find the mean, and explain why one more interview could change it a lot.
5. HARD Experiment design. You want to compare how much outdoor time drillers and office-based soil scientists report, but you suspect that asking the question first or last in the interview changes the answer. How would you test that, and what would make the comparison fair?

COMMON MISTAKES

- Fixing up a quotation to sound better. If you change the words, it is no longer a quotation; mark it as a paraphrase.
- Drawing a big conclusion from three people. Report the numbers, state the sample size, and keep claims small.
- Talking more than listening. Ask the question, wait through the silence, and let the person fill it.

> **Make it a game · Exact Words.** A parent reads a three-sentence description of a job from a book or an online life history, at normal speed, once. You write it down. Score one point for every sentence you got word for word and one bonus point if you correctly marked which parts you were unsure of as paraphrase. Then you read and the parent writes. Three rounds each.

> **Scripture.** “Surely there is a vein for the silver, and a place for gold where they fine it. Iron is taken out of the earth, and brass is molten out of the stone.” (Job 28:1–2, KJV)

Job honors the skill of the people who bring metals and stone out of the earth. The workers you interview carry on that craft, and recording their words carefully is a way of honoring it too.

Practice answers

1. For example: “What do you like most about your job, and what is hardest about it?” or “What does a good day at work look like?”
2. A direct quotation is the person’s exact words and goes inside quotation marks. A paraphrase is your summary in your own words and has no quotation marks. Never put quotation marks around words you are not sure were said exactly.
3. (a) Tape measure, named by 4 of 5. (b) $3 \div 5 \times 100 = 60\%$. (c) $4 + 3 + 2 + 1 + 2 + 1 = 13$ mentions.
4. Mean = $(8 + 7 + 1 + 4) \div 4 = 20 \div 4 = 5$ days. With only four values, one new answer carries a fifth of the weight; a fifth person answering 10 would raise the mean to 6, and answering 0 would lower it to 4. Small samples have means that swing easily.
5. Ask the same measurable question of a number of workers, but for half of them ask it first and for half ask it last, choosing which by a coin flip rather than by job. Keep the wording identical. Compare the mean answers from the first-asked and last-asked groups. If they differ

little, question order is not a problem and the driller versus soil scientist comparison can use all the answers; if they differ, ask it in the same position for everyone in the real comparison. A fair comparison also needs several people in each job, not one.

Unit 9 review

This is the Field Lab review. Answer each question with complete sentences or clear calculations, and draw the diagram neatly with labels. The review is worth 60 points.

1. (10 pts) Multiple choice. In a jar test, a soil settled into 2.0 cm of sand, 2.0 cm of silt and 1.0 cm of clay. What percentage is clay, and which layer is on top of the settled soil? (a) 20%, sand on top (b) 20%, clay on top (c) 40%, clay on top (d) 10%, silt on top
2. (10 pts) Explain in two or three sentences why a soil survey samples along a planned transect at a fixed depth rather than wherever the digging is easy.
3. (10 pts) A well is 48 m deep. An electric tape reads 11.2 m to water from the top of the casing, and the casing sticks up 0.4 m above ground. A 20 L bucket fills from the hose bib in 50 s. Find the depth to water below ground, the water column, and the flow rate in L/min.
4. (10 pts) Diagram item. Draw a labeled cross-section of a drilled well showing: ground surface, casing with cap, water table, depth to water, water column, pump and total depth. Then write one sentence on what an artesian well would show differently.
5. (10 pts) Your double pace is 1.5 m. From outcrop A (sandstone, no fizz) you pace 160 double paces to outcrop B (limestone, fizzes). The 1:24,000 map shows the contact 1.2 cm from A along the road. (a) How far is B from A in meters? (b) How far along the road is the mapped contact in meters? (c) Does the ground agree with the map? Explain.
6. (10 pts) Three workers answered, “Out of ten workdays, how many are mostly outdoors?” with 7, 5 and 3. (a) Find the mean. (b) Write the mean as a percentage of workdays. (c) In one sentence, say what a careful report should add about this result, and give one example of an open question you asked.

Unit project: my field lab binder

Gather the four field records into one binder: the five-site soil transect map with its jar-test table and a comparison to the Web Soil Survey; the well visit record with sketch, three numbers and bucket-test trials; the map-walk strip map with three outcrop descriptions and your contact line; and the three field interview cards with the tool tally and bar graph.

Add a one-page cover letter to a future student that explains which measurement you trust most, which one surprised you, and one place where the map or your prediction disagreed with the ground and what you did about it.

- **Method**: Each record shows that the sampling or measuring was planned and done the same way at every site, with repeats averaged where called for.
- **Records**: Sketches, tables and interview cards are complete, dated, labeled with units, and quotations are exact.
- **Calculation**: Percentages, water column, flow rate, pace conversions and means are computed correctly and shown.

- **Honesty and judgment**: Each record states where the ground agreed or disagreed with the map or prediction, notes the sample size, and does not overstate the result.

Answer key

1. (b). Clay = 1.0 ÷ 5.0 × 100 = 20%, and clay settles last, so it lies on top.
2. A planned line and spacing make the sampling fair and repeatable, so the survey covers different kinds of ground, not just the convenient spots. A fixed depth means that differences between samples are differences between sites, not between the litter layer and the subsoil. Together they let one site be compared honestly with another and with the county map.
3. Depth to water below ground = 11.2 − 0.4 = 10.8 m. Water column = 48 − 10.8 = 37.2 m. Flow rate = 20 L ÷ 50 s = 0.4 L/s = 24 L/min.
4. The drawing should show the casing rising a little above ground with a cap, a dashed water table line, water inside the casing from the water table to the bottom, a pump near the bottom, and brackets labeled depth to water (ground surface to water table), water column (water table to bottom) and total depth. An artesian well would show water standing in the casing above the top of the aquifer, because the aquifer is confined and under pressure; in a flowing artesian well it rises above the ground.
5. (a) 160 × 1.5 = 240 m. (b) 1.2 cm × 240 m per cm = 288 m. (c) The rock types match the map’s order (sandstone, then limestone), but B is already limestone at 240 m, so the real contact lies somewhere between A and B, short of the mapped 288 m. The map is right in kind and about 50 m or more off in position, which is only about 2 mm on paper.
6. (a) (7 + 5 + 3) ÷ 3 = 5 days. (b) 50%. (c) The report should state that the sample is only three people, so the mean describes those three and not all workers in those jobs. Example open question: “What did you do yesterday from start to finish?”