SCHOOL LAUNCH · LIFE SCIENCE K–8

Grade 6 Life Science: Animal Design and Behavior

A year of true stories about how animals fly, travel, find their way in the dark, hide, build and live together, from the buzzards the Wright brothers watched and Lazzaro Spallanzani's bats to Arctic terns, monarch butterflies, Jean-Henri Fabre's wasps, honeybee hives, the blue whale and the burrs that gave George de Mestral the idea for Velcro, each one taken apart to see how it was figured out and then observed, measured and tested at the kitchen table with a ruler, a stopwatch, a scale and a notebook.

First edition

> *"And God made the beast of the earth after his kind, and cattle after their kind, and every thing that creepeth upon the earth after his kind: and God saw that it was good." (Genesis 1:25, KJV)*

Course guide

This course studies how animals are built and how they behave, one great question at a time across a school year: how they fly, how they migrate, how they find their way by echoes, how they hide, how they know what to do without being taught, how they live together, how the giants are built, and what engineers have learned by copying them. Each unit is built around real moments in the history of natural science: Wilbur and Orville Wright watching soaring birds as they worked out how to balance a flying machine in 1899, the Italian priest and naturalist Lazzaro Spallanzani testing how bats find their way in the dark in 1793, Jean-Henri Fabre watching his wasps in the south of France, the tagging of monarch butterflies that led to the discovery of their winter forests in the mountains of Mexico in 1975, and the Swiss engineer George de Mestral pulling burrs off his dog after a walk in 1941.

Every lesson follows the same path. First comes **the story**: a real person, a real place and a real question. Then **how they figured it out**: what they watched, what they measured, what they tried that failed and what changed their minds. Then **the big idea** underneath, explained for a sixth grader and pointed toward high-school biology: lift and wing loading, navigation, the speed of sound, the square–cube law, instinct and learning, the life of a colony. Last, the student **observes and measures**: paper wings tested with paper clips for weight, an echo timed off a wall, a camouflage hunt counted and graphed, a web measured, a whale paced out in the yard. Every experiment ends with numbers in the nature notebook and a sentence about what they mean.

The thread of the year is **design and behavior**. Every animal in the course meets a real problem, such as staying in the air, crossing an ocean, hunting in the dark, escaping a predator or holding up an enormous body, and the student will learn to ask two questions of each one: how is it built for the job, and what does it do? Structure fits function, behavior fits the creature, and the numbers can be measured. The year ends with biomimicry, where engineers borrow from the animals: Velcro from burrs, swimsuits and ship coatings from shark skin, and dry adhesives from the feet of the gecko. Students who have taken the School Launch Engineering courses will find old friends here.

The faith thread runs underneath it all. “And God made the beast of the earth after his kind, and cattle after their kind, and every thing that creepeth upon the earth after his kind: and God saw that it was good” (Genesis 1:25). The prophet Jeremiah noticed that “the stork in the heaven knoweth her appointed times” (Jeremiah 8:7), and in Job 39 God asks Job whether the hawk flies by his wisdom. The course invites the student to ask the same question of the bat, the bee and the spider: who taught them? Careful observation is taught as an act of honesty and of thanks, and where a famous study has been argued over, as with the peppered moths, the student learns exactly what was observed and what it does and does not show.

WHO IT IS FOR

Written for students in grade 6 (about ages 11–12) who read on their own, work comfortably with decimals, fractions, ratios and percents, measure in centimeters, grams and seconds, and can draw a bar graph and a line graph. The course builds toward high-school biology. A parent or teacher reads along, holds the stopwatch, helps with the experiments and supervises outdoor work, field trips and any handling of insects or specimens. Nothing needs to be bought beyond ordinary household items, though a hand lens, a kitchen scale and a pair of binoculars are a great help.

HOW TO USE THIS COURSE

The weekly rhythm. The year has 32 lessons, one a week, in eight units of four, plus an optional ninth unit, the *Nature Lab*, which can be used in any season. Session 1 (about 45 minutes) is the warm-up, the teaching, the worked examples and the picture study. Session 2 (about 45 minutes) is the experiment, the nature notebook and the practice. In the last week of each unit, add a third session for the unit test and the unit project. Families who want a one-quarter version can follow the ★ **quarter path**: the 10 lessons marked with a star, at least one from every unit, which keep the key stories and the core experiments.

The nature notebook. Use one composition book (graph paper is best) for the whole year. Every experiment ends with something drawn, counted or measured: a wing traced and its area counted in squares, a migration route on a map with its distance worked out, an echo timing table, a camouflage tally, a sketch of a web with its spokes counted, a scale drawing of a blue whale. Date every page, label every column with its unit, and write one sentence saying what the numbers show. Measurements are metric throughout.

Experiments and safety. Each experiment names a question, a prediction, the one thing that changes (the variable), what stays the same and what is being compared (the control). A parent is nearby for every experiment. Watch wild animals; do not handle them. Never touch a bat, living or dead, because bats can carry rabies. Keep a respectful distance from bees, wasps and ant mounds, and know whether anyone in the family is allergic to stings. Wash hands after any outdoor work or specimen handling. In the United States the feathers, nests and eggs of most wild native birds are protected by law, so the specimen collection uses shells, shed snakeskins, leaves, poultry feathers or craft feathers instead.

Worked examples and practice. Each lesson has three worked examples, solved step by step with numbers: a rate, a ratio, a graph, a scale drawing. Then come ten practice items, including two that ask the student to read a data table or graph in the style of the science-reasoning sections of the SAT and ACT, and one that asks the student to design a fair experiment. Answers are in the lesson so the student can check his or her own work; a wrong answer is a reason to go back to the worked example, not a failure.

Unit tests and unit projects. Each unit ends with a unit test (60 points, 10 to 12 problems: multiple choice, short answer and one diagram to label or read) and a unit project that pulls the unit together, such as a glider built and flown for distance, a migration map, an echo-

ranging investigation, a camouflage study, a model beaver dam, a colony report, a scale model of a giant or an invention borrowed from nature. Keep the tests and project pages in one folder for the year.

A word about time. This course is written from a Christian view of creation, “In the beginning God created the heaven and the earth” (Genesis 1:1), and of the Flood (Genesis 6–9). Deep-time names such as “Jurassic” or “Ice Age” are taught as museum words, so students can read any sign or textbook. Wherever they come up, chiefly in Unit 7 with the sauropods and on museum visits in the Nature Lab, a ⏳ *Thinking About Time* box sets out what the sign says, what we actually observe, and how Christians read it.

SCOPE AND SEQUENCE

Unit 1: Flight (1–4)

The Wright brothers watching buzzards and other soaring birds as they worked out how to balance a flying machine (1899); wing shapes for soaring, gliding and darting; how insects beat their wings; and a paper-wing lab testing area, shape and load.

Unit 2: Migration (5–8)

The Arctic tern’s round trip between the Arctic and the Antarctic; the monarch butterflies’ journey to the mountain forests of Mexico, which takes more than one generation to complete; how birds find their way by the sun, the stars and the earth’s magnetism; and “the stork in the heaven knoweth her appointed times.”

Unit 3: Echolocation (9–12)

Lazzaro Spallanzani’s experiments on how bats fly in the dark (1793) and the later discovery that they hunt by sounds too high for us to hear; dolphins and their clicks; how sonar works by the same rule of sending out a sound and timing the echo; and an echo lab measuring the speed of sound.

Unit 4: Camouflage (13–16)

Chameleons and cuttlefish that change their color; the peppered moths of England and exactly what the studies observed; bright warning colors that say “do not eat me”; and a camouflage game in which the student counts and graphs what a hunter finds.

Unit 5: Instinct (17–20)

Jean-Henri Fabre and the wasps that follow their steps in order even when the plan no longer works; spiders that spin a complete orb web without being taught; beavers that build dams without blueprints; and the questions God asks Job about the wild animals in Job 39.

Unit 6: Social Animals (21–24)

The honeybee hive, its six-sided cells and the waggle dance decoded by Karl von Frisch; wolves and the life of the pack; elephant herds led by an old female; and leafcutter ants that

farm a fungus underground.

Unit 7: Giants: Whales and Dinosaurs (25–28)

The blue whale, the largest animal known; how the long-necked sauropods held up their necks and pumped blood to their heads; the square–cube law and why there is a limit to how big an animal can grow; and engineering a giant with scale models. A ⏳ Thinking About Time box reads the museum signs.

Unit 8: Biomimicry (29–32)

George de Mestral, the burrs on his dog and the hook-and-loop fastener he named Velcro (1941); shark skin and drag; the gecko's foot and sticking without glue; and a final design project in which the student invents something from nature.

Unit 9: Nature Lab (optional) (Any time)

Four outdoor and field-trip lessons for any season: a nature journal walk watching how animals move and behave, a backyard survey of the creatures that live nearby, a visit to a zoo, farm or museum, and a small specimen collection.

MATERIALS

- **Nature notebook (a graph-paper composition book)**: One for the whole year: sketches, traced wings, maps, data tables, line and bar graphs and one sentence about what each experiment showed.
- **A metric tape measure (at least 10 meters if you can borrow one), a meter stick and a 30-centimeter ruler**: For wing spans, glider flights, echo distances and pacing out a blue whale in the yard.
- **A stopwatch or a phone timer**: For flight times, echo timing, wingbeat counts and the camouflage game.
- **A kitchen scale that reads in grams**: For weighing paper wings, loads and scale models in Units 1 and 7.
- **A hand lens; binoculars if you have them**: For burrs, insect wings, spider webs and bird watching. A hand lens is enough to complete every lesson.
- **A calculator, a protractor and a world map or atlas**: For rates, ratios and scale, for wing angles and for tracing migration routes.
- **Paper, card stock, straws, paper clips, tape, glue and scissors**: For paper wings, gliders, model hives and the unit projects.
- **Household supplies for small experiments**: Colored paper and toothpicks or beads for the camouflage game, sticks, clay and a pan of water for the model beaver dam, modeling clay for scale models, and a strip of hook-and-loop fastener.
- **Zip-top bags, small boxes and disposable gloves**: For the Nature Lab specimen collection. Collect only shells, leaves, seeds, shed skins and other things that are lawful to keep.

- **Optional: one of the books or resources listed in a unit**: Never required. See the list in each unit.

GRADING

Grades come from the experiments, the nature notebook, the unit tests and the unit projects, because animals are learned by watching and measuring as well as by reading. An experiment whose results surprised the student but are honestly recorded and explained earns full credit.

- Experiments (prediction, a fair test, careful measuring and the explain-it step): 30%
- Nature notebook (dated pages, labeled drawings, tables and graphs with units, honest records): 20%
- Unit tests (eight tests of 60 points each): 30%
- Unit projects: 20%

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

- Grade the process, not just the result. Did the student predict, name the variable and the control, measure carefully, record honestly and explain what the numbers mean?
- A notebook page earns full marks when it has a date, a title, a labeled drawing, table or graph with units, and one sentence about what was learned.
- On the unit tests, give full credit for a correct method with a small arithmetic slip, and partial credit for a clear explanation that falls short.
- Practice items are for learning, not for grading. Check them together and go back to the worked examples when something is missed.
- The Nature Lab is optional and may be graded as extra notebook pages or not at all.

A NOTE TO PARENTS

You do not need to be a biologist to teach this course. Read the story aloud together, look at the picture, and then be the student's field partner: hold the stopwatch, read the tape measure, count the moths found in the camouflage game and write down the numbers. Ask "What do you predict?", "How could we make it a fair test?" and "What do the numbers show?" Those three questions are most of what a good science teacher does.

The course tells the history of science honestly. Where scientists disagreed or a famous study was later questioned, as with the peppered moths, the student learns what was actually observed and what it does and does not show. Dinosaurs and the ages printed on museum signs are handled in the ⏳ *Thinking About Time* boxes, so your child can read any book or sign with understanding and talk it over with you.

Above all, the course hopes your child will come away with wonder and gratitude: wonder at a tern that crosses the world and comes home, a bat that catches insects in the dark and a spider that spins a web it was never taught to build, and gratitude to the God who made them and saw that it was good. Along the way the student learns the habits of a good

naturalist: patient watching, careful counting, kindness to living things and honesty about what the evidence shows.

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- 9.1 Nature Journal Walk
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- 9.3 Zoo, Farm or Museum Visit
- 9.4 Specimen Collection

★ quarter path · ⏳ Thinking About Time box

UNIT 1

Flight

On the fifth day of creation God said, “Let the waters bring forth abundantly the moving creature that hath life, and fowl that may fly above the earth in the open firmament of heaven” (Genesis 1:20). For thousands of years people watched birds and insects fly and wished they could follow. In this unit you will learn what keeps a flier in the air: the four forces of lift, weight, thrust and drag, the shape of an airfoil, and the three ways a flier must steer: pitch, roll and yaw.

You will begin in 1899 with Wilbur and Orville Wright, two bicycle makers in Dayton, Ohio, who learned to balance in the air by watching buzzards twist their wingtips. You will measure and compare the wings of sparrows, falcons, albatrosses and vultures and discover why each shape fits the bird’s life. You will look inside the thorax of a fly and a bee to see how insects beat wings that have no muscles in them, hundreds of times a second. Finally you will step into the Wrights’ wind tunnel and run your own fair test with paper wings.

Throughout the unit you will work like a scientist: observing real birds and insects, keeping a nature and lab notebook, calculating speeds, ratios and averages, reading tables and graphs, and designing experiments that change only one thing at a time.

BEFORE YOU BEGIN

- Can multiply and divide decimals and find an average of several numbers
- Can measure in centimeters and meters and convert between them
- Can read a simple bar graph and line graph
- Knows that birds and insects are different kinds of animals with different body plans

MASTERY CHECKLIST

- I can name the four forces of flight and tell when they are balanced.
- I can explain how the Wright brothers learned roll control from buzzards and tested it with a kite.
- I can describe four bird wing shapes and calculate aspect ratio and wing loading.
- I can explain how insects move their wings with thorax muscles, and what elytra and halteres do.
- I can design a fair test with one independent variable, controlled variables and repeated trials, and graph my results.

OPTIONAL BOOKS AND RESOURCES

- **Turkey Vulture page, All About Birds (Cornell Lab of Ornithology)** (https://www.allaboutbirds.org/guide/Turkey_Vulture): Free. Photos, range map, sounds and identification tips for the bird the Wrights watched. Use it before the bird-watching sketchbook task in Lesson 1.1.

- **Wilbur and Orville Wright Papers, Library of Congress** (https://www.loc.gov/collections/wilbur-and-orville-wright-papers/): Free. Scanned letters, diaries, notebooks and the brothers' own glass-plate photographs, including the 1903 first-flight photo. A parent can help find the 1899 to 1903 materials.
- **Smithsonian National Air and Space Museum** (https://airandspace.si.edu/): Free online. Search the site for the 1903 Wright Flyer to see the original airplane and read about how it was built and flown. If you can visit Washington, it hangs in the museum.

1.1 The Wrights Watched Buzzards (1899) ★

OBJECTIVES

- Tell how Wilbur and Orville Wright learned about balance in the air by watching turkey vultures (buzzards) in 1899 and testing the idea with a twisted box and a kite.
- Name the four forces on a flying bird or airplane (lift, weight, thrust, drag) and the three ways a flier can turn (pitch, roll, yaw).
- Calculate a flying speed from distance and time and explain how a soaring bird climbs in a thermal without flapping.

Warm-up. Hold a sheet of notebook paper by its two short edges just below your lower lip, so it droops down in front of you. Blow hard straight across the top of the paper. What does the drooping end do? Now drop the sheet flat from shoulder height, then crumple a second sheet into a ball and drop both together. Which falls faster, and what do you think is holding the flat sheet up?

Video. Coming soon. Wright brothers 1899 kite, wing warping and the 1903 first flight explained (Smithsonian National Air and Space Museum, Library of Congress, NASA, Homeschool Pop (Alternate)), plus turkey vulture soaring in thermals nature footage (Cornell Lab of Ornithology).

KEY TERMS

lift
The upward push of the air on a wing as the wing moves through it. Lift holds a flier up against its weight.

weight
The downward pull of gravity on a flier. In steady level flight, lift balances weight.

thrust
The forward push that moves a flier ahead, from flapping wings, a propeller or an engine.

drag
The backward push of the air that slows a moving flier down. In steady flight, thrust balances drag.

thermal
A rising column of warm air over sun-heated ground. Soaring birds circle inside thermals to climb without flapping.

wing warping
The Wrights' method of twisting the tips of a wing in opposite directions so that one side gets more lift and the flier rolls, copied from the way buzzards twist their wingtips.

CORE IDEAS

The story. In the spring of 1899, two brothers who ran a bicycle shop in Dayton, Ohio, began to think hard about flying. Wilbur Wright was 32 and Orville was 27. Three years before, the German glider pilot Otto Lilienthal had been killed when his glider stalled and fell, and the brothers wanted to know why even the best flier in the world could lose control. On May 30, 1899, Wilbur wrote to the Smithsonian Institution in Washington and asked for whatever it had published about flight. While they waited and read, they went outdoors and watched. Over the fields near Dayton, turkey vultures, which Americans called buzzards, circled for minute after minute on wings that hardly ever flapped. When a gust of wind tipped a buzzard sideways, it righted itself almost at once.

How they figured it out. Wilbur noticed that a tipped buzzard did not flap harder. It changed the shape of its wingtips. In a letter to the engineer Octave Chanute in 1900 he wrote, “My observation of the flight of buzzards leads me to believe that they regain their lateral balance, when partly overturned by a gust of wind, by a torsion of the tips of the wings.” Torsion means twisting. One day in the shop, Wilbur was idly squeezing an empty cardboard box that had held a bicycle inner tube. As he pinched opposite corners, the top and bottom of the box twisted like a pair of wings, one end tilting up while the other tilted down. That gave him a way to copy the buzzard. That summer the brothers built a biplane kite about 1.5 meters across, rigged with cords so the flier on the ground could twist the wings. When the wings were twisted, the kite rolled to one side just as they had predicted. They called the idea **wing warping**.

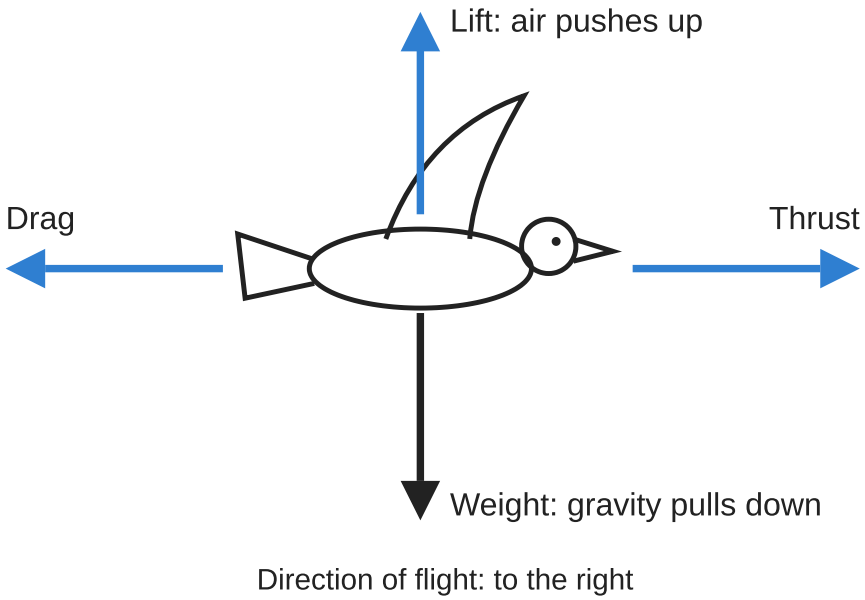
The big idea. Every flier, from a buzzard to a jumbo jet, feels four forces. **Weight** is gravity pulling down. **Lift** is the air pushing up on the moving wing. **Thrust** pushes forward, and **drag** is the air pushing back. When lift equals weight and thrust equals drag, a flier goes straight and level at a steady speed. A soaring buzzard makes no thrust at all. It glides on a gently sloping path, trading height for forward speed, the way a sled trades height for speed on a hill. To stay up for hours it looks for **thermals**, columns of warm air rising from sunny fields and roads. If the air in a thermal rises faster than the bird sinks, the bird goes up while barely moving a feather.

Steering in three directions. A boat or car turns in only one way, left or right. A flier can turn three ways. **Pitch** tips the nose up or down. **Roll** lifts one wingtip and lowers the other. **Yaw** swings the nose left or right. Many inventors of the 1890s worked mainly on bigger engines, but the Wrights believed the missing piece was control, especially roll. Their 1903 Flyer had a front elevator for pitch, wing warping for roll and a rear rudder for yaw. On December 17, 1903, at Kill Devil Hills near Kitty Hawk, North Carolina, Orville flew it for 12 seconds and about 37 meters. On the fourth flight that day Wilbur stayed up 59 seconds and covered about 260 meters.

Try it and see. On a sunny late morning, look for large dark birds circling high over open country. A turkey vulture holds its long wings in a shallow V, called a dihedral, and rocks gently from side to side as it tests the air. Count how many seconds pass between flaps.

Watch the spread “finger” feathers at the wingtips bend and twist. You are watching the very thing that taught the Wrights to steer.

God’s handiwork. The buzzard is not a pretty bird up close, with its bare red head, yet in the air it is a master pilot. It was flying with perfect balance long before anyone built a kite. The Wrights were careful observers who learned from what God had already made. Scripture invites us to do the same: “But ask now the beasts, and they shall teach thee; and the fowls of the air, and they shall tell thee” (Job 12:7).



The four forces on a flier. In steady level flight, lift balances weight and thrust balances drag.

PICTURE STUDY



Turkey Buzzard (Plate 151, The Birds of America), John James Audubon (engraved and colored by Robert Havell Jr.), 1830s · Hand-colored engraving and aquatint · Printed in London; copies of the original prints are held by many libraries and museums

John James Audubon set out to paint every bird in America life size. He shot, posed and studied his birds, then painted them in watercolor, and the engraver Robert Havell Jr. turned the paintings into huge printed plates for *The Birds of America*. The turkey vulture, which Audubon called the Turkey Buzzard, is the same bird the Wright brothers watched over the fields of Ohio.

Audubon was curious about how vultures find their food. He ran his own experiments with hidden carcasses and a stuffed deer skin, and he believed they hunted by sight. Later scientists found that turkey vultures also have a keen sense of smell. Good naturalists keep testing, even after a famous man has spoken.

Look closely

- Find the bare red head. Why might a bird that eats carrion be better off without head feathers?
- Look at the long feathers at the wingtip. How many separate “fingers” can you count?
- Compare the size of the wings with the size of the body. Are these wings built for quick flapping or for long soaring?
- Find the hooked beak and the feet. Do the feet look like an eagle’s gripping talons, or more like walking feet?

Talk about it

1. What did the Wrights learn from this bird, and which part of the bird taught it to them?

2. Audubon thought vultures found food by sight; later tests showed smell matters too. What does that teach us about how science works?
3. If you were drawing this bird in flight for a field guide, what three features would you be sure to show?

> **Safety first.** Watch wild birds only from a distance and never touch a vulture, a dead animal or a bird's nest. Never look at the sun, with bare eyes or through binoculars, while you are looking for birds overhead. Use scissors carefully, and fly paper gliders away from people's faces.

EXPERIMENT: THE WING-WARPING GLIDER TEST

You will build a paper glider with bendable wingtips and test the Wrights' buzzard idea: if one wingtip is twisted one way and the other wingtip the opposite way, the glider should roll and turn. This is a small experiment, so you will predict, test, measure and record.

You will need

- Three sheets of plain printer paper (A4 or letter size)
- Scissors and a ruler marked in centimeters
- One small paper clip
- Tape measure or meter stick, and a piece of masking tape to mark a launch line
- Lab notebook and pencil

Steps

1. **Question:** If I bend up the back edge of the right wingtip and bend down the back edge of the left wingtip, which way will the glider turn? Write your **prediction**.
2. Fold a simple dart-style paper glider with wide wings. Put the paper clip on the nose so it glides smoothly. At the back edge of each wingtip, cut two slits 2 cm long and 2 cm apart to make a small flap.
3. Mark a launch line on the floor with tape. Stand on the line and launch the glider gently straight ahead at shoulder height with both flaps flat. Measure how far left or right of a straight line it lands, in centimeters. Do three flights. This is your **control**.
4. Bend the right flap up and the left flap down, each about the same amount. Fly three more times and measure how far left or right it lands each time.
5. Now reverse them: right flap down, left flap up. Fly three more times and measure.
6. **What we change:** the flap positions. **What we keep the same:** the glider, the paper clip, the launch spot, the launch height and how hard you throw. **What we measure:** the direction and distance off the straight line.
7. Make a table with columns: Flap setting, Trial 1, Trial 2, Trial 3, Average (cm left or right). Write one sentence comparing your result with your prediction.

Tips

- Throw softly. A hard throw makes every glider loop and spoils the test.

- Watch the glider from behind as it leaves your hand. You may see it roll first, tipping one wing down, and then curve. That is what a buzzard does when it banks into a turn.
- If the control flights already curve, bend the tail edges a little to trim the glider until it flies nearly straight before you begin.

Check your work

- I wrote a prediction before I tested.
- I flew a control and kept everything the same except the flaps.
- I can explain how twisting the wingtips made one wing lift more than the other.

NATURE NOTEBOOK

1. Draw a turkey vulture in flight seen from the front, showing its wings in a shallow V (dihedral). Label the head, the primary “finger” feathers and the dihedral angle.
2. Draw the Wrights’ inner-tube box twisted between your fingers, then draw a biplane wing twisted the same way. Add arrows showing which wingtip gets more lift.
3. Spend 10 minutes watching birds outdoors. For one bird, record the date, time, weather, how many seconds it glides between flaps and whether it circles.

> **From history.** When Wilbur Wright wrote to the Smithsonian Institution on May 30, 1899, he called himself an enthusiast and asked for papers on flight. The Smithsonian sent pamphlets, including work by Otto Lilienthal and by the Smithsonian’s own Secretary, Samuel Langley, and suggested other books, among them Octave Chanute’s *Progress in Flying Machines*. Wilbur later wrote to Chanute, and the older engineer became the brothers’ friend and adviser. Today the original 1903 Wright Flyer hangs in the Smithsonian’s National Air and Space Museum in Washington, the same institution that answered Wilbur’s letter.

WORKED EXAMPLES

Example 1. On December 17, 1903, Orville Wright’s first flight covered about 37 meters in 12 seconds. What was the Flyer’s average speed over the ground in meters per second? About how many kilometers per hour is that?

1. Speed is distance divided by time: 37 m ÷ 12 s.
2. 37 ÷ 12 = 3.08, so the speed was about 3.1 meters per second.
3. To change meters per second to kilometers per hour, multiply by 3.6 (there are 3,600 seconds in an hour and 1,000 meters in a kilometer): 3.08 × 3.6 = 11.1.
4. The Flyer was flying into a strong headwind, so its speed through the air was much greater than its speed over the sand.

Answer: About 3.1 m/s over the ground, or about 11 km/h, roughly a fast jog.

Example 2. A turkey vulture has a wingspan of about 1.7 meters. The Wrights' 1899 test kite was about 1.5 meters across, and the 1903 Flyer had a wingspan of about 12.3 meters. How many times wider was the Flyer than a vulture? Was the kite bigger or smaller than the bird?

1. Divide the Flyer's span by the vulture's span: 12.3 m ÷ 1.7 m = 7.2.
2. Compare the kite and the bird: 1.5 m ÷ 1.7 m = 0.88.
3. A number less than 1 means the kite was a little smaller than the bird.

Answer: The Flyer was about 7 times as wide as a turkey vulture. The 1899 kite was a little smaller than a vulture, about 0.9 times its wingspan.

Example 3. Suppose a gliding vulture sinks 1.0 meter every second in still air. It enters a thermal where the air rises 2.5 meters every second. How fast does the bird climb, and how high will it rise in 2 minutes if it stays in the thermal?

1. The air lifts the bird 2.5 m each second while the bird sinks 1.0 m through the air: 2.5 − 1.0 = 1.5 m per second upward.
2. Change 2 minutes to seconds: 2 × 60 = 120 s.
3. Height gained = rate × time = 1.5 m/s × 120 s = 180 m.

Answer: The vulture climbs 1.5 meters per second and gains about 180 meters in 2 minutes, without flapping.

PRACTICE

1. EASY Name the four forces that act on a flying bird or airplane, and tell which way each one points.
2. EASY What is a thermal, and why do vultures and hawks circle inside one?
3. EASY What did Wilbur Wright conclude from watching buzzards regain their balance after a gust?
4. MEDIUM Match each motion to its name (pitch, roll or yaw): (a) the nose swings to the left; (b) the right wingtip rises and the left wingtip drops; (c) the nose tips down.
5. MEDIUM Wilbur's fourth flight on December 17, 1903, covered about 260 meters in 59 seconds. Find his average ground speed in meters per second, to one decimal place. How does it compare with Orville's first flight (about 3.1 m/s)?
6. MEDIUM Data reading. The table gives approximate figures for the four flights of December 17, 1903.
   Flight 1, Orville: 12 s, 37 m
   Flight 2, Wilbur: 12 s, 53 m
   Flight 3, Orville: 15 s, 61 m
   Flight 4, Wilbur: 59 s, 260 m

(a) What pattern do you see in the distances as the day went on? (b) Flight 4 lasted how many times as long as Flight 1? (c) Who flew the shortest flight by distance, and who flew the longest?

7. MEDIUM Data reading. A student used a phone app to track a soaring hawk's height every 20 seconds: 0 s, 100 m; 20 s, 130 m; 40 s, 160 m; 60 s, 190 m; 80 s, 182 m; 100 s, 174 m. (a) What was the hawk's rate of climb during the first 60 seconds? (b) What most likely happened at about 60 seconds? (c) How fast was it sinking after that?
8. HARD Many inventors in the 1890s worked mostly on building powerful engines. Explain in two or three sentences why the Wrights thought control was the bigger problem, and how buzzards helped them solve it.
9. HARD Experiment design. You want to know whether bending the wingtip flaps more strongly makes a paper glider turn more sharply. Write a testable question and name the independent variable, the dependent variable and two things you must keep the same.
10. CHALLENGE A 1.5 kg vulture has a weight of about 15 newtons (using 10 newtons for each kilogram). (a) How much lift must its wings make for it to fly level without climbing or sinking? (b) If a downdraft makes its lift fall to 12 N, what happens? (c) Why does the bird not need any thrust to keep moving forward while gliding?

COMMON MISTAKES

- Thinking birds stay up only by flapping. Many large birds soar for hours on rising air in thermals and wind blowing up over hills, flapping only now and then.
- Thinking something heavy cannot fly. Weight does not stop flight; a flier needs enough lift to balance its weight. The 1903 Flyer and its pilot weighed more than 300 kg and still flew.
- Thinking the Wrights' great idea was the engine. Engines were already being built. Their key breakthrough was control in all three directions, especially roll, which they learned from watching birds.

> **Make it a game · Pitch, Roll, Yaw.** One player is the pilot and stands with arms out like wings. The caller shouts a command: "Pitch up!" (lean back and lift your chin), "Pitch down!" (lean forward), "Roll right!" (tip your right arm down and left arm up), "Roll left!", "Yaw right!" (twist to face right) or "Yaw left!". Every correct move scores a point; a wrong move and you trade places with the caller. For a hard round, the caller names a bird problem, such as "A gust tipped your left wing down!", and the pilot must choose the right fix (roll right).

> **Scripture.** "But ask now the beasts, and they shall teach thee; and the fowls of the air, and they shall tell thee:" (Job 12:7, KJV)

The Wrights asked the fowls of the air, and a buzzard told them how to balance. Careful watching of what God made is one of the oldest ways to learn.

Practice answers

1. Lift (up), weight (down), thrust (forward) and drag (backward).
2. A thermal is a rising column of warm air over sun-heated ground. Soaring birds circle to stay inside it, so the rising air carries them upward without flapping.
3. He concluded that they twist (put “torsion” in) the tips of their wings, which gives one side more lift and rolls the bird back to level.
4. (a) yaw, (b) roll, (c) pitch.
5. 260 ÷ 59 = 4.4 m/s. That is about 1.3 m/s faster, or about 1.4 times the speed of the first flight.
6. (a) Each flight went farther than the one before. (b) 59 ÷ 12 ≈ 4.9, about 5 times as long. (c) Orville flew the shortest (Flight 1) and Wilbur flew the longest (Flight 4).
7. (a) It rose 90 m in 60 s, or 1.5 m per second. (b) It left the thermal (or the thermal weakened) and began to glide. (c) It lost 8 m every 20 s, or 0.4 m per second.
8. Lilienthal and others had shown that wings could lift a person, but gusts tipped gliders over and a pilot had no reliable way to level the wings again. A flier that cannot balance will crash no matter how strong its engine is. Watching buzzards twist their wingtips to level themselves gave the Wrights the idea of wing warping, a way to control roll.
9. Sample answer. Question: Does a larger flap bend make the glider land farther to the side? Independent variable: how far the flaps are bent (for example 0°, 20°, 45°). Dependent variable: how far left or right of the straight line the glider lands, in cm. Keep the same: the same glider and paper clip, the same launch height and spot, and the same gentle throw; do three trials at each setting.
10. (a) About 15 N, equal to its weight. (b) Weight is now greater than lift by 3 N, so the bird starts to sink. (c) A glider moves on a slightly downward path, so part of gravity’s pull acts along its path and keeps it moving forward against drag. It pays for its forward speed with height.

1.2 Wing Shapes

OBJECTIVES

- Describe four main bird wing shapes (elliptical, high-speed, long and narrow, slotted soaring) and match each to the way a bird lives.
- Explain how an airfoil makes lift by turning air downward, and what happens when the angle of attack is too steep (a stall).
- Calculate aspect ratio and wing loading from measurements and use them to compare birds in a data table.

Warm-up. Cut two strips of paper, one 20 cm by 3 cm and one 10 cm by 6 cm. Both have the same area. Hold each by one short end and swoop it through the air like a wing, slowly and then fast. Which one bends more? Which one do you think would make a better glider wing, and why?

Video. Coming soon. Bird wing shapes and how wings make lift (Cornell Lab of Ornithology, NASA Glenn Research Center, Smithsonian National Air and Space Museum, SciShow Kids), plus slow-motion footage of albatross, falcon, sparrow and vulture flight.

KEY TERMS

airfoil
The shape of a wing seen from the side: rounded at the front, thin at the back and usually curved. An airfoil moving through air at a slight tilt turns the air downward and makes lift.

angle of attack
The tilt of a wing compared with the oncoming air. A small angle gives lift; too steep an angle causes a stall.

stall
A sudden loss of lift when the angle of attack is too steep and the air stops flowing smoothly over the top of the wing.

aspect ratio
How long and narrow a wing is: the wingspan divided by the average width (chord) of the wing. Long, slender wings have a high aspect ratio.

wing loading
How much body mass each square meter of wing must hold up: mass ÷ wing area, in kilograms per square meter.

primary feathers
The long flight feathers attached to the “hand” bones at the outer part of a bird’s wing. In soaring birds they spread apart into slots at the tip.

CORE IDEAS

The story. Around the year 1505, in Florence, Italy, Leonardo da Vinci filled a small notebook with drawings of birds in flight. He watched kites and other birds tilt their wings and tails to ride the wind, and he sketched the same bird again and again at different moments. He wrote his notes backward, from right to left, in his famous mirror writing. Leonardo believed a bird works by the same laws as any machine, and so a person might one day copy it. He never built a machine that flew, but he asked the right question: why are wings shaped the way they are?

How they figured it out. Bird scientists answer Leonardo's question by measuring. They spread a wing flat on graph paper, trace around it and count the squares to find its area. They measure the **wingspan** from tip to tip and the **chord**, the width of the wing from front edge to back edge. Two numbers then tell a great deal. **Aspect ratio** is the span divided by the average chord, so a long, skinny wing has a high aspect ratio. **Wing loading** is the bird's mass divided by its wing area. A bird with low wing loading can fly slowly and float on weak air currents; a bird with high wing loading must fly fast to stay up.

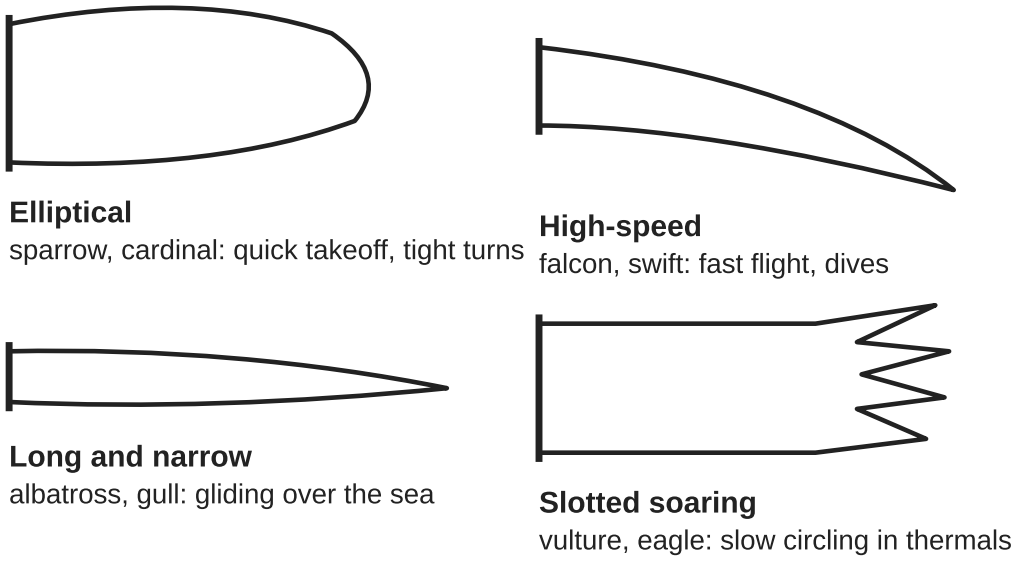
The big idea. Every wing is an **airfoil**: thick and rounded at the front, thin at the back, usually arched on top. Tilted slightly upward into the oncoming air, at a small **angle of attack**, it bends the flow of air downward behind it. Pushing air down means the air pushes the wing up, just as a swimmer pushes water back to move forward. At the same moment, the air pressure above the wing becomes lower than the pressure below, and that difference is lift. If the wing tilts too steeply, the air can no longer follow the curved top. It breaks into swirls, lift suddenly drops, and the wing **stalls**. A landing pigeon stalls its wings on purpose, just above the ledge.

Four kinds of wings. Shapes fit jobs. **Elliptical wings**, short and rounded, belong to sparrows, cardinals and other birds of woods and hedges; they give a quick, steep takeoff and tight turns between branches. **High-speed wings**, slim, pointed and swept back, belong to falcons and swifts; a peregrine falcon folds its wings and dives at more than 300 km/h. **Long, narrow wings** with a very high aspect ratio belong to albatrosses and gulls. The wandering albatross has the widest wingspan of any living bird, up to about 3.5 meters, and glides for hours over ocean waves, hardly flapping. **Slotted soaring wings**, long and broad with primary feathers spread like fingers at the tips, belong to vultures, eagles and big hawks. The slots help these heavy birds fly slowly without stalling as they circle tightly in thermals over land.

Built for flight. The wing is only part of the design. Many bird bones are hollow but braced inside with thin struts, light and strong like the trusses of a bridge. The breastbone has a tall ridge, the keel, where the great flight muscles attach; in strong fliers these muscles can be a fifth or more of the whole body's mass. Air sacs push air through the lungs in one direction, so a bird gets fresh oxygen on every breath in and every breath out.

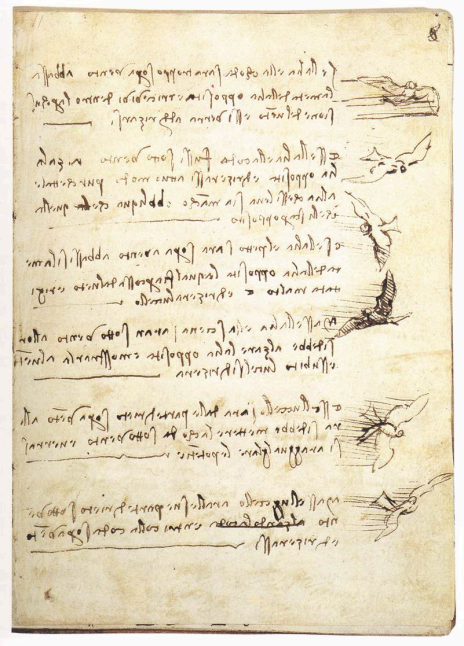
In the world today. Airplane designers face the same trade-offs. Sailplanes have long, thin wings like an albatross. Fast jets have swept, pointed wings like a falcon. Many airliners now

have upturned winglets at the tips, which, like a soaring bird's spread primaries, reduce the swirling air that forms at the end of a wing. **God's handiwork:** each bird has the wing that fits its life, the sparrow for the hedge and the albatross for the open sea. "But they that wait upon the LORD shall renew their strength; they shall mount up with wings as eagles" (Isaiah 40:31).



Four main wing shapes. Each is a right wing seen from above, with the body at the left.

PICTURE STUDY



Codex on the Flight of Birds, Leonardo da Vinci, about 1505 · Pen and ink, with some red chalk, on paper (a small notebook) · Biblioteca Reale (Royal Library), Turin, Italy

This little notebook is one of Leonardo da Vinci's most famous studies of nature. Its pages are covered with notes in mirror writing and small drawings of birds turning, gliding and balancing in the wind. Leonardo was trying to work out how a bird keeps its balance and how it uses the wind instead of its own strength.

Leonardo also sketched ideas for flying machines, but none of them could have flown with human muscle power. What lasted was his method: watch carefully, draw what you see and ask why. Four centuries later, the Wright brothers did the same thing with buzzards.

Look closely

- Find a small bird drawing. Is the bird flapping, or is it holding its wings still and tilting them?
- Compare the left and right wings of one drawn bird. Is one wing higher than the other? What might that do?
- Look at the handwriting. Leonardo wrote from right to left. How could you read it more easily?
- Notice how drawings and words are mixed on the same page. How is this like your own nature notebook?

Talk about it

1. Why do you think Leonardo drew the same bird several times on one page?
2. Leonardo watched birds but did not measure wing area or wing loading. What could measuring have added to his drawings?
3. Which of the four wing types in this lesson would a bird need to balance in strong gusts near a cliff?

> **Safety first.** Use scissors with care. Launch gliders gently and never toward a person's face. If you examine a real feather, use one from a craft store or a farm bird; wild bird feathers found outdoors should be looked at and photographed, then left, and hands washed after.

EXPERIMENT: LONG WINGS OR SHORT WINGS? A GLIDER TEST

Two gliders will have wings with exactly the same area but different shapes: one long and narrow, one short and wide. You will test which shape glides farther, just as bird scientists compare an albatross with a sparrow.

You will need

- Card stock or file folders
- Two drinking straws (the same kind)
- Tape, scissors, a ruler marked in centimeters
- Small paper clips or a little modeling clay for nose weight
- Meter stick or tape measure; masking tape for a launch line

- Lab notebook and pencil

Steps

1. **Question:** With the same wing area, does a long, narrow wing glide farther than a short, wide wing? Write your **prediction** and your reason.
2. Cut Wing A, 30 cm long and 4 cm wide (area 120 cm², aspect ratio 30 ÷ 4 = 7.5). Cut Wing B, 15 cm long and 8 cm wide (area 120 cm², aspect ratio 15 ÷ 8 ≈ 1.9).
3. Tape each wing across a straw about one-third of the way back from the front. Cut a tail 8 cm by 3 cm for each glider and tape it at the back end of the straw.
4. Add nose weight (paper clips or clay) until each glider glides smoothly instead of diving or swooping up. Write down how much weight each needed.
5. Launch each glider from the same height (stand on the launch line and release at shoulder height) with the same gentle push. Measure the distance from the line to the landing spot in centimeters. Do five trials for each glider.
6. **What we change:** the wing shape. **What we keep the same:** wing area, straw, tail, launch height, launch spot and push. **What we measure:** glide distance.
7. Record a table with columns: Glider, Aspect ratio, Trials 1 to 5 (cm), Average. Draw a bar graph of the two averages and write a conclusion.

Tips

- Fly indoors or on a calm day. A breeze will change every result.
- Long, thin card wings may sag. A strip of tape along the front edge stiffens them, the way a bird’s wing bones stiffen the front edge of its wing.
- If one throw is clearly spoiled (you bumped the table), write it down, mark it, and fly an extra trial.

Check your work

- Both wings had the same area, so shape was the only thing I changed.
- I calculated the aspect ratio of each wing.
- I can connect my result to why albatrosses and sparrows have such different wings.

NATURE NOTEBOOK

1. Draw the four wing shapes from memory and label each with one bird that has it and one job it is good for.
2. Trace around your own spread hand on 1 cm graph paper and count the squares to find its area. Then draw a bird wing beside it and label the primary feathers (on the “hand”) and the secondary feathers (on the forearm).
3. Draw an airfoil from the side, tilted slightly into the wind. Add arrows to show the air turned downward behind it and the lift pushing up.

> **From history.** In 1799 the English inventor Sir George Cayley engraved a small silver disc. On one side he drew the forces of lift and drag on a wing, and on the other a design

for a flying machine with a fixed wing, a tail and paddles for thrust. Cayley studied how birds glide and measured the lift of wings on a whirling arm. He was the first to separate the job of holding a craft up (a fixed wing) from the job of pushing it forward. In 1853 one of his full-size gliders carried a man across a small valley at Brompton Dale in Yorkshire. Cayley is often called the father of aeronautics.

WORKED EXAMPLES

Example 1. A wandering albatross has a wingspan of about 3.0 m and an average wing chord of about 0.20 m. A house sparrow has a span of about 0.24 m and an average chord of about 0.06 m. Find each aspect ratio. How many times higher is the albatross's?

(Use the map or drawing "The long, narrow wing (albatross) and the elliptical wing (sparrow) have very di" shown earlier in this lesson.)

1. Aspect ratio = span ÷ average chord.
2. Albatross: 3.0 m ÷ 0.20 m = 15.
3. Sparrow: 0.24 m ÷ 0.06 m = 4.
4. Compare: 15 ÷ 4 = 3.75.

Answer: Albatross 15, sparrow 4. The albatross's wing is about 3.75 times as long for its width, the shape of a long-distance glider.

Example 2. A turkey vulture with a mass of about 1.5 kg has a total wing area of about 0.45 m². A rock pigeon of about 0.35 kg has a wing area of about 0.07 m². Find the wing loading of each. Which bird must fly faster to stay up?

1. Wing loading = mass ÷ wing area.
2. Vulture: 1.5 kg ÷ 0.45 m² = 3.3 kg/m².
3. Pigeon: 0.35 kg ÷ 0.07 m² = 5.0 kg/m².
4. The higher the wing loading, the faster a bird must fly for its wings to make enough lift.

Answer: Vulture about 3.3 kg/m², pigeon about 5.0 kg/m². Although the vulture is more than four times heavier, the pigeon carries more mass on each square meter of wing and must fly faster. The vulture can drift slowly on thermals.

Example 3. A student traces a bird's spread wing on graph paper with 1 cm squares. She counts 180 squares that are completely inside the outline and 40 squares that are about half inside. Estimate the area of the wing in cm^2 and in m^2.

1. Count each full square as 1 cm^2: 180 cm^2.
2. Count each half square as ½ cm^2: 40 × ½ = 20 cm^2.
3. Add: 180 + 20 = 200 cm^2.
4. 1 m^2 = 100 cm × 100 cm = 10,000 cm^2, so 200 cm^2 ÷ 10,000 = 0.02 m^2.

Answer: About 200 cm^2, which is 0.02 m^2, for one wing. Double it for the area of both wings.

PRACTICE

1. EASY What is an airfoil? Describe its shape.
2. EASY Match each bird to its wing type: peregrine falcon, wandering albatross, house sparrow, bald eagle. Types: elliptical, high-speed, long and narrow, slotted soaring.
3. EASY What is a stall, and what causes it?
4. MEDIUM A gull's wing has a span of 1.4 m and an average chord of 0.16 m. Find its aspect ratio. Is it closer to an albatross (about 15) or a sparrow (about 4)?
5. MEDIUM Data reading. Rounded values for five birds:
   House sparrow: mass 0.03 kg, span 0.24 m, wing area 0.010 m^2
   Rock pigeon: 0.35 kg, 0.65 m, 0.07 m^2
   Peregrine falcon: 0.8 kg, 1.0 m, 0.13 m^2
   Turkey vulture: 1.5 kg, 1.7 m, 0.45 m^2
   Wandering albatross: 9 kg, 3.1 m, 0.61 m^2
   Find the wing loading (mass ÷ area) of each. Which bird has the highest and which the lowest?
6. MEDIUM Data reading. Using the same table, aspect ratio can also be found as span × span ÷ area. Calculate it for the falcon and the albatross. Which wing is more slender, and how does that fit where the bird lives?
7. HARD A pigeon coming in to land tilts its wings steeply and spreads its tail just above the ledge. Explain what is happening to the airflow and why this helps it land.
8. HARD In two or three sentences, explain why a turkey vulture and a peregrine falcon, which both fly over open country, have such different wings.
9. HARD Experiment design. You want to test whether wing loading affects how fast a paper glider must be thrown to glide well. Describe how you could change wing loading while keeping the wing shape the same, what you would measure and what you would keep the same.
10. CHALLENGE A 1.5 kg vulture eats a 0.5 kg meal at a carcass. Its wing area stays 0.45 m^2. Find its wing loading before and after. What does this mean for taking off, and what is one thing a gorged vulture might do?

COMMON MISTAKES

- Believing the air over the top of a wing must “catch up” with the air underneath and meet it at the back edge. There is no such rule; in fact the air over the top usually arrives sooner. Lift comes from the wing turning the air downward and the lower pressure above it.
- Thinking bigger wings are always better. A wing’s shape must fit the job. Long wings would tangle a sparrow in a hedge, and short rounded wings would tire an albatross over the ocean.
- Thinking hollow bird bones are weak. They are braced inside with struts, which makes them light but stiff and strong for their weight.

Make it a game · Name That Wing. Make 12 cards, each naming a bird: sparrow, robin, pheasant, peregrine falcon, chimney swift, swallow, albatross, gull, turkey vulture, bald eagle, red-tailed hawk, hummingbird. A player draws a card and has ten seconds to name its wing type (elliptical, high-speed, long and narrow, slotted soaring) and one reason it fits the bird’s life. One point for the type, one for the reason. The hummingbird card is a bonus: it hovers, so explain why it does not fit neatly into any of the four groups.

Scripture. “But they that wait upon the LORD shall renew their strength; they shall mount up with wings as eagles; they shall run, and not be weary; and they shall walk, and not faint.” (Isaiah 40:31, KJV)

An eagle’s broad, slotted wings let it rise on warm air without tiring itself by flapping. Isaiah uses that picture for the strength God gives to those who trust Him.

Practice answers

1. An airfoil is the side-view shape of a wing: rounded and thicker at the front edge, thin at the back edge and usually arched on top. Moving through the air at a slight tilt, it makes lift.
2. Peregrine falcon: high-speed. Wandering albatross: long and narrow. House sparrow: elliptical. Bald eagle: slotted soaring.
3. A stall is a sudden loss of lift. It happens when the angle of attack is too steep, so the air can no longer flow smoothly over the top of the wing and breaks into swirls.
4. 1.4 ÷ 0.16 = 8.75, about 9. It is in between: 8.75 is 4.75 more than the sparrow and 6.25 less than the albatross, so it is a little closer to the sparrow, yet more than twice as slender. Gulls are good gliders but also flap and maneuver over harbors and beaches.
5. Sparrow 3.0 kg/m², pigeon 5.0, falcon about 6.2, vulture about 3.3, albatross about 14.8. Highest: wandering albatross. Lowest: house sparrow (with the turkey vulture close behind).
6. Falcon: 1.0 × 1.0 ÷ 0.13 ≈ 7.7. Albatross: 3.1 × 3.1 ÷ 0.61 = 9.61 ÷ 0.61 ≈ 15.8. The albatross wing is far more slender. Long, narrow wings glide very efficiently, which suits a bird that travels huge distances over open ocean using the wind over the waves.
7. Tilting the wings steeply raises the angle of attack until the wings stall. The air breaks away from the top of the wing, so lift drops and drag rises sharply. The pigeon slows down quickly and drops gently onto the ledge, timing the stall for the last moment.

8. The vulture spends hours searching slowly for carrion, circling in thermals; its long, broad wings with slotted tips give low wing loading, so it can fly slowly without stalling. The falcon catches other birds in fast chases and dives; its slim, pointed, swept wings make little drag at high speed. Each wing suits the bird’s way of getting food.
9. Sample answer. Use one glider and add paper clips to the straw at its balance point (for example 0, 2, 4 and 6 clips) to raise the mass while the wing area and shape stay the same. Measure the glide distance and watch whether it dives; you could also time how long the glider takes to cross a 3 m stretch to estimate its speed. Keep the same wing, tail, balance point, launch height and launch spot, and do several trials at each mass.
10. Before: $1.5 \div 0.45 \approx 3.3$ kg/m². After: $2.0 \div 0.45 \approx 4.4$ kg/m², about a third higher. It now needs more speed to make enough lift, so takeoff is harder; it may need a long running hop into the wind or a perch to jump from, and vultures are known to throw up part of a meal to lighten themselves when frightened.

1.3 Insect Flight

OBJECTIVES

- Explain how insects move wings that have no muscles inside them, comparing direct flight muscles (dragonflies) with indirect flight muscles that squeeze the thorax (flies and bees).
- Describe special wing designs: the hooked wings of bees, the hard elytra of beetles and the halteres of true flies.
- Use wingbeat rates to calculate beats per minute and the time of one beat, and read a bar graph comparing insects.

Warm-up. Hold a plastic ruler flat on a table so that about 20 cm sticks out past the edge. Press the table end down hard and twang the free end. Listen. Now slide it so only 10 cm sticks out and twang again. Which length gives the higher sound? Which length moves back and forth faster? Keep your answer in mind: the buzz of a bee works the same way.

Video. Coming soon. Insect flight in slow motion: dragonfly, honeybee, housefly and beetle wings, halteres and how insect flight muscles work (Smithsonian, nature footage from high-speed camera channels, SciShow Kids, Deep Look style natural history channels).

KEY TERMS

exoskeleton
The hard outer covering of an insect, made mostly of chitin. An insect’s wings are thin, flat outgrowths of the exoskeleton.

thorax
The middle section of an insect’s body, between the head and the abdomen. The legs, the wings and the flight muscles are all attached to the thorax.

direct flight muscles
Flight muscles attached right to the bases of the wings, which pull each wing up or down. Dragonflies fly this way.

indirect flight muscles
Flight muscles that do not touch the wings but squeeze and stretch the box of the thorax, which levers the wings up and down. Flies, bees and wasps fly this way.

halteres
Tiny knobbed stalks in true flies that take the place of the hind wings. They beat with the wings and work as balance sensors, telling the fly when it starts to turn.

elytra
The hard front wings of a beetle. They do not flap for flight but cover and protect the folded hind wings, which do the flying.

CORE IDEAS

The story. In the late 1860s, in Paris, the French scientist Étienne-Jules Marey set out to measure something that happens too fast for any eye: the beat of an insect's wing. He held an insect so that the very tip of one wing lightly brushed a turning cylinder covered with black soot. Each beat left a tiny wavy mark in the soot. By counting the marks made during one turn of the cylinder, he could count wingbeats per second. Marey also glued a speck of shiny gold leaf to a wingtip and watched it in bright light. The flashing tip traced a looping figure eight in the air. The wing was not just flapping up and down. It was sweeping forward and back and twisting as it went.

How they figured it out. Marey's soot marks agreed with something anyone can hear. The buzz of an insect is the sound of its wings, and the pitch of the buzz matches the number of beats each second, just as a short twanged ruler vibrates faster and sounds higher than a long one. Large butterflies beat their wings only about 10 times a second and make no sound we can hear. A dragonfly beats about 30 times a second, a housefly about 200, a honeybee about 230 and a female mosquito about 500, which is why a mosquito whines and a bumblebee hums. Later scientists confirmed these numbers with high-speed cameras that take thousands of pictures every second.

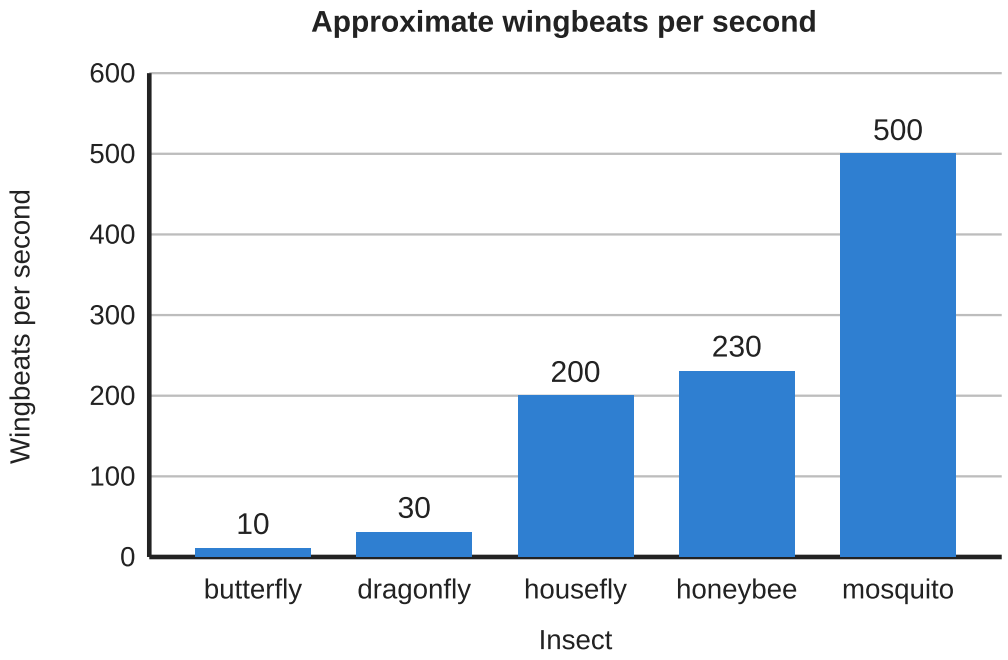
The big idea. An insect wing is a thin sheet of exoskeleton stiffened by veins. Unlike a bird's wing, it has no muscles or bones inside it, so all the power comes from the **thorax**. Dragonflies use **direct flight muscles** fastened to the base of each wing, and they can move their front and hind pairs separately to hover, dart sideways and even fly backward. Flies, bees and wasps use **indirect flight muscles**. One set pulls the roof of the thorax down; the wing rests on the side wall like a seesaw on its pivot, so when the roof goes down, the wing goes up. A second set shortens the thorax from front to back, the roof bulges up, and the wing goes down. The thorax is springy, like a plastic lid that clicks, and in many small insects one nerve signal sets the muscles vibrating several times. That is how a fly reaches 200 beats a second.

Four wings, many plans. The basic plan of a winged insect is four wings, but God has given insects many variations on that plan. A bee hooks its front and hind wings together with a row of tiny hooks, so they beat as one wing. A beetle's front wings are hardened into **elytra**, a shield that swings open so the folded, filmy hind wings can unfold and fly. A housefly or mosquito has only two wings; its hind wings have become **halteres**, tiny knobs that beat with the wings and sense turning, like a built-in balance sensor. Halteres help a fly stay steady through its quick twists and turns, even when it flips over to land upside down on a ceiling.

In the world today. For years people repeated a story that scientists had "proved" a bumblebee cannot fly. The rough calculation treated a bee's wing like the stiff wing of an airplane. Real insect wings flip over and sweep on every stroke, and a small whirlwind forms along the front edge of the wing, called a leading-edge vortex, that gives far more lift than a still wing could. In 1996 the zoologist Charles Ellington and his team at Cambridge watched

smoke curl over hawkmoth wings and saw this vortex. Engineers now build tiny flapping robots, such as Harvard's RoboBee, by copying insect wings and muscles.

God's handiwork. A housefly's whole flight system, muscles, springy thorax, folded veins and balance knobs, fits inside a body smaller than a pea. "O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches" (Psalm 104:24).



Approximate wingbeat rates. Real values vary with the species, size and temperature of the insect.

PICTURE STUDY



Stag Beetle, Albrecht Dürer, 1505 · Watercolor and gouache on paper · J. Paul Getty Museum, Los Angeles

Albrecht Dürer of Nuremberg was one of the greatest artists of Germany, and he studied nature as carefully as any scientist. In 1505 he painted this stag beetle so exactly that it seems ready to walk off the paper. Dürer painted it alone, not as a small detail in a bigger picture, which was unusual in his day. He was saying that even a beetle is worth looking at closely.

Stag beetles are clumsy but real fliers. On warm summer evenings the males lift their hard elytra, unfold their long hind wings and buzz heavily through the air, their great jaws held up in front.

Look closely

- Find the huge jaws. They look like a stag's antlers. What other parts of the head can you see?
- Find the smooth, shiny shell over the back. These are the elytra, the hardened front wings. Can you see the line where the two halves meet?
- Count the legs. Which body section are they joined to?
- Look at the shadow under the beetle. How does it make the beetle seem real and solid?

Talk about it

1. Where are the beetle's flying wings hidden in this painting? What protects them?
2. Dürer painted a beetle the way most artists painted kings. Why might a naturalist admire that choice?
3. If you could add one more drawing beside this one to show how a stag beetle flies, what would you draw?

> **Safety first.** Watch insects without handling them. Never touch or trap bees, wasps or hornets, and stay away from their nests; anyone with a sting allergy should keep their medicine nearby when outdoors. Use scissors and a sharp pencil point carefully when you make holes in the cardboard box, or ask an adult to make them.

EXPERIMENT: THE THORAX LEVER MODEL

You will build a cardboard model of a fly's thorax to see how indirect flight muscles move a wing they never touch. Then you will run a small experiment: does moving the pivot change how far the wingtip travels?

You will need

- A small cardboard box with a lid or top flap (a tissue box or shoebox)
- Two bendable drinking straws or two thin wooden skewers with the points cut off
- Tape, scissors, a ruler marked in centimeters and a sharp pencil
- A second ruler or a strip of card to measure the wingtip's rise
- Lab notebook and pencil

Steps

1. **Question:** If the roof of the thorax moves down the same small amount, how does the length of the wing inside the pivot change how far the wingtip rises? Write a **prediction**.
2. Cut away the box top except for one flap that can be pushed down, like the roof of a thorax. Poke a small hole in one side wall, 1 cm below the top edge. This hole is the pivot, like the edge of the thorax wall where the wing rests.
3. Push a straw “wing” through the hole so that 2 cm is inside the box and 15 cm sticks out. Tape the inside end to the underside of the roof flap.
4. Rest a ruler upright beside the wingtip. Push the roof down exactly 1 cm and measure how far the wingtip rises. Do three trials and find the average.
5. Now slide the straw so 4 cm is inside and still 15 cm is outside (use a longer straw, or tape on an extension), and tape it again. Repeat the 1 cm push and measure three times.
6. **What we change:** the inside length (pivot to roof). **What we keep the same:** the outside length, the hole and the 1 cm push. **What we measure:** how far the wingtip rises.
7. Make a table. Then divide the outside length by the inside length for each setup and compare that number with how many times farther the tip moved than the roof.

Tips

- The tip rises less than the simple lever math predicts if the straw bends or the tape slips, so press the tape down firmly.
- Push the roof down and let it spring back quickly several times. Your model wing flaps, even though nothing is pulling on the wing itself.
- Real insects use this lever trick to turn tiny muscle movements into large, fast wing strokes.

Check your work

- I can explain why pushing the roof down makes the wing go up.
- I changed only the inside length and measured the wingtip each time.
- I compared my results with the lever ratio.

NATURE NOTEBOOK

1. Watch a fly, bee or butterfly outdoors for 5 minutes with a magnifying glass from a safe distance. Record the date, the weather, what it landed on and whether its wings rested flat, folded or upright.
2. Draw an insect from the side and label the head, thorax, abdomen, the six legs and the wings. If it is a fly, add and label a haltere.
3. Draw a ladybug or other beetle twice: once resting with elytra closed, and once flying with elytra raised and hind wings spread.

From history. In 1999 the biologist Michael Dickinson and his team at the University of California, Berkeley, built "Robofly," a pair of large robot wings shaped like a fruit fly's. Because a real fly's wings are tiny and fast, they made the robot wings big and moved them slowly through a tank of mineral oil, which flows around a large slow wing the way air flows around a tiny fast one. Sensors on the wings measured the forces on every part of the stroke. The experiment showed how the leading-edge vortex, the flip of the wing at each turn and the wing meeting its own swirling wake together give insects their lift.

WORKED EXAMPLES

Example 1. A honeybee beats its wings about 230 times each second. How many wingbeats is that in one minute? In a 10-minute foraging trip?

1. There are 60 seconds in a minute: 230 × 60 = 13,800 beats per minute.
2. For 10 minutes: 13,800 × 10 = 138,000 beats.

Answer: About 13,800 beats per minute and about 138,000 beats on a 10-minute trip.

Example 2. A housefly beats its wings about 200 times a second. How long does one complete wingbeat (one down-and-up stroke) take, in seconds and in milliseconds?

1. If 200 beats fit in 1 second, one beat takes 1 ÷ 200 of a second.
2. 1 ÷ 200 = 0.005 s.
3. 1 second = 1,000 milliseconds (ms), so 0.005 × 1,000 = 5 ms.

Answer: One wingbeat takes 0.005 seconds, which is 5 milliseconds. A blink of your eye takes about 100 milliseconds, long enough for about 20 fly wingbeats.

Example 3. Use the bar graph of wingbeat rates. About how many times faster does a mosquito beat its wings than a butterfly? Than a honeybee?

(Use the map or drawing "Read each bar against the scale on the left." shown earlier in this lesson.)

1. Read the bars: mosquito about 500 per second, butterfly about 10, honeybee about 230.
2. Mosquito ÷ butterfly: 500 ÷ 10 = 50.
3. Mosquito ÷ honeybee: 500 ÷ 230 ≈ 2.2.

Answer: About 50 times as fast as the butterfly and a little more than twice as fast as the honeybee. That is why the mosquito's whine is so much higher than a bee's hum.

PRACTICE

1. EASY Insect wings have no muscles inside them. Where are the muscles that move them?
2. EASY What are halteres, and which insects have them?
3. EASY What are elytra, and do they flap during flight?
4. MEDIUM A dragonfly beats its wings about 30 times a second. How many beats is that in a minute? In an hour?
5. MEDIUM Data reading. From the bar graph: (a) List the five insects from slowest to fastest wingbeat. (b) About how many times faster does a housefly beat than a dragonfly?
   (Use the map or drawing "Use the scale at the left to read each bar." shown earlier in this lesson.)
6. MEDIUM Data reading. Approximate wing lengths and wingbeat rates:
   Butterfly (monarch): 50 mm, 10 per second
   Dragonfly: 45 mm, 30 per second
   Honeybee: 10 mm, 230 per second
   Housefly: 7 mm, 200 per second
   Mosquito: 3 mm, 500 per second
   (a) What general pattern links wing length and wingbeat rate? (b) Which pair of insects does not follow the pattern perfectly?
7. HARD In a thorax lever model, the wing has 1 cm inside the pivot and 6 cm outside. If the roof of the thorax moves down 0.5 mm, about how far does the wingtip move up?
8. HARD Someone tells you, "Scientists proved bumblebees can't fly." In two or three sentences, explain what was wrong with that calculation.
9. HARD Experiment design. Using a cardboard thorax model, you want to know whether a longer outside wing makes the tip travel farther for the same 1 cm push. Write a question, a prediction, and name the independent variable, the dependent variable and two controlled variables.
10. CHALLENGE The pitch of an insect's buzz matches its wingbeat rate. The musical note A above middle C vibrates 440 times a second, and the A one octave below vibrates 220 times a second. Which insect's buzz is close to each A? What happens to the pitch of a sound when the number of vibrations per second doubles?

COMMON MISTAKES

- Repeating the old saying that science proves a bumblebee cannot fly. That came from a rough calculation that treated a flapping wing like a fixed airplane wing. Measured properly, bee wings make plenty of lift.
- Thinking insect wings have muscles inside, like a bird's arm. Insect wings are thin sheets of exoskeleton with no muscles in them; the power comes from the thorax.
- Thinking every flying insect flaps four wings. Bees hook their two pairs together, beetles fly with only the hind pair while the elytra cover them, and true flies have just two wings plus halteres.

Make it a game · Buzz Match. One player hums a sound and the others guess which flier it imitates: a low hum for a bumblebee, a middle buzz for a housefly, a high thin whine for a mosquito, or silence with slow arm flaps for a butterfly. After each correct guess, the guesser must name one wing fact about that insect (for example, “flies have halteres” or “bees hook their wings together”) to score a point. For a bonus round, the hummer flaps arms slowly or quickly and the others must say whether the sound should go higher or lower.

Scripture. “O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches.” (Psalm 104:24, KJV)

“Manifold” means many and varied. Insects show it: two wings or four, hooked together or covered by a shield, each a different and wise plan for flight.

Practice answers

1. In the thorax, the middle section of the body. They either pull directly on the wing bases or squeeze the thorax so that it levers the wings up and down.
2. Halteres are tiny knobbed stalks in place of the hind wings. They beat with the wings and act as balance sensors. True flies have them, such as houseflies, fruit flies and mosquitoes.
3. Elytra are the hardened front wings of a beetle. They do not flap to power flight. They lift up and out of the way and protect the folded hind wings, which do the flying.
4. 30 × 60 = 1,800 beats per minute; 1,800 × 60 = 108,000 beats per hour.
5. (a) Butterfly (10), dragonfly (30), housefly (200), honeybee (230), mosquito (500). (b) 200 ÷ 30 ≈ 6.7, about 7 times as fast.
6. (a) Insects with shorter wings generally beat them faster. (b) The housefly and the honeybee: the housefly has shorter wings but beats them slightly slower than the honeybee. The pattern is a trend, not a perfect rule.
7. The tip moves 6 ÷ 1 = 6 times as far as the inner end: 0.5 mm × 6 = 3 mm upward.
8. The rough calculation treated a bee’s wing like a stiff, still airplane wing moving steadily through the air. A real bee wing beats very fast, sweeps and flips over on every stroke, and makes a swirling leading-edge vortex that gives extra lift. When scientists measured how real insect wings move, the lift was easily enough.
9. Sample answer. Question: Does a longer outside wing make the tip rise farther? Prediction: doubling the outside length will double the rise. Independent variable: the outside length (for example 10, 15 and 20 cm). Dependent variable: how far the wingtip rises, in cm. Controlled: the inside length, the same 1 cm push, the same straw and hole; three trials each.
10. The honeybee (about 230 per second) buzzes close to the low A (220). The mosquito (about 500) whines a little above the higher A (440). Doubling the vibrations per second raises the pitch by one octave, so the mosquito sounds about an octave above the bee.

1.4 Paper-Wing Lab

OBJECTIVES

- Design and carry out a fair test with paper wings, naming the independent, dependent and controlled variables and running repeated trials.
- Calculate averages and glide ratios from your own measurements and display the results in a table and a line graph.
- Explain how the Wright brothers used a homemade wind tunnel in 1901 to test wing shapes one change at a time.

Warm-up. Find a maple “helicopter” seed (or fold a strip of paper in half lengthwise and twist one end). Drop it from as high as you can safely reach, then drop a pebble of about the same size beside it. Count “one thousand one, one thousand two” as they fall. Which lands first? Make a list of three things you could change about a paper spinner that might make it fall more slowly.

Video. Coming soon. Wright brothers 1901 wind tunnel and how scientists run a fair test, plus how to make a paper helicopter and paper glider experiment (Smithsonian National Air and Space Museum, NASA STEM, Science Max, Homeschool Pop (Alternate)), and slow-motion maple seed (samara) spinning footage.

KEY TERMS

independent variable
The one thing you choose to change on purpose in an experiment, such as the rotor length of a paper helicopter.

dependent variable
The thing you measure to see whether it changes because of the independent variable, such as the time to fall.

controlled variables
Everything you keep the same so that it cannot affect the result, such as drop height, paper type and number of paper clips.

trial
One run of a test. Scientists repeat trials and average them because single measurements always vary a little.

glide ratio
How far forward a glider travels for each unit of height it drops: horizontal distance ÷ height lost. A glide ratio of 5 means 5 m forward for every 1 m down.

wind tunnel
A tube or box in which a fan blows a steady stream of air past a model, so wings can be measured indoors under the same conditions every time.

CORE IDEAS

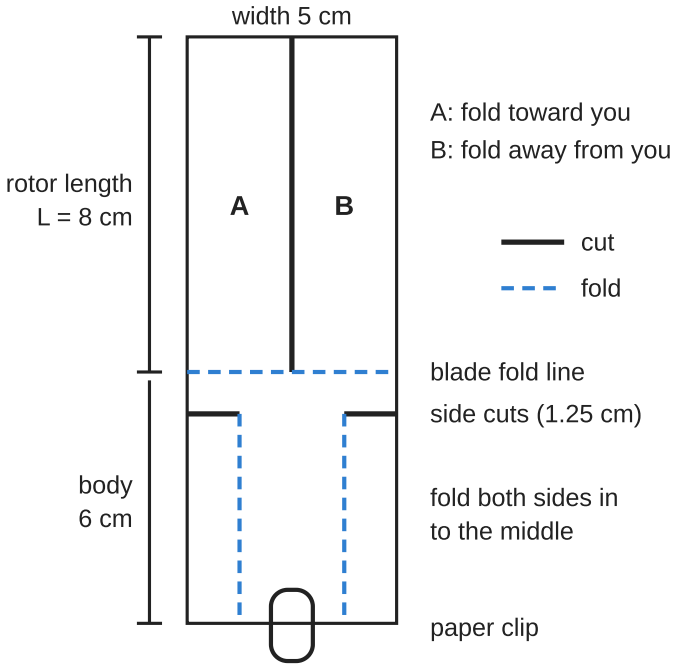
The story. In August 1901 the Wright brothers came home to Dayton from the sand dunes of Kitty Hawk tired and discouraged. Their new glider had made only about a third of the lift that the published tables of the day said it should. Wilbur later admitted that on the way home he told Orville that people would not fly for fifty years. Then the brothers did what good scientists do when the numbers do not match. They stopped trusting the old tables and decided to measure for themselves. That autumn, in the back of their bicycle shop, they built a wooden **wind tunnel** about 1.8 meters long, with a fan at one end driven by the shop's engine.

How they figured it out. Inside the tunnel they mounted small model wings cut from sheet metal on delicate balances they made from bicycle spokes and pieces of hacksaw blade. The balance showed how much lift and drag each model made. Over a few weeks they tested about 200 wing shapes: flat and curved, thick and thin, square-tipped and rounded, long and short. They changed *one thing at a time* and kept the wind, the tilt and the wing area the same, and they wrote every number in tables. Their results showed that long, narrow wings gave much better lift for their drag. Their 1902 glider had wings about 9.8 meters long and 1.5 meters wide, roughly twice as slender as the 1901 glider. With it they made hundreds of good glides that fall.

The big idea. The Wrights' method is the heart of every experiment. Start with a **question** you can measure. Make a **prediction** with a reason. Choose one **independent variable** to change. Decide on the **dependent variable** you will measure. List the **controlled variables** you will keep the same. Run several **trials** for each setting and find the average, because no two drops or throws are exactly alike. Put your results in a table and a graph, look for a pattern, and write a conclusion that says what you found, even if your prediction was wrong. An honest record of a failed prediction taught the Wrights more than any lucky success.

Try it and see. In this lab you will test a paper helicopter, which spins as it falls like a maple seed. Its two rotor blades are pushed up by the air as it drops and are tilted so that the air also pushes them sideways, which sets them turning. The spinning blades act like a wing moving through the air and make enough lift to slow the fall. You will change the rotor length and measure the fall time. If you have extra time, you will also fly a paper glider from a measured height and work out its **glide ratio**, the same number engineers use to rate sailplanes. Modern sailplanes can travel more than 40 meters forward for each meter they drop.

God's handiwork. Long before any paper helicopter, God made seeds that fly. A maple seed's single wing is weighted at the seed end and spins as it falls, so a gust can carry it far from its parent tree to find open ground. The dandelion floats on a parachute of fine hairs. When we test and measure these designs, we are doing what the psalmist describes: "The works of the LORD are great, sought out of all them that have pleasure therein" (Psalm 111:2).



Paper helicopter pattern. Solid lines are cuts; dashed lines are folds. Fold blade A toward you and blade B away from you.

PICTURE STUDY



First Flight, December 17, 1903, Photograph by John T. Daniels, using the Wright brothers' camera, December 17, 1903 · Glass-plate photographic negative · Library of Congress, Washington, D.C.

Orville Wright set up the brothers' camera on a tripod, aimed it at the end of the launching rail and asked John T. Daniels, a man from the nearby lifesaving station who had come to help, to squeeze the rubber bulb if the machine got into the air. Daniels had never taken a

photograph before. He snapped the shutter just as the Flyer rose a little above the rail at about 10:35 in the morning.

This photograph became one of the most famous pictures ever taken. It records the moment that four years of watching buzzards, twisting boxes, flying kites, testing gliders and measuring model wings in a wind tunnel finally paid off.

Look closely

- Find Orville. Where is he lying, and what does that tell you about how the Flyer was steered?
- Find Wilbur. He has been running alongside to steady the wing. What is he doing now?
- Look for the front elevator and the rear rudder. Which direction is each meant to control?
- Look at the ground. What do you see that shows where the Flyer started its run?

Talk about it

1. The Flyer’s first flight lasted only about 12 seconds. Why was it still such an important moment?
2. What tests did the Wrights run before this day that made success possible?
3. Daniels had never used a camera. Why does it matter for science that someone recorded this moment?

> **Safety first.** Use scissors carefully. When dropping helicopters from a height, stand on a sturdy step stool or the bottom of a staircase with an adult watching; never stand on a chair with wheels, a table or a railing. Keep the landing area clear of people and pets.

EXPERIMENT: THE PAPER HELICOPTER EXPERIMENT

You will run a full fair test, just as the Wrights did with their model wings. You will change the length of a paper helicopter’s rotor blades and measure how long it takes to fall a fixed distance. Then you will graph your data and write a conclusion.

You will need

- Several sheets of plain printer paper (all the same kind)
- Scissors, ruler marked in centimeters and a pencil
- Small paper clips, all the same size
- Stopwatch (a phone timer works)
- Tape measure and masking tape to mark a 2.0 m drop height on a wall or doorframe
- A helper, a sturdy step stool, lab notebook and graph paper

Steps

1. **Question:** How does the length of the rotor blades affect the time a paper helicopter takes to fall 2.0 meters? Write your **prediction** and the reason for it.

2. Make four helicopters from strips 5 cm wide, following the pattern. Keep the body the same each time (6 cm long, with the same side cuts and one paper clip), but make the rotor blades 4 cm, 6 cm, 8 cm and 10 cm long. So the strips are 10, 12, 14 and 16 cm long.
3. Mark a height of 2.0 m on a wall. Hold each helicopter by the paper clip with the blades level with the mark, and let go without pushing. Your helper starts the stopwatch at release and stops it when the helicopter touches the floor.
4. Do five trials for each rotor length. If a helicopter hits a wall or fails to spin, mark the trial and repeat it.
5. **What we change (independent variable):** rotor length. **What we measure (dependent variable):** fall time in seconds. **What we keep the same (controlled variables):** paper type, strip width, body length, paper clips, drop height, the way it is released and the room (no fans or open windows).
6. Record a table: Rotor length (cm), Trials 1 to 5 (s), Average (s). Plot the averages on a line graph with rotor length on the horizontal axis and fall time on the vertical axis.
7. Write a conclusion: Was your prediction right? What pattern did you find? Which result surprised you? What would you test next?

Tips

- Reaction time causes most timing error. Have the same person run the stopwatch for every trial so the error is about the same each time.
- Very long blades may flop instead of spinning. That is a real result; record it.
- Extra test: fly a paper glider from a measured launch height, measure how far forward it lands and divide distance by height to find its glide ratio.

Check your work

- I changed only one variable and listed my controlled variables.
- I did five trials for each setting and averaged them correctly.
- My graph has a title, labeled axes with units and evenly spaced scales.
- My conclusion says what I found, honestly, even where it did not match my prediction.

NATURE NOTEBOOK

1. Draw the Wrights' wind tunnel as you imagine it from the description: a long box, a fan at one end, a model wing on a balance inside. Label the parts and draw arrows for the airflow.
2. Draw your fastest-falling and slowest-falling helicopters side by side, full size, and write their average fall times beneath them.
3. Collect and press a maple seed, an ash seed or a dandelion seed head (or draw one from a photo). Label the part that acts as a wing or a parachute.

> **From history.** In the autumn of 1902 the Wrights returned to Kill Devil Hills with their new glider, built from their wind tunnel measurements, and made hundreds of glides,

some longer than 180 meters. During that season they added a movable rudder and connected it to the wing-warping controls, so the glider could roll and turn smoothly together. It was the first craft with working control of pitch, roll and yaw. They applied for a patent on their control system in March 1903, and it was granted in 1906. The only big piece still missing was power: an engine and propellers, which they built themselves that next year with the help of their mechanic, Charlie Taylor.

WORKED EXAMPLES

Example 1. A helicopter with 8 cm blades fell 2.0 m in five trials: 2.1 s, 2.3 s, 2.0 s, 2.2 s and 1.9 s. Find the average fall time and the average speed of the fall.

1. Add the trials: 2.1 + 2.3 + 2.0 + 2.2 + 1.9 = 10.5 s.
2. Divide by the number of trials: 10.5 ÷ 5 = 2.1 s.
3. Average speed = distance ÷ time = 2.0 m ÷ 2.1 s ≈ 0.95 m/s.

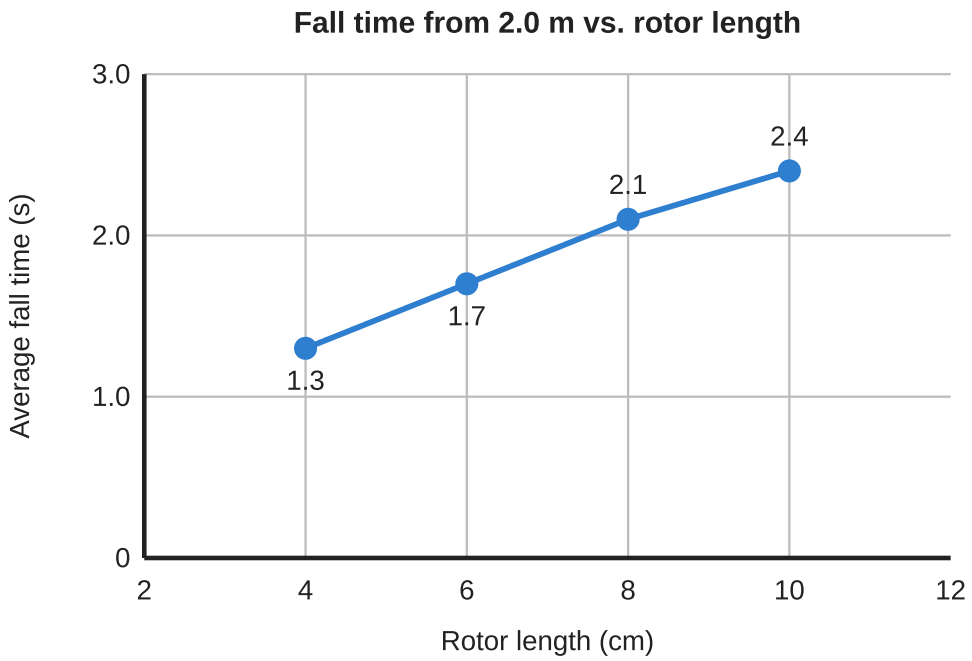
Answer: The average fall time is 2.1 seconds, and the helicopter fell at about 0.95 meters per second, a little less than 1 meter each second.

Example 2. A paper glider launched from a height of 1.5 m lands 6.0 m in front of the launch line. A second glider launched from the same height lands 9.0 m away. Find the glide ratio of each.

1. Glide ratio = horizontal distance ÷ height lost.
2. Glider 1: 6.0 m ÷ 1.5 m = 4.0.
3. Glider 2: 9.0 m ÷ 1.5 m = 6.0.

Answer: Glider 1 has a glide ratio of 4 (4 m forward for each meter down) and glider 2 has a glide ratio of 6, so glider 2 is the more efficient glider.

Example 3. Sample class data: rotor 4 cm, average 1.3 s; 6 cm, 1.7 s; 8 cm, 2.1 s; 10 cm, 2.4 s. Use the line graph to describe the pattern and estimate the fall time for a 7 cm rotor.



Sample data: average fall time from 2.0 m for four rotor lengths.

1. Read the graph from left to right: as rotor length increases, fall time increases.
2. Find the increase for each 2 cm step: 1.7 − 1.3 = 0.4 s; 2.1 − 1.7 = 0.4 s; 2.4 − 2.1 = 0.3 s. The rise is slowing slightly.
3. A 7 cm rotor is halfway between 6 cm and 8 cm, so estimate halfway between 1.7 s and 2.1 s: (1.7 + 2.1) ÷ 2 = 1.9 s.

Answer: Longer rotors fall more slowly, with each extra 2 cm adding about 0.3 to 0.4 seconds. A 7 cm rotor should take about 1.9 seconds. (Estimating between measured points is called interpolation and is safer than guessing far beyond your data.)

PRACTICE

1. EASY In the paper helicopter experiment, what is the independent variable and what is the dependent variable?
2. EASY Why do scientists repeat each trial several times and average the results?
3. EASY Name four controlled variables in the helicopter experiment.
4. MEDIUM Fall times for one helicopter were 1.8 s, 2.0 s, 1.9 s and 2.3 s. Find the average.
5. MEDIUM A glider launched from 1.2 m lands 7.2 m away. What is its glide ratio? From how high would you need to launch it to reach 12 m?

6. MEDIUM Data reading. Use the line graph of rotor length and fall time. (a) Estimate the fall time for a 9 cm rotor. (b) Which 2 cm step gave the smallest increase in fall time? *(Use the map or drawing "Sample data from four rotor lengths." shown earlier in this lesson.)*
7. MEDIUM Data reading. A student kept the rotor at 8 cm and changed the number of paper clips: 1 clip, trials 2.2, 2.1, 2.3 s; 2 clips, trials 1.7, 1.8, 1.6 s; 3 clips, trials 1.4, 1.3, 2.4 s. (a) Find each average. (b) One trial looks wrong. Which one, and what should the student do?
8. HARD A student made a helicopter with 10 cm blades out of card stock and one with 4 cm blades out of tissue paper and found the card stock one fell more slowly. Explain why this test cannot tell what caused the difference, and how to fix it.
9. HARD Experiment design. Design an experiment to test whether wing area affects how far a paper glider glides. Include a question, a prediction, the independent, dependent and controlled variables, and how many trials you will do.
10. CHALLENGE The Wrights' 1901 glider had wings about 6.7 m long and 2.1 m wide. Their 1902 glider, designed after the wind tunnel tests, had wings about 9.8 m long and 1.5 m wide. Find the aspect ratio of each and explain what the change shows about their wind tunnel results.

COMMON MISTAKES

- Changing two things at once, such as blade length and paper type. Then no one can tell which change caused the result. Change only one variable at a time.
- Trusting a single trial. One drop can be thrown off by a draft or a slow thumb on the stopwatch. Repeat and average.
- Hiding or erasing results that do not fit the prediction. A surprising result must be checked and recorded honestly; sometimes it is the most important result of all, as the Wrights found in 1901.

> **Make it a game · Variable Detective.** A caller describes a quick experiment, sometimes fair and sometimes flawed: "Sam dropped a big helicopter from the stairs and a small one from the table to see which falls slower." The detectives race to call out "Fair!" or "Foul!" and, if foul, name the extra variable that changed (here, drop height). Score one point for the right call and one for naming the hidden variable. Then trade roles and invent your own tricky experiments.

> **Scripture.** "The works of the LORD are great, sought out of all them that have pleasure therein." (Psalm 111:2, KJV)

This verse was carved over the doorway of the Cavendish Laboratory in Cambridge, England, in the Latin of the Vulgate. Every careful experiment is a way of seeking out the works of the Lord with delight.

Practice answers

1. Independent variable: the rotor (blade) length. Dependent variable: the time it takes to fall 2.0 m.
2. Every measurement varies a little because of reaction time, small air currents and slight differences in release. Averaging several trials reduces the effect of these random errors and gives a more trustworthy value.
3. Any four of: paper type, strip width, body length, number and size of paper clips, drop height, how it is released, the person timing, no fans or drafts in the room.
4. 1.8 + 2.0 + 1.9 + 2.3 = 8.0 s; 8.0 ÷ 4 = 2.0 s.
5. 7.2 ÷ 1.2 = 6. To travel 12 m with a glide ratio of 6, it needs 12 ÷ 6 = 2.0 m of height.
6. (a) About 2.25 s, halfway between 2.1 s (8 cm) and 2.4 s (10 cm); 2.2 to 2.3 s is acceptable. (b) From 8 cm to 10 cm (an increase of 0.3 s, compared with 0.4 s for the other steps).
7. (a) 1 clip: 6.6 ÷ 3 = 2.2 s. 2 clips: 5.1 ÷ 3 = 1.7 s. 3 clips: 5.1 ÷ 3 = 1.7 s as written. (b) The 2.4 s trial with 3 clips does not fit the pattern (the others are 1.3 and 1.4 s). The student should note it, look for a cause (perhaps a slow stopwatch press or a draft) and run another trial rather than quietly erase it. Without it, the 3-clip average would be about 1.35 s, so more mass makes the helicopter fall faster.
8. Two variables were changed at once: blade length and paper type (which also changes mass and stiffness). Either one could have caused the difference. To fix it, make both helicopters from the same paper and change only the blade length, then test paper type separately with the blade length held the same.
9. Sample answer. Question: Does a larger wing area make a glider glide farther? Prediction: a larger wing will glide farther because it makes more lift at low speed. Independent variable: wing area (for example 80, 120 and 160 cm^2, all with the same aspect ratio). Dependent variable: glide distance in cm. Controlled: paper type, fuselage, tail, nose weight adjusted to the same balance point, launch height, launch spot and gentle push, calm indoor air. Do five trials for each wing and average them.
10. 1901: 6.7 ÷ 2.1 ≈ 3.2. 1902: 9.8 ÷ 1.5 ≈ 6.5. The aspect ratio about doubled. The wind tunnel had shown that long, narrow wings give more lift for their drag, so they built a much more slender wing, the same lesson the albatross teaches.

Unit 1 review

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

1. (5 pts) Multiple choice. In steady, level flight at a constant speed, which statement is true? (a) Lift is greater than weight. (b) Thrust equals drag and lift equals weight. (c) Drag is greater than thrust. (d) There is no weight while flying.
2. (5 pts) What did Wilbur Wright notice about buzzards in 1899, and how did a twisted cardboard box help him copy it?
3. (5 pts) A vulture glides into a thermal where the air rises 2.0 m each second. In still air the bird sinks 0.8 m each second. How fast does it climb, and how much height does it gain in 90 seconds?
4. (5 pts) Multiple choice. A pilot lifts the right wingtip and lowers the left wingtip. This motion is called: (a) pitch (b) yaw (c) roll (d) drag.
5. (5 pts) A bird’s wing has a span of 1.2 m and an average chord of 0.15 m. Find its aspect ratio. Would you expect this bird to be a forest songbird or an open-sea glider? Explain.
6. (5 pts) Data reading. Bird A: mass 0.8 kg, wing area 0.13 m². Bird B: mass 1.5 kg, wing area 0.45 m². Find the wing loading of each. Which bird can fly more slowly without stalling, and which wing shape would you expect it to have?
7. (5 pts) Explain what happens to the air over a wing when the angle of attack becomes too steep. What is this called?
8. (5 pts) Multiple choice. Which insect flies with only two wings and has halteres in place of its hind wings? (a) honeybee (b) dragonfly (c) housefly (d) ladybug beetle.
9. (6 pts) A mosquito beats its wings about 500 times a second. (a) How many beats is that in one minute? (b) How long does one wingbeat take, in milliseconds?
10. (6 pts) Explain how a fly’s indirect flight muscles move its wings even though the muscles do not touch the wings.
11. (8 pts) Diagram and experiment. (a) Draw a bird in flight and label four arrows for lift, weight, thrust and drag. (b) A student wants to know whether the number of paper clips changes how fast a paper helicopter falls. Name the independent variable, the dependent variable and three controlled variables, and say how many trials you would do and why.

Unit project: design a bird-inspired glider

Choose one of the four bird wing shapes (elliptical, high-speed, long and narrow, or slotted soaring) and design a paper or card glider that copies it. Draw the bird and your glider side by side in your notebook with measurements, and calculate your wing’s area, aspect ratio and wing loading (mass ÷ area).

Then run a fair test comparing your bird-inspired glider with a plain rectangular wing of the same area: launch each from the same height at least five times, measure the glide distance, average the trials and calculate each glide ratio. Present a one-page report with your

question, prediction, variables, data table, bar graph and a paragraph explaining your results and how the bird's wing fits its way of life.

- **Observation and design**: The bird and glider drawings are careful and labeled, and the glider clearly copies the chosen wing shape, with correct measurements of span, chord and area.
- **Fair test**: Only the wing shape changes; controlled variables are listed and kept the same; at least five trials are run for each glider.
- **Data and math**: The data table, averages, aspect ratio, wing loading and glide ratios are correct and shown with units; the graph has a title and labeled axes.
- **Explanation**: The conclusion states the result honestly, compares it with the prediction and explains it using lift, drag and the bird's way of life.

Answer key

1. (b) Thrust equals drag and lift equals weight.
2. He noticed that a buzzard tipped by a gust regained its balance by twisting its wingtips, one up and one down. Twisting an empty inner-tube box showed him how two wings could be twisted in opposite directions, which became wing warping for roll control.
3. 2.0 − 0.8 = 1.2 m/s upward. 1.2 m/s × 90 s = 108 m.
4. (c) roll.
5. 1.2 ÷ 0.15 = 8. That is a fairly high aspect ratio (a sparrow is about 4, an albatross about 15), so it is more like a good glider over open country or water, such as a gull, than a forest songbird with short rounded wings.
6. A: 0.8 ÷ 0.13 ≈ 6.2 kg/m². B: 1.5 ÷ 0.45 ≈ 3.3 kg/m². Bird B has the lower wing loading, so it can fly more slowly; it is likely a slotted soaring wing like a vulture's. (Bird A matches a peregrine falcon.)
7. The air can no longer follow the curved top of the wing; it breaks away into swirls, lift drops suddenly and drag rises. This is called a stall.
8. (c) housefly.
9. (a) 500 × 60 = 30,000 beats per minute. (b) 1 ÷ 500 = 0.002 s = 2 milliseconds.
10. The wing rests on the side wall of the thorax like a lever on a pivot, with its inner end attached to the roof of the thorax. One set of muscles pulls the roof down, which levers the wings up. Another set shortens the thorax from front to back, the roof bulges up, and the wings go down. The springy thorax and muscles vibrate fast enough for about 200 beats a second.
11. (a) Lift arrow pointing up from the body, weight arrow pointing down, thrust arrow pointing forward in the direction of flight and drag arrow pointing backward; all four labeled (4 points). (b) Independent: number of paper clips. Dependent: fall time (or fall speed). Controlled (any three): rotor length, paper type, strip width, body length, drop height, release method, no drafts, same timer. At least three to five trials for each setting, averaged, because single measurements vary (4 points).

UNIT 2

Migration

Every spring and autumn, billions of animals set out on journeys across continents and oceans, and most of them arrive on time at places they have never been taught to find. In this unit you will follow the Arctic tern from Greenland to the edge of Antarctica and back, the longest yearly migration ever measured. You will climb a Mexican mountain with Fred Urquhart to find the winter home of the monarch butterfly, sit with Stephen Emlen as his buntings hop under a planetarium sky, and hold in your imagination the “arrow stork” that flew from Africa to Germany with a spear through its neck.

Along the way you will work like a real field scientist. You will calculate distances and daily rates from tracking data, estimate a population by tag and recapture, read footprint counts from an orientation cage, measure the angle between a sun compass and a magnetic compass, and graph the changing length of the day where you live. You will learn why animals migrate (food, daylight and the right place to raise young), how they find their way (sun, stars, the earth’s magnetic field and landmarks), and how they know when to go (day length and an inner yearly clock).

The unit ends with the words of Jeremiah: “the stork in the heaven knoweth her appointed times.” God built a calendar and a compass into creatures as small as a half-gram butterfly and as large as a stork. Watching them keep their appointed times is a lesson in wonder, and a call for us to be at least as faithful as the birds.

BEFORE YOU BEGIN

- Can multiply and divide multi-digit numbers and decimals, and find a percent
- Knows the compass directions (N, NE, E, and so on) and can read a simple world map with the equator
- Knows that the earth’s tilt causes the seasons and that the hemispheres have opposite seasons
- Has completed Unit 1 (Flight) or knows the basic difference between long, narrow wings and short, rounded wings

MASTERY CHECKLIST

- I can define migration and describe the Arctic tern’s yearly route and why it lives in two summers.
- I can explain the monarch’s generations, including the super generation, and use tag-and-recapture data to estimate a population.
- I can describe how birds use a sun compass, a star compass and a magnetic compass, and explain the difference between a compass sense and a map sense.
- I can explain how photoperiod and an inner yearly clock set the timing of migration, and how storks soar on thermals.
- I can calculate rates, percents, averages and glide distances from migration data.

- I can explain what Jeremiah 8:7 teaches by comparing the birds' faithfulness with people's.

OPTIONAL BOOKS AND RESOURCES

- **Monarch Watch (University of Kansas)** (https://www.monarchwatch.org/): Information on monarch biology and migration, and the fall tagging program in which families and schools can order tags and report recoveries. Pairs with Lesson 2.2.
- **Journey North** (https://journeynorth.org/): Free. Maps of first sightings of monarchs, hummingbirds, orioles and other migrants reported by ordinary people each season. Use it for the arrival dates in the Lesson 2.4 project, and report your own sightings.
- **All About Birds, from the Cornell Lab of Ornithology** (https://www.allaboutbirds.org/): Free. Bird identification guides with range maps that show breeding and wintering areas, plus sounds and photos. Look up the Arctic tern, the indigo bunting and the birds in your own yard.

2.1 Arctic Terns: Pole to Pole ★

OBJECTIVES

- Define migration and describe the yearly round trip of the Arctic tern between its Arctic nesting grounds and Antarctic waters.
- Explain how a light-level geolocator lets scientists track a 100-gram bird across the world, and calculate what fraction of a bird's mass a tag may safely be.
- Use the tilt of the earth to explain why the Arctic tern lives in two summers each year, and compute distances and daily rates from tracking data.

Warm-up. Hold a single paper clip in one hand and a bar of soap or a small apple (about 100 grams) in the other. The paper clip is close to the mass of the tracker scientists put on an Arctic tern; the soap is close to the mass of the bird. Close your eyes. Could you fly to the bottom of the world and back carrying that paper clip? Write one guess: how far do you think a tern flies in a year?

Video. Coming soon. Arctic tern migration and geolocator tracking; search nature footage channels, Cornell Lab of Ornithology, the Smithsonian, BBC Earth clips of terns diving and nesting, and Homeschool Pop (Alternate) or SciShow Kids for bird migration basics.

KEY TERMS

migration
A regular round trip that an animal makes each year (or each season) between two places, usually between where it breeds and where it finds food in the other season.

breeding grounds
The place where a migrating animal mates, builds a nest or den and raises its young.

wintering grounds
The place where a migrating animal spends the season when it is not breeding. For the Arctic tern, this is the edge of the Antarctic pack ice during the southern summer.

geolocator
A tiny tag that records light level and time. From the length of each day and the time of local noon, scientists can estimate where the animal was.

stopover
A place where a migrating animal rests and feeds for days or weeks partway through its journey.

latitude
How far north or south of the equator a place is, measured in degrees from 0° at the equator to 90° at the poles.

CORE IDEAS

The story. In the summer of 2007, a Danish biologist named Carsten Egevang and his team worked among the nesting Arctic terns on Sand Island, a low gravel island off the northeast coast of Greenland. Arctic terns are slim gray and white seabirds with a black cap, a blood-red bill and a long forked tail. Each one weighs only about 100 grams. The scientists gently caught dozens of terns at their nests and fastened to a plastic leg ring a tiny tracker called a **geolocator**, which weighed only 1.4 grams. The next summer the terns came back to the very same island, and the team caught some of the same birds again. When they read the trackers and published the results in 2010, the world was amazed: in one year the average tern had flown about **70,900 kilometers**, the longest yearly migration ever measured for any animal.

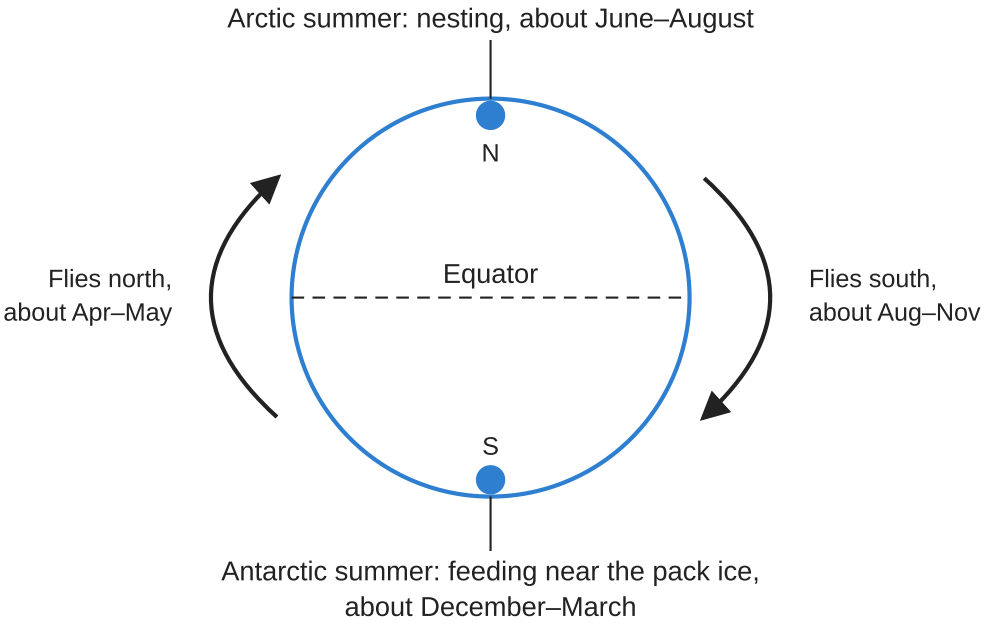
How they figured it out. A geolocator has no satellite radio. It simply records how bright the light is, over and over, along with the time. That turns out to be enough. The *length of the day* tells how far north or south the bird was (its latitude), because days are long near the poles in summer and close to 12 hours at the equator. The *time of local noon*, when the sun is highest, tells how far east or west it was, because noon comes later the farther west you go. The method is only accurate to a hundred kilometers or two, but on a trip of tens of thousands of kilometers that is plenty. The tracks showed the terns leaving Greenland in August and September, then stopping for about three or four weeks in the middle of the North Atlantic to feed in rich waters. That **stopover** was like a filling station. Then some birds followed the coast of West Africa while others crossed to the coast of Brazil. All of them ended up near the edge of the Antarctic pack ice in the Weddell Sea. In spring they came home in a giant S-shaped path up the middle of the Atlantic, riding the great wind belts, and the trip north was much faster than the trip south.

The big idea. Migration is a regular round trip between two places, timed by the seasons. Animals migrate to follow food and good conditions for raising young, not simply to escape the cold. The Arctic tern's secret is the tilt of the earth. Because the earth's axis is tilted about 23.5°, the Northern Hemisphere has summer while the Southern Hemisphere has winter, and six months later the seasons swap. By nesting in the Arctic in June and July and feeding near Antarctica from about December to March, the tern lives in **two summers every year**. Near both poles in summer the sun barely sets, so the Arctic tern probably sees more daylight than any other creature on earth. Long days mean long hours for catching small fish and krill, and the polar seas in summer swarm with food.

Built for the trip. Remember the wing shapes from Unit 1. The Arctic tern has long, narrow, pointed wings, spanning about 76 to 85 centimeters on a body only about 33 to 36 centimeters long. Wings like these glide and flap with very little wasted energy. The tern feeds on the way by hovering and then plunge-diving into the sea for small fish. It is also long-lived: banded terns have been found alive more than 30 years after they were first banded. A tern that lives 30 years may fly more than 2 million kilometers in its lifetime, enough to fly to the moon and back nearly three times.

In the world today. Tracking has gone on since Egevang's study. Terns tracked from the Farne Islands, off the coast of northeast England, wandered even farther; one bird's yearly trip was measured at about 96,000 kilometers. You can join this work in a small way. Bird-banding offices in many countries collect reports from ordinary people who find a banded bird, and every report adds a dot to the map.

God's handiwork. A bird the mass of a bar of soap crosses the whole planet, finds a stopover in the open ocean, and comes back to the same gravel island it left a year before. No one gave it a map. David wrote, "If I take the wings of the morning, and dwell in the uttermost parts of the sea; Even there shall thy hand lead me" (Psalm 139:9–10). The tern lives in those uttermost parts, and the same hand leads it.



The Arctic tern's year: it lives in the northern summer and then the southern summer. (Diagram, not to scale; months are approximate.)

PICTURE STUDY



Arctic Tern, from The Birds of America, John James Audubon (engraved by Robert Havell Jr.), 1827–1838 (published in parts) · Hand-colored engraving and aquatint · Audubon's original watercolors are at the New-York Historical Society; prints of the engraved plates are in many libraries and museums.

John James Audubon (1785–1851) set out to paint every bird of North America life-size. He studied living birds in the field and posed his specimens on wires so they looked alive. His paintings were engraved on copper and colored by hand in London by Robert Havell Jr., and published as *The Birds of America*, 435 giant plates in all.

Audubon knew the Arctic tern from the cold northern coasts of North America. He did not know where it went in winter. In the 1900s, banded terns found far in the Southern Hemisphere showed where they go, and more than 150 years after Audubon, trackers like Egevang's mapped the whole route. As you look, think about which parts of this bird are built for a trip from pole to pole.

Look closely

- Find the black cap, the red bill and the red legs. How did Audubon make the bird stand out from the background?
- Look at the tail. What shape is it? Why might a bird that hovers and turns quickly over the water need a tail like this?
- Study the wings. Are they long and narrow or short and rounded? What did you learn in Unit 1 about wings of that shape?
- Is the bird shown resting or in motion? What clues tell you?

Talk about it

1. Audubon painted this bird without knowing it flew to Antarctica. What would you add to the picture now that we know?
2. Why do you think Audubon chose to paint birds life-size, even though it made his book enormous and costly?

EXPERIMENT: THE BACKPACK TEST: DOES EXTRA MASS SHORTEN A FLIGHT?

Bird researchers follow a rule of thumb: a tracking tag should be only a small fraction of the bird's body mass, often less than about 3 percent. In this experiment you will find out why, using paper gliders as your "birds" and paper clips as "trackers."

Question: How does adding mass to a glider change how far it flies? **Prediction:** Write yours before you begin. **What we change:** the number of paper clips. **What we keep the same:** the glider design, the launch height, the launch push and the room. **What we measure:** the glide distance in centimeters.

You will need

- Three sheets of the same printer paper
- Six small paper clips of the same size
- A kitchen scale that reads in grams
- A metric tape measure or meter stick
- Masking tape to mark the launch line
- Lab notebook and pencil

Steps

1. Fold one sheet into a simple dart glider. Weigh it on the kitchen scale and record its mass in grams. Weigh three paper clips together and divide by 3 to find the mass of one clip.
2. Mark a launch line on the floor with tape. Stand behind it and launch the glider at shoulder height with a gentle, level push. Practice until your launches feel the same each time.
3. Fly the glider 5 times with no paper clips. Measure each distance from the line to where the nose first touches the floor. Record all 5 distances.
4. Clip 1 paper clip to the bottom of the glider, under its middle. Fly 5 times and record. Repeat with 2 clips and then 3 clips, always in the same spot.
5. For each trial, find the average of the 5 distances. Also find the clips' mass as a percent of the glider's mass: (mass of clips ÷ mass of glider) × 100.
6. Make a bar graph with "Percent added mass" on the horizontal axis and "Average glide distance (cm)" on the vertical axis.
7. Write a conclusion: Did adding mass change the flight? About what percent of added mass first made a clear difference?

Tips

- A single throw can be lucky or unlucky. That is why you fly 5 times and average.
- If the clips make the glider nose-dive at once, move them a little toward the back and keep them in that new spot for every trial.
- A paper glider is a model, not a bird. A real tern flaps, adjusts and can carry extra fat. But the model shows why scientists keep tags small.

Check your work

- I named the variable I changed, the variables I kept the same, and what I measured.
- I flew each trial 5 times and found the average.
- I calculated the added mass as a percent of the glider's mass and graphed my results.

NATURE NOTEBOOK

1. Draw an Arctic tern from a photograph or Audubon's plate. Label the black cap, red bill, forked tail and long pointed wings, and write next to each label how it helps on a long flight.
2. Draw a globe and trace the tern's route: Greenland, the North Atlantic stopover, the coasts of Africa and Brazil, the Weddell Sea, and the S-shaped path home. Mark the equator.
3. Make a two-column chart titled "Two Summers." In one column list what the tern finds in the Arctic in June; in the other, what it finds near Antarctica in January.

> **From history.** Long before geolocators, John James Audubon wondered whether birds return to the same place each year. Around 1803, as a young man living at Mill Grove, his family's farm near Philadelphia, he tied a fine silver thread around the legs of young eastern phoebes in a nest near a creek. The next spring he found phoebes wearing his threads nesting nearby. It is often called the first bird-banding experiment in America, and it asked the same question Egevang asked two centuries later: where does this bird go, and does it come back?

WORKED EXAMPLES

Example 1. An Arctic tern flies about 70,900 km each year. If it lives 30 years and migrates every year, about how far does it fly in a lifetime? The moon is about 384,400 km from the earth. How many trips to the moon *and back* is that?

1. Lifetime distance: 70,900 km × 30 = 2,127,000 km, or about 2.1 million km.
2. One trip to the moon and back: 384,400 km × 2 = 768,800 km.
3. Number of round trips: 2,127,000 ÷ 768,800 ≈ 2.77.

Answer: About 2.1 million kilometers, nearly 3 round trips to the moon (about 2.8).

Example 2. The geolocators in the Greenland study weighed 1.4 g, and an Arctic tern weighs about 100 g. What percent of the bird's mass is the tag? Many researchers keep tags under about 3 percent of body mass. What is the heaviest tag that would follow that guideline for a 100 g tern?

1. Percent of body mass = (tag mass ÷ bird mass) × 100.
2. (1.4 g ÷ 100 g) × 100 = 1.4%.
3. Heaviest tag under the 3 percent guideline: 0.03 × 100 g = 3 g.
4. Compare: 1.4 g is less than half of 3 g, so the tag is well within the guideline.

Answer: The tag is 1.4% of the bird's mass. The guideline allows up to about 3 g.

Example 3. Suppose a tracker shows that a tern flew about 25,000 km on its trip north in 40 days. What was its average distance per day? If it were flying all 24 hours of each day, what would its average speed be in km per hour?

1. Average per day = total distance ÷ days = 25,000 km ÷ 40 days = 625 km per day.
2. Average per hour = 625 km ÷ 24 hours ≈ 26 km per hour.
3. Real terns stop to feed and rest, so their actual flying speed is faster than this average. The average counts the resting time too.

Answer: 625 km per day, or about 26 km per hour averaged over the whole day.

PRACTICE

1. EASY Define migration in your own words. Name the Arctic tern's breeding grounds and its wintering grounds.
2. EASY What two things does a geolocator record? Which one tells latitude and which tells longitude?
3. EASY Why does the Arctic tern see more daylight than almost any other animal?
4. MEDIUM The distance around the earth at the equator is about 40,075 km. About how many times around the earth is one year of tern migration (70,900 km)?
5. MEDIUM Data reading. A student made this table of sample geolocator estimates for one tern (positive latitude = north, negative = south):
   June: 74° August: 72° September: 50° October: 15° November: −30° December: −62° January: −66° February: −65° March: −60° April: −25° May: 25°
   (a) Between which two months did the bird cross the equator going south? (b) Between which two months did it cross going north? (c) In how many of the listed months was it south of the equator?
6. MEDIUM Data reading. Tracking studies give these approximate yearly round-trip distances: Arctic tern 70,900 km; sooty shearwater (a Pacific seabird) 64,000 km. (a)

Which bird flew farther, and by how many kilometers? (b) By what percent is the tern's distance greater than the shearwater's? Round to the nearest whole percent.

7. MEDIUM A tern has a wingspan of 80 cm and a body length of 35 cm. Write the ratio of wingspan to body length as a decimal, rounded to one place. What does this tell you about its wing shape?
8. HARD The terns did not fly in a straight line. They paused for weeks in the middle of the North Atlantic and came home in an S-shaped path. Give two reasons a longer path could still be the better path.
9. HARD Experiment design. A scientist worries that carrying a 1.4 g geolocator might make terns less likely to return the next year. Describe an experiment to test this. Name the independent variable, the dependent variable, two things to keep the same, and the control group.
10. CHALLENGE One of the oldest Arctic terns ever recorded was 34 years old. If it migrated 70,900 km every year for 34 years, how far did it fly? How many times around the equator (40,075 km) is that, to the nearest whole number?

COMMON MISTAKES

- Thinking birds migrate mainly to escape the cold. Most migrants travel to follow food and good conditions for raising young; the Arctic tern actually flies *toward* the coldest continent, because its summer seas are rich in food.
- Thinking seasons come from the earth being closer to the sun. Seasons come from the tilt of the earth's axis, which is why the Northern and Southern Hemispheres have opposite seasons and the tern can enjoy two summers.
- Thinking a tracker must use a satellite. A light-level geolocator only records light and time; scientists work out the bird's path from day length and the time of noon after they recover the tag.

> **Make it a game · Tern Route Relay.** Tape signs in five rooms or spots in the yard: Greenland, North Atlantic Stopover, West Africa or Brazil, Weddell Sea, and back to Greenland. Each player is a tern. At each stop, a parent asks a question from this lesson (for example, "What does day length tell a geolocator?"). A right answer earns a "fish" token and lets you fly on; a wrong answer means you must "rest and feed" for one turn. The first tern back to Greenland with at least four fish wins.

> **Scripture.** "If I take the wings of the morning, and dwell in the uttermost parts of the sea; Even there shall thy hand lead me, and thy right hand shall hold me." (Psalm 139:9–10, KJV)

The Arctic tern really does dwell in the uttermost parts of the sea, from Greenland to the edge of Antarctica. David's point is that there is no place so far away that God is not there. The tern's journey is a picture of that: wherever it flies, it never leaves the hand that made it.

Practice answers

1. Migration is a regular round trip between two places that an animal makes with the seasons. The Arctic tern breeds in the Arctic (for example, Greenland) and spends the northern winter near the edge of the Antarctic pack ice (for example, the Weddell Sea).
2. It records light level and time. Day length tells latitude (north or south); the time of local noon tells longitude (east or west).
3. Because of the earth's tilt, it spends the northern summer in the Arctic and the southern summer near Antarctica. Near the poles in summer the sun barely sets, so it lives in nearly constant daylight in both summers.
4. 70,900 ÷ 40,075 ≈ 1.77, so about 1.8 times around the earth.
5. (a) Between October (15° N) and November (30° S). (b) Between April (25° S) and May (25° N). (c) Six months have negative latitude: November, December, January, February, March and April.
6. (a) The Arctic tern, by 70,900 − 64,000 = 6,900 km. (b) 6,900 ÷ 64,000 × 100 ≈ 10.8%, about 11% greater.
7. 80 ÷ 35 ≈ 2.3. The wings span more than twice the body length, so they are long and narrow, a shape that glides and flies long distances efficiently.
8. (1) The stopover had rich feeding waters, so the birds could refuel; a straight route over poor water could leave them starving. (2) The S-shaped path follows the great wind belts over the Atlantic, so tailwinds save energy even though the path is longer. (Other good answers: avoiding storms, following coasts with food.)
9. Sample answer: At the same colony in the same year, give trackers (on leg rings) to one group of terns and give only a plain leg ring of the same kind to a similar group. Independent variable: whether the bird carries a geolocator. Dependent variable: the percent of birds seen back at the colony the next year (or their nesting success). Keep the same: colony, year, age and sex mix of birds, how they are caught and handled, the leg ring. Control group: birds with a plain ring and no tracker. Compare the return rates of the two groups; similar rates suggest the tag does little harm.
10. 70,900 × 34 = 2,410,600 km, about 2.4 million km. 2,410,600 ÷ 40,075 ≈ 60.2, so about 60 times around the earth.

2.2 Monarchs to Mexico

OBJECTIVES

- Tell how Fred Urquhart’s tagging volunteers and the 1975 discovery in the mountains of Mexico solved the mystery of where eastern monarchs spend the winter.
- Describe the monarch’s complete metamorphosis and its yearly cycle of generations, including the long-lived “super generation” that makes the trip south.
- Use tag-and-recapture data to calculate rates, recovery percents and population estimates.

Warm-up. Pour about a cup of dried beans into a bowl. Without counting them all, how could you estimate how many there are? Write down one method. Then think: how could a scientist estimate how many butterflies live in a forest, when they can never count every one?

Video. Coming soon. Monarch butterfly migration to the mountain forests of Michoacán, Mexico, and monarch tagging; search nature footage channels, Smithsonian, U.S. Fish and Wildlife Service, Monarch Watch, Journey North, and Homeschool Pop (Alternate) or SciShow Kids for metamorphosis.

KEY TERMS

complete metamorphosis
A life cycle with four very different stages: egg, larva (caterpillar), pupa (chrysalis) and adult.

host plant
The one kind of plant a caterpillar can eat. Monarch caterpillars eat only milkweed.

diapause
A resting state in which an insect’s growth or breeding is paused. Fall monarchs are in a breeding diapause: they do not mate or lay eggs until spring.

super generation
The monarchs born in late summer that fly to Mexico, live about 8 months, and start the next spring’s journey north.

overwintering
Spending the winter in one place in a resting state, as monarchs do in the fir forests of Mexico.

tag and recapture
A method of marking animals, releasing them and later finding some of them again to learn where they went or how many there are.

CORE IDEAS

The story. Fred Urquhart, a zoologist at the University of Toronto, had wondered about monarch butterflies since he was a boy. Every autumn they disappeared to the south. Where were they going? In the 1940s he and his wife, Norah, began sticking tiny paper labels on monarch wings. Each label had a number and a request to send it back to the zoology department in Toronto. In 1952 they asked the public for help, and over the next twenty years thousands of volunteers, many of them schoolchildren and teachers, tagged monarchs across North America. The returned tags pointed southwest, toward Texas and Mexico, and then the trail went cold. In the early 1970s the Urquharts placed advertisements in Mexican newspapers asking for help. A man named Ken Brugger answered, and he and Catalina Aguado searched the mountains west of Mexico City by car and on foot. In January 1975 they found it: a mountainside forest where the fir trees were so heavy with butterflies that the branches sagged.

How they figured it out. In January 1976 Urquhart, then in his sixties, climbed the mountain to see for himself. While he sat among the orange clouds, a branch cracked under the weight of the butterflies and fell. On one of the monarchs from that branch was a white tag. It had been put on by a volunteer in Minnesota, more than 2,500 kilometers away. That single tag proved that the monarchs of the north really did fly to this mountain. This is how **tag and recapture** works: most tagged animals are never seen again, but each one that is found draws a line on the map, and many lines together show the path.

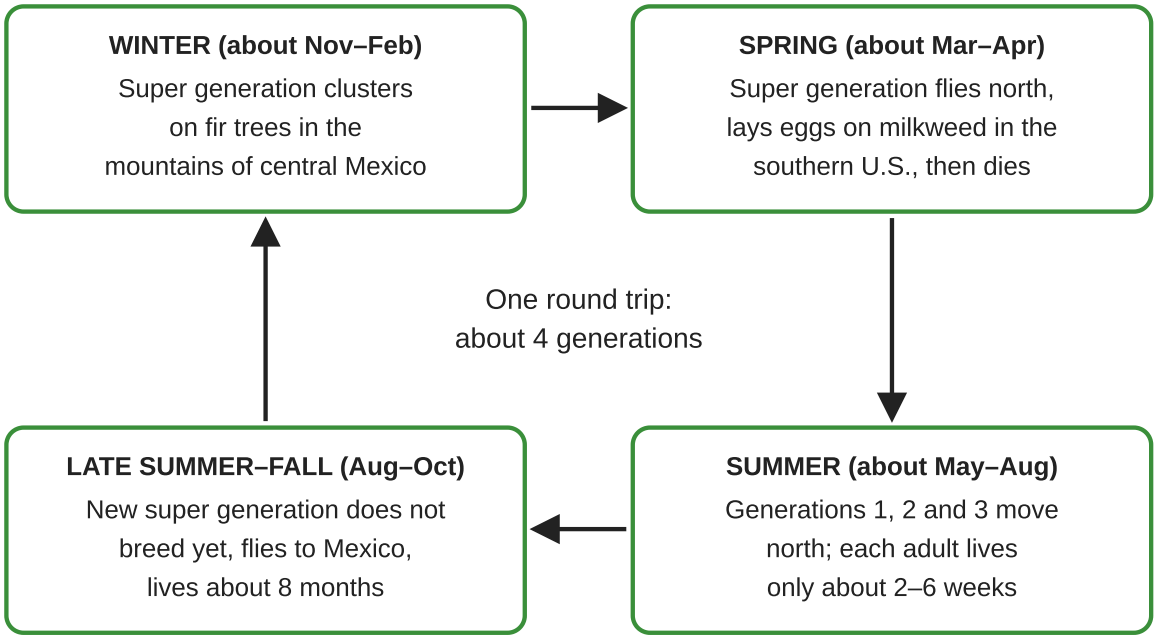
The big idea. Monarchs go through **complete metamorphosis**: egg, caterpillar, chrysalis and adult. A female lays her eggs only on milkweed, the monarch's **host plant**. In summer, an adult monarch lives only about 2 to 6 weeks. No summer butterfly could survive a trip to Mexico and back. But the butterflies that come out of their chrysalises in late summer are different. The shorter days, cooler nights and aging milkweed of late summer put them into **diapause**: they do not mate or lay eggs. Instead they drink nectar, store fat and fly south, as much as 4,000 kilometers or more. This **super generation** lives about 8 months. It overwinters in the oyamel fir forests about 3,000 meters up in the mountains of central Mexico, where it is cool enough to rest without using up stored fat but rarely cold enough to freeze. In late winter the butterflies wake, mate and fly north to Texas and the southern United States, lay eggs on the new milkweed and die. Their children and grandchildren move north in three or four short-lived generations until, the next August, a new super generation is born far in the north and the whole cycle begins again.

The great puzzle. Think about what that means. The monarch that flies to Mexico in October has never been there. Neither has its mother or its grandmother. Its last ancestor to make the trip was a great-great-grandparent, and yet it finds the same few mountains. Scientists have learned part of the answer. Monarchs steer by a **sun compass**: they fly at an angle to the sun and correct that angle as the sun moves across the sky. To do that, they need to know the time, and in 2009 researchers showed that monarchs keep time with tiny clocks in their antennae. When the antennae were painted black so they could not sense light, the butterflies lost their way; when they were painted with clear paint, they flew

correctly. Monarchs also seem to sense the earth's magnetic field. But how they find those exact mountains is still being studied.

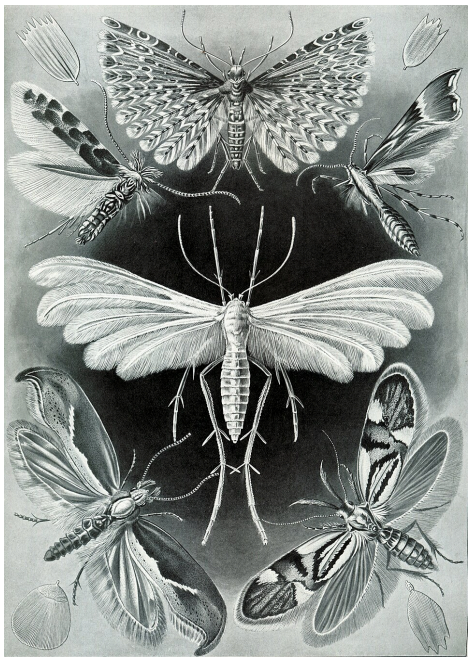
In the world today. Monarchs west of the Rocky Mountains fly a shorter route to groves of trees along the California coast. The eastern population still travels to Mexico. Groups such as Monarch Watch, at the University of Kansas, send tags to families and schools every fall, and Journey North collects sightings from ordinary people each spring. Many families plant milkweed in gardens and along fences so the summer generations have places to lay eggs. In Mexico, villagers who live near the forests guide visitors and help protect the trees.

God's handiwork. "To every thing there is a season, and a time to every purpose under the heaven" (Ecclesiastes 3:1). The monarch's whole year is a chain of seasons: a time to breed, a time to rest, a time to fly. A butterfly weighing about half a gram carries inside it, from egg to wing, the timing and the direction for a journey none of its parents could teach it.



The eastern monarch's year: about four generations make one round trip. (Months are approximate.)

PICTURE STUDY



Tineida (Plate 58), from Art Forms in Nature (Kunstformen der Natur), Ernst Haeckel, 1899–1904 (published in parts) · Lithograph · Published in Leipzig and Vienna; copies of the book are in many libraries and natural-history collections.

Ernst Haeckel (1834–1919) was a German zoologist who drew living things with great patience. His book *Art Forms in Nature* has 100 plates of creatures from jellyfish to hummingbirds, each arranged like a design.

This plate shows small moths, among them the feathery plume moths and the diamondback moth. Moths and butterflies together make up the order **Lepidoptera**, a name that means “scale wings”: the colors on their wings come from thousands of tiny overlapping scales, like shingles on a roof. Haeckel drew some of those scales greatly enlarged. The monarch belongs to this same order.

Look closely

- Count the moths on the page. How did Haeckel arrange them? Is the page itself symmetrical?
- Choose one moth. Is its left wing a mirror image of its right wing?
- Find a plume moth, whose wings are split into thin feathery strips. How do you think such a wing can still carry the moth through the air?
- Find the magnified drawings of wing scales. How are they like shingles on a roof?

Talk about it

1. If you added a monarch to this plate, where would you put it, and what colors would you use?

2. Haeckel arranged real animals to look like a work of design. What does that tell you about how he saw the living world?

EXPERIMENT: TAG AND RECAPTURE WITH BEANS

Scientists can never count every monarch, fish or deer. Instead they mark some, let them mix back into the population, then catch a sample and see how many are marked. If 1 out of every 5 in the sample is marked, then about 1 out of every 5 in the whole population is marked. This is called the tag-and-recapture (or mark-recapture) method, and you will test it with beans.

Question: How close does tag and recapture come to the true number? **Prediction:** Write yours. **What we change:** the size of the sample we take. **What we keep the same:** the number of marked beans, how well we mix, and the bowl. **What we measure:** how many marked beans are in each sample, and the estimate we calculate.

You will need

- About 2 cups of one kind of dried beans (white or light-colored beans work best)
- A marker
- A large bowl and a cup or scoop
- Calculator
- Lab notebook and pencil

Steps

1. Scoop out exactly 40 beans and mark each one with a dot of marker. These are your “tagged monarchs.” Let the ink dry.
2. Pour the 40 marked beans back into the bowl and mix very well with your hands for a full minute, so the tagged beans spread through the “forest.”
3. Without looking, scoop out a sample of about 30 beans. Count the total in the sample and the number that are marked. Record both.
4. Calculate your estimate: population ≈ (number marked at first × number in sample) ÷ (number marked in sample). Return the beans and mix again.
5. Repeat with a sample of about 60 beans and then about 100 beans. Record each estimate.
6. Finally, count every bean in the bowl to find the true number. For each sample size, find how far off your estimate was.
7. Write a conclusion: Did bigger samples give better estimates? Why does good mixing matter?

Tips

- If a sample has no marked beans at all, you cannot divide by zero. Take a bigger sample.

- Real monarch tags work only if tagged butterflies mix in and behave like untagged ones. That is why tags must be small and light.
- Do several samples of the same size and average them to see how much luck affects a single sample.

Check your work

- I used the tag-and-recapture formula correctly for each sample.
- I compared each estimate to the true count.
- I explained how sample size and mixing affect the estimate.

NATURE NOTEBOOK

1. Draw the four stages of the monarch's complete metamorphosis in a circle: egg on a milkweed leaf, striped caterpillar, green chrysalis with gold dots, and adult. Label each stage and give how long it lasts.
2. Draw the monarch's wing pattern: orange with black veins and a black border with white dots. Draw a male's hindwing with the small black spot on a vein, which females do not have.
3. On a map of North America, draw arrows for the monarch's fall trip south and the spring trips north by different generations. Mark the mountains of central Mexico.

> **From history.** After the overwintering forests became known, Mexico acted to protect them. The government set aside the butterfly mountains as protected land in 1986, and the area was later enlarged into the Monarch Butterfly Biosphere Reserve. In 2008 the reserve was named a World Heritage Site. Many of the guides who lead visitors up the trails are local farmers and their families, whose care for the forest now helps feed their own households.

WORKED EXAMPLES

Example 1. Suppose a monarch tagged near Toronto, Canada, on August 30 is found in the mountains of Michoacán, Mexico, 75 days later. The straight-line distance is about 3,300 km. What was its average distance per day?

1. Average distance per day = distance ÷ time.
2. 3,300 km ÷ 75 days = 44 km per day.
3. The real path was longer than a straight line, so the butterfly actually flew more than 44 km on an average day.

Answer: At least 44 km per day on average.

Example 2. Using round numbers, a summer monarch adult lives about 30 days and a super-generation monarch lives about 240 days (8 months). How many times longer does the super generation live? What fraction of a super-generation monarch's life would a summer monarch's whole adult life fill?

1. Ratio: 240 days ÷ 30 days = 8.
2. So the super generation lives about 8 times as long.
3. Fraction: 30 ÷ 240 = 1/8.

Answer: About 8 times as long; a summer adult's life is about 1/8 of a super-generation monarch's life.

Example 3. A team tags 40 monarchs in a meadow. Two days later they net 50 monarchs in the same meadow, and 8 of them have tags. Estimate the number of monarchs in the meadow.

1. In the sample, 8 out of 50 are tagged, or 8/50 = 0.16 (16%).
2. If 16% of the whole population is tagged, and 40 monarchs are tagged, then 0.16 × population = 40.
3. Population = 40 ÷ 0.16 = 250. (Shortcut: 40 × 50 ÷ 8 = 250.)

Answer: About 250 monarchs.

PRACTICE

1. EASY Name the four stages of complete metamorphosis in order.
2. EASY What is the monarch's host plant, and why does it matter for migration?
3. EASY Who found the monarchs' winter home in Mexico, and in what year?
4. MEDIUM How is the super generation different from the summer generations? Give three differences.
5. MEDIUM Data reading. A school tags monarchs each fall and records how many tags are later reported from Mexico.
   Year A: 200 tagged, 2 recovered
   Year B: 350 tagged, 3 recovered
   Year C: 500 tagged, 6 recovered
   Year D: 400 tagged, 2 recovered
   (a) Find the recovery percent for each year. (b) Which year had the highest recovery percent? (c) Why is the year with the most recoveries not automatically the year with the best recovery rate?
6. MEDIUM Data reading. In a flight-simulator study of fall monarchs, scientists recorded the percent of butterflies that flew in the normal southwest direction:
   Antennae untouched: 85%

Antennae coated with clear paint: 80%
Antennae coated with black paint: 20%
(a) Why did the scientists include the clear-paint group? (b) What do the results suggest about the antennae?

7. MEDIUM A monarch weighs about 0.5 g. How many monarchs would it take to equal the mass of one 100 g Arctic tern?
8. HARD In a tag-and-recapture study, 60 monarchs are tagged. Later, a sample of 90 monarchs includes 12 tagged ones. Estimate the population. Then name one thing that would make the estimate wrong.
9. HARD Experiment design. A student wants to know whether shorter days alone cause monarchs to enter breeding diapause. Describe an experiment, naming the independent variable, the dependent variable, the control group and two things to keep the same.
10. CHALLENGE Explain in a short paragraph why the monarch migration is called a puzzle, even though scientists know about the sun compass.

COMMON MISTAKES

- Thinking the same butterfly flies to Mexico and back every year like a tern. Only the super generation flies south and partway north; the round trip takes about four generations.
- Thinking caterpillars can eat any leaf. Monarch caterpillars eat only milkweed, their host plant.
- Thinking a chrysalis is a resting “sleep.” Inside the chrysalis the caterpillar’s body is being rebuilt into a butterfly; it is one of the busiest stages of its life.

> **Make it a game · Generation Relay.** Players stand in a line across the yard or room, from “Mexico” at one end to “Canada” at the other. The first player (the super generation) carries a token from Mexico partway north and hands it to the next player (generation 1), who carries it farther, and so on. Before each hand-off, the carrier must answer a question from the lesson. For the fall trip, one player alone must carry the token the whole way back to Mexico while answering three questions in a row. Talk about why the last runner had to go so far alone.

> **Scripture.** “To every thing there is a season, and a time to every purpose under the heaven:” (Ecclesiastes 3:1, KJV)

The monarch’s year is a lesson in seasons. A butterfly born in July breeds and dies within weeks; one born in late August waits months to breed and flies to Mexico first. The same kind of insect behaves in two very different ways, each right for its season.

Practice answers

1. Egg, larva (caterpillar), pupa (chrysalis), adult.

2. Milkweed. Monarch caterpillars eat only milkweed, so each generation moving north needs milkweed to lay eggs on.
3. Ken Brugger and Catalina Aguado, in January 1975, answering Fred Urquhart’s request for help.
4. It is born in late summer; it is in diapause and does not breed until spring; it lives about 8 months instead of 2 to 6 weeks; it flies thousands of kilometers to Mexico and overwinters there.
5. (a) A: 2 ÷ 200 = 1.0%; B: 3 ÷ 350 ≈ 0.86%; C: 6 ÷ 500 = 1.2%; D: 2 ÷ 400 = 0.5%. (b) Year C. (c) Different numbers were tagged each year, so you must divide by the number tagged to compare fairly.
6. (a) It is a control for the paint itself: it shows that paint alone does not ruin the flight; only blocking light does. (b) The antennae must sense light to keep the butterfly’s time-compensated sun compass working; when light is blocked, most monarchs lose their direction.
7. 100 ÷ 0.5 = 200 monarchs.
8. 60 × 90 ÷ 12 = 450 monarchs. It would be wrong if tagged monarchs did not mix evenly with the others, if tags fell off, if tagged butterflies were more likely to die or leave, or if many new butterflies arrived between tagging and sampling.
9. Sample answer: Raise two groups of monarch caterpillars from eggs indoors. Give one group long summer days of light (for example, 16 hours) and the other short late-summer days (for example, 12 hours). Independent variable: hours of light per day. Dependent variable: whether the new adults mate and lay eggs (or whether females’ eggs develop) within a set time. Control: the long-day group. Keep the same: temperature, kind and freshness of milkweed, cage size, number of butterflies, and the age of eggs at the start.
10. No single monarch makes the whole round trip. The butterfly that flies to Mexico in the fall is three or four generations removed from the last one that was there, so it cannot have learned the way from a parent. A sun compass with an antenna clock explains how it holds a direction, but not fully how it knows when to start, how far to go, and how to find the same small group of mountains. The direction and timing seem to be built in from the egg, and scientists are still working out exactly how.

2.3 How Birds Navigate

OBJECTIVES

- Describe the classic experiments that showed birds use a sun compass, a star compass and a magnetic compass.
- Explain the difference between a compass sense (knowing a direction) and a map sense (knowing where you are), using the starling displacement experiment.
- Calculate homing speeds, clock-shift errors (15° per hour) and percents from orientation-cage data.

Warm-up. Stand in the middle of a room, close your eyes, and have someone turn you slowly around three times. Keep your eyes closed and point to the front door. Open your eyes. How far off were you? Now list every clue you normally use to know which way you are facing.

Video. Coming soon. How migrating birds navigate by the sun, stars and earth's magnetic field; search Cornell Lab of Ornithology, Smithsonian, nature footage of night migration, planetarium bird experiments, and Homeschool Pop (Alternate) or SciShow Kids for animal navigation.

KEY TERMS

navigation
Finding the way from one place to another, which needs both knowing direction and knowing position.

compass sense
The ability to hold a direction, such as "fly south-southwest," without necessarily knowing where you are.

map sense
The ability to know where you are compared to your goal, so you can correct your course if you are moved or blown off course.

sun compass
Using the sun's position plus an inner clock to find direction. The sun moves about 15° across the sky each hour, so the animal must adjust for the time of day.

star compass
Using the pattern of stars that turn around the fixed point of the North Star (in the Northern Hemisphere) to find north at night.

magnetic field
The invisible field around the earth, produced by its iron core, that makes a compass needle point north. Its lines dip steeply near the poles and run nearly level near the equator.

CORE IDEAS

The story. In the 1960s a young American scientist named Stephen Emlen wanted to know how indigo buntings, small blue songbirds, find their way when they migrate at night. He invented a clever cage. He rolled blotting paper into a funnel, set an ink pad at the bottom, and covered the top with a screen so the bird could see the sky. A bird that is ready to migrate becomes restless at night and keeps hopping in the direction it wants to fly. Each hop up the paper left an inky footprint. In the morning Emlen unrolled the paper and counted the footprints in each direction. Then he took his buntings into a **planetarium**, a domed room where a projector shows the night sky. When the planetarium sky showed the stars in their true positions, the buntings hopped in the right direction for the season. When the stars were turned off, they hopped every which way.

How they figured it out. Emlen went further. He raised young buntings that had never seen the night sky. Some grew up under a planetarium sky that turned around the North Star, as the real sky does; others under a sky that turned around the bright star Betelgeuse. When migration season came, each bird treated the center of rotation of its own sky as north. The buntings were not born knowing the shapes of the constellations. They were born knowing to *learn* the still point of the sky and use it as north. That is a **star compass**. Earlier, in the 1950s, the German scientist Gustav Kramer had shown that caged starlings use a **sun compass**: when he used mirrors to make the sunlight come in at a different angle, the birds turned to match. Other researchers shifted pigeons' inner clocks by keeping them in a room with the lights on and off at the wrong hours. The pigeons then misread the sun and flew off course by about 15° for every hour their clocks were shifted. In the 1960s, Wolfgang Wiltschko in Germany placed European robins in cages surrounded by electric coils and changed the **magnetic field** around them. The robins changed direction to match. Birds have a magnetic compass too, and it reads the dip of the field lines rather than north and south the way a needle does.

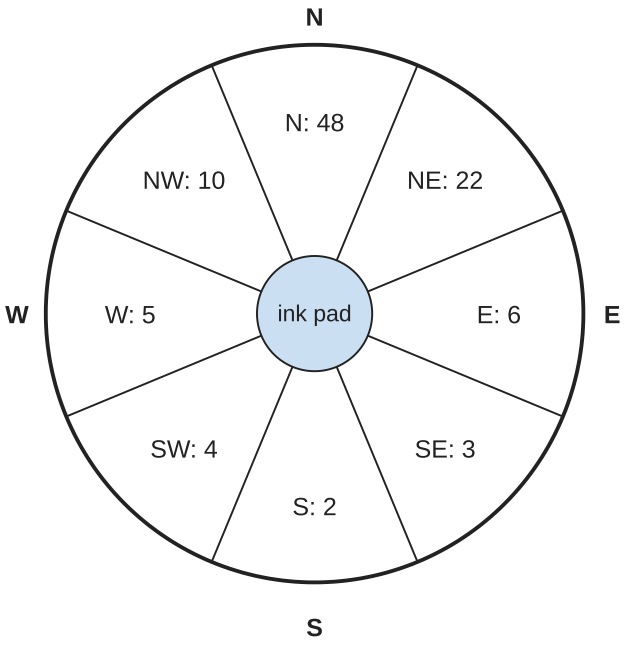
The big idea. A compass is not a map. Knowing which way is south does not tell you where you are. In the 1950s the Dutch scientist A. C. Perdeck caught thousands of starlings in the Netherlands that were migrating southwest toward their winter homes in Belgium, northern France and southern England. He carried them by airplane to Switzerland and let them go. The adult birds, who had made the trip before, turned and flew northwest toward their usual winter grounds: they had a **map sense**. The young birds kept flying southwest, the inborn direction, and ended up in Spain and southern France. Young birds on their first trip seem to carry an inborn program, "fly this direction for about this long," and they build a map from experience.

Many clues together. Birds use more than one compass, and they check one against another, like a ship's navigator with a compass, a sextant and a chart. The magnetic field works in clouds. The stars work on clear nights. The setting sun and the band of polarized light in the evening sky help birds set their direction before a night flight. Coastlines, mountain ranges and rivers are landmarks. Seabirds and homing pigeons also seem to use smell. In 1952 a Manx shearwater was taken from its nest burrow on Skokholm, a small

island off Wales, flown across the ocean and released at Boston. Twelve and a half days later it was back in its own burrow, about 4,900 kilometers away.

In the world today. Scientists are still studying exactly how a bird senses the magnetic field. One leading idea is that special molecules in the eye react to the field, so a bird may in some way “see” it. Another idea involves tiny bits of iron-rich material in the body. The question is not settled, and young scientists today are working on it.

God’s handiwork. “He telleth the number of the stars; he calleth them all by their names” (Psalm 147:4). The God who set the stars in place also made a small blue bird that looks up at them and knows which way to go. Ship captains learned to use the sun, the stars and the magnetic compass over many centuries; the bunting is born ready to learn and use them.



Footprint counts from one night in an Emlen funnel (sample data for a bird ready for spring migration). Total: 100 marks.

PICTURE STUDY



Descending Geese at Katata, from Eight Views of Ōmi, Utagawa Hiroshige, 1857 · Woodblock print, ink and color on paper · Impressions are in many museum collections in Japan, Europe and North America.

Utagawa Hiroshige (1797–1858) was one of the great Japanese masters of the woodblock print. In a set called *Eight Views of Ōmi*, he showed famous scenes around Lake Biwa, the largest lake in Japan. One of the eight views is wild geese coming down to rest at Katata, a village on the lake shore.

Wild geese fly south from Siberia to spend the winter in Japan, and their arrival in autumn was a favorite subject of Japanese poets and painters. People in Japan watched this migration for centuries, just as people in Israel watched the storks and people in North America watched the Canada geese.

Look closely

- Find the geese. Are they flying in a tidy line, a V, or a loose group? Which direction are they heading?
- Look at the lake and the shore. What makes this a good place for tired geese to land?
- How did Hiroshige show the distance between the near shore and the far sky? Look at the size of things and the colors.
- What time of day or year do you think it is? What clues did the artist give?

Talk about it

1. These geese came from far away. Using what you learned in this lesson, list three clues they might have used to find Lake Biwa.
2. Why do you think artists in many lands have loved to paint birds arriving or leaving with the seasons?

> **Safety first.** Use the sewing needle carefully and store it in a pincushion or tape when not in use; younger siblings should not handle it. Never look at the sun, even for a moment, and never look at it through anything. Wipe up spilled water right away.

EXPERIMENT: TWO COMPASSES: SUN AND MAGNET

Birds can use the sun and the earth's magnetic field. You will build one of each kind of compass and test whether they agree.

Question: Does a shadow-stick (sun) compass point the same way as a magnetic needle compass? **Prediction:** Write yours. **What we change:** the kind of compass. **What we keep the same:** the place in the yard and the day. **What we measure:** the angle between the two "north" lines, in degrees, using a protractor.

You will need

- A sewing needle and a strong magnet (a refrigerator magnet may be too weak; a magnet from a toy kit works well)
- A small piece of cork or a bottle cap, and a shallow bowl of water
- A straight stick about 1 meter long, and small stones or tent pegs to mark shadows
- A large protractor and a long string
- A watch or clock
- Lab notebook and pencil

Steps

1. Magnetic compass: Stroke the needle with one end of the magnet about 30 times, always in the same direction, lifting the magnet away between strokes.
2. Lay the needle on the cork and float it in the bowl of water, away from metal. Let it settle. Mark the line it points along with two stones. One end points north.
3. Sun compass: On a sunny day, push the stick straight up into flat ground in the same spot. In the late morning, mark the tip of its shadow with a stone.
4. Keep marking the shadow tip every 20 to 30 minutes until mid-afternoon. The shortest shadow is at local noon, and in the Northern Hemisphere it points almost due north.
5. Draw a line from the stick to the shortest-shadow mark. Compare it to your needle line. Measure the angle between them with the protractor and string.
6. Record the time of local noon you found. Write a conclusion: Did the two compasses agree? If not, by how many degrees did they differ?

Tips

- Never look up at the sun. Look only at the shadow on the ground.
- A small difference is expected. In most places, magnetic north is not exactly the same as true north; the difference is called magnetic declination, and it changes from place to place.

- Local noon is usually not exactly 12:00 on the clock, because of time zones and daylight saving time. That is the same fact a geolocator uses to estimate longitude.

Check your work

- I built and used both a magnetic compass and a sun compass.
- I found local noon from the shortest shadow.
- I measured and recorded the angle between the two north lines and explained what might cause a difference.

NATURE NOTEBOOK

1. Draw a side view of an Emlen funnel: the ink pad, the paper funnel, the screen on top and the bird. Label each part and write one sentence about what the footprints show.
2. On a clear night, find the Big Dipper and use its two “pointer stars” to find the North Star. Sketch what you see and mark north on your drawing.
3. Make a table with three columns: Clue, When it works, When it fails. Fill it in for the sun, the stars, the magnetic field and landmarks.

> **From history.** The magnetic compass came into use by sailors in China and in Europe by about the 1100s and 1200s. For centuries afterward, sailors crossed oceans using the compass, the sun at noon and the North Star. They had to learn these skills from teachers and books. When scientists in the twentieth century discovered that small songbirds use the same three guides, many were amazed that a bird should be born ready to do what took sailors years to learn.

WORKED EXAMPLES

Example 1. In 1952 a Manx shearwater released at Boston returned to its burrow off Wales, about 4,900 km away, in about 12.5 days. What was its average distance per day?

1. Average per day = distance ÷ time.
2. 4,900 km ÷ 12.5 days = 392 km per day.
3. This is an average over the whole trip, including any time spent resting or feeding on the sea.

Answer: About 392 km per day.

Example 2. The sun appears to move across the sky about 360° in 24 hours. A pigeon's inner clock is shifted 6 hours by changing the lights in its room. By about how many degrees will it misjudge its direction when it uses the sun?

1. Degrees per hour: 360° ÷ 24 hours = 15° per hour.
2. Clock shifted 6 hours: 15° × 6 = 90°.
3. So the bird will fly off course by about a right angle.

Answer: About 90°.

Example 3. Use the Emlen funnel diagram. (a) What percent of the footprints point N, NE or NW? (b) In what direction was this bird trying to go?

(Use the map or drawing "Footprint counts by direction (sample data)." shown earlier in this lesson.)

1. Total marks: 48 + 22 + 6 + 3 + 2 + 4 + 5 + 10 = 100.
2. Northern three sectors: 48 + 22 + 10 = 80.
3. Percent: 80 ÷ 100 × 100 = 80%.
4. The largest single count is N (48), so the bird was trying to go north.

Answer: (a) 80%. (b) North, as a songbird would in spring.

PRACTICE

1. EASY Name four kinds of clues birds use to navigate.
2. EASY Why does a bird using a sun compass need an inner clock?
3. EASY What is the difference between a compass sense and a map sense?
4. MEDIUM A pigeon's clock is shifted 4 hours. About how many degrees off course will it fly when using the sun?
5. MEDIUM Data reading. In Perdeck's experiment, starlings caught in the Netherlands were released in Switzerland. Recoveries showed:
   Adults: most found in northern France and southern England (northwest of the release site)
   Young birds: most found in Spain and southern France (southwest of the release site)
   (a) Which group kept its usual compass direction? (b) Which group corrected for being moved? (c) What does this tell you about how birds learn to navigate?
6. MEDIUM Data reading. An Emlen funnel test on a bunting in autumn gave these footprint counts: N 3, NE 2, E 4, SE 12, S 41, SW 25, W 8, NW 5. (a) What is the total? (b) What percent of the marks are in S, SE or SW? (c) Is this what you expect in autumn? Explain.
7. MEDIUM In Emlen's planetarium test, young buntings raised under a sky that turned around Betelgeuse treated Betelgeuse as north. What does this show?

8. HARD Robins in a cage hop north in spring. Scientists use electric coils to reverse the direction the magnetic field lines dip, while the night sky is hidden. Predict what the robins will do, and explain.
9. HARD Experiment design. You want to test whether a migrating songbird needs to see the stars to choose its direction on a night when the magnetic field is normal. Describe your experiment: independent variable, dependent variable, control group and two things to keep the same.
10. CHALLENGE Why might it be safer for a bird to have several compasses instead of one? Give an example of a situation where each of these would fail: the sun compass, the star compass, landmarks.

COMMON MISTAKES

- Thinking birds simply remember the way. Many young birds migrate alone on their first trip, with no adult to follow; they rely on an inborn direction and compass senses.
- Thinking a compass alone is enough to navigate. A compass gives direction, but you also need a map sense to know where you are if you are blown or carried off course.
- Thinking the North Star is the brightest star. It is only medium-bright; what makes it useful is that it stays almost still while the other stars turn around it.

> **Make it a game · Which Compass?.** A parent describes a situation, such as “a cloudy night over the ocean,” “a sunny afternoon over the desert,” or “a young bird blown far off course.” Players race to name the best navigation clue for that situation and explain why in one sentence. Score 1 point for a correct clue and 1 more for a good reason. First to 10 points is the Master Navigator.

> **Scripture.** “He telleth the number of the stars; he calleth them all by their names.” (Psalm 147:4, KJV)

The stars are not scattered at random; God knows each one. Emlen’s buntings show that He also made creatures able to read the turning sky. The order of the heavens is something both birds and people can rely on.

Practice answers

1. Any four: the sun, the stars, the earth’s magnetic field, landmarks such as coastlines, rivers and mountains, polarized light at sunset, and smell.
2. Because the sun moves across the sky (about 15° each hour). To get a direction from the sun, the bird must know what time it is and adjust for where the sun should be.
3. A compass sense tells direction (which way is south). A map sense tells position (where you are compared to your goal), so you can correct your course.
4. 15° × 4 = 60°.
5. (a) The young birds kept flying southwest, their inborn direction. (b) The adults corrected and flew toward their usual winter grounds. (c) Young birds are born with a compass direction (and a sense of how long to fly), but a map sense is learned from experience on earlier trips.

6. (a) 3 + 2 + 4 + 12 + 41 + 25 + 8 + 5 = 100. (b) 41 + 12 + 25 = 78, so 78%. (c) Yes. In autumn indigo buntings migrate south toward their winter homes, so most hops point south.
7. The birds are not born knowing particular star patterns. They are born ready to learn the still center around which the stars turn, and to treat that point as north.
8. They will turn and hop south. The robin’s magnetic compass reads the dip (inclination) of the field lines, not the north or south end like a needle, so reversing the dip makes “toward the pole” seem to be the opposite way.
9. Sample answer: Put birds of the same kind, age and migratory condition in Emlen funnels on the same nights. Group A sees a clear starry sky; Group B is under an opaque cover so it sees no stars. Independent variable: whether stars are visible. Dependent variable: the main direction of footprints and how tightly grouped they are. Control: Group A (stars visible, normal conditions). Keep the same: magnetic field, time of night, funnel size, temperature, and the birds’ season and feeding. If both groups orient equally well, the birds can use the magnetic field without stars.
10. Each clue fails in some conditions, so having several lets the bird check one against another and keep going. Sun compass: fails on heavily overcast days or at night. Star compass: fails on cloudy nights and in daytime. Landmarks: fail over the open ocean or in fog, and for young birds that have never seen them. The magnetic field works in clouds and darkness, so it can fill these gaps.

2.4 "The Stork in the Heaven Knoweth Her Appointed Times" (Jeremiah 8:7)

OBJECTIVES

- Tell how the "arrow stork" of 1822 and early bird-banding proved that European storks fly to Africa, and how older ideas about where birds go in winter were tested and dropped.
- Explain how day length (photoperiod) and an inner yearly clock set the "appointed times" of migration, and how white storks use thermals to soar along land routes.
- Calculate day-length changes, average arrival dates and glide distances, and explain what Jeremiah 8:7 teaches by comparing the birds' obedience with Israel's.

Warm-up. Look at a calendar and think about your own year. Write down three things that happen at about the same time every year in your home or town (a holiday, the first frost, the first robin, the start of school). How do you know when each is coming? Now guess: how could a bird with no calendar know when to leave?

Video. Coming soon. White stork migration over Israel, Gibraltar and the Bosporus, storks soaring on thermals, and storks nesting on European rooftops; search nature footage channels, BBC Earth clips, Cornell Lab of Ornithology, and Homeschool Pop (Alternate) or Moody Science classics for bird instinct and migration.

KEY TERMS

instinct
A complex behavior an animal does correctly the first time, without being taught, such as a young bird's first migration.

photoperiod
The number of hours of daylight in a day. Changes in photoperiod tell many animals and plants what season is coming.

circannual rhythm
An inner clock that runs on a cycle of about one year, even if the animal is kept indoors where day length never changes.

migratory restlessness
The fidgety, hopping, wing-fluttering behavior of a caged bird at the season when it would be migrating. German scientists call it *Zugunruhe*.

thermal
A rising column of warm air over ground heated by the sun. Soaring birds such as storks circle upward inside thermals without flapping.

phenology

The study of when yearly events happen in nature, such as the first flowers, the arrival of migrating birds, or the first frost.

CORE IDEAS

The story. In the spring of 1822, near the village of Klütz in northern Germany, a hunter shot a white stork and found something astonishing. Through its neck was a wooden spear about 80 centimeters long. The spear had been carved in central Africa. The stork had been speared in Africa during the winter, survived, and flown thousands of kilometers back to Germany with the spear still in its neck. The bird was preserved and is still kept at the University of Rostock. The Germans call it the *Pfeilstorch*, the "arrow stork." Later about two dozen more storks with African arrows or spears were found in Europe. The arrow stork was proof you could hold in your hands: Europe's storks spend the winter in Africa.

How they figured it out. For a long time people were not sure where birds went in winter. The Greek thinker Aristotle wrote that some birds hide away in holes and sleep through the cold. In 1555 the Swedish writer Olaus Magnus reported that fishermen in the north sometimes pulled up swallows from lakes in winter, as if they slept in the mud. These ideas were tested and dropped as people gathered real evidence. Spears in storks were one kind of evidence. Another began in 1899, when the Danish teacher Hans Christian Mortensen fastened numbered metal rings to the legs of birds. Soon after, at the bird observatory of Rossitten on the Baltic coast, Johannes Thienemann ringed white storks, and rings came back from Africa, some from as far as South Africa. The ring, not the guess, settled the question.

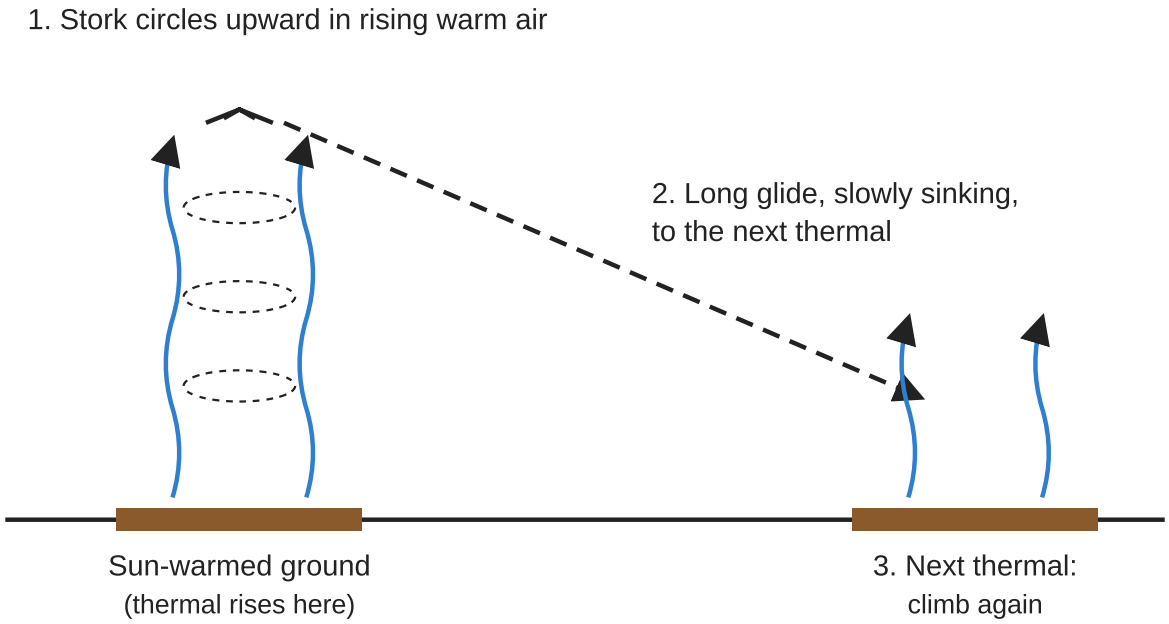
The big idea. About 2,600 years ago the prophet Jeremiah wrote, "Yea, the stork in the heaven knoweth her appointed times; and the turtle and the crane and the swallow observe the time of their coming" (Jeremiah 8:7). The "turtle" is the turtledove. Every bird in that verse migrates through the land of Israel. Scientists now know part of how birds keep their appointed times. The first signal is **photoperiod**, the length of the day. As spring days grow longer, light entering a bird's eyes and even passing through its skull sets off changes in its hormones. The bird eats more and puts on fat for fuel, and it becomes restless. In the 1960s and 1970s the German scientist Eberhard Gwinner kept warblers indoors under the very same day length all year. They still became restless and fat at about the right seasons, year after year. Their inner yearly clock, a **circannual rhythm**, kept running without any outside clue. Day length keeps that clock set to the real calendar.

Built for the route. A white stork stands about a meter tall, with a wingspan of about 2 meters. Flapping such big wings for thousands of kilometers would use enormous energy, so storks **soar**. They wait until the sun warms the ground, then circle upward in rising columns of warm air called **thermals**. At the top they glide, sinking slowly, to the next thermal. Thermals form over land, not over the sea, so storks avoid long water crossings. Western European storks funnel across the narrow Strait of Gibraltar into Africa. Eastern storks cross at the Bosporus in Turkey, follow the eastern shore of the Mediterranean through Israel and the Jordan Valley, and pass into Africa. That is why Jeremiah could watch them: Israel lies on

one of the great bird highways of the world, and hundreds of millions of birds of many kinds pass over it every spring and autumn.

What Jeremiah meant. Jeremiah was not giving a science lesson. He was rebuking his people. The verse ends, “but my people know not the judgment of the LORD.” The storks, doves, cranes and swallows keep the times God set for them without fail. Israel, made in God’s image and taught His law, had turned away and did not heed Him. If a bird can keep its appointed times, how much more should people who have been given God’s Word listen and obey?

In the world today. In many European towns storks still build huge stick nests on rooftops, chimneys and church towers, and people count the days until they return. When white storks had almost vanished from Switzerland, a Swiss man named Max Bloesch began a stork station at Altreu in 1948 and raised young storks there. Storks nest again across the Swiss countryside today. People in many countries put up nesting platforms on poles for them, a simple act of care for creatures God made.



How a stork soars: climb in a thermal, glide to the next one, and climb again. (Not to scale.)

PICTURE STUDY



Storks (Bociany), Józef Chełmoński, 1900 · Oil on canvas · National Museum, Warsaw, Poland

Józef Chełmoński (1849–1914) was a Polish painter who loved the countryside of his homeland: its fields, horses, birds and the farm families who worked the land. Poland has more nesting white storks than almost any other country, and in Polish villages the return of the storks each spring is a happy sign that warm weather has come.

In this painting Chełmoński shows country people pausing to watch storks pass overhead. As you look, think of Jeremiah watching the same kind of birds pass over Israel on their way north.

Look closely

- Find the storks. How many can you count? Are they flapping or soaring with their wings held out?
- Find the people. Where are they looking? What do their faces and bodies tell you about how they feel?
- Look at the sky and the light. What season and what time of day do you think it is?
- How much of the painting is sky, and how much is land? Why might the painter have given the sky so much room?

Talk about it

1. Why do you think the arrival of storks meant so much to farm families long ago?
2. What yearly event in nature do you watch for? How would you paint it?

EXPERIMENT: APPOINTED TIMES: A DAY-LENGTH AND ARRIVAL GRAPH

Birds read the length of the day. In this project you will graph the day length where you live through a whole year and mark when birds arrive and leave, to see whether the “appointed times” line up with the changing light.

Question: At what day length do migrating birds return to my area? **Prediction:** Write yours. **What we change:** the date. **What we keep the same:** the location (your town). **What we measure:** the hours of daylight on the 1st and 15th of each month, and the dates birds are first seen.

You will need

- A sunrise and sunset table for your town for a whole year (from an almanac, a newspaper or a weather website)
- Graph paper, ruler and colored pencils
- Calculator
- A bird field guide, or arrival dates from a parent, a local bird club or an online sightings map such as eBird or Journey North
- Lab notebook and pencil

Steps

1. For the 1st and 15th of each month, find the sunrise and sunset times. Subtract to find the day length in hours and minutes. (Change minutes to decimal hours: divide the minutes by 60.)
2. Make a line graph: dates along the horizontal axis, hours of daylight (0 to 24) up the vertical axis. Plot your 24 points and connect them with a smooth curve.
3. Mark the longest day (near June 21) and the shortest day (near December 21) and the two dates when the day is closest to 12 hours (the equinoxes).
4. Choose three migrating birds in your area (for example, a swallow, a hummingbird, a warbler or a goose). Find their usual spring arrival and fall departure dates.
5. Draw a colored arrow on your graph at each arrival and departure date. Read across to find the day length on that date.
6. Write a conclusion: Do your birds arrive while days are growing longer? Do they leave while days are growing shorter? Which bird’s timing surprised you?

Tips

- Watch out for daylight saving time: subtracting sunrise from sunset still gives the correct day length, because both times shift by the same hour.
- Day length is only one clue. Food, weather and wind also affect the exact day a bird arrives, which is why arrival dates vary by a few days each year.
- Keep this graph. Next spring you can add your own first-sighting dates and become a real phenology observer.

Check your work

- I calculated day length correctly for at least 24 dates and graphed them.
- I marked the solstices, the equinoxes and three birds' arrival and departure dates.
- I wrote a conclusion comparing bird timing with day length.

NATURE NOTEBOOK

1. Draw a white stork standing on its nest on a chimney. Label its long red bill, long red legs, white body and black flight feathers, and note its height (about 1 meter) and wingspan (about 2 meters).
2. Draw a simple map of Europe, the Mediterranean Sea and Africa. Draw the western stork route over the Strait of Gibraltar and the eastern route over the Bosporus and through Israel. Write why storks avoid crossing the open sea.
3. Copy Jeremiah 8:7 in your best handwriting. Under it, draw the four birds it names: stork, turtledove, crane and swallow.

> **From history.** In 1703 a pamphlet printed in London, usually credited to the English minister and teacher Charles Morton, took up the question of where Jeremiah's stork, turtle, crane and swallow go. Its answer was the moon! The writer reasoned that the birds vanish so completely that they must leave the earth, and he guessed the trip took about two months. It sounds funny today, but the writer was asking an honest question and taking Scripture's words about the birds' "appointed times" seriously. It took the arrow stork and leg rings to supply the real answer: Africa.

WORKED EXAMPLES

Example 1. In a town near 52° N, such as in northern Germany, the day is about 10 h 50 min long on March 1 and about 12 h 50 min long on April 1 (31 days later). How much does the day length grow, in total and on average per day?

1. Total change: 12 h 50 min − 10 h 50 min = 2 h 0 min = 120 min.
2. Average change per day: 120 min ÷ 31 days ≈ 3.9 min per day.
3. So in March the day grows by nearly 4 minutes every day, a clear signal that spring is coming and storks are on their way.

Answer: About 2 hours in total, or about 3.9 minutes per day.

Example 2. A family records the date the storks return to the nest on their village church each spring for five years: March 28, April 2, March 30, April 1, March 27. What is the average arrival date? What is the range?

1. Count each date as days after the end of February: March 28 = 28, April 2 = 31 + 2 = 33, March 30 = 30, April 1 = 32, March 27 = 27.
2. Sum: 28 + 33 + 30 + 32 + 27 = 150. Average: 150 ÷ 5 = 30, which is March 30.
3. Range: latest − earliest = 33 − 27 = 6 days.

Answer: Average arrival March 30; range 6 days. The storks keep their appointed time within about a week.

Example 3. A stork circles up a thermal to 1,500 m above the ground. It then glides with a glide ratio of about 10 to 1 (it travels 10 m forward for every 1 m it sinks). How far can it glide before reaching the ground? If thermals are about 12 km apart, can it reach the next one?

(Use the map or drawing "Climb, glide, climb again. (Not to scale.)" shown earlier in this lesson.)

1. Glide distance = height × glide ratio = 1,500 m × 10 = 15,000 m.
2. 15,000 m ÷ 1,000 = 15 km.
3. 15 km is more than 12 km, so the stork reaches the next thermal with height to spare: it will have sunk only 12,000 m ÷ 10 = 1,200 m, leaving it about 300 m above the ground.

Answer: About 15 km; yes, it reaches a thermal 12 km away with about 300 m of height to spare.

PRACTICE

1. EASY Name the four birds in Jeremiah 8:7. What is the "turtle" in that verse?
2. EASY What was the Pfeilstorch, and what did it prove?
3. EASY Why do storks avoid flying across wide stretches of sea?
4. MEDIUM Define photoperiod and circannual rhythm. How do they work together?
5. MEDIUM Data reading. A scientist keeps warblers indoors where the light is on for exactly 12 hours every day of the year. She records the average hours of nighttime restlessness per night:
   Jan 0 Feb 1 Mar 3 Apr 4 May 1 Jun 0 Jul 0 Aug 2 Sep 4 Oct 3 Nov 1 Dec 0
   (a) In which two months was restlessness highest? (b) Wild warblers of this kind migrate in spring and fall. Do the caged birds match? (c) What does this experiment show, since day length never changed?
6. MEDIUM Data reading. Here are the first swallow sightings at one farm for four years: Year 1: April 12; Year 2: April 9; Year 3: April 15; Year 4: April 12. (a) What is the

average date? (b) What is the range? (c) Name one thing that might make the swallows a few days early or late in a given year.

7. MEDIUM A stork climbs to 1,200 m and glides at a ratio of 12 to 1. How far can it glide, in kilometers?
8. HARD Explain how the evidence changed people's ideas about where swallows and storks go in winter. Name one old idea and two kinds of evidence that replaced it.
9. HARD Experiment design. Design an experiment to test whether longer days cause caged songbirds to start putting on fat in spring. Give the independent variable, dependent variable, control group and two variables to keep the same.
10. CHALLENGE Jeremiah 8:7 compares birds and people. In a short paragraph, explain the comparison and why it makes a strong point.

COMMON MISTAKES

- Thinking birds leave only when it turns cold. Many migrants leave in late summer while it is still warm; the shortening days and their inner clocks start the journey before the cold comes.
- Thinking instinct means an animal is thinking it through or was taught. Instinct is behavior an animal does right the first time without learning, like a young bird's first migration.
- Thinking soaring birds fly by flapping all the way. Storks, vultures and eagles mostly soar, climbing in thermals and gliding between them, which saves enormous energy.

> **Make it a game · Appointed Times Calendar Race.** Write twelve month names on cards and lay them in a circle on the floor. A parent calls out an event ("storks arrive in Germany," "monarchs reach Mexico," "Arctic terns nest in Greenland," "the longest day of the year"). Players race to stand on the right month and explain how the animal knows the time (day length, inner clock, weather). Score a point for the right month and a point for a good reason. Review all four lessons of the unit this way.

> **Scripture.** "Yea, the stork in the heaven knoweth her appointed times; and the turtle and the crane and the swallow observe the time of their coming; but my people know not the judgment of the LORD." (Jeremiah 8:7, KJV)

God built a calendar into the birds, and they keep it. Jeremiah used what everyone in Israel could see each spring and autumn to call his people back to God. When you watch the birds return, let it remind you to keep your own "appointed times" with God in prayer and in His Word.

Practice answers

1. The stork, the turtle, the crane and the swallow. The "turtle" is the turtledove, a migrating dove, not a reptile.
2. A white stork found in Germany in 1822 with an African spear through its neck. It proved that European storks spend the winter in Africa and fly back.

3. They travel by soaring on thermals, which form over sun-warmed land, not over the sea. Over water they would have to flap their huge wings, which uses far more energy.
4. Photoperiod is the number of hours of daylight. A circannual rhythm is an inner clock that runs on a cycle of about a year. The inner clock keeps the bird’s yearly cycle going, and the changing photoperiod keeps that clock set to the real calendar.
5. (a) April and September (4 hours each). (b) Yes; the peaks fall in spring (March–April) and fall (August–October), the migration seasons. (c) The birds have an inner yearly clock (a circannual rhythm) that tells them when to migrate even without changing day length.
6. (a) (12 + 9 + 15 + 12) ÷ 4 = 48 ÷ 4 = 12, so April 12. (b) 15 − 9 = 6 days. (c) Weather along the route, such as storms, headwinds or a cold spell with few flying insects; or tailwinds that speed them up.
7. 1,200 m × 12 = 14,400 m = 14.4 km.
8. Old ideas: birds sleep in holes or in the mud of lakes (Aristotle, Olaus Magnus), or even fly to the moon. Evidence: storks shot in Europe carrying African spears (the 1822 Pfeilstorch); numbered leg rings put on birds in Europe and later found in Africa (Mortensen, Thienemann). Careful observation and recovered rings replaced guesses.
9. Sample answer: In late winter, divide birds of the same kind, age and health into two rooms. Room A keeps short winter days (for example, 9 hours of light). Room B’s light is lengthened by a little each day, as in spring. Independent variable: day length. Dependent variable: body mass or fat score, measured weekly. Control: Room A (short days). Keep the same: temperature, food and water (all they want), cage size, number of birds. If Room B birds gain fat sooner, longer days trigger fattening.
10. The stork, turtledove, crane and swallow keep the times God set for them every year without fail. Israel, who had God’s law and prophets, did not know or follow “the judgment of the LORD.” The point is strong because birds have no Bible and no teachers, yet they obey the order God built into them; people, made in His image and given His Word, have far less excuse for not listening. The verse calls us to be at least as faithful as the birds.

Unit 2 review

Answer each question. For multiple-choice questions, write the letter of the best answer. Show your work for calculations and use complete sentences for explanations. The test is worth 60 points.

1. (5 pts) Multiple choice. Why does the Arctic tern see more daylight than almost any other animal?
   (a) It flies closer to the sun than other birds.
   (b) It spends the northern summer in the Arctic and the southern summer near Antarctica.
   (c) It migrates only in the daytime.
   (d) It lives at the equator, where days are longest.
2. (5 pts) A geolocator records only light level and time. Explain how scientists use these to estimate a bird’s latitude and longitude.
3. (5 pts) An Arctic tern flies about 70,900 km each year. (a) How far does it fly in 25 years? (b) A tracker on the tern weighs 1.4 g and the tern weighs 100 g. What percent of its body mass is the tracker?
4. (5 pts) Multiple choice. Which monarchs fly from Canada and the northern United States to the mountains of Mexico?
   (a) The generation born in early spring in Texas
   (b) Every generation, each making the full round trip
   (c) The super generation, born in late summer, which lives about 8 months
   (d) Only the caterpillars, which are carried by the wind
5. (5 pts) Name the four stages of complete metamorphosis, and explain why milkweed is important to the monarch migration.
6. (5 pts) Scientists tag 80 monarchs in a field. A week later they catch 60 monarchs there, and 12 have tags. Estimate the number of monarchs in the field. Show your work.
7. (5 pts) Multiple choice. In Emlen’s planetarium experiment, young indigo buntings raised under a sky that turned around the star Betelgeuse later treated Betelgeuse as north. This shows that the buntings:
   (a) are born knowing the exact shapes of the constellations
   (b) learn the still center of the turning sky and use it as north
   (c) navigate only by the magnetic field
   (d) cannot migrate at night
8. (5 pts) The sun moves about 15° across the sky each hour. A homing pigeon’s inner clock is shifted 3 hours. About how many degrees off course will it fly when it uses its sun compass? Explain why the clock matters.
9. (5 pts) In Perdeck’s experiment, starlings migrating from the Netherlands were carried to Switzerland and released. Young birds flew southwest and ended up in Spain; adults turned toward their usual winter grounds. Use the terms compass sense and map sense to explain the difference.
10. (5 pts) Data reading. Storks returned to a village nest on these dates over four years: April 1, March 29, April 4, March 30. (a) What is the average arrival date? (b) What is

the range? (c) What does photoperiod have to do with this timing?

11. (5 pts) Diagram. Draw a side-view diagram showing how a white stork travels using thermals. Label: sun-warmed ground, thermal (rising warm air), the stork circling upward, and the glide to the next thermal. Then calculate: a stork at 1,000 m with a glide ratio of 10 to 1 can glide how many kilometers?
12. (5 pts) Write out Jeremiah 8:7 (KJV) or summarize it closely, and explain the comparison God makes in it.

UNIT PROJECT: MY MIGRATION ATLAS

Make a migration atlas of at least six pages. Include (1) a world map of the Arctic tern's yearly route with the stopover and the equator marked; (2) a North America map and a generations-cycle diagram for the monarch; (3) a diagram of an Emlen funnel and your sun-and-magnet compass record; (4) a map of the white stork's routes around the Mediterranean with a thermal-soaring diagram; and (5) your day-length graph with bird arrival dates from Lesson 2.4.

End with a one-page essay titled "Appointed Times" explaining how migrating animals know when to go and where to go, using at least four facts from the unit and Jeremiah 8:7.

- **Accuracy**: Routes, places, months and labels are correct; the generation cycle and diagrams match the lessons.
- **Data and calculations**: The compass record, tag-and-recapture work and day-length graph are complete, with correct calculations and units.
- **Explanation**: The essay clearly explains timing (photoperiod and inner clock) and navigation (sun, stars, magnetic field, map sense), and connects them to Jeremiah 8:7.
- **Care**: Maps and drawings are neat, colored, titled and easy to read, like a real naturalist's notebook.

Answer key

1. (b). Because of the earth's tilt, the hemispheres have opposite seasons, and near the poles in summer the sun barely sets.
2. Day length tells latitude, because days are longer or shorter depending on how far north or south you are and the season. The time of local noon (when the light is at its middle point) tells longitude, because noon comes later the farther west you are.
3. (a) 70,900 × 25 = 1,772,500 km, about 1.8 million km. (b) 1.4 ÷ 100 × 100 = 1.4%.
4. (c).
5. Egg, larva (caterpillar), pupa (chrysalis), adult. Milkweed is the monarch's only host plant; the caterpillars eat nothing else, so each generation moving north needs milkweed to lay its eggs on.
6. Population ≈ (80 × 60) ÷ 12 = 4,800 ÷ 12 = 400 monarchs.
7. (b).
8. 15° × 3 = 45°. A sun compass works only if the bird knows the time, because the sun is in a different part of the sky at different hours; a shifted clock makes the bird misread where the sun should be.

9. The young birds had only a compass sense: an inborn direction (southwest), which they kept following from the new place. The adults also had a map sense learned from earlier trips, so they knew they had been moved and corrected their course toward their real goal.
10. (a) Count days after the end of February: 32, 29, 35, 30. Sum = 126; 126 ÷ 4 = 31.5, so about March 31 or April 1. (b) 35 − 29 = 6 days. (c) Lengthening days in late winter (photoperiod), together with the stork's inner yearly clock, trigger the hormone changes, fattening and restlessness that start migration, so the birds arrive at about the same time every year.
11. Diagram should show warm ground with rising-air arrows, a stork spiraling up inside the thermal, a long sloping glide line down to a second thermal, all labeled. Calculation: 1,000 m × 10 = 10,000 m = 10 km.
12. "Yea, the stork in the heaven knoweth her appointed times; and the turtle and the crane and the swallow observe the time of their coming; but my people know not the judgment of the LORD." The birds faithfully keep the times God set for them, but Israel, who had God's law, did not heed Him. People made in God's image and given His Word should be at least as faithful as the birds.

UNIT 3

Echolocation

How does a bat catch a moth on a moonless night, or a dolphin find a fish in murky water? Both creatures “see” with sound. They make a call or a click, listen for the **echo**, and judge distance by how long the echo takes to come back. This skill is called **echolocation**, and in this unit you will learn how it was discovered, how it works, and how people learned to do the same thing with machines.

You will start in 1793 with Lazzaro Spallanzani, the Italian priest-scientist who puzzled over bats flying perfectly in total darkness, and follow the mystery to Harvard in 1938, when bat calls were first detected. You will meet Kathy the dolphin, who swam a maze of pipes with her eyes covered, and see how her melon and jaw work as a sound lens and a listening ear. You will learn how the loss of the *Titanic* led to the first sonar, and how echoes now map the sea floor and let doctors see inside the body. Finally you will measure the speed of sound yourself, clapping at a wall like a giant bat.

All through the unit you will use one rule: **distance = speed × echo time ÷ 2**, with sound traveling about 340 m/s in air and 1,500 m/s in seawater. And you will see that the Maker who “planted the ear” (Psalm 94:9) built into small creatures an echo system that took people thousands of hours of work to imitate.

BEFORE YOU BEGIN

- Can multiply and divide decimals, and find an average
- Can convert between seconds and milliseconds and between hertz and kilohertz
- Can plot points on a graph and draw a straight line through them
- Knows that sound is a vibration that travels through air, water and solids

MASTERY CHECKLIST

- I can tell how Spallanzani and Jurine showed that bats find their way with their ears, and how Griffin solved the mystery in 1938.
- I can explain echolocation and calculate distance from echo time in air and in water, remembering to divide by two.
- I can label a dolphin’s phonic lips, melon, jaw fat and inner ear and explain what each does.
- I can explain how sonar was invented, the difference between active and passive sonar, and why it was not simply copied from bats.
- I can measure the speed of sound with echoes, average my trials, find percent error and read a distance-time graph.
- I can design a fair test that changes one variable, keeps the others the same and measures a result.

OPTIONAL BOOKS AND RESOURCES

- **Bat Conservation International** (https://www.batcon.org/): Free. Photos, facts and short articles about bats of the world, including how echolocation works and how to watch bats safely at dusk.
- **Discovery of Sound in the Sea (University of Rhode Island)** (https://dosits.org/): Free. Clear explanations and sound clips of dolphin clicks, whale songs and sonar, with sections written for students and teachers. Good for Lessons 3.2 and 3.3.
- **NOAA Ocean Service: What is sonar?** (https://oceanservice.noaa.gov/facts/sonar.html): Free. A short page from the National Oceanic and Atmospheric Administration on how ships use sonar to map the sea floor (Lesson 3.3).

3.1 Spallanzani's Bats (1793) ★

OBJECTIVES

- Tell how Lazzaro Spallanzani and Charles Jurine used careful tests in 1793 and 1794 to show that bats find their way with their ears, not their eyes.
- Explain echolocation: an animal makes a sound, listens for the echo, and uses the echo's timing to judge distance.
- Use the speed of sound in air (about 340 m/s) to calculate echo times and distances, remembering that sound travels there and back.

Warm-up. Close your eyes and have a helper stand somewhere in the room and snap their fingers once. Point to where you think they are, then open your eyes. Try it three times from different spots. Now try once with one ear covered by your hand. Was it harder? What did your ears tell you that your eyes did not?

Video. Coming soon. Bat echolocation explained for students, with slow-motion footage of bats catching insects in the dark and a bat detector turning ultrasound into clicks; search Smithsonian, Bat Conservation International, Homeschool Pop (Alternate), SciShow Kids and nature footage channels.

KEY TERMS

echolocation
Finding objects by making sounds and listening to the echoes that bounce back. Bats, dolphins and a few birds do it.

echo
A sound that has bounced off a surface and come back to the listener.

frequency
How many sound vibrations happen each second, measured in hertz (Hz). High frequency sounds have a high pitch. 1 kilohertz (kHz) = 1,000 Hz.

ultrasound
Sound too high in frequency for people to hear, above about 20,000 Hz (20 kHz). Most bat calls are ultrasound.

variable
Something that can change in an experiment. A good experiment changes one variable at a time and keeps the others the same.

control
The part of an experiment left normal, so the changed groups have something to be compared with.

CORE IDEAS

The story. In the summer of 1793, in the university town of Pavia in northern Italy, a sixty-four-year-old priest and professor named Lazzaro Spallanzani was puzzling over a strange fact. He kept a tame owl. When he blew out the candle in a closed room, the owl, which sees well in dim light, flew into the walls and furniture in total darkness. But bats in the same black room flew perfectly. They swooped, turned and never struck anything. How could a bat find its way where even an owl was helpless?

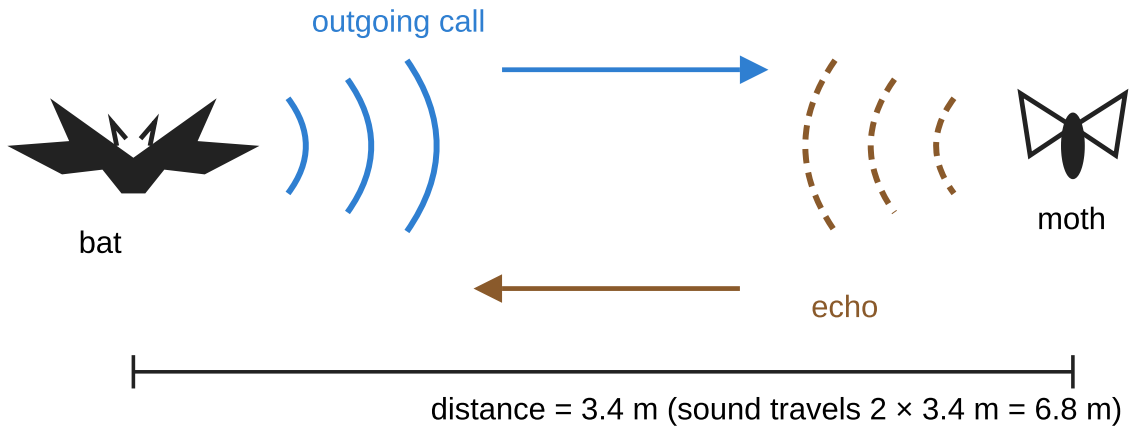
How they figured it out. Spallanzani tested one idea at a time, the way a good scientist still does. First, eyes: he covered bats' eyes, and even tested bats that could not see at all. They still flew through his rooms without hitting the walls, and they slipped between thin threads he had strung across the room. Bats with no sight that he released outdoors were caught again days later with their stomachs full of insects. So eyes were not the answer. He wrote to other naturalists about his puzzle, and in Geneva a surgeon named Charles Jurine tried the next idea in 1794: he gently plugged bats' ears with wax. Now the bats blundered into walls and could hardly fly. When the plugs came out, they flew well again. Spallanzani repeated the test and agreed: bats "see" with their ears. But he could not explain how, because the bats seemed to fly in silence. Many scientists, including the famous Georges Cuvier, decided bats must feel the air with their wings, and the ear experiments were half forgotten for over a hundred years.

The big idea. The mystery was solved in 1938 at Harvard University. A student named Donald Griffin brought bats to a physicist, G. W. Pierce, who had built a machine that could pick up sounds too high for human ears. The machine crackled with bat calls! Bats are not silent at all. They shout in **ultrasound**, sounds above about 20,000 Hz, the top of human hearing. Many bats call between 20 and 100 kHz. The sound hits a moth or a wall and bounces back as an **echo**. The bat's brain measures how long the echo took. A short delay means the object is close; a longer delay means it is farther away. In 1944 Griffin named this **echolocation**. Since sound in air travels about 340 meters per second, an echo from a moth 3.4 m away returns in just 0.02 s (see the figure). Notice the sound must go to the moth *and back*, so the path is twice the distance.

Try it and see. A hunting bat changes its calls as it closes in. While searching it may call about 10 times a second. As it nears an insect it calls faster and faster, up to about 200 calls a second in a final "feeding buzz," so it gets fresh news about where the insect is right up to the catch. Bats also hear which way the echo comes from, because it reaches one ear a tiny moment before the other. Some can sense a wire thinner than a pencil lead. Scientists today use bat detectors that lower the pitch so people can hear the clicks and buzzes on a summer evening.

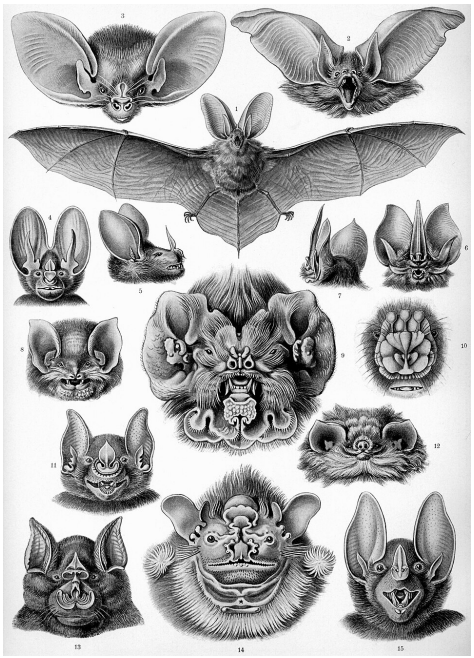
In the world today. There are more than 1,400 kinds of bats, and they are not blind: all of them have working eyes. Most large fruit bats find food mainly by sight and smell, while most small insect-eating bats echolocate. A single little brown bat can eat many hundreds of insects in a night, so bats are a great help to farmers and gardeners. They should be watched, not handled: a bat on the ground may be sick, and bats can carry rabies.

God’s handiwork. Spallanzani was a Catholic priest as well as a scientist, and he never stopped asking questions of nature. The tiny bat carries a sound maker, two sensitive ears and a brain that does echo arithmetic faster than any calculator, all in a body that can weigh less than 10 grams. “He that planted the ear, shall he not hear?” (Psalm 94:9).



A bat’s call travels to the moth and the echo travels back, so the sound covers twice the distance: 2 × 3.4 m = 6.8 m.

PICTURE STUDY



Chiroptera (Bats), Plate 67 of Kunstformen der Natur, Ernst Haeckel, 1899–1904 (published in parts) · Color lithograph (printed plate) · Published in Leipzig in the book *Art Forms in Nature*; copies are in many libraries

Ernst Haeckel was a German zoologist and artist who drew living things with great care and arranged them in beautiful patterns. His book *Art Forms in Nature* came out in parts

between 1899 and 1904. In this plate he gathered the faces of many kinds of bats.

Look closely and you will see that a bat's face is built for sound. Many bats have enormous ears to catch faint echoes, and some, such as the horseshoe bats and leaf-nosed bats, send their calls out through the nose. The odd leaf-shaped flaps around their noses help aim the sound like a megaphone.

Look closely

- Find the bat with the largest ears. How big are its ears compared with its head?
- Find a bat with a leaf-shaped flap on its nose. What might that flap do to a sound coming out of the nose?
- Look at the folds and ridges inside the ears. Why might a wrinkled ear catch sound better than a smooth one?
- How did Haeckel arrange the bats on the page? Is there a pattern or symmetry?

Talk about it

1. Which bats on this plate do you think echolocate through their mouths and which through their noses? What clue did you use?
2. Why would a scientist draw a bat's face in such detail instead of just its whole body?
3. If you could design a face for hearing echoes, what would you give it?

> **Safety first.** Never touch a bat, alive or dead. Bats can carry rabies. If a bat is in your house or on the ground, keep away and tell an adult, who can call animal control. In the project, the blindfolded partner stays seated, and the board is held still and never closer than 20 cm to their face.

EXPERIMENT: CAN YOU HEAR A WALL? A SPALLANZANI-STYLE TEST

Spallanzani and Jurine tested bats with eyes covered and with ears plugged. You will run a gentle version on a person. Question: **Can a blindfolded person tell, by sound alone, whether a large board is held in front of their face?** Many people can, faintly, by making a steady "shhh" and listening to how it changes.

Prediction: Write whether you think your partner will score better than guessing, and whether covering their ears will make a difference.

You will need

- A large, hard, flat object about 30 cm × 40 cm (a big hardcover book, cutting board or tray)
- A blindfold or scarf
- Ear muffs or two soft hands for covering the ears
- A coin
- Lab notebook, pencil and a tape measure

- A quiet room

Steps

1. Seat your partner in a chair in the middle of a quiet room, at least 1.5 m from any wall. Put on the blindfold.
2. Your partner makes a steady, soft “shhh” sound (or hums) the whole time during each trial.
3. Before each trial, flip the coin silently. Heads: hold the board upright 30 cm in front of your partner’s face. Tails: hold nothing. Moving in the same way both times keeps your footsteps from giving away the answer.
4. Your partner says “board” or “no board.” Record the coin, the answer and whether it was correct. Do not say whether they were right until the end.
5. Do 20 trials with ears open. This is your normal condition, like Spallanzani’s bats with nothing changed.
6. Do 20 more trials with your partner’s ears covered by ear muffs. This changes only one variable: hearing.
7. Count correct answers for each condition and turn them into percentages. (Guessing alone would give about 50%.)
8. Switch places and repeat, so each of you gets a score.
9. Write a conclusion: Did sound help? Did covering the ears change the score? How is this like Jurine’s wax-plug test?

Tips

- What we change: ears open or covered. What we keep the same: the board, the 30 cm distance, the room, the sound your partner makes. What we measure: the number of correct answers out of 20.
- The coin flip keeps the tester from falling into a pattern the partner could learn. Scientists call this randomizing.
- If scores are near 50%, try a closer distance such as 20 cm, and keep it the same for every trial.

Check your work

- I recorded 40 trials in a neat table with the coin result, the answer and right or wrong.
- I found the percentage correct for each condition and compared it with 50%.
- I can name the variable I changed and three things I kept the same.

NATURE NOTEBOOK

1. Draw the bat-and-moth echo diagram in your notebook. Label the call, the echo, the distance and the total path (twice the distance).
2. Make a three-column table of Spallanzani’s and Jurine’s tests: What was changed, What the bats did, What it showed.

3. On a warm evening, from a porch or yard, watch the sky at dusk for 15 minutes. Record the time, the temperature, how many bats you see and how their flight looks (straight, zigzag, sudden dives). Do not go near bats or touch one.

From history. Spallanzani was famous long before his bat experiments. In the 1760s he boiled meat broth in flasks and sealed the necks with heat. No little living things appeared in the sealed flasks, while they quickly grew in open ones. This argued against the old idea that life arises by itself from nonliving matter (spontaneous generation). About a hundred years later Louis Pasteur settled the question with his swan-neck flasks, building on Spallanzani's careful work.

WORKED EXAMPLES

Example 1. A bat calls when a moth is 3.4 m away. Sound travels about 340 m/s in air. How long until the echo returns to the bat?

(Use the map or drawing "The echo path is twice the distance to the moth." shown earlier in this lesson.)

1. The sound goes to the moth and back: total path = 2 × 3.4 m = 6.8 m.
2. Time = distance ÷ speed = 6.8 m ÷ 340 m/s = 0.02 s.
3. In thousandths of a second (milliseconds): 0.02 s = 20 ms.

Answer: 0.02 s, or 20 milliseconds.

Example 2. A big brown bat's call is about 50 kHz. People hear up to about 20 kHz. How many times higher is the bat's call than the highest sound we can hear? Can we hear it?

1. Write both in the same unit: 50 kHz = 50,000 Hz; 20 kHz = 20,000 Hz.
2. Ratio = 50,000 ÷ 20,000 = 2.5.
3. Since 50,000 Hz is above 20,000 Hz, the call is ultrasound.

Answer: 2.5 times higher. It is ultrasound, so we cannot hear it without a bat detector.

Example 3. A class re-creates the pattern of Jurine's test with a model data set (made-up numbers shaped like his results). Each group of bats made 20 flights through a room with threads. Normal bats: 1 collision. Eyes covered: 2 collisions. Ears plugged: 16 collisions. Find the percent of flights with a collision for each group, and state the conclusion.

1. Percent = collisions ÷ flights × 100.
2. Normal: 1 ÷ 20 × 100 = 5%. Eyes covered: 2 ÷ 20 × 100 = 10%. Ears plugged: 16 ÷ 20 × 100 = 80%.
3. Covering the eyes barely changed the result (5% to 10%), but plugging the ears raised collisions sixteen-fold (5% to 80%). The normal group is the control.

Answer: 5%, 10% and 80%. Hearing, not sight, is what the bats need to avoid obstacles in the dark.

PRACTICE

1. EASY What did Spallanzani notice in 1793 when he put his owl and some bats in a completely dark room?
2. EASY Define echolocation in your own words. Which sense does it use?
3. EASY A bat calls at 45 kHz. Can a person hear it? Explain.
4. MEDIUM A moth is 1.7 m from a bat. Using 340 m/s, how long does the echo take to return?
5. MEDIUM A bat hears the echo from a tree 0.05 s after it calls. How far away is the tree?
6. MEDIUM Data reading. A bat's calls were recorded during one hunt:
   Search phase: 10 calls per second
   Approach phase: 50 calls per second
   Final buzz: 200 calls per second
   (a) In which phase does the bat call fastest? (b) How many times faster is the final buzz than the search phase? (c) Give a reason the bat calls faster as it gets closer.
7. HARD Data reading. Model data (made-up, shaped like the 1790s results), 20 flights per group:
   Normal: 1 collision
   Eyes covered: 1 collision
   One ear plugged: 9 collisions
   Both ears plugged: 17 collisions
   Mouth gently held closed: 15 collisions
   (a) Which group is the control? (b) Which two changes caused the most collisions? (c) What does the last row suggest about where the sound comes from?
8. HARD Experiment design. A scientist wants to test, without harming bats, whether bats need echoes to avoid obstacles. She has a flight room, hanging chains, a speaker that can play loud ultrasound noise and a camera. Describe her experiment: what she changes, what she keeps the same, what she measures and what result would support the echo idea.

9. CHALLENGE Spallanzani showed that bats need their ears but could not explain how. Why was he stuck, and why did Cuvier's idea that bats feel their way by touch with their wings seem reasonable for over a hundred years?
10. CHALLENGE A bat flies at 5 m/s. How far does it fly between calls when it calls 10 times per second? When it calls 200 times per second in the feeding buzz? Why does this matter?

COMMON MISTAKES

- Thinking bats are blind ("blind as a bat"). Every kind of bat has working eyes; insect-eating bats simply rely on echoes when it is dark.
- Forgetting that the echo travels there and back. The distance to the object is half of speed × time.
- Thinking all bats echolocate the same way. Most large fruit bats find food by sight and smell, some bats call through their noses, and call pitch differs by kind.

> **Make it a game · Bat and Moth.** Play in a clear room or yard with four or more people standing in a circle as the "cave walls." One player is the bat and wears a blindfold; one or two are moths inside the circle. The bat calls "Bat!" and each moth must answer "Moth!" every time. Using only the echoes of the moths' voices, the bat tries to tag a moth. The circle players gently stop the bat from wandering out. When a moth is caught, it becomes the next bat. Walk only, no running.

> **Scripture.** "He that planted the ear, shall he not hear? he that formed the eye, shall he not see?" (Psalm 94:9, KJV)

The bat's ear catches echoes too high for us to hear at all. The Maker of every ear hears and sees far more than any creature He has made.

Practice answers

1. The owl flew into walls and objects, but the bats flew without hitting anything. This made him ask how bats could find their way without light.
2. Echolocation is finding things by making sounds and listening to the echoes that bounce back. It uses the sense of hearing.
3. No. 45 kHz = 45,000 Hz, which is above the top of human hearing (about 20,000 Hz), so it is ultrasound.
4. Path = 2 × 1.7 = 3.4 m. Time = 3.4 ÷ 340 = 0.01 s (10 ms).
5. Total path = 340 × 0.05 = 17 m. That is there and back, so the tree is 17 ÷ 2 = 8.5 m away.
6. (a) The final buzz. (b) 200 ÷ 10 = 20 times faster. (c) The insect is close and moving, so the bat needs fresh updates very often to know exactly where it is at the moment of the catch. Also, close echoes return quickly, so the bat can call again sooner.
7. (a) The normal group. (b) Both ears plugged (17) and mouth held closed (15). (c) The bat must make its sound with its mouth; if it cannot call, it gets no echoes, so it hits things even though its ears work. (One plugged ear also hurts, because two ears help judge direction.)
8. Change: whether the ultrasound noise is on or off (the noise drowns out echoes). Keep the same: the same bats, the same room, the same chain spacing, the same darkness and number

of flights. Measure: the number of chain collisions per 20 flights, counted from the camera. Run several bats and many flights each way. If collisions rise a lot when the noise is on but not when a sound people can hear (that does not cover bat calls) is played, that supports the idea that bats need their echoes.

9. Bat calls are ultrasound, too high for human ears, so the bats seemed silent. Without hearing any sound, it made no sense that bats were listening. Feeling air currents with the sensitive skin of the wings seemed like a reasonable explanation. Only in 1938, when Pierce's machine detected the ultrasound calls, could Griffin show that the bats were hearing their own echoes.
10. At 10 calls per second, the time between calls is 0.1 s, so it flies $5 \times 0.1 = 0.5$ m. At 200 calls per second, the time is 0.005 s, so it flies $5 \times 0.005 = 0.025$ m = 2.5 cm. In the buzz the bat gets a new "picture" every 2.5 cm, precise enough to catch a moving insect.

3.2 Dolphins: Seeing with Sound Underwater ★

OBJECTIVES

- Describe how Kenneth Norris showed that a dolphin with its eyes covered could swim through a maze and find food by echolocation.
- Label the parts of a dolphin’s head used in echolocation (phonic lips, melon, jaw fat, inner ear) and tell what each does.
- Calculate echo times in water using the speed of sound in seawater (about 1,500 m/s) and compare it with the speed in air.

Warm-up. Fill a sink or large bowl with water. Put one ear gently against the outside of the bowl (not in the water) and have a helper tap two spoons together under the water. Then have them tap the spoons the same way in the air beside the bowl. Which sounded louder and sharper? What does that tell you about water and sound?

Video. Coming soon. Dolphin echolocation clicks and the melon, with underwater footage of dolphins hunting and Navy marine mammal training; search NOAA Fisheries, Smithsonian Ocean, Homeschool Pop (Alternate), SciShow Kids and nature footage channels.

KEY TERMS

toothed whale
A whale with teeth instead of baleen plates. Dolphins, porpoises, orcas and sperm whales are toothed whales, and they echolocate.

click
A very short, sharp burst of sound a dolphin uses for echolocation. Each click lasts far less than a thousandth of a second.

phonic lips
Pairs of fatty lips in a dolphin’s nasal passage, just below the blowhole, that snap together to make clicks.

melon
The rounded, fat-filled forehead of a dolphin. It focuses the clicks into a beam aimed forward, like a lens.

acoustic fat
Special fat inside the dolphin’s lower jaw that carries returning echoes back to the inner ear.

whistle
A longer, tone-like dolphin sound used to communicate with other dolphins, not to echolocate.

CORE IDEAS

The story. In the late 1950s, at Marineland of the Pacific on the coast of southern California, a young zoologist named Kenneth Norris carefully fitted two soft rubber suction cups over the eyes of a bottlenose dolphin named Kathy. Then he lowered a maze of hanging metal pipes into her tank. Kathy could not see a thing, yet she swam through the maze without touching a pipe. When a piece of fish was dropped into the water, she swung her head from side to side, clicking, and swam straight to it. Norris and his co-workers published the experiment in 1961. It showed beyond doubt what earlier scientists, such as Winthrop Kellogg in Florida, had strongly suspected: dolphins echolocate, just as bats do.

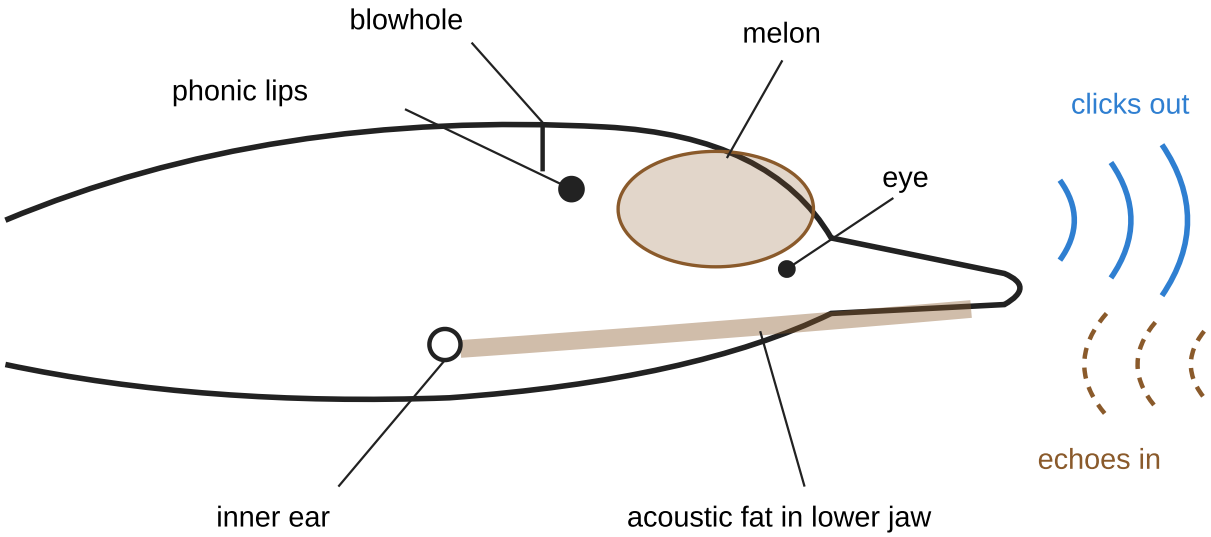
How they figured it out. Underwater microphones, called hydrophones, picked up Kathy's sound: rapid trains of clicks, many of them ultrasound. The scientists then asked a harder question. Where does the sound come from, and how does it get back in? A dolphin has no vocal cords like ours. Its clicks are made by **phonic lips**, small fatty lips in the air passage below the **blowhole**. Air squeezed past them makes them snap together. The click passes forward into the **melon**, the rounded fatty forehead, which bends and focuses the sound into a narrow beam out in front. Norris himself later suggested how echoes come back: not mainly through the tiny ear openings, but through the lower jaw. The thin jawbone is filled with **acoustic fat** that carries the echo to the inner ear (see the figure).

The big idea. Sound in seawater travels about 1,500 meters per second, roughly 4.4 times faster than in air (about 340 m/s). So the same distance gives a shorter echo time underwater. A fish 75 m away sends an echo back in 0.1 s. A dolphin usually waits for each echo to come back before it sends the next click, so it clicks slowly when scanning far away and faster as it closes in, ending in a rapid buzz, much like a bat. Echoes tell a dolphin more than distance. Experiments show trained dolphins can tell apart objects of the same shape made of different materials, and can find a small metal ball well over 100 m away. Because sound passes into soft bodies, a dolphin may even "see" the air-filled swim bladder inside a fish, or a fish buried in sand.

Try it and see. Dolphins make two main kinds of sound. **Clicks** are for finding things. **Whistles** are for talking: each bottlenose dolphin has its own signature whistle, almost like a name, that others learn. Your warm-up showed that sound travels well through water, which is why the ocean is a world of sound. Even in clear ocean water daylight fades to darkness within a few hundred meters, and in murky bays a diver may barely see an arm's length. Sound goes much farther, so a hunter that "sees" with sound has a great advantage.

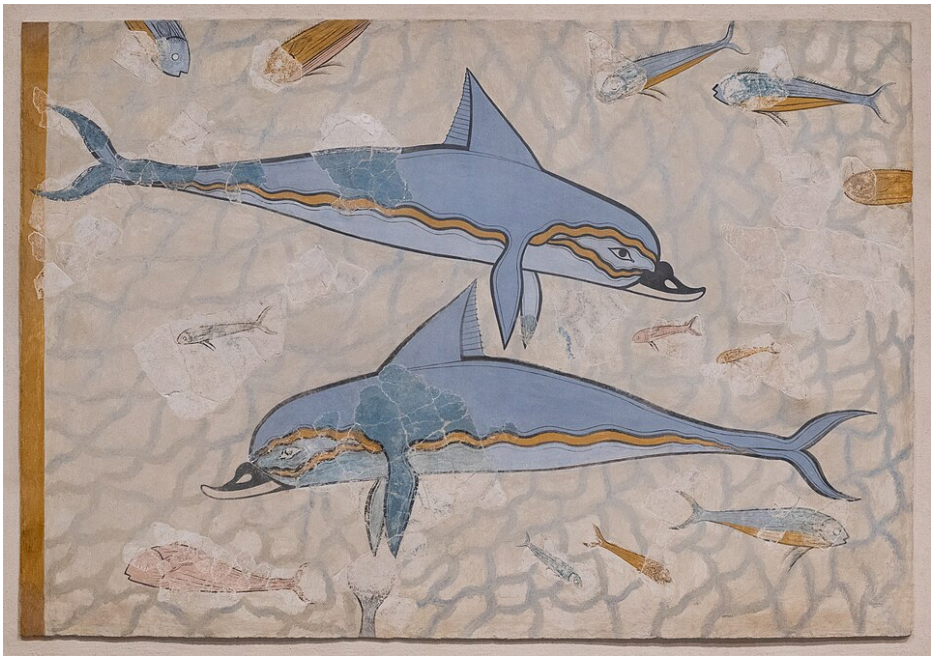
In the world today. All toothed whales studied so far echolocate, from porpoises to orcas to the great sperm whale, whose clicks are among the loudest sounds made by any animal. Baleen whales, like the humpback, sing but are not known to echolocate. Since the 1960s the United States Navy has trained bottlenose dolphins, now based in San Diego, to find objects on the sea floor, including old mines, because in shallow, cluttered water a dolphin's sonar still outperforms many machines.

God's handiwork. A dolphin is a mammal: it breathes air through its blowhole, is born alive and drinks its mother's milk. Yet it hunts in dark water with a sound maker, a sound lens and a jaw that listens, all working together as one system. "O LORD, how manifold are thy works! in wisdom hast thou made them all" (Psalm 104:24).



Clicks are made at the phonic lips, focused by the melon and sent forward. Echoes return through the acoustic fat of the lower jaw to the inner ear.

PICTURE STUDY



The Dolphin Fresco, Unknown Minoan painter, about 1500 BC (archaeologists' estimate) · Fresco (paint on wet plaster), restored from fragments · Heraklion Archaeological Museum, Crete, Greece; a copy is on the wall at the palace of Knossos

On the island of Crete, the ancient people we call the Minoans lived by the sea and loved to paint it. In the early 1900s, the British archaeologist Arthur Evans dug up the great palace at Knossos and found broken pieces of plaster painted with dolphins and fish. The pieces were put back together, and missing parts were filled in, to make the picture we see today.

The painter had clearly watched real dolphins. Look for the curved backs, the beak-like snouts and the pale bellies, the same countershading that helps living dolphins blend in with the water from above and below.

Look closely

- Count the dolphins. How many are swimming the same direction?
- Find the smaller fish. How did the painter show that the dolphins are much bigger than the fish around them?
- Look at the dolphins' heads. Can you find the rounded forehead, where the melon is?
- Which parts look like original old plaster and which may have been filled in by restorers?

Talk about it

1. What do you think the Minoans admired about dolphins?
2. If the painter could have heard dolphin clicks, how might they have shown sound in the picture?
3. Why do you think scientists and artists both need to watch an animal carefully for a long time?

> **Safety first.** Work with water only on a counter or floor that can get wet, and wipe up spills right away so no one slips. Keep electrical devices away from the water. Do not put your head or ears into the water.

EXPERIMENT: DOES SOUND TRAVEL BETTER THROUGH WATER?

Dolphins live in a world where sound travels farther and faster than in air. Question: **Does a sound reach your ear more strongly through air, water or a solid?**

Prediction: Rank air, water and wood from best to worst at carrying sound, and write why.

You will need

- Two zip-top sandwich bags
- Water
- A wooden ruler or wooden cutting board
- Two metal spoons
- A towel
- Lab notebook and pencil

Steps

1. Fill one zip bag with water and squeeze out the air. Fill the other with air and seal it. Make them about the same thickness.
2. Rest your head on the towel on a table with one ear facing up. Cover the other ear with your hand.
3. Trial 1 (air bag): hold the air bag against your ear. Your partner holds two spoons against the far side of the bag and clicks them together gently, the same way each time.
4. Rate the loudness from 1 (barely hear it) to 5 (very loud). Do 3 clicks and record each rating.
5. Trial 2 (water bag): repeat with the water bag. Trial 3 (wood): put your ear on the wooden board and have your partner click the spoons touching the far end of the board.
6. Trial 4 (nothing): your partner clicks the spoons in the air the same distance away, with nothing touching your ear.
7. Find the average rating for each condition and make a bar graph.
8. Switch places so each person is tested, and see if the pattern holds.
9. Write a conclusion: Which material carried sound best? How does this help explain why dolphins hear echoes through the fat in their jaws, and why sound is so useful in the sea?

Tips

- What we change: the material between the spoons and your ear. What we keep the same: the spoons, how hard they are tapped, the distance, the listener. What we measure: the loudness rating.
- Ratings are a little bit subjective. Using several listeners and several trials makes the result more trustworthy.
- Bonus: tie a metal spoon to the middle of a 1 m string, press the string ends against your ears, and let the spoon swing against a table. The string carries the sound straight to your ears and the spoon rings like a bell.

Check your work

- I tested four conditions with three trials each and recorded every rating.
- I made a bar graph of the average ratings with a title and labeled axes.
- I can explain how my result connects to a dolphin’s jaw and melon.

NATURE NOTEBOOK

1. Draw a dolphin’s head from the side. Label the blowhole, phonic lips, melon, lower jaw fat and inner ear. Use arrows to show the click going out and the echo coming in.
2. Make a two-column comparison chart: Bat and Dolphin. Compare where each lives, how it makes its sound, how the echo gets in, and the speed of sound where it hunts.
3. If you live near the coast or can visit an aquarium, watch dolphins for 10 minutes. Record how often they surface to breathe (count breaths per minute) and any head-

scanning motions. If not, use nature footage.

> **From history.** More than 2,300 years ago, the Greek naturalist Aristotle studied dolphins carefully in his *History of Animals*. He noted that a dolphin breathes air through a blowhole, gives birth to live young and nurses them with milk, so it is not like a fish, even though it lives in the sea. He also wrote that dolphins make sounds, though he could not have known they hunt with them. Naturalists did not fully settle where to place dolphins in their classifications until Linnaeus, in the 1750s, put whales and dolphins among the mammals.

WORKED EXAMPLES

Example 1. A dolphin clicks at a fish 75 m away. Sound travels 1,500 m/s in seawater. How long until the echo returns?

1. Total path (there and back) = 2 × 75 m = 150 m.
2. Time = 150 m ÷ 1,500 m/s = 0.1 s.
3. That is 100 milliseconds.

Answer: 0.1 s (100 ms).

Example 2. How many times faster is sound in seawater (1,500 m/s) than in air (340 m/s)? If an echo takes 0.1 s in air, how far away was the object?

1. Ratio = 1,500 ÷ 340 ≈ 4.4.
2. In air, total path = 340 m/s × 0.1 s = 34 m.
3. Object distance = 34 ÷ 2 = 17 m (compared with 75 m in water for the same 0.1 s).

Answer: About 4.4 times faster. In air, a 0.1 s echo means the object is 17 m away; in water, 75 m away.

Example 3. A dolphin waits for each echo before clicking again. What is the most clicks per second it can make when scanning a target 150 m away? When the target is 15 m away?

1. At 150 m: path = 300 m; echo time = 300 ÷ 1,500 = 0.2 s. Clicks per second = 1 ÷ 0.2 = 5.
2. At 15 m: path = 30 m; echo time = 30 ÷ 1,500 = 0.02 s. Clicks per second = 1 ÷ 0.02 = 50.
3. The target 10 times closer allows 10 times as many clicks per second.

Answer: At most 5 clicks per second at 150 m, and 50 clicks per second at 15 m.

PRACTICE

1. EASY What did Kenneth Norris put over the eyes of the dolphin Kathy, and what did she do?
2. EASY Match each part to its job: (a) phonic lips, (b) melon, (c) acoustic fat in the lower jaw. Jobs: focuses clicks into a beam; carries echoes to the inner ear; makes the clicks.
3. EASY What is the difference between a dolphin's clicks and its whistles?
4. MEDIUM A dolphin hears an echo from a rock 0.04 s after clicking. How far away is the rock?
5. MEDIUM A sperm whale's echo returns from a squid after 0.8 s. How far away is the squid?
6. MEDIUM Data reading. Scientists measured the time between a dolphin's clicks as it scanned targets at different distances:
   20 m: 30 ms
   40 m: 55 ms
   80 m: 110 ms
   120 m: 165 ms
   (a) Describe the pattern. (b) Predict the time between clicks for a target at 60 m. (c) The echo time for 40 m is 2 × 40 ÷ 1,500 = 0.053 s = 53 ms. Compare this with the click interval. What does it suggest?
7. HARD Data reading. Model data (made-up numbers shaped like Navy tests) for how often a trained dolphin correctly found a small metal ball:
   40 m: 100%
   70 m: 95%
   100 m: 70%
   115 m: 50%
   130 m: 20%
   (a) At what distance did the dolphin succeed half the time? (b) Between which two distances did success drop the most? (c) Give one reason success falls with distance.
8. HARD Experiment design. You want to test whether a trained dolphin can tell an aluminum cylinder from a plastic cylinder of exactly the same size and shape by echolocation alone. Describe your setup, what you change, what you keep the same, what you measure and how you make sure the dolphin is not getting hints from the trainer.
9. CHALLENGE Why is echolocation more useful to a dolphin hunting in the sea than eyesight alone? Give two reasons with science behind them.
10. CHALLENGE A dolphin is 300 m from a school of fish. If it waits for every echo before the next click, what is the most clicks it can make per second? Explain why a dolphin's clicks speed up into a buzz as it closes in.

COMMON MISTAKES

- Thinking dolphins are fish. Dolphins are mammals: they breathe air, are born alive and drink milk.

- Thinking dolphins hear echoes mainly through ear openings like ours. Their ear openings are tiny; most echoes travel through the fat in the lower jaw to the inner ear.
- Using the speed of sound in air (340 m/s) for underwater problems. In seawater sound travels about 1,500 m/s.

Make it a game · Click or Whistle?. A parent describes a dolphin moment, such as "Kathy is looking for a fish in murky water" or "A mother calls her calf back to her side." Answer "Click!" if the dolphin is finding something or "Whistle!" if it is talking. For a bonus point, solve a quick echo problem the parent gives (for example, "echo after 0.2 s, how far?" Answer: 150 m). First to ten points wins.

Scripture. "O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches. So is this great and wide sea, wherein are things creeping innumerable, both small and great beasts." (Psalm 104:24–25, KJV)

The psalmist looked at the sea and saw the wisdom of God in its creatures. Scientists studying the dolphin's melon and jaw are discovering just how wise that design is.

Practice answers

1. Soft rubber suction cups. Even though she could not see, she swam through a maze of hanging pipes without touching them and found pieces of fish by clicking.
2. (a) Phonic lips make the clicks. (b) The melon focuses clicks into a beam. (c) The jaw fat carries echoes to the inner ear.
3. Clicks are short bursts used for echolocation (finding things). Whistles are longer tones used to communicate with other dolphins; each dolphin has its own signature whistle.
4. Path = 1,500 × 0.04 = 60 m. Distance = 60 ÷ 2 = 30 m.
5. Path = 1,500 × 0.8 = 1,200 m. Distance = 1,200 ÷ 2 = 600 m.
6. (a) The farther the target, the longer the time between clicks; doubling the distance roughly doubles the interval. (b) About 80 to 85 ms (halfway between 55 and 110). (c) The 55 ms interval is just a little longer than the 53 ms echo time, which suggests the dolphin waits for each echo to return (plus a short moment to process it) before clicking again.
7. (a) 115 m. (b) Between 115 m and 130 m, where it fell 30 points (from 50% to 20%). (c) The sound spreads out and weakens on the way there and back, so the echo from a far, small ball is very faint and harder to pick out from background noise.
8. Cover the dolphin's eyes with soft eyecups (or hide the targets behind a screen that sound passes through). Change: which cylinder is lowered into the water (chosen randomly by coin flip or a list). Keep the same: size, shape, depth, distance and how the target is lowered, so splashes give no clue. Measure: the percentage of correct choices (the dolphin touches a paddle for aluminum or another for plastic) over many trials, compared with 50% for guessing. The person working with the dolphin must not know which target is in the water, so they cannot give accidental hints.
9. First, light fades quickly in water, especially in murky bays and at night, while sound travels far. Second, sound moves about 4.4 times faster in water than in air and passes into soft bodies, so the dolphin gets quick, detailed echoes and can even detect fish hidden in sand or the air-filled swim bladder inside a fish. (Other good reasons: it works in total darkness; it can tell materials apart.)

10. Path = 600 m; echo time = 600 ÷ 1,500 = 0.4 s; at most 1 ÷ 0.4 = 2.5 clicks per second. As the dolphin gets closer, echoes return sooner, so it can click more often and get more frequent updates on the moving fish, ending in a rapid buzz just before the catch.

3.3 Sonar: People Learn to Echolocate

OBJECTIVES

- Tell how Reginald Fessenden and Paul Langevin built the first sonar after the Titanic disaster, and how later scientists compared it with bats and dolphins.
- Explain the difference between active and passive sonar and name three ways people use echoes today (ocean mapping, fish finders, medical ultrasound, parking sensors).
- Calculate ocean depth from echo time and read an echo-sounding profile to find the deepest and shallowest points.

Warm-up. Stand about 3 m from a hard wall and say “Hello!” sharply. Now try in a room full of soft things, such as a bedroom with curtains, a bed and pillows. Where did your voice sound “bigger” or ring more? Write one sentence about which surfaces send sound back best.

Video. Coming soon. How sonar and echo sounding work, including ocean-floor mapping, fish finders and ultrasound imaging; search NOAA Ocean Exploration, NOAA Ocean Service, U.S. Navy history, Smithsonian, Science Max and Homeschool Pop (Alternate) channels.

KEY TERMS

sonar
A machine that uses sound underwater to find objects and measure distance. The name comes from SOund NAvigation and Ranging.

active sonar
Sonar that sends out its own sound pulse (a “ping”) and listens for the echo, as a bat or dolphin does.

passive sonar
Sonar that only listens for sounds other things make, such as a ship’s engine or a whale’s song, without sending a ping.

transducer
The part of a sonar that changes electricity into sound to send a ping, and changes the returning echo back into electricity.

echo sounder
A sonar pointed straight down from a ship to measure the depth of the water from the echo time.

ultrasound imaging
Using very high-pitched sound echoes to make pictures of the inside of the body, such as a baby before birth.

CORE IDEAS

The story. On the night of April 14, 1912, the great ship *Titanic* struck an iceberg in the North Atlantic and sank, and more than 1,500 people were lost. The lookouts had seen the ice too late. Inventors on both sides of the ocean asked the same question: could a ship find an iceberg in the dark or fog, before anyone could see it? In April 1914, on the U.S. Revenue Cutter *Miami* on the foggy Grand Banks off Newfoundland, the Canadian-born inventor Reginald Fessenden lowered a large underwater sound maker of his own design, a kind of electric drum, over the side. He sent out a loud note, and back came an echo from an iceberg about 3 km away. He also heard an echo from the sea floor below. A ship had echolocated for the first time.

How they figured it out. When the First World War began, the danger was not ice but submarines. In France, the physicist Paul Langevin, working with the engineer Constantin Chilowsky, found a better sound maker. Certain crystals, like quartz, change shape very slightly when electricity is applied to them, and they make electricity when squeezed by sound. A quartz **transducer** could send out an ultrasound ping and then turn the faint echo back into an electric signal. By 1918 Langevin could pick up echoes from a submarine, though the war ended before his device was used in battle. In the 1940s Americans named the invention **SONAR**.

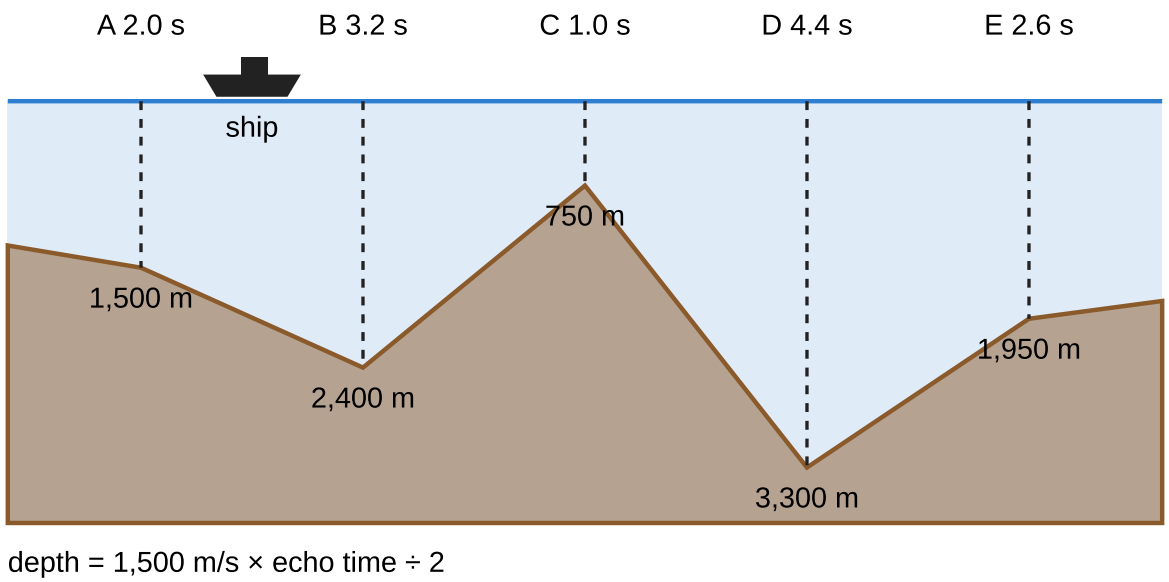
The big idea. Sonar works on the same rule as a bat or dolphin: time the echo, multiply by the speed of sound, and divide by two because the sound went there and back. **Active sonar** sends a ping and listens; **passive sonar** only listens. An **echo sounder** points straight down. If a ping returns in 4 s in seawater (1,500 m/s), the sound traveled 6,000 m, so the sea is 3,000 m deep. Ships crossing the ocean with echo sounders drew the first good profiles of the sea floor, revealing underwater mountains, long ridges and deep trenches (see the figure).

Copied from nature? Here is a surprise: sonar was *not* copied from bats. The first sonar was built in 1914, while bat echolocation was not proven until Donald Griffin heard bat ultrasound in 1938. When Griffin realized what bats were doing, sonar and radar were already being built, and he named the bat's skill "echolocation" in 1944. People invented the same idea God had already built into His creatures long before. Since then, engineers have learned a great deal *from* the animals. Bats and dolphins still beat many machines at finding small targets among clutter, such as a moth among leaves or a mine on a rocky sea floor, so engineers study their changing pitches and click patterns to design better sonar. A cane for blind people developed in England sends out ultrasound like a bat and buzzes the handle when something is ahead.

In the world today. Echoes are at work all around you. Fishermen use fish finders that show schools of fish under the boat. Cars have small ultrasound sensors in the bumper that beep faster as you back toward a wall. In 1958, in Glasgow, Scotland, the doctor Ian Donald published the first pictures showing how ultrasound echoes could be used to see a baby before birth, and today ultrasound imaging lets doctors see hearts, babies and organs

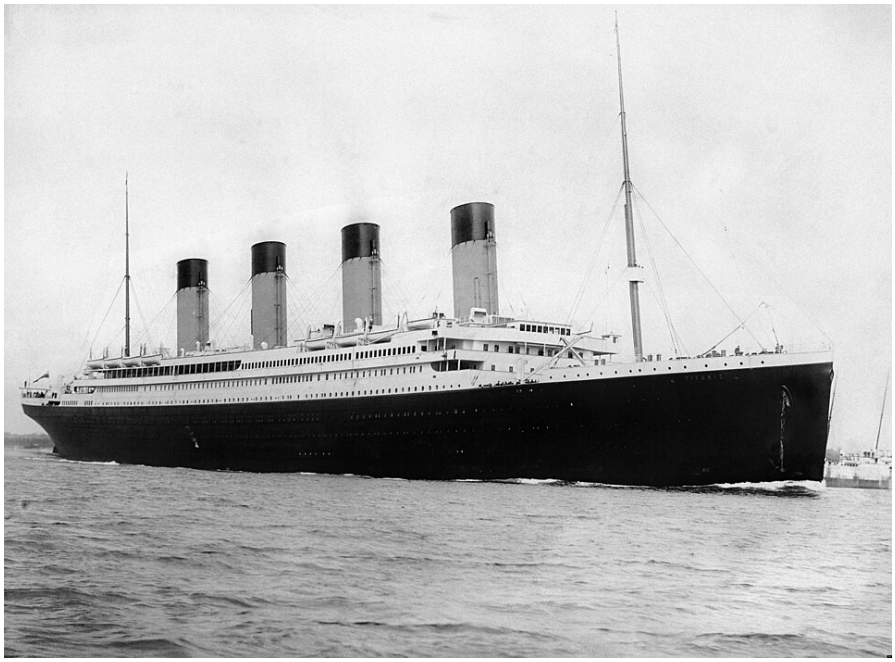
without any surgery. Some blind people even teach themselves to echolocate by clicking their tongues and listening, and can sense walls, cars and trees.

God's handiwork. It took people the hard lessons of the *Titanic* and a war, plus years of work by brilliant engineers, to build a crude echo machine. A tiny bat and a dolphin carry better ones, working from birth. Job said: "But ask now the beasts, and they shall teach thee" (Job 12:7). We can learn from the beasts and from their Maker.



An echo-sounding profile. Each echo time gives the depth at that point: depth = 1,500 m/s × time ÷ 2.

PICTURE STUDY



RMS Titanic Departing Southampton, Francis Godolphin Osbourne Stuart (photographer), April 10, 1912 · Black-and-white photograph · Public domain photograph; prints are held in many collections

This photograph shows the *Titanic* leaving Southampton, England, at the start of her first and only voyage. She was the largest ship afloat, about 269 m long, and many believed she was nearly unsinkable. Four days later she struck an iceberg at night.

The loss of the *Titanic* led to new safety rules, a patrol to watch for ice, and inventors' efforts to "hear" icebergs underwater. Fessenden's echo test in 1914 grew directly out of that night.

Look closely

- Count the funnels. (One of the four was only for air and looks, not smoke.)
- Find the waterline. How much of the ship is below water that you cannot see?
- Look for the lifeboats along the top deck. Do there seem to be many or few for a ship this size?
- Look at the people or small boats near the ship, if you can find them. How do they help you judge the ship's size?

Talk about it

1. An iceberg hides most of its size under water, much like this ship. Why would sound be better than eyes for finding the hidden part?
2. How does a terrible event sometimes lead people to invent things that save many lives later?
3. If the *Titanic* had carried a 1914-style echo machine, what might the crew have done differently?

> **Safety first.** The wooden skewer has a sharp point. Use the blunt end for probing, or snip the point off first with an adult's help. Keep skewers away from eyes and faces.

EXPERIMENT: SHOEBOX SEA FLOOR: MAP WHAT YOU CANNOT SEE

Before computers drew sea-floor maps, ships measured one point at a time and plotted the depths by hand. You will map a hidden sea floor the same way. Question: **How many soundings do you need to get a true picture of a hidden landscape?**

Prediction: Will 5 soundings in a line be enough to find the highest "mountain" and the deepest "trench"? What about 10 or 15?

You will need

- A shoebox with a lid
- Modeling clay or play dough (about 500 g)
- A wooden skewer or thin dowel at least 15 cm long, marked every 1 cm with a marker
- A ruler and pencil
- Graph paper and a lab notebook
- A partner to build the hidden sea floor

Steps

1. Your partner, out of your sight, builds a sea floor in the bottom of the box with clay: a ridge, a trench, a seamount (underwater mountain) and some flat plain. Then they put the lid on.
2. Draw a straight line down the middle of the lid, end to end. Poke 15 small holes along it, 2 cm apart, and number them.
3. First mapping run: use only every third hole (5 soundings). Lower the skewer gently until it touches clay, read the depth in cm at the lid, and record it.
4. Pretend the box is a real ocean: 1 cm in the box = 200 m of real ocean. Convert each depth to meters, and find the echo time a real ship would hear (time = 2 × depth ÷ 1,500).
5. Plot your 5 depths on graph paper (hole number across, depth going down) and connect the points to draw a profile.
6. Second run: sound all 15 holes and draw a new profile in a different color on the same graph.
7. Open the box and compare. Which profile matched the real shape better? What did the 5-sounding map miss?
8. Write a conclusion answering the question, and explain why modern ships use sonar that pings many times every second.

Tips

- What we change: the number of soundings. What we keep the same: the hidden sea floor, the line of holes, the way you read the skewer. What we measure: depth at each hole.
- Hold the skewer straight up and down and read it at the same place each time, or your depths will not be fair.
- Lower the skewer gently. A real ship cannot poke the sea floor, and you should not dent your partner’s clay.

Check your work

- My table has hole number, depth in cm, depth in meters (scaled) and echo time in seconds.
- I drew two profiles on one graph with a title, labels and a key.
- I can explain why more soundings give a truer map.

NATURE NOTEBOOK

1. Draw a timeline: 1793 Spallanzani, 1794 Jurine, 1912 *Titanic*, 1914 Fessenden, 1918 Langevin, 1938 Griffin and Pierce, 1944 the word “echolocation,” 1958 Donald’s ultrasound. Write one line for each.
2. Draw a ship using active sonar and a submarine using passive sonar. Use arrows to show what sound each one sends or hears.
3. List three places you have met echo technology (a car, a doctor’s office, a fishing trip, a phone app) and draw the sound path for one of them.

From history. In the 1950s, at Columbia University's Lamont Geological Observatory in New York, a mapmaker named Marie Tharp worked through stacks of echo-sounding records collected by ships crossing the Atlantic. Plotting depth after depth by hand, she drew profiles of the sea floor and noticed a deep valley running down the middle of a great undersea mountain range, the Mid-Atlantic Ridge. With her colleague Bruce Heezen she published maps of the ocean floor that showed, for the first time, what the bottom of the sea looks like: mountains, valleys and plains as rugged as any on land, all found by listening to echoes.

WORKED EXAMPLES

Example 1. An echo sounder's ping returns from the sea floor in 4.0 s. Sound travels 1,500 m/s in seawater. How deep is the water?

1. Total path = speed × time = 1,500 m/s × 4.0 s = 6,000 m.
2. That path is down and back up, so depth = 6,000 ÷ 2 = 3,000 m.
3. Check: 3,000 m down + 3,000 m up = 6,000 m; 6,000 ÷ 1,500 = 4.0 s. ✓

Answer: 3,000 m deep (3 km).

Example 2. A ship sails in a straight line and records echo times at five points: A 2.0 s, B 3.2 s, C 1.0 s, D 4.4 s, E 2.6 s. Find the depth at each point. Where is there probably an underwater mountain, and where is the deepest water?

(Use the map or drawing "The profile drawn from the five echo times." shown earlier in this lesson.)

1. Depth = 1,500 × time ÷ 2 = 750 × time.
2. A: 750 × 2.0 = 1,500 m. B: 750 × 3.2 = 2,400 m. C: 750 × 1.0 = 750 m. D: 750 × 4.4 = 3,300 m. E: 750 × 2.6 = 1,950 m.
3. C is much shallower than its neighbors B and D, so it is probably an underwater mountain (seamount). D has the longest echo time, so it is the deepest point.

Answer: A 1,500 m; B 2,400 m; C 750 m (seamount); D 3,300 m (deepest); E 1,950 m.

Example 3. A car's parking sensor hears its ultrasound echo from a wall 0.006 s after sending it. Sound travels 340 m/s in air. How far is the wall?

1. Total path = 340 m/s × 0.006 s = 2.04 m.
2. Distance to wall = 2.04 ÷ 2 = 1.02 m.
3. Round sensibly: about 1 m. The sensor would beep quickly to warn the driver.

Answer: About 1.0 m.

PRACTICE

1. EASY What disaster led inventors to try to find icebergs with sound, and who first did it in 1914?
2. EASY What does SONAR stand for? What is the difference between active and passive sonar?
3. EASY True or false: Engineers invented sonar by copying bats. Explain.
4. MEDIUM Fessenden’s iceberg was about 3 km (3,000 m) away. How long did the echo take to return through seawater?
5. MEDIUM An echo sounder hears the bottom 0.4 s after the ping. How deep is the lake? (Use 1,500 m/s; fresh water is close to this.)
6. MEDIUM Data reading. A ship recorded these echo times across part of the ocean:
   Point 1: 6.0 s
   Point 2: 5.8 s
   Point 3: 3.0 s
   Point 4: 2.8 s
   Point 5: 6.2 s
   (a) Find the depth at points 1, 3 and 5. (b) Describe the shape of the sea floor. (c) How much higher is the floor at point 4 than at point 5?
7. HARD Data reading. Approximate values for medical ultrasound:
   2 MHz: sees about 20 cm deep, coarse detail
   5 MHz: about 8 cm deep, medium detail
   10 MHz: about 4 cm deep, fine detail
   (1 MHz = 1,000,000 Hz.) (a) As frequency goes up, what happens to depth and detail? (b) Which frequency would a doctor choose to look at a heart deep in the chest? At a small tendon just under the skin? (c) How many times higher is 10 MHz than a 50 kHz bat call?
8. HARD Experiment design. You have a toy ultrasound distance sensor that shows distance on a screen. You wonder whether it measures distance as well to a soft surface (a pillow) as to a hard one (a wooden board). Design a fair test.
9. CHALLENGE Why do bats and dolphins still beat many machines at finding a small target among clutter, and what are engineers doing about it?
10. CHALLENGE A deep ocean trench is about 11,000 m deep. How long would an echo sounder ping take to return from the bottom? If the ship pings once each time the echo returns, how many pings per minute is that?

COMMON MISTAKES

- Thinking sonar was copied from bats. Sonar came first (1914); bat echolocation was proven later (1938). Since then, engineers have learned from the animals.
- Forgetting to divide by two. The echo time covers the trip down and back up.
- Using the speed of sound in air for water problems. In water use about 1,500 m/s; in air about 340 m/s.

Make it a game · Ping! Depth Captain. One player is the ship's sonar and calls out an echo time, such as "Ping! 2 seconds!" The other players race to call out the depth in seawater (750 m for every second: here 1,500 m). The fastest correct answer becomes the next sonar operator. For a hard round, the operator says "Air!" before the time, and players use 170 m for every second instead.

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)

Engineers who study bats and dolphins to improve their sonar are doing what Job described: asking the creatures and learning from them.

Practice answers

1. The sinking of the *Titanic* in April 1912 after it hit an iceberg. Reginald Fessenden detected an iceberg by echo in April 1914.
2. SOund NAvigation and Ranging. Active sonar sends a ping and listens for the echo; passive sonar only listens to sounds other things make.
3. False. Sonar was first built in 1914, but bat echolocation was not proven until 1938. People invented the idea on their own; only later did engineers study bats and dolphins to improve sonar.
4. Path = 2 × 3,000 = 6,000 m. Time = 6,000 ÷ 1,500 = 4 s.
5. Path = 1,500 × 0.4 = 600 m. Depth = 600 ÷ 2 = 300 m.
6. (a) Point 1: 750 × 6.0 = 4,500 m. Point 3: 750 × 3.0 = 2,250 m. Point 5: 750 × 6.2 = 4,650 m. (b) Deep plain, then a broad rise (a ridge or seamount) at points 3 and 4, then deep again. (c) Point 4 is 750 × 2.8 = 2,100 m deep; 4,650 − 2,100 = 2,550 m higher.
7. (a) Higher frequency gives finer detail but cannot see as deep. (b) Deep heart: 2 MHz (needs depth). Tendon near the skin: 10 MHz (needs detail, little depth). (c) 10,000,000 ÷ 50,000 = 200 times higher.
8. Change: the target surface (board or pillow). Keep the same: the true distance (measure it with a tape, for example 50 cm, 100 cm and 150 cm), the size of the target, the angle (square to the sensor), the room. Measure: the distance the sensor shows, 5 readings at each distance for each surface, and how often it shows no reading. Compare the error (sensor reading minus true distance) for the two surfaces. Prediction: the hard board returns a stronger echo, so its readings should be more accurate and reliable, while the soft pillow absorbs more sound.
9. Cluttered places, such as leaves around a moth or rocks around a mine, send back many confusing echoes. Bats and dolphins change their calls, pitches and click timing moment by moment and their brains sort the target's echo from the clutter very well. Engineers record and study these call patterns and try to copy them in new sonar designs, and the Navy still uses trained dolphins for some searches.
10. Path = 22,000 m. Time = 22,000 ÷ 1,500 ≈ 14.7 s. Pings per minute = 60 ÷ 14.7 ≈ 4 pings per minute.

3.4 Echo Lab: Measure the Speed of Sound

OBJECTIVES

- Tell how William Derham measured the speed of sound from a church tower in the early 1700s and why timing many events makes a measurement more accurate.
- Measure the speed of sound outdoors using echoes from a large wall, then calculate an average and a percent error.
- Make and read a graph of distance against echo time and use it to find the speed of sound and to predict new values.

Warm-up. Watch a helper at the far end of a field or a long hallway clap two blocks together while you watch closely. Do you see the clap a tiny moment before you hear it? Now count “one-thousand-one” between a lightning flash and its thunder the next time a storm passes (from indoors). Write down what this tells you about light and sound.

Video. Coming soon. Measuring the speed of sound with echoes and clapping, plus counting the seconds between lightning and thunder; search Science Max, NOAA SciJinks, Smithsonian and Moody Science classics.

KEY TERMS

speed of sound
How fast sound travels: about 340 m/s in air at room temperature, a little faster in warm air and slower in cold air; about 1,500 m/s in water.

interval
The time between one event and the next, such as between one clap and the next.

average (mean)
The sum of several measurements divided by how many there are. Averaging several trials gives a more trustworthy result.

percent error
How far a measurement is from the accepted value, as a percent: (difference ÷ accepted value) × 100.

reaction time
The short delay, often about 0.2 s, between seeing or hearing something and pressing a button. It adds error to hand timing.

slope
How steep a line on a graph is: the change going up divided by the change going across. On a distance-time graph it gives a speed.

CORE IDEAS

The story. In the early 1700s, William Derham, the rector (pastor) of the parish church in Upminster, a village east of London, climbed his church tower with a telescope and a pendulum that swung once every half second. Several miles away, at times agreed in advance, guns were fired. Derham watched for the flash, which reaches the eye almost instantly, and then counted the swings of his pendulum until the boom arrived. He repeated the test over and over, with big guns and small, in different weather. In 1709 he reported to the Royal Society in London that sound travels about 1,142 English feet each second. That is about 348 meters per second, very close to modern measurements.

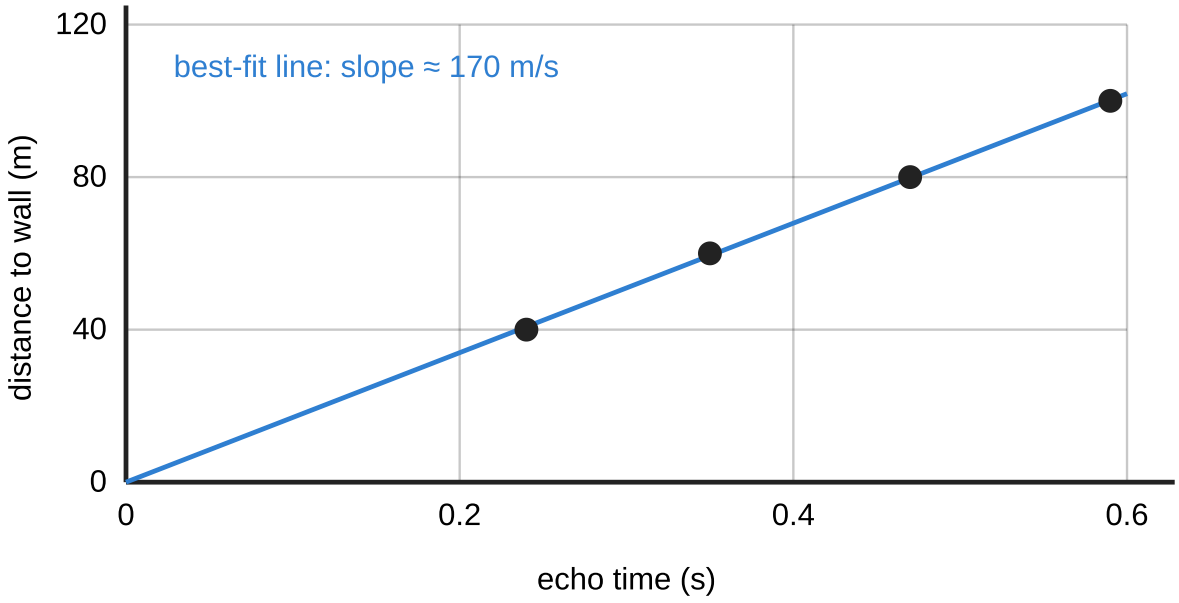
How they figured it out. Derham's secret was patience. A single measurement can be spoiled by a slow hand or a gust of wind, but many measurements averaged together come close to the truth. He also tested one thing at a time. He found that loud and soft sounds travel at the same speed, and that the wind blowing with or against the sound made a small difference. Derham was also a naturalist who studied insects and birds, and he wrote a famous book, *Physico-Theology* (1713), showing the wisdom of God in the works of creation.

The big idea. Today's accepted value for the speed of sound in dry air is about 343 m/s at 20 °C. It changes with temperature: a handy rule is speed ≈ 331 + 0.6 × (temperature in °C). So sound is about 331 m/s at freezing and about 349 m/s on a hot 30 °C day. In this unit we round to 340 m/s. You can measure it yourself with an echo, just as a bat does, but on a bigger scale. If you stand 85 m from a large flat wall, your clap travels 170 m there and back, which takes 0.5 s, long enough to hear the echo separately.

Try it and see. Timing one half-second echo with a stopwatch is hard, because your **reaction time** is about 0.2 s, almost half the thing you are measuring! The trick, used by teachers for many years, is to clap in a steady rhythm so that each new clap lands exactly on the echo of the one before. Then the time between claps equals the echo time. A partner times 20 intervals (21 claps). If 20 intervals take 10.0 s, one interval is 0.50 s, and the speed is 170 m ÷ 0.50 s = 340 m/s. Any reaction-time error is now shared over 20 intervals, so it becomes small. Repeating at different distances and making a graph of distance against echo time gives a straight line, and its **slope** tells you the speed (see the figure).

In the world today. The same arithmetic keeps people safe in storms. Light from lightning reaches you almost at once, but the thunder travels at about 340 m/s, roughly 1 km every 3 seconds. Count the seconds from flash to thunder and divide by 3 to estimate the distance in kilometers. If you can hear thunder at all, you are close enough to be struck, so go indoors.

God's handiwork. A bat does this same echo calculation in thousandths of a second, without a stopwatch or a calculator. In this lab you will do slowly, with tape measure and pencil, what God made the bat to do in an instant. "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter" (Proverbs 25:2).



Distance to the wall against echo time from a family's echo lab. The straight line shows that distance and echo time are proportional.

PICTURE STUDY



Staffa, Fingal's Cave, Joseph Mallord William Turner, 1832 · Oil on canvas · Yale Center for British Art, New Haven, Connecticut (Paul Mellon Collection)

In 1831 the English painter J. M. W. Turner sailed by steamboat to Staffa, a tiny island off the west coast of Scotland. Staffa is made of tall six-sided columns of dark basalt rock, and the sea has hollowed out a great cave among them called Fingal's Cave. Its Gaelic name means something like "the cave of melody," because the waves rolling into it boom and echo like

music. Two years before Turner's visit, the composer Felix Mendelssohn heard those echoes and wrote his overture *The Hebrides*.

Turner's steamboat had a rough trip back in bad weather, and he painted that struggle: a little steamer pushing through heavy seas with the island and its echoing cave behind.

Look closely

- Find the steamship. Which way is its smoke blowing, and what does that tell you about the wind?
- Find the island of Staffa. How did Turner show it, sharp and clear or misty?
- Where is the sun? How does the light change the colors of the sea and sky?
- Turner does not paint every detail. Which parts look most like quick, swirling brushstrokes?

Talk about it

1. Why would a cave with hard rock walls make strong echoes? Would a cave lined with sand or moss echo as much?
2. How does Turner make you feel the noise and motion of a storm in a silent painting?
3. If you could stand inside Fingal's Cave and clap, how could you use the echo to estimate how deep the cave is?

> **Safety first.** Do the echo lab in a safe open space such as a park or school field, well away from roads and parking lots, with an adult present. Clap the blocks with fingers on the outside edges so they are not pinched. Never stay outdoors to time thunder: count from inside a building or a hard-topped car.

EXPERIMENT: ECHO LAB: CLAP YOUR WAY TO THE SPEED OF SOUND

Question: **How fast does sound travel in air, and does the echo time grow in step with the distance?**

Prediction: Write your guess for the speed of sound in m/s, and predict what will happen to the time between claps if you stand twice as far from the wall.

You will need

- A large, flat, hard wall with an open field in front of it (a school building, gym wall, church wall or barn), at least 100 m of open ground
- Two flat wooden blocks or boards for clapping (or clap your hands loudly)
- A 30 m or 50 m tape measure (or a measuring wheel, or a pace you have measured)
- A stopwatch or phone stopwatch
- A thermometer for the air temperature
- Lab notebook, pencil and graph paper

Steps

1. Measure 100 m straight out from the wall and mark the 40, 60, 80 and 100 m spots with sticks or cones. Record the air temperature.
2. Stand at 100 m facing the wall. Clap the blocks once, sharply, and listen for the echo. A quiet day with little wind works best.
3. Now clap in a steady rhythm, adjusting your speed until each clap lands exactly on the echo of the clap before. The echo will seem to disappear into your claps.
4. When the rhythm is steady, your partner starts the stopwatch on one clap (count it as zero) and stops it on the 20th clap after that, so 20 intervals are timed.
5. Interval = total time ÷ 20. Speed = (2 × distance) ÷ interval. Record both.
6. Do 3 trials at 100 m, then switch jobs and repeat at 80 m, 60 m and 40 m.
7. Find the average speed for each distance and for the whole lab. Compare it with the rule speed ≈ 331 + 0.6 × temperature, and find your percent error.
8. Make a graph of distance (up the side) against interval, which is the echo time (across the bottom). Draw the best straight line through the points and the origin.
9. Write a conclusion: your measured speed, your percent error, whether echo time grew in step with distance, and the biggest source of error.

Tips

- What we change: the distance from the wall. What we keep the same: the wall, the clapper, the way of timing (20 intervals), the weather as much as possible. What we measure: the time for 20 intervals.
- If the clapping rhythm is too fast to keep up, move farther back. Below about 40 m the echo is too quick for most people to match.
- Keep your back to open space and face the wall squarely; a building corner or trees nearby can send confusing extra echoes.

Check your work

- My data table lists distance, three timed trials, intervals and speeds, with units on every number.
- I calculated an average speed and a percent error and showed my work.
- My graph has a title, labeled axes with units, plotted points and a best-fit line.

NATURE NOTEBOOK

1. Draw a bird’s-eye map of your echo lab site: the wall, your marked distances, where the clapper and timer stood, and any trees or buildings that might cause extra echoes.
2. Draw Derham in his church tower watching for a gun flash miles away, with a dotted line for light and a wavy line for sound. Label which arrives first.
3. Keep a thunder log for the next storm (from indoors): time of each flash, seconds until thunder, and the estimated distance in km. Is the storm coming closer or moving away?

> **From history.** Sound can do surprising things along curved walls. In the Whispering Gallery that circles the inside of the great dome of St Paul’s Cathedral in London, a

whisper spoken close to the wall can be heard clearly by a listener on the far side, more than 30 m away. In 1878 the English physicist Lord Rayleigh explained why: the sound clings to the smooth curved wall, bouncing along it again and again instead of spreading out across the dome. Today engineers use the same “whispering gallery” idea with light in tiny sensors.

WORKED EXAMPLES

Example 1. You stand 85 m from a large wall and clap in rhythm with the echoes. Twenty intervals take 10.0 s. What speed of sound did you measure?

1. One interval (the echo time) = 10.0 s ÷ 20 = 0.50 s.
2. Sound travels to the wall and back: 2 × 85 m = 170 m.
3. Speed = 170 m ÷ 0.50 s = 340 m/s.

Answer: 340 m/s.

Example 2. Four trials at 20 °C gave 330, 352, 345 and 337 m/s. Find the average and the percent error. (Accepted value at 20 °C: 331 + 0.6 × 20 = 343 m/s.)

1. Sum = 330 + 352 + 345 + 337 = 1,364 m/s. Average = 1,364 ÷ 4 = 341 m/s.
2. Difference from accepted value = 343 − 341 = 2 m/s.
3. Percent error = 2 ÷ 343 × 100 ≈ 0.6%.

Answer: Average 341 m/s; percent error about 0.6%.

Example 3. A family measured these echo times: 40 m, 0.24 s; 60 m, 0.35 s; 80 m, 0.47 s; 100 m, 0.59 s. Use the graph to find the speed of sound and predict the echo time at 120 m.

(Use the map or drawing “The slope of the line is about 170 m/s; double it for the speed of sound.” shown earlier in this lesson.)

1. The points lie on a straight line through the origin, so distance and echo time are proportional.
2. Slope of the best-fit line: about 102 m ÷ 0.60 s = 170 m/s. This is the distance to the wall, which is half the total path, so the speed of sound = 2 × 170 = 340 m/s.
3. At 120 m: echo time = 2 × 120 ÷ 340 = 240 ÷ 340 ≈ 0.71 s.

Answer: About 340 m/s; at 120 m the echo time would be about 0.71 s.

PRACTICE

1. EASY How did William Derham measure the speed of sound, and what result did he report in 1709?
2. EASY Why does the echo lab need you to stand at least about 40 m from the wall?
3. EASY Why do we time 20 intervals instead of just one?
4. MEDIUM You count 9 seconds between a lightning flash and its thunder. About how far away was the lightning?
5. MEDIUM Use speed ≈ 331 + 0.6 × T to find the speed of sound at 0 °C and at 30 °C. Which day gives shorter echo times?
6. MEDIUM Data reading. Four families did the echo lab on the same day:
   Family A: 60 m, 20 intervals in 7.0 s
   Family B: 80 m, 20 intervals in 9.4 s
   Family C: 100 m, 20 intervals in 11.8 s
   Family D: 100 m, 20 intervals in 15.0 s
   (a) Find each family's speed. (b) Which result is an outlier? (c) Suggest what may have gone wrong.
7. HARD Data reading. Use the echo-lab graph (points 40 m, 0.24 s; 60 m, 0.35 s; 80 m, 0.47 s; 100 m, 0.59 s). (a) What distance matches an echo time of 0.30 s? (b) If the line were steeper, would sound be faster or slower? (c) Why does the best-fit line go through the origin (0, 0)?
8. HARD Experiment design. You want to test whether air temperature changes the speed of sound using the echo lab. Describe your plan: what you change, what you keep the same, what you measure and what you predict.
9. CHALLENGE At 85 m, one echo interval is really 0.50 s. Suppose the timer stops the watch 0.2 s late. What speed do you get if you timed only 1 interval? If you timed 20 intervals?
10. CHALLENGE In your lab, the echo from a wall 85 m away took 0.5 s. A bat hears the echo from a moth 0.85 m away. How long does the bat's echo take, and how many times shorter is it than yours? What does this tell you about the bat's brain?

COMMON MISTAKES

- Using the one-way distance instead of the round trip. In the echo lab, the sound travels to the wall and back, so use 2 × distance.
- Thinking loud sounds travel faster than soft ones. Loudness does not change the speed of sound; temperature and the material it travels through do.
- Thinking one careful measurement is enough. Averages of several trials, and timing many intervals, give much more trustworthy results.

> **Make it a game · Thunder Countdown.** A parent flashes a flashlight (the "lightning") and then, after some seconds, says "BOOM!" Everyone counts the seconds silently. The first person to call out the correct distance in kilometers (seconds ÷ 3) scores a point. For

harder rounds, the parent says “echo” instead of “boom,” and players must find the distance to a wall (340 × seconds ÷ 2). Play to ten points.

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)

Derham searched out the speed of sound from a church tower, and you can search it out with two wooden blocks and a wall. Careful measuring is an honorable way to explore God’s world.

Practice answers

1. From his church tower in Upminster he watched for the flash of guns fired miles away and timed how long the sound took to arrive, using a pendulum, many times. He reported about 1,142 feet per second, about 348 m/s.
2. Close to the wall the echo returns so quickly that you cannot hear it separately from the clap or keep a rhythm with it. Farther away gives a longer echo time that you can match and time.
3. Your reaction time (about 0.2 s) adds error to each start and stop. Timing 20 intervals spreads that error over all 20, so the error in each interval becomes very small.
4. 340 m/s × 9 s = 3,060 m, about 3 km (or 9 ÷ 3 = 3 km).
5. 0 °C: 331 m/s. 30 °C: 331 + 18 = 349 m/s. The warm day gives shorter echo times because sound travels faster.
6. (a) A: interval 0.35 s, speed 120 ÷ 0.35 ≈ 343 m/s. B: 0.47 s, 160 ÷ 0.47 ≈ 340 m/s. C: 0.59 s, 200 ÷ 0.59 ≈ 339 m/s. D: 0.75 s, 200 ÷ 0.75 ≈ 267 m/s. (b) Family D. (c) They may have clapped too slowly (skipping past the echo), counted the wrong number of intervals, or measured the distance wrong.
7. (a) About 51 m (170 m/s × 0.30 s). (b) Faster: a steeper line means more distance for the same echo time. (c) At zero distance there is no trip to make, so the echo time is zero.
8. Change: the air temperature, by doing the lab on a cold early morning and again on a warm afternoon (record both temperatures). Keep the same: the wall, the distance (for example 100 m), the clapper and timer, the method (20 intervals), and pick calm days to keep wind the same. Measure: the time for 20 intervals, 3 or more trials each, and calculate the speed. Prediction: the warmer air gives a higher speed (about 0.6 m/s faster for each 1 °C), so the 20 intervals take a little less time. Because the difference is small (about 12 m/s for 20 °C), many careful trials are needed.
9. 1 interval: measured 0.70 s; speed = 170 ÷ 0.70 ≈ 243 m/s (far off). 20 intervals: measured 10.2 s, interval 0.51 s; speed = 170 ÷ 0.51 ≈ 333 m/s (close). Timing many intervals shrinks the effect of reaction-time error.
10. Bat’s echo: 2 × 0.85 ÷ 340 = 0.005 s (5 ms). 0.5 ÷ 0.005 = 100 times shorter. The bat must sense and use echo delays of a few thousandths of a second, far too short for a person with a stopwatch, so its brain works as a remarkably fast and precise timer.

Unit 3 review

Answer each question. Show your work for every calculation, include units, and use complete sentences for explanations. Use 340 m/s for the speed of sound in air and 1,500 m/s in seawater unless told otherwise. The test is worth 60 points.

1. (4 pts) Multiple choice. In the 1790s, bats with their ears plugged with wax crashed into walls, but bats that could not see flew normally. What did this show? (a) Bats find their way by smell. (b) Bats find their way by hearing. (c) Bats feel the air with their wings. (d) Bats are blind.
2. (6 pts) A bat hears the echo from a moth 0.03 s after it calls. (a) How far away is the moth? (b) The bat’s call is 60 kHz. Can a person hear it? Explain.
3. (6 pts) Spallanzani proved bats needed their ears but could not explain how. Explain why he was stuck and what Donald Griffin and G. W. Pierce discovered in 1938.
4. (4 pts) Multiple choice. Which part of a dolphin focuses its clicks into a forward beam? (a) the blowhole (b) the lower jaw (c) the melon (d) the flippers
5. (8 pts) Diagram. Draw the side view of a dolphin’s head. Label the blowhole, phonic lips, melon, acoustic fat in the lower jaw and inner ear. Draw arrows showing the path of a click going out and the echo coming back, and write one sentence telling what each labeled part does.
6. (5 pts) A dolphin’s echo from a fish returns in 0.06 s. How far away is the fish? If the same echo time were measured in air, how far away would the object be?
7. (4 pts) Multiple choice. Which statement is true? (a) Sonar was invented by copying bats after Griffin’s discovery. (b) The first sonar was built in 1914, before bat echolocation was proven in 1938. (c) Sonar uses light instead of sound. (d) Passive sonar sends out pings.
8. (6 pts) A ship’s echo sounder recorded these echo times: Point 1: 3.0 s; Point 2: 1.2 s; Point 3: 5.0 s. (a) Find the depth at each point. (b) Which point is probably on top of an underwater mountain? Which is deepest?
9. (4 pts) Explain the difference between active and passive sonar, and give one everyday use of echoes besides ships.
10. (6 pts) In the echo lab you stand 102 m from a wall. Twenty clap intervals take 12.0 s. (a) What is one echo time? (b) What speed of sound did you measure? (c) Why do we time 20 intervals instead of one?
11. (7 pts) Data reading and experiment design. Three trials on a 25 °C day gave 338, 350 and 344 m/s. (a) Find the average. (b) Use speed ≈ 331 + 0.6 × T to find the expected value and the percent error. (c) Name one variable you would keep the same if you repeated the lab on a cold morning to test the effect of temperature.

Unit project: seeing with sound: my echolocation report

Prepare a lab report and display on echolocation. Include your full Echo Lab report from Lesson 3.4 (question, prediction, data table, calculations, graph of distance against echo time, average speed and percent error, and conclusion). Beside it, make a poster or notebook

spread with three labeled diagrams: a bat catching a moth, a dolphin's head with its click and echo paths, and a ship using an echo sounder over a sea-floor profile, each with one worked echo calculation.

Finish with a short paragraph explaining how Spallanzani, Griffin, Norris and Fessenden each added to what we know, and one sentence on what the bat and dolphin show about the wisdom of their Maker.

- **Accuracy**: Diagrams are labeled correctly, every calculation uses the right speed of sound and divides by two, and units are shown.
- **Lab records**: The echo lab data are complete and dated, trials are averaged, the graph has a title, labeled axes and a best-fit line, and the percent error is correct.
- **Explanation**: The paragraph correctly tells the order of discoveries (bats 1793, sonar 1914, bat ultrasound 1938, dolphins about 1960) and what each showed.
- **Care**: The work is neat, clearly organized and easy for a reader to follow.

Answer key

1. (b) Bats find their way by hearing.
2. (a) Path = 340 × 0.03 = 10.2 m; distance = 10.2 ÷ 2 = 5.1 m. (b) No. 60 kHz = 60,000 Hz, above the human limit of about 20,000 Hz, so it is ultrasound.
3. Bat calls are ultrasound, too high for human ears, so the bats seemed silent and it made no sense that they were listening to anything. In 1938 Pierce's machine for detecting high-pitched sound picked up the bats' ultrasound calls, and Griffin showed the bats were hearing the echoes of their own calls. He later named this echolocation.
4. (c) The melon.
5. A correct diagram shows: the blowhole on top of the head; the phonic lips just below it, which make the clicks; the melon (rounded forehead) in front, which focuses clicks into a beam; an arrow from the melon out in front of the snout; an echo arrow returning to the lower jaw; the fat in the lower jaw, which carries the echo back; and the inner ear near the back of the jaw, which hears it. (2 points for correct placement of parts, 2 for the arrows, 4 for the five jobs.)
6. Water: 1,500 × 0.06 = 90 m path; distance 45 m. Air: 340 × 0.06 = 20.4 m path; distance 10.2 m.
7. (b). Sonar came first; since then engineers have learned from bats and dolphins to improve it.
8. (a) Depth = 750 × time. Point 1: 2,250 m. Point 2: 900 m. Point 3: 3,750 m. (b) Point 2 is probably on an underwater mountain (shallowest). Point 3 is deepest.
9. Active sonar sends out its own ping and listens for the echo; passive sonar only listens to sounds other things make. Everyday uses: car parking sensors, fish finders, medical ultrasound imaging (any one).
10. (a) 12.0 ÷ 20 = 0.60 s. (b) Speed = 2 × 102 ÷ 0.60 = 204 ÷ 0.60 = 340 m/s. (c) Reaction-time error (about 0.2 s) is spread over 20 intervals, so it becomes small in each one.
11. (a) (338 + 350 + 344) ÷ 3 = 1,032 ÷ 3 = 344 m/s. (b) Expected = 331 + 15 = 346 m/s; error = 2 ÷ 346 × 100 ≈ 0.6%. (c) Any one: the same wall, the same distance, the same clapper and timer, the same timing method (20 intervals), similar calm wind.

UNIT 4

Camouflage

Some animals live by hiding and some by shouting. In this unit you will meet the cuttlefish, a cousin of the octopus that repaints its skin in half a second with tiny sacs of pigment, and the panther chameleon, which changes from green to orange by tuning a grid of crystals in its skin. You will follow the peppered moths of England, pale and dark, through soot-blackened woods and back again, and learn exactly what the famous study showed and what it did not. Then you will turn to animals that want to be seen: monarchs, poison dart frogs and wasps whose bright colors warn, and the clever bluffers that copy them.

Along the way you will work like real scientists: Teyssier and Milinkovitch in Geneva, Hanlon at Woods Hole, Kettlewell and Majerus in the English woods, Bates on the Amazon, Brower with his blue jays and the painter Abbott Thayer, who discovered countershading. You will calculate recapture percents, read learning curves, use a Punnett square and finish by playing the bird in a Camouflage Game that models natural selection over three generations. In every lesson you will ask: **what does the evidence actually show?** And you will see, in the skin and wings of these creatures, the wisdom of the One who made every thing “after his kind” (Genesis 1:25).

BEFORE YOU BEGIN

- Can calculate a percent from a fraction (for example, 18 out of 20 is 90%)
- Can read a simple bar graph and line graph
- Knows the basic idea of dominant and recessive traits and how to fill a Punnett square (review in Lesson 4.2 if needed)
- Can name the parts of a simple experiment: question, prediction, variables and conclusion

MASTERY CHECKLIST

- I can explain how a cuttlefish changes color with chromatophores and how a chameleon changes color with tiny crystals.
- I can tell the peppered moth story, calculate Kettlewell’s recapture percents and explain what the study showed and what it did not show.
- I can explain warning coloration and tell the difference between Batesian and Müllerian mimicry.
- I can explain countershading and draw a diagram of how it works.
- I can run a fair camouflage simulation, calculate survival rates and describe how a population changes over generations.

OPTIONAL BOOKS AND RESOURCES

- **Biodiversity Heritage Library** (https://www.biodiversitylibrary.org/): Free. Search for Henry Walter Bates’s 1862 mimicry paper in the *Transactions of the Linnean Society*

and for Gerald and Abbott Thayer's *Concealing-Coloration in the Animal Kingdom* (1909) to see the original plates and paintings.

- **Smithsonian American Art Museum** (https://americanart.si.edu/): Free online collection. Search for Abbott Thayer to see *Peacock in the Woods* (Lesson 4.2) and his other camouflage studies.
- **Monterey Bay Aquarium** (https://www.montereybayaquarium.org/): Free animal pages and live cams. Look up cuttlefish, octopus and other masters of camouflage before or after Lesson 4.1.

4.1 Chameleons and Cuttlefish ★

OBJECTIVES

- Explain how a cuttlefish changes color with chromatophores worked by muscles and nerves, and how a panther chameleon changes color by tuning tiny crystals in its skin.
- Describe the three main cuttlefish camouflage patterns (uniform, mottle and disruptive) and the checkerboard experiments that revealed them.
- Use ratios, rates and data tables to compare how much and how fast animal colors change.

Warm-up. Find an old CD or DVD and a glass of water with one drop of food coloring in it. Tilt the CD under a lamp and watch the rainbow slide across it. Now look at the colored water from every angle. Which color changes when you tilt it, and which stays the same? The CD has no paint on it at all. Write one guess about where its colors come from.

Video. Coming soon. Cuttlefish camouflage and chromatophores up close, and panther chameleon color change; search Monterey Bay Aquarium, Smithsonian, PBS Nature, KQED Deep Look and slow-motion nature footage of cephalopod skin.

KEY TERMS

camouflage
Color, pattern, shape or behavior that makes an animal hard to see or hard to recognize against its surroundings.

cephalopod
A mollusk with arms around its head, such as an octopus, squid or cuttlefish. Cephalopod means “head-foot.”

chromatophore
A tiny stretchy sac of colored pigment in the skin. In cuttlefish, small muscles pull it wide to show color or let it shrink to hide color.

iridophore
A skin cell holding layers or grids of tiny crystals that reflect certain colors of light. Chameleons change color mainly with these cells.

structural color
Color made by the shape and spacing of tiny structures that reflect light, not by pigment. A CD, a soap bubble and a blue jay’s feather show structural color.

disruptive coloration
Bold patches of light and dark that break up an animal’s outline so the eye cannot find its true shape.

CORE IDEAS

The story. In 2015, at the University of Geneva in Switzerland, Jérémie Teyssier and Michel Milinkovitch set out to answer an old question: how does a chameleon change color? They studied panther chameleons from Madagascar. A calm male panther chameleon is mostly green. When a rival male comes into view, he can turn bright yellow and orange within a minute or two. For years many books said chameleons do this by moving pigment around. The Geneva team looked at the skin with powerful microscopes and found something else. Under the yellow pigment lies a layer of cells called **iridophores**, packed with tiny crystals of guanine lined up in a neat grid. When the chameleon is relaxed, the crystals sit close together and reflect blue light. Blue light shining up through yellow pigment looks green. When the chameleon is excited, the grid spreads apart, and the crystals reflect longer waves of light: yellow, orange and red. The color comes from spacing, not paint. It is **structural color**, like the rainbow on a CD.

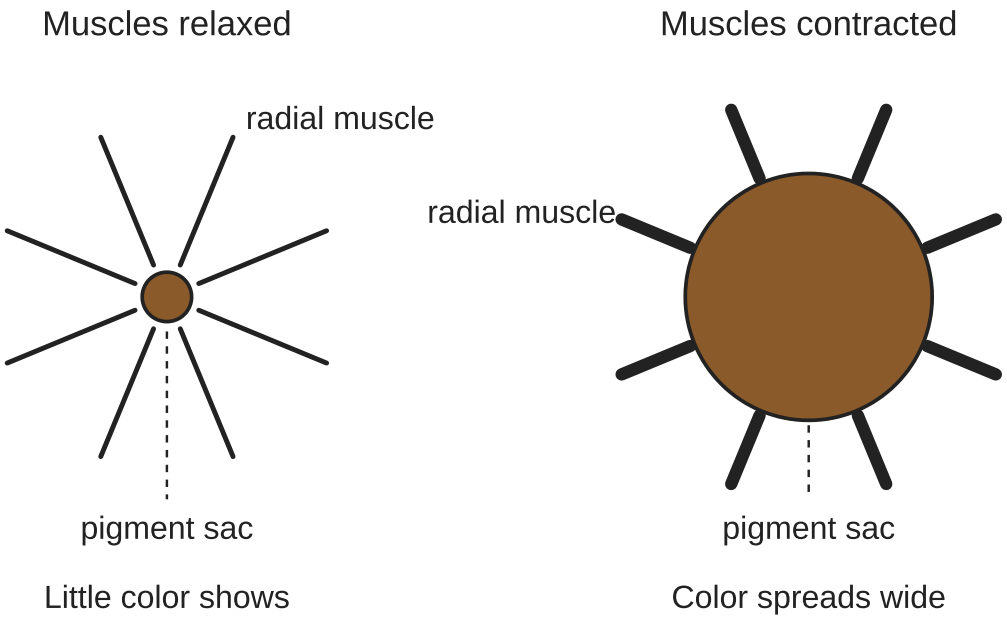
How they figured it out. To test their idea, the Geneva scientists soaked small pieces of chameleon skin in salty or less salty water. This made the cells swell or shrink, which pushed the crystals apart or together, and the skin changed color just as a living chameleon does. Cuttlefish do it a different way. At the Marine Biological Laboratory in Woods Hole, Massachusetts, Roger Hanlon and Chuan-Chin Chiao placed common cuttlefish on boards of black and white squares. On small squares the cuttlefish turned an even or finely **mottled** color. When the white squares were about the size of the white patch on the cuttlefish's own back, the animal flashed a bold **disruptive** pattern of light and dark blocks. By changing one thing at a time (square size, contrast, the number of white squares), they learned what the cuttlefish was "reading" in the background. Scientists now group most cuttlefish camouflage into three kinds: uniform, mottle and disruptive.

The big idea. A cuttlefish is not a fish at all. It is a **cephalopod**, a cousin of the octopus and squid, with eight arms, two long feeding tentacles and an internal shell called a cuttlebone. Its skin holds thousands of **chromatophores**: elastic sacs of yellow, red or brown-black pigment, each ringed by tiny muscles. Nerves run straight from the brain to those muscles. When the muscles pull, the sac stretches wide and its color shows. When they relax, the sac shrinks to a speck. Because nerves work fast, a cuttlefish can change its whole pattern in less than a second. Below the chromatophores lie reflecting cells that add shine and white. A chameleon's change runs through cells swelling and shrinking, so it is slower: seconds to minutes. Both are kinds of **camouflage** and signaling, but they use two different tools: pigment moved by muscle, and crystals tuned like a prism.

In the world today. One popular idea is wrong: a chameleon set on a plaid shirt will not turn plaid. Chameleons change color mostly to send messages to other chameleons (calm, angry, ready to court) and to warm up or cool down, since darker skin soaks up more sunlight. The Geneva team also found a deeper layer of crystals that reflects much of the sun's invisible infrared light, which may help keep the lizard from overheating. Cuttlefish, by contrast, really do match their surroundings. That is the deepest puzzle of all: experiments show cuttlefish eyes have only one kind of light-sensing pigment, so most scientists think

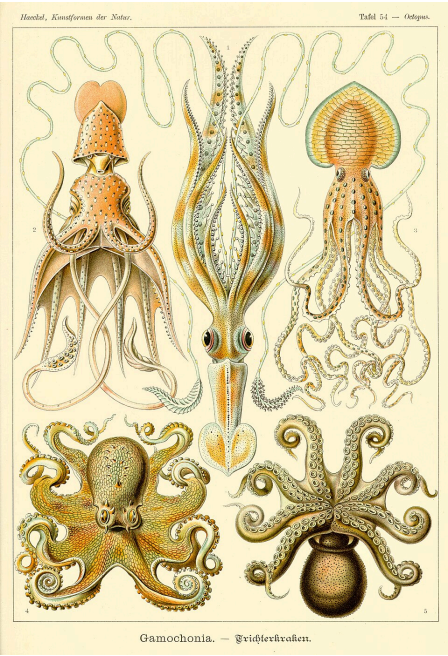
they cannot see color the way we do, yet they blend in beautifully. Engineers are now trying to copy cephalopod skin to make thin sheets that change color on command.

God's handiwork. Job was told, "ask now the beasts, and they shall teach thee… and the fishes of the sea shall declare unto thee" (Job 12:7–8). A cuttlefish has no paint box and takes no art lessons, yet in half a second it paints its skin to match sand, gravel or a checkerboard. A chameleon carries a crystal prism in its skin and tunes it with a feeling. Every new microscope shows more order hidden in the skin of these creatures. Studying them closely is one way of learning to praise the One who thought of them first.



A chromatophore relaxed and stretched. When the ring of radial muscles contracts, it pulls the pigment sac wide and the color shows.

PICTURE STUDY



Gamochonia (Octopuses and Squids), Plate 54 from Art Forms in Nature, Ernst Haeckel, 1904 (the book was published in parts, 1899–1904) · Color printed plate from a book, made from Haeckel's drawings · *Kunstformen der Natur* (Art Forms in Nature), Leipzig; copies are held in many libraries, including the Library of Congress

Ernst Haeckel was a German zoologist at the University of Jena who drew sea creatures with great care. His book *Art Forms in Nature* came out in parts between 1899 and 1904, with one hundred plates of animals and plants arranged almost like stained-glass windows. This plate, number 54, shows octopuses and squids, the closest cousins of the cuttlefish. The common octopus appears twice, once from above and once from below.

Haeckel worked from preserved specimens and from his own sketches at the seashore, so the colors you see are his best record of the animals. Living octopuses and cuttlefish can change those colors in an instant, which no printed plate can show.

Look closely

- Count the arms on one octopus. How many do you find? (Octopuses have eight; squids and cuttlefish have eight arms plus two long tentacles.)
- Find the rows of suckers. Do they run in one line or two on each arm?
- Look for spots and speckles on the skin. These are where the chromatophores lie.
- Notice how Haeckel arranged the animals on the page. Is it balanced from left to right?

Talk about it

1. Why can no drawing or photograph fully show what a cephalopod's skin can do?
2. If you could draw one cuttlefish beside these animals, what parts would be different?

3. Haeckel mixed science and art. What did he gain by arranging the animals so beautifully?

> **Safety first.** Balloons can cause choking, so keep them and any broken pieces away from small children, and use a latex-free balloon if anyone in the house has a latex allergy.

EXPERIMENT: MODEL CHROMATOPHORE: HOW MUCH COLOR DOES STRETCHING SHOW?

A chromatophore is a stretchy sac of pigment. You will use a balloon as a model sac and measure how much the colored area grows as it stretches. This is a small experiment, so you will write down your question, prediction and variables before you start.

You will need

- One round balloon (light colored)
- A dark permanent marker
- A metric ruler and a soft tape measure (or a strip of paper to wrap and mark)
- Lab notebook and pencil
- Calculator (optional)

Steps

1. Question: When a pigment sac stretches wider, how many times bigger does its colored area become?
2. Prediction: Write your guess. If the dot gets 3 times wider, will its area be 3 times bigger, or more?
3. Blow the balloon up a tiny amount (about one short breath) and pinch the neck. With the marker, fill in a solid round dot 1 cm across. Measure it carefully.
4. What we change: how many breaths of air go into the balloon. What we keep the same: the same balloon, the same dot, the same way of measuring. What we measure: the width of the dot in centimeters.
5. Make a table with columns: Breaths, Dot width (cm), Times wider than start, Times more area (width ratio × width ratio).
6. Add one breath at a time, up to five breaths. After each breath, measure the dot’s width across its middle and record it.
7. Fill in the last two columns. Then look at the color of the dot. Does it look paler as it stretches?
8. Write a conclusion of two or three sentences. Compare your area numbers to your prediction, and explain why a cuttlefish can show a lot of color from a tiny sac.

Tips

- Measure the dot the same way each time, straight across through the middle.
- To find “times more area,” multiply the width ratio by itself. A dot 3 times wider covers about 9 times the area.

- Do not overinflate the balloon. Stop if it feels tight.

Check your work

- I wrote a question, a prediction and the variables before measuring.
- My table has at least five measurements in centimeters.
- I can explain why stretching a sac a little makes a big change in color area.

NATURE NOTEBOOK

1. Draw the two states of a chromatophore (relaxed and stretched) like the figure, and label the pigment sac and radial muscles.
2. Draw three small squares and fill them with a cuttlefish uniform pattern, a mottle pattern and a disruptive pattern. Under each, write the kind of sea floor where it would hide best.
3. Draw a panther chameleon twice, calm and excited. Label the colors and write one sentence explaining what the crystals are doing in each drawing.

> **From history.** The color changes of the octopus and the chameleon were noticed long before microscopes. In the 300s BC the Greek philosopher Aristotle, who studied sea animals on the island of Lesbos, wrote in his *History of Animals* that the octopus hunts by changing its color to look like the stones around it, and he described the chameleon's changing skin as well. More than two thousand years later, scientists with electron microscopes are still filling in the details of what he saw.

WORKED EXAMPLES

Example 1. Suppose a cuttlefish chromatophore is 0.2 mm wide when relaxed and 1.0 mm wide when fully stretched. How many times wider does it get? How many times more area of color does it show? (Treat the sac as a circle.)

(Use the map or drawing "Stretching the sac 5 times wider shows 25 times more color." shown earlier in this lesson.)

1. Width ratio: 1.0 mm ÷ 0.2 mm = 5. The sac gets 5 times wider.
2. The area of a circle grows with the width times the width, so the area ratio is 5 × 5 = 25.
3. Check with the circle formula. Relaxed radius 0.1 mm: area = 3.14 × 0.1 × 0.1 = 0.0314 mm². Stretched radius 0.5 mm: area = 3.14 × 0.5 × 0.5 = 0.785 mm².
4. 0.785 ÷ 0.0314 = 25. The two methods agree.

Answer: 5 times wider and 25 times more colored area. A small pull on the muscles makes a big change in how much color shows.

Example 2. Suppose a cuttlefish switches from a sand-colored pattern to a bold disruptive pattern in 0.5 seconds, and a panther chameleon goes from calm green to orange in 2 minutes. How many times faster is the cuttlefish's change?

1. Put both times in the same unit. 2 minutes × 60 seconds per minute = 120 seconds.
2. Divide the slower time by the faster time: 120 s ÷ 0.5 s = 240.
3. Explain the reason: the cuttlefish's chromatophores are pulled by muscles that take orders straight from nerves, while the chameleon's crystals move only as whole cells slowly swell or shrink.

Answer: The cuttlefish's change is 240 times faster in this example.

Example 3. A scientist places a cuttlefish on checkerboards with different square sizes and counts how often it shows a disruptive pattern in 20 trials on each board. The cuttlefish's white back patch is about 20 mm wide. Results (sample data): 2 mm squares: 1 of 20 trials. 10 mm squares: 6 of 20. 20 mm squares: 17 of 20. 60 mm squares: 4 of 20. Find the percent for each board and state the pattern.

1. Percent = (trials with disruptive pattern ÷ total trials) × 100.
2. 2 mm: 1 ÷ 20 = 0.05, so 5%. 10 mm: 6 ÷ 20 = 0.30, so 30%.
3. 20 mm: 17 ÷ 20 = 0.85, so 85%. 60 mm: 4 ÷ 20 = 0.20, so 20%.
4. The highest value is on the 20 mm board, the size that matches the cuttlefish's own white patch. Squares much smaller or much larger produced few disruptive patterns.

Answer: 5%, 30%, 85% and 20%. The cuttlefish showed its disruptive pattern most often when the light squares were about the size of its own white patch.

PRACTICE

1. EASY What is a chromatophore, and what makes it show more color?
2. EASY Is a cuttlefish a fish? What group of animals does it belong to, and name two of its relatives.
3. EASY According to the 2015 Geneva study, what changes inside a panther chameleon's skin when it turns from green to orange?
4. MEDIUM A friend says, "If you put a chameleon on a checkered tablecloth, it will turn checkered." Is this right? Explain.
5. MEDIUM A chromatophore stretches from 0.3 mm wide to 1.2 mm wide. How many times wider is it, and about how many times more area of color does it show?
6. MEDIUM Data reading. A model of chameleon skin gives these results (made-up data shaped like the real finding): Crystal spacing 130 nm → color reflected: blue. Spacing 150 nm → green-yellow. Spacing 170 nm → orange. Spacing 190 nm → red. (A) As

crystal spacing increases, what happens to the color reflected? (B) Which spacing would most likely be measured in a calm chameleon whose skin looks green under yellow pigment?

7. MEDIUM Data reading. A cuttlefish was tested 20 times on each background (sample data). Sand: uniform 16, mottle 3, disruptive 1. Gravel: uniform 2, mottle 14, disruptive 4. Large checkerboard: uniform 1, mottle 3, disruptive 16. (A) Which background produced the most mottle patterns? (B) What percent of trials on the large checkerboard were disruptive? (C) Which statement do the data support best: (a) the cuttlefish uses one pattern everywhere, (b) the pattern depends on the background, (c) the cuttlefish prefers sand?
8. HARD A 20 cm cuttlefish has a white back patch 2 cm wide. If a larger cuttlefish 30 cm long has a patch in the same proportion, how wide is its patch? About what checkerboard square size would most likely trigger its disruptive pattern?
9. HARD Explain in two or three sentences why a cuttlefish can change color much faster than a chameleon.
10. CHALLENGE Experiment design. Most scientists think cuttlefish are colorblind. Design an experiment to test whether a cuttlefish chooses its pattern by the color of the background or by its brightness (how light or dark it is). Name your independent variable, dependent variable, what you keep the same and what result would support each idea.

COMMON MISTAKES

- Thinking chameleons copy whatever background they sit on. They change mostly to signal and to control temperature, and they cannot copy a plaid or a checkerboard.
- Thinking all animal color comes from pigment. Much of a chameleon’s color is structural color, made by the spacing of tiny crystals that reflect light.
- Calling the cuttlefish a fish. It is a mollusk and a cephalopod, a relative of the octopus and squid, with an internal shell called a cuttlebone.

Make it a game · Cuttlefish Says. A parent holds up a background: a sandy towel, a pile of gravel or pebbles, or a black-and-white checkered cloth or board. You have three seconds to “change your skin” by holding up the right pattern card (uniform, mottle or disruptive) that you drew beforehand. Score one point for each correct match. For a bonus point, say whether a chameleon would change for that background, and why not.

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)

A cuttlefish painting its skin in half a second and a chameleon tuning crystals with its mood are lessons from the creatures themselves. Careful study lets them “declare” the wisdom of the One who made them.

Practice answers

1. A chromatophore is a tiny stretchy sac of pigment in the skin. In cuttlefish, a ring of small muscles pulls the sac wide so its color covers more area; when the muscles relax, the sac shrinks and the color nearly disappears.
2. No. A cuttlefish is a mollusk in the cephalopod group. Its relatives include the octopus and the squid.
3. The tiny guanine crystals in its iridophore cells spread farther apart, so they reflect longer waves of light (yellow, orange, red) instead of blue. It is a change in structural color, not mainly a moving of pigment.
4. No. Chameleons change color mainly to signal to other chameleons (calm, angry, courting) and to control body temperature. They do not copy the pattern under them. Cuttlefish come much closer to matching their background.
5. 1.2 ÷ 0.3 = 4 times wider. Area grows by 4 × 4 = 16 times.
6. (A) As spacing increases, the reflected color shifts from blue toward red (longer wavelengths). (B) 130 nm, the closely packed spacing that reflects blue; blue light seen through yellow pigment looks green.
7. (A) Gravel (14 of 20). (B) 16 ÷ 20 = 80%. (C) Statement (b): the pattern chosen depends on the background.
8. The patch is 2 ÷ 20 = 1/10 of the body length. 30 cm × 1/10 = 3 cm. Squares about 3 cm wide (30 mm) would most likely trigger the disruptive pattern.
9. A cuttlefish’s chromatophores are opened by muscles, and those muscles are controlled directly by nerves from the brain, so they can act in a fraction of a second. A chameleon’s color depends on crystals that move only as whole skin cells swell or shrink, which takes seconds to minutes.
10. Sample design: Make two kinds of checkerboards with the same square size. One uses blue and yellow squares that look equally bright in a black-and-white photo (color differs, brightness the same). The other uses gray squares that differ in brightness. Independent variable: whether the squares differ in color or in brightness. Dependent variable: which pattern the cuttlefish shows (count disruptive patterns in 20 trials each). Keep the same: square size, tank, lighting, time of day, the same cuttlefish, rest time between trials. If the cuttlefish goes disruptive on the brightness board but not on the color-only board, it is reading brightness, not color. If it responds to both equally, color may matter.

4.2 Peppered Moths: What the Study Showed

OBJECTIVES

- Tell the history of the peppered moth from the first dark moth near Manchester in 1848, through Kettlewell's experiments in the 1950s, to Majerus's careful study in the 2000s.
- Calculate recapture percentages from real data and use a Punnett square to predict dark and pale offspring.
- Explain what the study showed (birds shifting the numbers of two color forms within one species) and what it did not show.

Warm-up. Lay a sheet of plain white paper beside a sheet of newspaper. Tear 10 small bits of white paper and 10 small bits of paper you have colored dark with a pencil, each about 1 cm. Scatter 5 of each color on each sheet. Ask someone to look for three seconds and point to every bit they saw. Which bits were spotted most on each sheet?

Video. Coming soon. Peppered moth natural selection, Kettlewell's experiments and the light and dark forms of Biston betularia; search the Natural History Museum (London), HHMI BioInteractive, Smithsonian, Homeschool Pop (Alternate) and nature footage of moths resting on bark.

KEY TERMS

variation
Differences among members of the same kind, such as light and dark peppered moths or tall and short pea plants.

natural selection
The process in which living things with traits that fit their surroundings better survive and have more young, so those traits become more common.

frequency
How common something is in a group, often written as a percent. Example: 98 of 100 moths dark is a frequency of 98%.

mark-release-recapture
A field method in which animals are marked, set free and later caught again; the share caught again estimates how many survived.

dominant
Describes a version of a gene (an allele) that shows its trait even when only one copy is present. In peppered moths the dark allele is dominant.

lichen
A crusty or leafy growth on bark and rock made of a fungus and an alga living together. Pale lichens make tree trunks look light and speckled.

CORE IDEAS

The story. The peppered moth of Britain is pale gray-white, sprinkled with black specks like salt and pepper. It flies at night and rests by day on trees, where pale speckled lichens grow on the bark. In 1848 a collector named R. S. Edleston caught a nearly all-black peppered moth near Manchester, England. Manchester was a city of cotton mills burning coal. Soot settled on the trees, killed the lichens and darkened the bark. Over the next fifty years the black form, called **carbonaria**, became more and more common around the mill towns. By 1895 about 98 out of every 100 peppered moths near Manchester were dark. In 1896 the naturalist J. W. Tutt suggested a reason: birds were finding and eating the pale moths on dark trunks more often than the dark ones.

How they figured it out. Tutt's idea was not tested carefully in the field until Bernard Kettlewell of Oxford University took it into the woods. In 1953, in a sooty wood near Birmingham, he marked moths with a small dot of paint under the wing, released them, and then caught as many as he could again in traps over the following nights. Of 447 dark moths released, he recaptured 123 (27.5%). Of 137 pale moths, he recaptured only 18 (13.1%). In 1955 he did the opposite test in a clean, lichen-covered wood in Dorset. There pale moths came back about twice as often as dark ones (12.5% against 6.3%). The same year, the animal scientist Niko Tinbergen filmed wild birds plucking moths from tree trunks. The prediction held in both places: whichever moth stood out was eaten more.

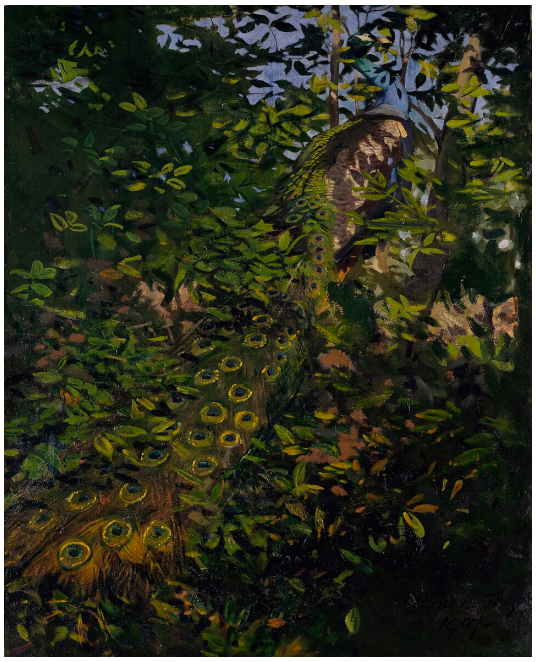
What critics said, and what the newer study showed. Later scientists found real weaknesses. Kettlewell released many moths at once, more than would live naturally in one wood, and some were set out by day on trunks, though peppered moths often rest on the undersides of high branches. Some famous textbook photos were made by placing moths on bark for the camera. These are fair criticisms, and honest scientists took them seriously. So from 2001 to 2007, Michael Majerus of Cambridge University ran a careful new study. He released 4,864 moths, only a few each night, let each moth choose its own resting place, and watched at dawn with binoculars to see which ones birds ate. In his clean Cambridge countryside, birds took dark moths more often than pale ones. Majerus died in 2009; his colleagues published the results in 2012. The main finding of Kettlewell was confirmed.

The big idea. Here is what the study showed: **natural selection** by birds changed the **frequency** of two color forms that already existed. When Britain passed its Clean Air Act in 1956 and the air cleared, lichens returned, and the dark form became rare again. Both forms are one species, *Biston betularia*, and they mate with each other freely. The dark color is controlled by a **dominant** allele, so the forms follow Mendel's rules (see worked example 3). In 2016 scientists traced the dark form to a piece of DNA inserted into a gene called *cortex*. Here is what the study did not show: it did not show a moth turning into a new kind of creature, or how moths, wings or eyes first came to be. The moths began as peppered moths and ended as peppered moths.

God's handiwork. The peppered moth is a true and observed example of **variation** within a kind, just as Genesis 1:25 describes living things reproducing "after their kind." It is also a model of how science should work. A claim was made, tested, criticized and tested again

more carefully. Proverbs 18:17 says that the first one to state his case seems right “but his neighbour cometh and searcheth him.” Good scientists welcome the neighbor who searches.

PICTURE STUDY



Peacock in the Woods, Abbott Handerson Thayer and Richard S. Meryman, 1907 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C.

Abbott Thayer was an American painter from New Hampshire who spent years studying how animals hide. He painted this picture with his student Richard Meryman for a book on animal camouflage that his son Gerald published in 1909. Thayer believed that even a peacock, one of the most brilliant birds in the world, blends into the sunlit leaves of its home forest.

Not everyone agreed. In 1911 Theodore Roosevelt, a keen naturalist and hunter, wrote a long reply saying that Thayer had taken a good idea too far: many brightly colored animals are plainly easy to see. Like the peppered moth story, this painting reminds us that a claim must be tested with evidence, not just argued from one picture.

Look closely

- Find the “eyes” on the tail feathers. What in the forest do they look like?
- Find a place where you cannot tell where the bird stops and the leaves begin.
- Now find a place where the bird stands out clearly.
- Where is the light coming from? How does it change the colors of the feathers?

Talk about it

1. Do you think a real peacock is well hidden in the woods? What evidence would you need to decide?

2. An artist can choose the background in a painting. Why does that make a painting weaker evidence than an experiment?
3. How is the argument between Thayer and Roosevelt like the criticism of the peppered moth photos?

EXPERIMENT: BIRD'S-EYE MOTH HUNT

You will copy the logic of Kettlewell's experiment with paper moths on two kinds of "bark." A helper plays the bird. You will test whether a moth's color decides how often it is found, record the data and calculate the percent that survived.

You will need

- Two sheets of white paper and a gray pencil or charcoal stick (to make "lichen bark" and "sooty bark")
- Plain white paper and a soft dark pencil or black marker (to make moths)
- Scissors and a metric ruler
- Removable tape or a glue stick
- A timer and a helper to be the bird
- Lab notebook

Steps

1. Question: Does a moth's color change how often a "bird" finds it on light bark compared with dark bark?
2. Prediction: Write which color you think will survive best on each bark, and why.
3. Make the bark. Sheet A (clean, lichen bark): speckle white paper lightly with gray pencil. Sheet B (sooty bark): shade a sheet heavily with pencil or charcoal until it is dark gray.
4. Make 20 moths, each a triangle about 2 cm wide: 10 pale (white with a few gray specks) and 10 dark (fully shaded).
5. What we change: the bark (A or B). What we keep the same: number of moths (5 pale and 5 dark on each sheet), moth size, the hunting time (10 seconds), the distance from the eyes (about 1 m) and the same helper. What we measure: how many of each color are found.
6. Tape 5 pale and 5 dark moths to Sheet A while the helper looks away. Hold the sheet up 1 m from the helper. The helper has 10 seconds to point at every moth seen. Remove the moths that were found.
7. Count the survivors of each color and record. Repeat with Sheet B. Then do three rounds on each sheet, moving the moths each time.
8. Add up your rounds. Calculate the percent of each color that survived on each bark: survivors ÷ total placed × 100.
9. Make a bar graph like Kettlewell's, with bars for pale and dark on each bark. Write a conclusion and one way your model is different from real birds and real moths.

Tips

- Place moths in random spots, not in neat rows, and change places each round so the bird cannot remember them.
- Keep the hunting time exactly the same each round. A timer makes this fair.
- If your helper finds every moth, shorten the time or move the sheet farther away for all rounds.

Check your work

- I wrote a question, a prediction and the variables before testing.
- I ran at least three rounds on each bark and calculated percents correctly.
- My graph and conclusion explain which color survived best on each bark and why.

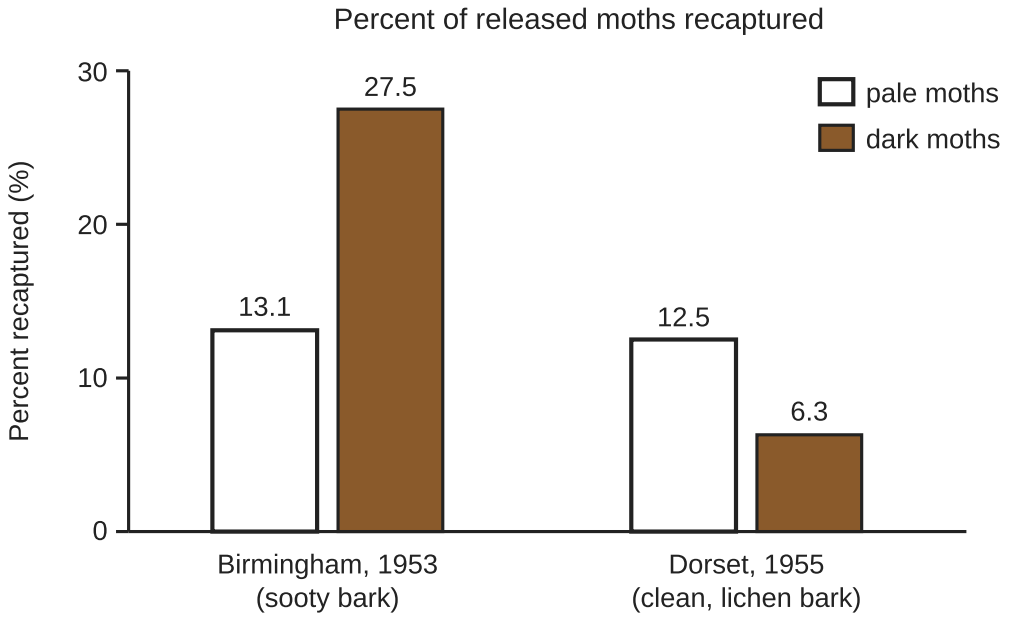
NATURE NOTEBOOK

1. Draw a pale and a dark peppered moth side by side, each on a strip of bark that hides it. Label typica (pale) and carbonaria (dark).
2. Make a timeline from 1848 to 2016 with these marks: first dark moth, 98% dark near Manchester, Kettlewell's experiments, the Clean Air Act, Majerus's study, the *cortex* gene found.
3. Write two short lists titled "What the study showed" and "What the study did not show."

> **From history.** Niko Tinbergen, who filmed birds eating peppered moths for Kettlewell in 1955, was one of the founders of the study of animal behavior. He was born in the Netherlands and later taught at Oxford. In 1973 he shared the Nobel Prize in Physiology or Medicine with Konrad Lorenz and Karl von Frisch, the scientist who discovered how honeybees "dance" to tell one another where food is (see Unit 6).

WORKED EXAMPLES

Example 1. In the sooty wood near Birmingham in 1953, Kettlewell released 447 dark moths and recaptured 123. He released 137 pale moths and recaptured 18. Find the percent of each form recaptured, and how many times more often dark moths were recaptured.



Kettlewell's recapture results in a sooty wood and a clean wood.

1. Dark: 123 ÷ 447 = 0.275, so 27.5% were recaptured.
2. Pale: 18 ÷ 137 = 0.131, so 13.1% were recaptured.
3. Compare: 27.5 ÷ 13.1 ≈ 2.1.
4. Interpret: in the sooty wood, dark moths survived to be caught again about twice as often as pale ones, as the bird-predation idea predicted.

Answer: Dark 27.5%, pale 13.1%. Dark moths were recaptured about 2.1 times as often.

Example 2. In the clean, lichen-covered Dorset wood in 1955, Kettlewell released 496 pale moths and recaptured 62. He released 473 dark moths and recaptured 30. Which form did better here, and by about how much?

1. Pale: 62 ÷ 496 = 0.125, so 12.5%.
2. Dark: 30 ÷ 473 = 0.063, so 6.3%.
3. Compare: 12.5 ÷ 6.3 ≈ 2.0.
4. Interpret: on pale, lichen-covered bark the result reversed. Pale moths were recaptured about twice as often as dark ones.

Answer: Pale moths did better: 12.5% against 6.3%, about twice as often. The two woods together make a strong test, because the result flipped when the background flipped.

Example 3. In peppered moths, the dark allele (C) is dominant over the pale allele (c). Two dark moths that each carry one pale allele (Cc × Cc) mate and produce 200 offspring. Use a Punnett square to predict how many will be dark and how many pale.

1. Write one parent's alleles (C, c) across the top and the other's (C, c) down the side.
2. Fill the four boxes: CC, Cc, Cc, cc.
3. Any box with at least one C is dark (C is dominant): CC, Cc, Cc are dark, which is 3 of 4. Only cc is pale, 1 of 4.
4. Dark: 3/4 × 200 = 150. Pale: 1/4 × 200 = 50.

Answer: About 150 dark and 50 pale, a 3 : 1 ratio. Two dark parents can have pale young, which shows the pale allele was hidden, not lost.

PRACTICE

1. EASY Name the two main color forms of the peppered moth and describe each.
2. EASY Why did tree trunks around Manchester become dark in the 1800s?
3. EASY What method did Bernard Kettlewell use to test whether birds ate more of one color, and in which two places did he do it?
4. MEDIUM A student releases 150 marked paper "moths" in a model and recaptures 45. What percent were recaptured?
5. MEDIUM Data reading. The table gives the percent of dark peppered moths in one English area (rounded sample data shaped like the real records): 1960: 90%. 1970: 85%. 1980: 70%. 1990: 45%. 2000: 15%. 2010: 5%. (A) Between which two listed years did the percent drop the most? (B) Describe the overall trend. (C) Which event in the lesson best explains this trend?
6. MEDIUM Data reading. Use the bar graph of Kettlewell's results. (A) In which wood did pale moths survive better than dark moths? (B) In which group was the recapture percent the highest? (C) Which statement best fits the graph: (a) dark moths always

survive better, (b) the moth that matches the bark survives better, (c) moth color makes no difference?
(Use the map or drawing "Use this graph for problem 6." shown earlier in this lesson.)

7. MEDIUM A dark moth that carries one pale allele (Cc) mates with a pale moth (cc). What fraction of the young should be dark? What if the dark parent were CC instead?
8. HARD Critics pointed out that some textbook photos of peppered moths were staged. Does that mean the whole study was wrong? Explain using Majerus's work.
9. HARD In two or three sentences, explain what the peppered moth study showed and what it did not show.
10. CHALLENGE Experiment design. Design a better version of Kettlewell's test that answers the critics. Include your question, what you change, what you keep the same, what you measure and how you would avoid two of the problems critics raised.

COMMON MISTAKES

- Thinking each moth changed its own color to match the bark. No single moth changed. Dark and pale moths were both already there, and birds changed how many of each survived.
- Calling the dark moth a new species. Dark and pale moths are the same species, mate with each other, and follow simple Mendel ratios.
- Thinking that because some photos were staged, the whole study was fake. The photos were a poor illustration, but the main result was confirmed by Majerus's careful study.

Make it a game · Spot the Moth. One player hides five paper moths (some pale, some dark) on a bookshelf, a rug or a tree trunk outdoors while the other looks away. The seeker gets 15 seconds. Score one point for each moth found. The hider scores one point for each moth that "survives." Switch roles and backgrounds. After four rounds, say which color won on which background and why.

Scripture. "He that is first in his own cause seemeth just; but his neighbour cometh and searcheth him." (Proverbs 18:17, KJV)

Kettlewell made his case; critics searched it; Majerus searched again. A good scientist welcomes careful checking, because truth has nothing to fear from it.

Practice answers

1. Typica: the pale form, white-gray with black speckles. Carbonaria: the dark, nearly all-black form.
2. Coal smoke from mills and homes left soot on the trees and killed the pale lichens that had made the bark look light and speckled.
3. Mark-release-recapture: he marked moths, released them and counted how many of each color were caught again. He worked in a sooty wood near Birmingham (1953) and a clean wood in Dorset (1955).
4. 45 ÷ 150 = 0.30, so 30%.

5. (A) 1990 to 2000, a drop of 30 percentage points. (B) The dark form became steadily less common, from 90% to 5%. (C) Cleaner air after the Clean Air Act of 1956: lichens returned and bark grew lighter, so birds found dark moths more easily.
6. (A) The clean Dorset wood (12.5% pale against 6.3% dark). (B) Dark moths in the sooty Birmingham wood, 27.5%. (C) Statement (b).
7. Cc × cc gives Cc, Cc, cc, cc: 2 of 4, so one half dark and one half pale. CC × cc gives Cc in every box: all the young are dark (but each carries a hidden pale allele).
8. No. Staged photos were a fair criticism of how the story was illustrated, and some of Kettlewell's methods (high numbers released, daytime release) could be improved. But Majerus repeated the test carefully from 2001 to 2007 with 4,864 moths released a few at a time, moths choosing their own resting places, and real birds watched at dawn. Birds still ate more of the moth that stood out, so the main finding held.
9. It showed that birds eating the moths that stood out changed how common the two existing color forms were, first toward dark and then back toward pale as the air cleared. It did not show a moth changing into a new kind of animal, or explain where moths, wings or eyes came from; the moths stayed one species, *Biston betularia*, the whole time.
10. Sample: Question: Do wild birds eat more pale or dark peppered moths on the trees of one wood? Change: moth color (pale or dark). Keep the same: the wood, the season, the number of each color released each night (small and equal), the time of release, how the moths are marked. Measure: how many of each color are eaten by birds (watched at dawn) or recaptured. Fixes: release only a few moths per night so numbers are natural, and release them at night so each moth chooses its own resting place (often under branches) instead of being placed on trunks. Repeat over several years.

4.3 Warning Colors

OBJECTIVES

- Define warning coloration and give examples such as the monarch butterfly, poison dart frogs, yellowjackets and the skunk.
- Explain Batesian and Müllerian mimicry using Bates's Amazon butterflies and the monarch and viceroy.
- Read a learning-curve graph and calculate percents and ratios from predator-test data.

Warm-up. Walk through your house and garage with a parent and look for warning labels and signs: a cleaning bottle, a "wet floor" sign, a stop sign in a picture, caution tape, a fire extinguisher. List the colors you see. Which two or three colors keep showing up? Why do you think people chose them?

Video. Coming soon. Warning coloration and mimicry: monarch and viceroy butterflies, poison dart frogs, coral snakes and their look-alikes; search Smithsonian, National Park Service, HHMI BioInteractive, SciShow Kids, Homeschool Pop (Alternate) and nature footage of birds rejecting monarchs.

KEY TERMS

warning coloration
Bright, high-contrast colors (often red, orange or yellow with black) that tell predators an animal is poisonous, bad-tasting or dangerous. Scientists call it aposematism.

predator
An animal that hunts and eats other animals, called its prey.

toxin
A poison made by a living thing or taken in from its food.

model
In mimicry, the truly dangerous or bad-tasting animal whose look is copied.

Batesian mimicry
When a harmless, tasty animal looks like a dangerous or bad-tasting one, and so is avoided. Named for Henry Walter Bates.

Müllerian mimicry
When two or more bad-tasting or dangerous animals share a similar warning pattern, so predators learn to avoid all of them faster. Named for Fritz Müller.

CORE IDEAS

The story. In February 1867 Charles Darwin was puzzled by caterpillars. Camouflage made sense to him: a green caterpillar on a green leaf is hidden from birds. But why are some caterpillars bright and gaudy, as if they wanted to be seen? He wrote to his fellow naturalist

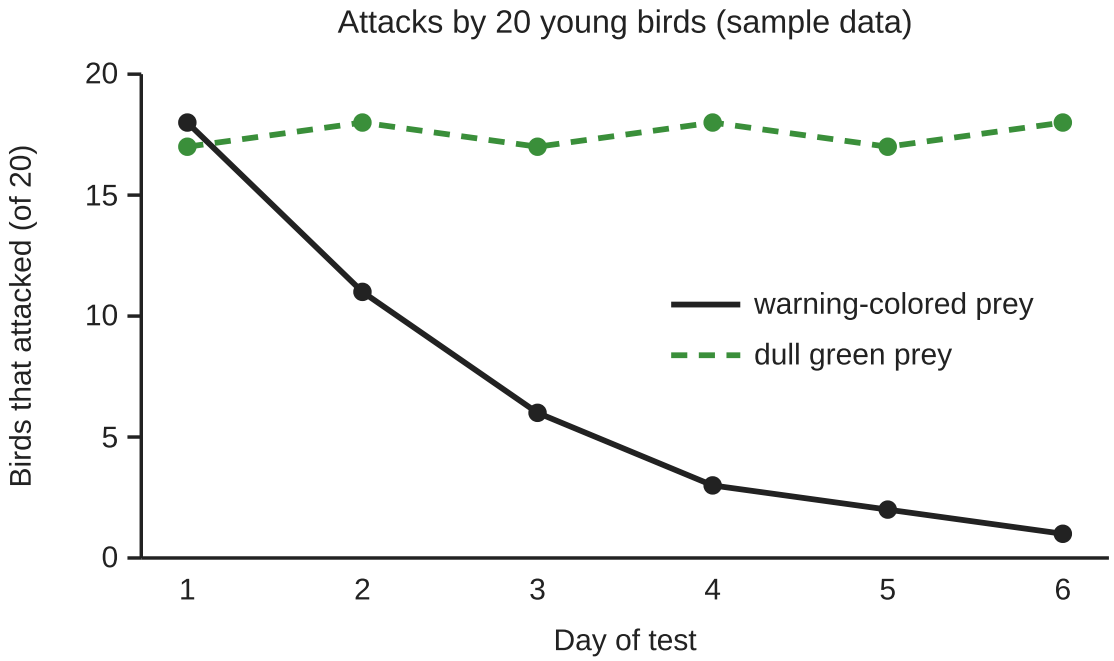
Alfred Russel Wallace. Wallace answered with a bold guess: perhaps those caterpillars taste bad, and their colors are a sign that says to every bird, “Don’t eat me.” A bird that pecked one would spit it out and remember. Wallace asked other naturalists to test the idea. John Jenner Weir, who kept birds in a large aviary in London, offered them many kinds of caterpillars over the next two years. The birds gladly ate the dull green and brown ones, but they refused or quickly dropped bright ones such as the spotted caterpillar of the magpie moth.

How they figured it out. Henry Walter Bates had spent eleven years collecting insects along the Amazon River in Brazil, from 1848 to 1859. He noticed that some butterflies from completely different families looked almost exactly alike. In 1862 he explained why: some kinds tasted terrible to birds, and some tasty kinds had come to look like them and were avoided too. This is **Batesian mimicry**, a bluff. In 1878 the German naturalist Fritz Müller, who lived in southern Brazil, added a second idea. When two kinds of bad-tasting butterflies share the same pattern, a young bird needs to learn only one lesson, and both kinds lose fewer members while it learns. This is **Müllerian mimicry**, a team.

The big idea. Warning coloration is the opposite of camouflage. Instead of hiding, the animal shouts: red, orange or yellow with black, colors that stand out against green leaves. The monarch butterfly’s caterpillars eat milkweed, which holds bitter heart poisons, and they store those **toxins** in their bodies. In the 1960s Lincoln Brower fed monarchs to blue jays; a jay that ate one soon vomited, and afterward it refused monarchs on sight. The viceroy butterfly looks so much like the monarch that it was long called a harmless Batesian mimic. But in 1991 David Ritland and Lincoln Brower tested viceroys on birds and found that viceroys taste bad too. The two are a Müllerian team. Other warning-colored animals include the poison dart frogs of Central and South America, yellowjackets and wasps, ladybugs and the black-and-white skunk.

In the world today. People use the same color code. Stop signs are red; caution tape, school buses and hazard signs are yellow, often with black. Our eyes, like a bird’s, notice these colors quickly. The lesson for a young naturalist is practical: a brightly colored wild animal may be dangerous, so look but do not touch. And do not trust a color rhyme to tell a dangerous snake from a harmless one. The rhymes about red, yellow and black bands work only for some snakes in one part of the world and have exceptions. Interestingly, poison dart frogs raised in zoos on crickets and fruit flies are not poisonous; wild frogs get their toxins from the ants and mites they eat.

God’s handiwork. A warning signal works only if two things fit together: the bright color of the prey and the learning mind of the predator. The bird pecks once, learns, and both the bird and the next butterfly are spared. Scripture prizes the same kind of learning: “A prudent man foreseeth the evil, and hideth himself; but the simple pass on, and are punished” (Proverbs 22:3). The blue jay that remembers its lesson is a small picture of prudence.



Sample data: young birds quickly learn to avoid warning-colored prey but keep eating dull green prey.

PICTURE STUDY

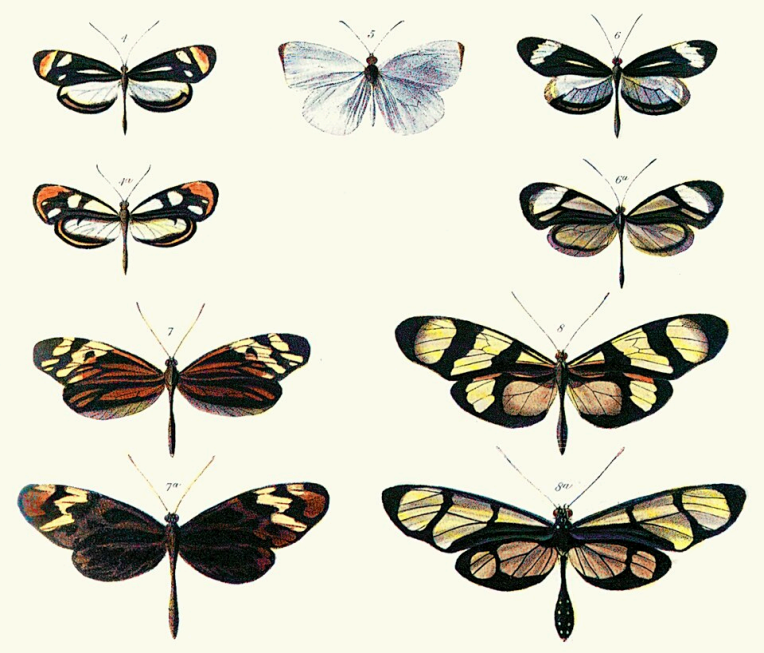


Plate of Amazon butterflies (Heliconidae) illustrating mimicry, Henry Walter Bates (specimens and descriptions); plate printed for the Linnean Society, 1862 · Hand-colored printed plate · *Transactions of the Linnean Society of London*, volume 23 (1862), plate 56; scanned copies are freely viewable online

This plate comes from the paper in which Henry Walter Bates first explained mimicry. He drew on the thousands of insects he collected during his eleven years on the Amazon. The butterflies on his plates look so alike that even a trained eye has to study the wings closely to tell the families apart.

Bates found that the tell-tale differences are in places a bird would not notice in flight, such as the pattern of veins in the wings and the shape of the body. A hungry bird sees only the bold colors and decides in an instant.

Look closely

- Find two butterflies that look almost the same. What colors do they share?
- Look closely at the edges and veins of their wings. Can you find any difference?
- Look at the shapes of the wings. Are they long and narrow or short and round?
- Read the small labels, if you can. Why did Bates number or name each one?

Talk about it

1. Why would a tasty butterfly be safer if it looked like a bad-tasting one?
2. Why might a scientist in 1862 have needed a careful hand-colored plate instead of a photograph?
3. What would happen to the bluff if the tasty mimics became much more common than the bad-tasting models?

> **Safety first.** Do not touch or pick up brightly colored wild animals such as fuzzy caterpillars, newts, frogs, wasps or bees: some sting, some have irritating hairs, and some have toxins in their skin. Milkweed sap can irritate the eyes, so wash your hands after handling milkweed. Look, sketch and photograph instead.

EXPERIMENT: WHICH COLORS SAY “STAY AWAY”?

Birds learn the warning code by experience. Do people read the same code? You will run a small survey experiment with paper “bugs” that differ only in color pattern, and find out which ones people are least willing to pick up.

You will need

- Card stock or index cards and scissors
- Markers or colored pencils: green, brown, red, yellow, orange, blue and black
- A metric ruler
- A small box or tray to hold the bugs
- Lab notebook and pencil
- At least 10 people to survey (family, friends, neighbors)

Steps

1. Question: Which color patterns do people read as a warning?
2. Prediction: Rank the six bugs from “most likely to be picked up” to “least likely.”
3. Cut six identical oval bugs, each 5 cm long. Color them: (1) plain green, (2) plain brown, (3) red with black spots, (4) yellow with black stripes, (5) orange with black stripes, (6) plain blue.

4. What we change: only the color pattern. What we keep the same: size, shape, paper, the question we ask, and that each person sees all six bugs at once. What we measure: which bug each person says they would be least willing to touch if it were real.
5. Shuffle the bugs into a new order before each person, so position does not affect the choice.
6. Ask each person: “If these were real bugs on a leaf, which one would you be least willing to pick up?” Record the answer. Then ask which one they would pick up most easily.
7. Make a tally table and a bar graph of “least willing” votes for each bug. Calculate each bug’s percent of votes.
8. Write a conclusion: Did people choose the same warning colors birds learn to avoid? Which bug surprised you?

Tips

- Do not tell people what the lesson is about until after they answer, or you may change their choice.
- Ask each person alone, so no one copies someone else.
- Ten people is a small sample. If you can, survey more, and compare children with adults.

Check your work

- I changed only the color pattern and kept the bugs the same size and shape.
- I recorded every answer and calculated percents correctly.
- My conclusion compares people’s choices with what birds learn about warning colors.

NATURE NOTEBOOK

1. Draw a monarch and a viceroy side by side. Label one difference you can see (the viceroy has a black line across the hind wings).
2. Make a two-column chart titled “Hiders and Shouters.” List four animals that use camouflage and four that use warning colors.
3. Draw a simple learning curve: one line that falls as a bird learns to avoid a warning pattern, and one flat line for prey it keeps eating. Label the axes.

> **From history.** Henry Walter Bates did not travel to the Amazon alone. In 1848 he sailed from England to Pará (now Belém), at the mouth of the Amazon, with his friend Alfred Russel Wallace, the same man who later answered Darwin’s question about bright caterpillars. Wallace returned to England in 1852; Bates stayed until 1859 and brought home specimens of more than 14,000 species, most of them insects, many of them new to science. His book *The Naturalist on the River Amazons* (1863) is still a fine read.

WORKED EXAMPLES

Example 1. Use the learning-curve graph (sample data: 20 young birds that had never seen either kind of prey, tested once a day). How many birds attacked the warning-colored prey on day 1 and on day 4? Give each as a percent and find the drop in percentage points.

(Use the map or drawing "Read the solid line for warning-colored prey and the dashed line for dull green " shown earlier in this lesson.)

1. Read the solid line at day 1: 18 birds. 18 ÷ 20 = 0.90, so 90%.
2. Read the solid line at day 4: 3 birds. 3 ÷ 20 = 0.15, so 15%.
3. Drop: 90% − 15% = 75 percentage points.
4. Compare with the dashed line: attacks on dull green prey stayed near 17 to 18 each day, so the birds were still hungry and hunting. They learned to avoid only the warning pattern.

Answer: Day 1: 18 birds (90%). Day 4: 3 birds (15%). A drop of 75 percentage points in three days.

Example 2. In a caged-bird test like Weir's (sample numbers), birds were offered 40 dull green caterpillars and 40 brightly patterned caterpillars. They ate 34 green ones and 4 bright ones. What percent of each kind was eaten, and how many times more often were green ones eaten?

1. Green: 34 ÷ 40 = 0.85, so 85% eaten.
2. Bright: 4 ÷ 40 = 0.10, so 10% eaten.
3. Ratio: 85 ÷ 10 = 8.5.

Answer: 85% of green and 10% of bright caterpillars were eaten. Green ones were eaten 8.5 times as often.

Example 3. In a meadow live 300 bad-tasting model butterflies and 100 tasty Batesian mimics that look just like them. If a young bird catches one of these look-alikes at random, what is the chance it gets a bad-tasting one? What happens to that chance if the numbers flip to 100 models and 300 mimics?

1. Total look-alikes in the first meadow: 300 + 100 = 400. Chance of a model: 300 ÷ 400 = 0.75, so 75%.
2. In the flipped meadow: total is still 400. Chance of a model: 100 ÷ 400 = 0.25, so 25%.
3. Interpret: when models are common, most birds that try the pattern get a nasty lesson and learn to avoid it, protecting the mimics too. When mimics are common, most birds get a tasty meal and learn that the pattern means food.

Answer: 75% in the first meadow, but only 25% when mimics outnumber models. Batesian mimicry works best when the mimics are rarer than their models.

PRACTICE

1. EASY What is warning coloration? Give three examples of animals that use it.
2. EASY Where does the monarch butterfly get its toxins?
3. EASY Match each to its meaning: (A) Batesian mimicry, (B) Müllerian mimicry. Meanings: (1) two bad-tasting animals share one warning pattern; (2) a harmless, tasty animal copies a dangerous one.
4. MEDIUM Data reading. Use the learning-curve graph. (A) On which day did fewer than half of the 20 birds first attack the warning-colored prey? (B) About how many birds attacked dull green prey on day 6?
   (Use the map or drawing "Use this graph for problems 4 and 5." shown earlier in this lesson.)
5. MEDIUM Data reading. In the same experiment, why did the scientist also offer dull green prey every day? Choose the best answer: (a) to give the birds more food, (b) as a control, to show the birds were still hungry and hunting, so the drop in attacks came from learning about the warning pattern, (c) because green is a warning color.
6. MEDIUM In a class field test, 15 lizards were offered a red-and-black beetle. 12 refused it. What percent refused it? What percent ate it?
7. HARD A forest has 50 bad-tasting model butterflies and 200 tasty mimics. What is the chance that a bird catching one look-alike at random gets a bad-tasting one? Is this a good situation for the mimics? Explain.
8. HARD Scientists once called the viceroy a harmless mimic of the monarch. What did Ritland and Brower find in 1991, and how did it change the kind of mimicry?
9. MEDIUM A friend says, "I know a rhyme about snake colors, so I can tell which snakes are safe to pick up." Give two reasons this is unwise.
10. CHALLENGE Experiment design. Design a humane experiment to test whether young chickens learn to avoid a color faster when it is paired with a bad (but harmless) taste.

Name your independent variable, dependent variable, control group and two things you would keep the same.

COMMON MISTAKES

- Thinking bright colors are a kind of camouflage. Warning colors are meant to be seen; they work by standing out, not by hiding.
- Thinking every brightly colored animal is poisonous. Batesian mimics are harmless bluffers, so color alone does not prove danger (though you should still not handle them).
- Thinking predators are always born knowing what to avoid. Many birds learn the warning code by tasting once, which is why the learning curve drops over days.

Make it a game · Danger or Bluff?. Make cards of real animals: monarch, viceroy, yellowjacket, hover fly (a harmless fly striped like a wasp), coral snake, scarlet kingsnake (a harmless look-alike), ladybug, poison dart frog, skunk. A parent shows a card. Say "Danger!" if the animal is truly toxic or dangerous, or "Bluff!" if it is a harmless mimic. Score a point for each correct call and a bonus point if you name the model it copies.

Scripture. "A prudent man foreseeth the evil, and hideth himself; but the simple pass on, and are punished." (Proverbs 22:3, KJV)

The bird that heeds the warning colors is spared a sick stomach. Wisdom means noticing warnings and learning from them, in nature and in life.

Practice answers

1. Bright, high-contrast colors that tell predators an animal is poisonous, bad-tasting or dangerous. Examples: monarch butterfly, poison dart frog, yellowjacket, ladybug, skunk (any three).
2. From milkweed. Its caterpillars eat milkweed leaves, which hold bitter heart poisons, and store the toxins in their bodies, which carry over into the adult butterfly.
3. A matches 2 (a bluff). B matches 1 (a team).
4. (A) Day 3 (6 birds, 30%). On day 2, 11 birds (55%) still attacked. (B) 18 birds.
5. (b). The dull green prey is the control. Attacks on it stayed high, so the birds had not simply stopped eating; they had learned to avoid the warning pattern.
6. Refused: 12 ÷ 15 = 0.80, so 80%. Ate it: 3 ÷ 15 = 20%.
7. 50 ÷ 250 = 0.20, so 20%. It is a bad situation for the mimics: 80% of the time a bird gets a tasty meal, so birds learn that the pattern means food, and both mimics and models get eaten more.
8. They tested viceroys on birds and found that viceroys also taste bad. So the viceroy is not just bluffing; the monarch and viceroy are a Müllerian pair, two bad-tasting butterflies sharing a warning pattern.
9. The rhymes work only for some snakes in one part of the world and have exceptions, and colors can be hard to judge in poor light or on a young or faded snake. The safe rule is to look at any wild snake from a distance and never handle it.

10. Sample: Offer chicks crumbs of chick feed dyed two colors. For the test group, one color is dipped in a bitter but harmless liquid (scientists often use a weak quinine solution); for the control group, both colors taste normal. Independent variable: whether the colored crumbs taste bitter. Dependent variable: how many crumbs of that color each chick pecks per trial, over several days. Keep the same: crumb size, number of crumbs offered, time of day, how hungry the chicks are, the light, the length of each trial. If test chicks peck the bitter color less and less while control chicks do not, they have learned the warning.

4.4 The Camouflage Game

OBJECTIVES

- Explain countershading, background matching and disruptive coloration, starting from Abbott Thayer's 1896 discovery.
- Run a multi-round predator-and-prey game with controlled variables and record survival data.
- Calculate percent survival and the change in color frequency over generations, and graph the results.

Warm-up. In a dim room, hold an egg or a white ball under a lamp or flashlight shining straight down from above. Look at it from the side. Which part is bright and which part is in shadow? That shading is how your eyes know the egg is round. Now think: if you were allowed to paint the egg, how could you paint it so it looked flat, like a cardboard cutout?

Video. Coming soon. Countershading and camouflage in animals (deer, sharks, penguins, fish) and classroom natural-selection simulations with colored dots; search Smithsonian, HHMI BioInteractive, Science Max, Homeschool Pop (Alternate) and nature footage of camouflaged animals.

KEY TERMS

countershading
Coloring that is darker on the back and lighter on the belly. It cancels the shadow made by light from above, so a rounded body looks flat and hard to see. Also called Thayer's law.

background matching
Camouflage in which an animal's colors and pattern match the place where it lives, like a brown moth on brown bark.

population
All the members of one species living in one place at the same time.

survival rate
The percent of a group that is still alive after a set time: survivors ÷ starting number × 100.

simulation
A model or game that copies the main parts of a real process so it can be studied quickly and safely.

CORE IDEAS

The story. Abbott Handerson Thayer was an American painter who loved to roam the woods of Dublin, New Hampshire. As an artist he knew exactly how painters make a flat canvas look round: they make the top of an object bright and the bottom dark, as sunlight from

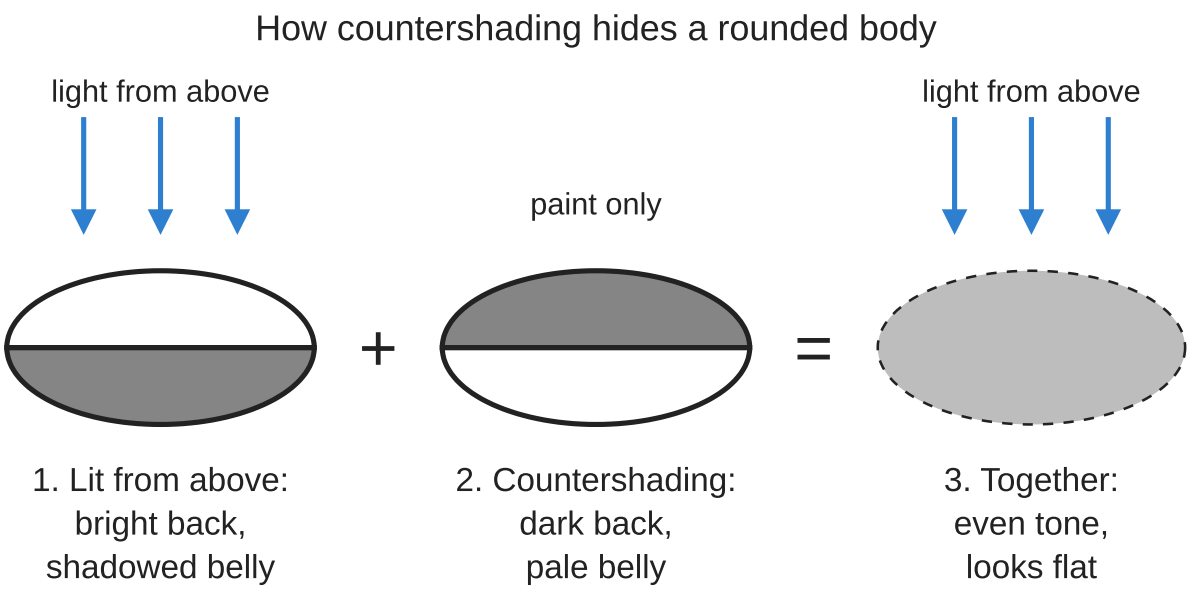
above does. One day it struck him that many animals are colored the other way around, dark on the back and white on the belly. In 1896 he published his idea in *The Auk*, the journal of the American Ornithologists' Union, under the title "The Law Which Underlies Protective Coloration." He showed it with simple painted models. A model painted one even color all over stood out plainly in the open air. A model painted dark on top and white underneath seemed to melt away at a short distance.

How it works. Light from the sky makes the top of any rounded body bright and leaves the belly in shadow. Our eyes, and the eyes of hawks and foxes, read that change from light to shadow as "something solid and round is here." **Countershading** paints the opposite: dark where the light is strongest, pale where the shadow falls. The two cancel out, and the body looks flat and the same tone from top to bottom, so it seems to vanish into the background. You can see countershading on white-tailed deer, gray squirrels, many fish such as mackerel, sharks, penguins and countless caterpillars. Today scientists still call it Thayer's law. Thayer stretched his ideas too far later on, claiming that nearly every animal color was for hiding, but his countershading discovery has held up for more than a century.

The big idea. In this lesson you put all the kinds of camouflage together and test them in a game. Animals hide by **background matching** (the peppered moth on bark), by disruptive patterns that break up the outline (the cuttlefish on a checkerboard), by countershading (the deer) and by shape and stillness (a stick insect). In the Camouflage Game you play the bird. You hunt colored paper dots scattered on a patterned background for a fixed time. The survivors "have young" of their own color, and you hunt again. After a few rounds, you count how the **population** has changed. This is a **simulation** of natural selection, the same process the peppered moth study measured in the wild.

In the world today. Real scientists use games like this too. In 2005 a team led by Innes Cuthill of the University of Bristol pinned hundreds of paper "moths" (each with a dead mealworm as bait) to oak trees in a British woodland and counted how many were eaten by birds. Paper moths with bold patches that touched their edges survived longer than plain ones, which was strong evidence for disruptive coloration. Like those scientists, you must keep the game fair: the same number of dots, the same size, the same hunting time and the same rules each round. A model can never copy nature perfectly, so a good scientist always lists how the model differs from the real thing.

God's handiwork. "O LORD, how manifold are thy works! in wisdom hast thou made them all" (Psalm 104:24). Thayer, a painter, saw in the white belly of a deer the same rule of light and shadow he used at his easel. The Creator who made the light also made the eye that reads it and the coat that answers it. Every time you find a hidden creature on a walk, you are seeing that wisdom up close.



Thayer's law: countershading paint cancels the shadow made by light from above, so a round body looks flat.

PICTURE STUDY



The Fox Hunt, Winslow Homer, 1893 · Oil on canvas · Pennsylvania Academy of the Fine Arts, Philadelphia

Winslow Homer painted *The Fox Hunt* in his studio at Prouts Neck, on the rocky coast of Maine, during a hard winter. It is one of the largest paintings he ever made. In a deep snow, hungry crows sometimes mob a fox, and here the hunter has become the hunted.

Look at the picture as a camouflage scientist. In autumn woods a red fox blends with brown leaves and grass. In white snow it stands out sharply. Unlike the arctic fox, which turns white in winter, the red fox keeps its color all year.

Look closely

- Find the fox. How quickly did your eye find it, and why?
- Count the crows. Are they hidden or easy to see against the snow and sky?
- Find the red berries. What other color in the painting do they echo?
- Look at the fox's legs and the snow. What does the deep snow do to the fox's speed?

Talk about it

1. In what season and place would the fox's red coat be good camouflage?
2. Why might hunger make the crows bold enough to attack a fox?
3. If you could paint this fox into a different background so that it was hidden, what would you paint?

> **Safety first.** Hole-punched paper dots are a choking hazard for babies and toddlers, so play at a table or on a cloth away from small children and gather every dot afterward. If you play outdoors on grass, check the area first for anything sharp and wash your hands afterward.

EXPERIMENT: THE CAMOUFLAGE GAME: THREE GENERATIONS

You will be the bird. Colored dots are your prey. You will hunt for a fixed time, let the survivors reproduce, and repeat for three generations, recording the population each time. Then you will graph how the colors changed.

You will need

- A hole punch
- Construction paper in five colors: red, yellow, white, green and brown
- A patterned background about 1 m by 1 m: a flowered sheet, a patterned rug, a towel, or an area of lawn with leaves
- A timer
- Five small cups or envelopes, one for each color
- A helper (or take turns as bird)
- Lab notebook, ruler and colored pencils

Steps

1. Question: On this background, which colors of prey survive best, and how does the population change over three generations?
2. Prediction: Look closely at the background. Write which color you think will be most common after three rounds, and why.
3. Punch 20 dots of each color (100 prey in all). Keep extra dots of every color in the cups for later rounds.
4. Variables. What we change: the color of the prey. What we keep the same: dot size, background, hunting time (30 seconds), picking one dot at a time with one hand,

standing at the same spot. What we measure: the number of each color that survive.

5. Generation 1: while the bird looks away, scatter all 100 dots evenly over the background. The bird hunts for 30 seconds, picking up one dot at a time and dropping it in a cup before taking the next.
6. Count the survivors of each color by gathering the dots still on the background. Record them in a table with columns: Color, Start, Eaten, Survived, Survival rate (%).
7. Reproduce: give each survivor one “offspring” of the same color from the extra dots. Record the new population of each color and the percent of the whole population each color makes up.
8. Repeat for Generations 2 and 3, using the new population each time and the same 30-second hunt.
9. Draw a bar graph for each generation, or a line graph with one line per color, showing the percent of the population that each color makes up.
10. Bonus test: roll two paper tubes from white paper. Shade the top half of one tube dark gray (countershaded). Lay both on their sides on a windowsill or under an overhead lamp. From 2 meters away, which looks more solid and round? Record what you see.
11. Write a conclusion: Which color won, how did the population change, and how is this game like and unlike the peppered moths?

Tips

- Use the same bird for every generation if you can, so skill does not change between rounds.
- If the bird finds almost every dot, shorten the time to 20 seconds for all rounds; if almost none, lengthen it. Keep it the same once you start.
- The dots do not change color. Only the number of each color changes. That is what natural selection does to a population.

Check your work

- I wrote my question, prediction and variables before the first hunt.
- My table shows survivors and survival rates for three generations, with correct arithmetic.
- My graph and conclusion explain which colors increased, which decreased and why.

NATURE NOTEBOOK

1. Copy the countershading figure and add a fourth drawing: a deer standing in a meadow under the sun, with its dark back and white belly labeled.
2. Draw your game background and three dots on it: the best-hidden color, the worst-hidden color and one in between. Label each.
3. Go outside and find one animal or insect that is camouflaged. Draw it where you found it and write which kind of camouflage it uses.

From history. Artists helped bring camouflage to war at sea. In 1917, during World War I, the British marine painter Norman Wilkinson proposed “dazzle” painting: covering ships in bold, clashing stripes and angles. Dazzle did not hide a ship, but, like the disruptive patterns of a cuttlefish, it made the ship’s outline, size and direction hard to judge through an enemy submarine’s periscope. Thousands of British and American ships were painted this way before the war ended.

WORKED EXAMPLES

Example 1. In Generation 1 of a game on a leafy brown-and-green background, each color started with 20 dots. Survivors: red 2, yellow 4, white 6, green 13, brown 15. Find each color’s survival rate and the total number eaten.

1. Survival rate = survivors ÷ 20 × 100.
2. Red: 2 ÷ 20 = 10%. Yellow: 4 ÷ 20 = 20%. White: 6 ÷ 20 = 30%.
3. Green: 13 ÷ 20 = 65%. Brown: 15 ÷ 20 = 75%.
4. Total survivors: 2 + 4 + 6 + 13 + 15 = 40. Eaten: 100 − 40 = 60.

Answer: Red 10%, yellow 20%, white 30%, green 65%, brown 75%. 60 dots were eaten and 40 survived. The colors that match the leaves survived best.

Example 2. Continue the game. Each survivor has one offspring of its own color, so every color doubles. What is the new population of each color, and what percent of the whole population is brown now compared with the start?

1. Double each: red 4, yellow 8, white 12, green 26, brown 30.
2. New total: 4 + 8 + 12 + 26 + 30 = 80.
3. Brown now: 30 ÷ 80 = 0.375, so 37.5%.
4. Brown at the start: 20 ÷ 100 = 20%. The brown share grew by 17.5 percentage points in one generation.

Answer: Red 4, yellow 8, white 12, green 26, brown 30 (total 80). Brown went from 20% of the population to 37.5%.

Example 3. A bird player hunted 24 dots on plain white paper in 12 seconds. On a busy flowered sheet, the same player found 24 dots in 30 seconds. Find the hunting rate on each background in dots per second, and how many times faster the bird hunted on plain paper.

1. Rate = dots found ÷ time.
2. Plain paper: 24 ÷ 12 s = 2.0 dots per second.
3. Flowered sheet: 24 ÷ 30 s = 0.8 dots per second.
4. Compare: 2.0 ÷ 0.8 = 2.5.

Answer: 2.0 dots per second on plain paper and 0.8 dots per second on the flowered sheet. The bird hunted 2.5 times faster on the plain background, so the busy background gave the prey more protection.

PRACTICE

1. EASY What is countershading, and how does it help an animal hide?
2. EASY Who first explained countershading in print, and in what year?
3. EASY Name four kinds of camouflage and one animal example for each.
4. MEDIUM In a game, 25 yellow dots were scattered and 7 survived the hunt. What was the survival rate of yellow? What percent was eaten?
5. MEDIUM Data reading. A student recorded the percent of the population that was brown in each generation: Start 20%, Generation 1 37.5%, Generation 2 52%, Generation 3 64%. (A) Describe the trend. (B) Between which two generations was the increase largest? (C) If the trend continues, which is the most reasonable prediction for Generation 4: (a) 20%, (b) about 72%, (c) 130%?
6. MEDIUM Data reading. The same player hunted for 30 seconds on four backgrounds. Dots found: plain white paper 30, newspaper 21, patterned rug 14, leafy lawn 9. (A) Which background protected the prey best? (B) What was the hunting rate on newspaper in dots per second? (C) What is one variable that must stay the same for this comparison to be fair?
7. MEDIUM Why must every round of the game use the same hunting time and the same number of dots?
8. HARD Give two ways the Camouflage Game is like the peppered moth story and two ways it is different from real moths and birds.
9. HARD After three generations on a green lawn, green dots made up most of the population. Then the game moved to a plain white sheet for Generation 4. Predict what happens to the green dots and the white dots, and explain.
10. CHALLENGE Experiment design. Design an experiment to test Thayer’s idea that countershading makes a rounded object harder to see. Include your question, independent variable, dependent variable, at least three things you keep the same, and how many trials you would run.

COMMON MISTAKES

- Thinking camouflage only means matching color. Animals also hide with pattern, shading (countershading), outline-breaking patches, shape and keeping still.
- Thinking the dots (or moths) that survived changed their color to fit in. No individual changed; the population changed because more of some colors survived to have young.
- Thinking one game proves what happens in nature. A simulation shows how a process could work; field studies with real animals are needed to test it.

Make it a game · Hide It in Plain Sight. Each player secretly picks one small object (a button, a leaf, a pencil) and hides it in plain sight in one room: nothing may be covered or put inside anything. Other players have 60 seconds to spot it without touching. Hidden objects score one point for each player who failed to find them. After each round, the hider explains which kind of camouflage they used: background matching, disruptive pattern, countershading or shape.

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)

A deer's white belly, a moth's speckled wing and a cuttlefish's changing skin are some of the "manifold works" the psalmist praised. The more we look, the more riches we find.

Practice answers

1. Countershading is coloring that is darker on the back and lighter on the belly. Light from above makes the back bright and the belly shadowed; the dark back and pale belly cancel that shading, so the body looks flat and blends into the background.
2. Abbott Handerson Thayer, an American painter, in 1896 (in the bird journal *The Auk*).
3. Background matching: peppered moth on bark. Disruptive coloration: cuttlefish on a checkerboard. Countershading: white-tailed deer (or shark, penguin, mackerel). Shape and stillness (looking like an object): stick insect. Other correct examples are fine.
4. 7 ÷ 25 = 0.28, so 28% survived. 100% − 28% = 72% were eaten.
5. (A) Brown becomes a larger share of the population every generation. (B) From the start to Generation 1 (17.5 percentage points; later gains were 14.5 and 12). (C) (b) about 72%. It cannot go above 100%, and the gains are getting smaller.
6. (A) The leafy lawn (only 9 found). (B) 21 ÷ 30 = 0.7 dots per second. (C) Any one of: the same player, the same hunting time, the same number, size and colors of dots, the same lighting, the same distance.
7. So that the only thing that changes is the color of the prey (and the background, if that is being tested). If the time or numbers changed, we could not tell whether a change in survivors came from color or from the different rules.
8. Alike: a predator finds the prey that stand out; the better-matching colors survive and become more common over generations. Different (any two): paper dots do not move, hide or choose resting places; real offspring do not always match their parents exactly (they follow rules like Mendel's); the predator is a person, and birds see some colors differently, including ultraviolet; real hunting goes on over many years and seasons, not 30 seconds.

9. Green dots will now stand out on white and be eaten more, so their share will fall. White dots will be hard to see and survive better, so their share will rise (if there are any white dots left to reproduce). The best color depends on the background, as with the peppered moths when the air cleared.
10. Sample: Question: Does painting a cylinder dark on top and pale underneath make it harder to spot? Make 10 paper tubes of the same size: 5 plain gray and 5 countershaded (darker on top, lighter underneath). Independent variable: the paint pattern. Dependent variable: how many seconds an observer needs to find each tube, or how many tubes are found in 20 seconds. Keep the same: tube size, overall average shade, the light coming from above, the background (for example, grass), the distance of the observer, and the time limit. Run trials with at least 5 different observers who have not seen the setup, moving the tubes each time, and compare average finding times.

Unit 4 review

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

1. (4 pts) Multiple choice. A cuttlefish shows more of a color when (a) pigment is made fresh in its skin, (b) tiny muscles pull its chromatophores wide, (c) it eats colored food, (d) the water warms up.
2. (5 pts) Explain how a panther chameleon changes from green to orange, according to the 2015 Geneva study, and give one real reason chameleons change color.
3. (4 pts) Multiple choice. A cuttlefish placed on a board of white squares about the size of the white patch on its own back will most likely show (a) a uniform pattern, (b) a fine mottle, (c) a bold disruptive pattern, (d) no change.
4. (6 pts) In the sooty Birmingham wood (1953), Kettlewell recaptured 123 of 447 dark moths and 18 of 137 pale moths. Calculate each recapture percent and state what the result suggests.
5. (6 pts) In two or three sentences, explain what the peppered moth study showed and what it did not show.
6. (5 pts) In peppered moths, dark (C) is dominant over pale (c). Draw a Punnett square for Cc × cc. What fraction of the young will be dark?
7. (4 pts) Multiple choice. Which is an example of Batesian mimicry? (a) a monarch and a viceroy, both bad-tasting, (b) a harmless hover fly striped like a wasp, (c) a green caterpillar on a green leaf, (d) a deer with a white belly.
8. (6 pts) Explain why a blue jay that once ate a monarch will usually refuse monarchs afterward. Then explain what Ritland and Brower discovered about viceroys in 1991.
9. (6 pts) Data reading. Twenty young birds were offered warning-colored prey once a day. Number that attacked: Day 1: 18. Day 2: 11. Day 3: 6. Day 4: 3. (A) What percent attacked on Day 1 and on Day 4? (B) What does the trend show? (C) Name a control that would make this experiment stronger.
10. (8 pts) Diagram. Draw three ovals to show how countershading works. Label: (1) an evenly colored body lit from above (bright back, shadowed belly), (2) the countershading paint (dark back, pale belly), (3) the result when both are combined. Add an arrow showing the direction of light, and write one sentence explaining why the result is hard to see.
11. (6 pts) In a camouflage game, each of five colors started with 20 dots. Survivors: red 3, white 5, yellow 4, green 12, brown 16. (A) What was the survival rate of brown? (B) If every survivor has one offspring of its own color, what is the new total population? (C) What percent of the new population is brown?

Unit project: my camouflage field guide and lab report

Make a small field guide of six hand-drawn animals: two that hide by camouflage (choose different kinds, such as background matching and countershading), two that warn with

bright colors, and one mimic with its model. Under each drawing, write the animal's name, where it lives, which strategy it uses and one fact you learned in this unit.

Then design your own camouflaged paper creature for a background you choose in your home or yard. Test it against a brightly colored "control" creature of the same size with at least five observers, timing how long each takes to find both. Write a lab report with your question, prediction, variables, data table, a bar graph of average finding times, and a conclusion that compares your results with the peppered moths or the Camouflage Game.

- **Accuracy**: Animals, strategies and facts are correct, and Batesian and Müllerian mimicry are used correctly.
- **Experiment**: The test has a clear question, a control creature, controlled variables and at least five observers.
- **Data and math**: Finding times are recorded in seconds, averages are calculated correctly and graphed with labeled axes.
- **Care and explanation**: Drawings are neat and labeled, and the conclusion explains what the evidence shows and one limit of the test.

Answer key

1. (b). Radial muscles, controlled by nerves, stretch the pigment sacs so the color covers more area.
2. Its iridophore cells hold tiny guanine crystals in a grid. When the chameleon is calm, the crystals are close and reflect blue, which looks green under yellow pigment; when excited, the grid spreads and reflects longer waves (yellow, orange, red). Chameleons change color mainly to signal to other chameleons (or to warm up or cool down), not to copy their background.
3. (c) a bold disruptive pattern.
4. Dark: 123 ÷ 447 = 27.5%. Pale: 18 ÷ 137 = 13.1%. Dark moths were recaptured about twice as often, suggesting birds found and ate more pale moths on the dark, sooty bark.
5. It showed that bird predation changed how common the dark and pale forms were, first toward dark in sooty woods and back toward pale after the air was cleaned (confirmed by Majerus's careful study). It did not show a moth becoming a new kind of animal or explain where moths came from; both forms stayed one species, *Biston betularia*.
6. Boxes: Cc, Cc, cc, cc. Half (2 of 4) will be dark and half pale.
7. (b). A harmless animal copies the warning pattern of a dangerous one.
8. Monarch caterpillars eat milkweed and store its bitter heart poisons, so a jay that eats a monarch vomits and learns to link the orange-and-black pattern with sickness. In 1991 Ritland and Brower found that viceroys also taste bad to birds, so the monarch and viceroy are a Müllerian pair, not a model and a harmless Batesian mimic.
9. (A) Day 1: 90%. Day 4: 15%. (B) The birds quickly learned to avoid the warning-colored prey. (C) Offer dull, tasty prey (such as plain green caterpillars) each day too, to show the birds were still hungry and hunting.
10. Oval 1: light top, dark bottom, light arrow pointing down from above. Oval 2: dark top, light bottom. Oval 3: one even tone. Explanation: the dark back and pale belly cancel the light-and-shadow shading that tells our eyes an object is round, so the body looks flat and blends into

the background. (2 points for each correct oval with labels, 1 for the light arrow, 1 for the explanation.)

11. (A) 16 ÷ 20 = 80%. (B) Survivors total 3 + 5 + 4 + 12 + 16 = 40; doubled, the new population is 80. (C) Brown doubles to 32; 32 ÷ 80 = 40%.

UNIT 5

Instinct

A digger wasp that never met its mother stings a cricket in exactly the right three places. A garden spider that never saw a web spins a perfect one, even on a space station. A young beaver that never saw a dam piles sticks on a loudspeaker because it hears running water. Each of these animals does something wise that no one taught it. Scientists call this **instinct**: behavior an animal is born able to do, correctly, the first time.

In this unit you will work like the naturalists who discovered these things. You will follow Jean-Henri Fabre as he tricks a wasp in the dust of Provence, ride along with the Skylab spiders Arabella and Anita, measure beaver ponds with Lewis Henry Morgan and test beavers with Lars Wilsson's loudspeaker. You will run your own tests on ants, spider webs, model dams and pill bugs, always changing one thing and keeping the rest the same.

The unit ends with one of the oldest science questions ever asked, from God Himself to Job: "Doth the hawk fly by thy wisdom, and stretch her wings toward the south?" (Job 39:26). You will learn how scientists tell an instinct from a learned behavior, how the two work together, and why every instinct points back to the Creator who gave each kind its own wisdom.

BEFORE YOU BEGIN

- Can find a percent from a part and a whole and compute a simple average
- Can read a bar graph, a line graph and a data table
- Knows the basic parts of an insect (head, thorax, abdomen, six legs) and of a fair experiment (variables and controls)
- Can measure length in centimeters and volume in liters

MASTERY CHECKLIST

- I can define instinct, learned behavior, reflex and fixed action pattern and sort real behaviors into each.
- I can tell how Fabre showed that hunting wasps paralyze their prey and what his moved-cricket test revealed.
- I can name the parts of an orb web, describe the order a spider builds them and explain what silk is made of.
- I can explain how and why beavers build dams and lodges and what Wilsson's loudspeaker test showed.
- I can describe an isolation experiment such as Spalding's hooded chicks and design a fair test of an inborn behavior.
- I can explain how Job 39 points to God as the giver of animal instinct.

OPTIONAL BOOKS AND RESOURCES

- **Jean-Henri Fabre's insect books (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/search/?query=Fabre): Free. English translations of Fabre's insect books, such as *The Life of the Spider*; look also for his chapters on hunting wasps. Read aloud his own account of the cricket-hunting Sphex (Lesson 5.1) and the garden spider's web (Lesson 5.2). Choose short passages; the chapters are long.

5.1 Fabre's Wasps ★

OBJECTIVES

- Define instinct, learned behavior and fixed action pattern, and sort real animal behaviors into instinct or learned.
- Tell how Jean-Henri Fabre showed that hunting wasps paralyze their prey instead of killing it, and what his moved-cricket test revealed about instinct.
- Calculate percents, ratios and rates from simple behavior data, and design a fair test of an insect's behavior.

Warm-up. Hold a sheet of paper about 30 cm in front of a partner's face and, without warning, flick it toward them (do not touch them). Did they blink? Ask them to try not to blink, and do it again. Now list three things you do that you had to be taught (tying shoes, riding a bike, reading) and one thing a newborn baby does that no one teaches (sucking, grasping a finger, crying when hungry). Today you will meet a wasp that does something far more complicated than a blink, and does it right the first time.

Video. Coming soon. Digger wasp or hunting wasp dragging a cricket or caterpillar into its burrow, plus a short biography of Jean-Henri Fabre; search nature footage channels, Smithsonian, BBC Earth style insect footage, SciShow, Deep Look (KQED) and Moody Science classics.

KEY TERMS

instinct
A complex behavior an animal is born able to do and does correctly the first time, without being taught or practicing.

learned behavior
A behavior an animal gains by experience, practice or being taught, such as a dog learning to sit or a crow learning where food is kept.

fixed action pattern
A chain of instinctive steps that, once started by a trigger, runs in the same order every time until it is finished.

stimulus
Something in the surroundings that an animal senses and responds to, such as a sound, a smell, a shape or a touch. The plural is stimuli.

paralyze
To make an animal unable to move while it is still alive.

ganglion
A small cluster of nerve cells that acts as a control center. Insects have a chain of ganglia; the ones in the thorax control the legs and wings.

CORE IDEAS

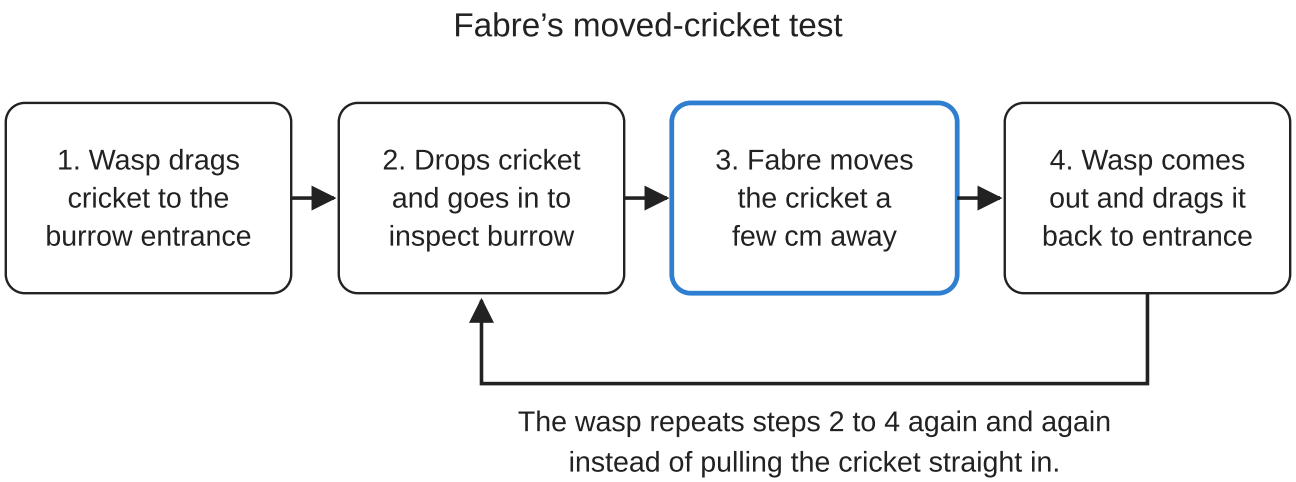
The story. Jean-Henri Fabre was born in 1823 in a poor farming village in southern France. As a boy he herded ducks and filled his pockets with beetles. As a man he taught school, and he spent every free hour lying in the dust, watching insects. In the 1850s he read an article by a French doctor named Léon Dufour about a wasp called *Cerceris*, which fills its burrow with beetles for its young to eat. Dufour had noticed something strange: the beetles in the burrow stayed fresh and soft for weeks, as if they had just been caught. He guessed that the wasp injected a fluid that kept the dead beetles from spoiling. Fabre was not satisfied. He dug up burrows himself and looked closely. The beetles were not dead at all. Their joints still bent, their insides still worked, and some lived on for weeks in a box on his table. They were **paralyzed**: alive, but unable to move, a fresh food supply for the wasp's grub.

How they figured it out. Fabre watched the wasp hunt and found that it stings each beetle in one exact spot on its underside, near the joint of the front legs. In the kinds of beetles *Cerceris* hunts, the **ganglia** that run the legs are bunched close together right there, so one sting quiets them all. Then Fabre studied a larger digger wasp he called the yellow-winged Sphex, which hunts field crickets. It stings a cricket three times, once for each of the three nerve centers in the cricket's thorax. Then it drags the cricket home by its antennae, leaves it at the edge of the burrow, goes inside to inspect, comes back out and pulls the cricket in. Here Fabre made his famous test. While the wasp was inside, he moved the cricket a few centimeters away. The wasp came out, found the cricket, dragged it back to the edge, and went inside to inspect *again*. Fabre moved it again, and again, dozens of times. The wasp never once simply pulled the cricket straight in.

The big idea. An **instinct** is a complex behavior an animal is born able to do, correctly, the first time. A **learned behavior** comes from experience or teaching. The Sphex's hunt is a **fixed action pattern**: a chain of steps that runs in order once a **stimulus** starts it. Each finished step is the signal for the next. When Fabre broke the chain, the wasp did not reason, "I already checked the burrow." It went back to the step the situation called for and ran the program from there. Instinct is wonderfully exact in the conditions the animal was made for and strangely rigid when those conditions change. Wasps are a perfect animal for studying it, because the mother seals her egg in the burrow with its crickets and flies away. She dies before her young come out the next summer. The young wasp grows up alone underground, digs its way out, never meets its mother and still hunts the right prey and stings the right spots.

In the world today. Scientists still use Fabre's method: change one thing and watch what the animal does. In the 1930s the Dutch scientist Niko Tinbergen set a ring of pinecones around the burrow of a digger wasp called a beewolf. While the wasp was away hunting, he moved the ring a short distance. The returning wasp landed in the middle of the pinecones and searched for a doorway that was not there. That test showed that the wasp had *learned* landmarks around its own burrow. So a wasp's life is a mix: the hunting program is inborn, but the map of home is learned. Writers about computers and the mind even borrowed Fabre's wasp to make up the word "sphexish," meaning a machine or creature that keeps repeating its steps without noticing that something has changed.

God’s handiwork. Fabre was amazed that a wasp with a brain smaller than a pinhead “knew” the nerve map of its prey better than many students of anatomy. He pointed out that a half-learned sting would be useless: a cricket stung in the wrong place either dies and rots or kicks free. Fabre did not accept the idea that such exact skills were built up little by little, and he saw in them a wisdom the wasp itself did not possess. The Bible invites us to do what Fabre did: “ask now the beasts, and they shall teach thee” (Job 12:7). A good naturalist watches patiently, tests carefully and gives thanks to the One who wrote the program.



Fabre’s moved-cricket test. Each time the cricket was moved, the wasp went back to step 2 and inspected the burrow again.

PICTURE STUDY



Insects and a Sprig of Rosemary, Jan van Kessel the Elder, 1653 · Oil on panel (about 11.5 by 14 cm, smaller than a postcard) · National Gallery of Art, Washington, D.C.

Jan van Kessel the Elder was a Flemish painter from Antwerp who painted insects so carefully that naturalists today can still name many of them. This tiny picture sets about a dozen insects around a sprig of rosemary, each painted as if it had just landed on the page.

Van Kessel lived about two hundred years before Fabre and painted insects lying still, probably from specimens on his worktable. Fabre wanted to see insects alive and at work. As you look, ask what a painting can tell you about an insect's body, and what only patient watching outdoors can tell you about its behavior.

Look closely

- Count the insects. How many different kinds can you find?
- Find the bumblebee. How many legs can you see, and do they all attach to the same part of the body?
- Find a beetle. How are its hard front wings different from the butterfly's wings?
- Find the smallest insects near the edges. Which body parts did the painter still show clearly?

Talk about it

1. This painting shows insects' bodies but not their behavior. What could you learn about a wasp only by watching it alive, as Fabre did?
2. Why might a painter put a flowering plant in the middle of a picture of insects?
3. If you painted the insects in your own yard, which would you choose and why?

> **Safety first.** Wasps and bees can sting, and some ants bite or sting (fire ants especially). Watch insects from at least an arm's length away, never poke or disturb a wasp or ant nest, and work with an adult. If anyone in your family is allergic to stings, choose a different activity or stay well back. Wash your hands after the project.

EXPERIMENT: BREAK THE TRAIL: A FABRE-STYLE ANT TEST

Fabre's secret was simple: watch an animal doing its normal job, then change one small thing and see what happens. You will do the same with ants. Many ants leave an invisible scent trail between their nest and food. Question: **Do foraging ants follow a scent on the ground more than they follow what they see?**

Prediction: write what you think will happen when you wipe a band across the trail. What we change: whether the trail is wiped. What we keep the same: the place, the bait, the time of day and the way we count. What we measure: how many ants cross a line each minute and how many turn back.

You will need

- A small card or bottle cap with a drop of honey or sugar water
- A stopwatch or clock with a second hand
- A magnifying glass
- A damp cloth or paper towel
- A ruler and a pencil
- Lab notebook

Steps

1. Find a line of small ants on a sidewalk or patio (not fire ants). Place the bait card about 1 meter from where they are coming from and wait 20 to 30 minutes for a trail to form.
2. Pick a spot halfway along the trail. Imagine a line across it. For 1 minute, count how many ants cross the line toward the bait. Do this 2 times and record both counts. This is your baseline.
3. With the damp cloth, wipe a band about 5 cm wide across the trail at your line. Start the timer.
4. For each of the next 5 minutes, count how many ants cross the wiped band and how many reach the edge of the band and turn back or wander. Record each minute in a table.
5. Control test: on a second trail (or the same trail 30 minutes later), wipe a band of the same size on the ground *beside* the trail without touching it. Count the same way. This shows whether the wiping action itself, rather than the missing scent, bothers the ants.
6. Make a line graph with minutes on the bottom axis and ants crossing per minute on the side axis, one line for each test.
7. Write a conclusion of 3 to 4 sentences: Was your prediction right? What does the result suggest the ants were following? What would you test next?

Tips

- Count the same direction every time (toward the bait), or your numbers will not be fair to compare.
- If the ants cross the band right away, try a wider band or wipe with a little soapy water, then compare.
- Fabre repeated his tests many times. If you can, do the whole test on two or three different days.

Check your work

- I stated a question and a prediction before I began.
- I counted a baseline and a control as well as the wiped trail.
- I recorded my counts in a table and made a graph.
- I wrote a conclusion that uses my data as evidence.

NATURE NOTEBOOK

1. Draw a cricket from the side, about 10 cm long. Label the head, thorax and abdomen, and mark with three small X’s the three thorax ganglia the Sphex stings.
2. Copy the four-step diagram of Fabre’s moved-cricket test in your own words, and add a fifth box: “What a thinking wasp would have done.”
3. Make a two-column chart titled “Instinct or Learned?” and write at least four animal behaviors you have seen yourself in each column.

From history. Fabre bought a weedy, stony plot of land in Sérignan, Provence, in 1879 and called it the Harmas, an old local word for untilled ground. He let the thistles and wild plants grow so that insects would come to him, and he watched them there for the rest of his long life. One of his best-known demonstrations used pine processionary caterpillars, which travel nose to tail following a silk thread. Fabre led a line of them onto the rim of a large flowerpot until the head of the line met the tail. The caterpillars kept marching around the rim, following the thread, for about a week before the circle finally broke up. Fabre's ten volumes of insect observations, the *Souvenirs Entomologiques*, were translated into many languages and made generations of readers into insect watchers.

WORKED EXAMPLES

Example 1. A naturalist repeats Fabre's moved-cricket test 40 times with one wasp. The wasp goes back into the burrow to inspect it in 38 of the 40 trials. In what percent of the trials did the wasp re-inspect the burrow?

1. Write the part over the whole: 38 ÷ 40.
2. Divide: 38 ÷ 40 = 0.95.
3. Change the decimal to a percent by multiplying by 100: 0.95 × 100 = 95%.

Answer: 95% of the trials. The behavior is very consistent, which is what we expect from a fixed action pattern.

Example 2. Suppose a digger wasp with a mass of 0.4 g drags home a paralyzed cricket with a mass of 1.2 g. How many times its own mass is the wasp pulling? If a 40 kg student pulled a load in the same ratio, how heavy would the load be?

1. Ratio of prey mass to wasp mass: 1.2 g ÷ 0.4 g = 3.
2. The wasp pulls 3 times its own mass.
3. For the student: 40 kg × 3 = 120 kg.

Answer: 3 times its own mass; the student would have to drag 120 kg, about the mass of a large adult man and a bicycle together.

Example 3. Sample data: a naturalist measures how deep a wasp has dug its burrow. At 0 minutes the depth is 0 cm, at 10 minutes 3 cm, at 20 minutes 6 cm and at 30 minutes 9 cm. What is the digging rate? If the rate stays steady, how deep will the burrow be at 40 minutes?

1. Find the change in depth: 9 cm − 0 cm = 9 cm.
2. Find the change in time: 30 min − 0 min = 30 min.
3. Rate = change in depth ÷ change in time = 9 cm ÷ 30 min = 0.3 cm per minute.
4. In 10 more minutes the wasp digs 0.3 × 10 = 3 cm more: 9 cm + 3 cm = 12 cm.

Answer: 0.3 cm per minute; about 12 cm deep at 40 minutes if the rate stays the same.

PRACTICE

1. EASY In your own words, what is an instinct? Give one example from this lesson.
2. EASY Label each behavior instinct (I) or learned (L): (a) a spiderling spins its first web; (b) a horse comes running when it hears the feed bucket rattle; (c) a newly hatched sea turtle crawls toward the bright ocean; (d) a parrot says “Hello”; (e) a young wasp digs out of its burrow and hunts crickets.
3. EASY Léon Dufour thought the beetles in the *Cerceris* burrow were dead but preserved. What did Fabre observe that showed they were alive?
4. MEDIUM Why does the yellow-winged Sphex sting a cricket three times, while *Cerceris* stings its beetle only once?
5. MEDIUM Data reading. A student repeats the moved-cricket test, changing how far the cricket is moved. Sample data:
   Distance moved 2 cm: wasp re-inspected 10 of 10 times
   Distance moved 5 cm: 10 of 10
   Distance moved 10 cm: 9 of 10
   Distance moved 20 cm: 10 of 10
   (a) What was the independent variable? (b) In how many of all 40 trials did the wasp re-inspect? (c) Does distance seem to matter much? Explain.
6. MEDIUM Data reading. In the ant trail test, a student counted ants crossing a line each minute. Before wiping: 12 per minute. After wiping a band across the trail: minute 1, 2 ants; minute 2, 3 ants; minute 3, 6 ants; minute 4, 10 ants; minute 5, 12 ants. (a) By how many ants per minute did the crossing drop in minute 1? (b) In which minute did the crossing first get back to at least 10? (c) Give one possible reason the ants recovered.
7. MEDIUM Suppose a Sphex mother stores 4 crickets in each cell of her burrow and makes 10 cells in one summer. How many crickets does she hunt? How many stings does that take if each cricket gets 3 stings?
8. HARD Inspecting the burrow before pulling in the cricket is usually a good habit for a wasp. Why might it help in nature? Then explain why the same habit looked foolish in Fabre’s test.

9. HARD Experiment design. A scientist wants to know whether a young digger wasp must watch other wasps to learn how to hunt. Describe an experiment. Name the independent variable, the dependent variable and two things to keep the same.
10. CHALLENGE Write 3 to 4 sentences: Tinbergen's pinecone test showed that a beewolf wasp learns landmarks. Fabre's cricket test showed that a Sphex follows a fixed program. How can both be true about wasps?

COMMON MISTAKES

- Thinking instinct means the animal is thinking things through. The Sphex does its job perfectly but cannot change its plan when the situation changes, which is why Fabre's test fooled it again and again.
- Thinking young animals must learn everything by watching their parents. A digger wasp never meets its mother, yet it hunts, stings and builds correctly the first time.
- Thinking a behavior must be all instinct or all learned. Many behaviors are a mix: a wasp's hunt is inborn, but the landmarks around its burrow are learned.

Make it a game · Fixed Action Pattern Freeze. One player is the wasp and must act out a five-step routine in exact order: (1) find the cricket, (2) sting it three times, (3) drag it to the burrow, (4) go inside and check, (5) pull it in. The other player is Fabre and may call "Moved!" at any time after step 4. The wasp must go back to step 3 and continue from there. Fabre scores a point each time the wasp forgets to start over; the wasp scores a point each time it finishes the routine correctly. Switch roles, then talk about what a thinking animal would do differently.

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. Who knoweth not in all these that the hand of the LORD hath wrought this?" (Job 12:7–9, KJV)

Fabre spent his life "asking the beasts" by watching and testing them. The wasp's skill teaches us something it does not understand itself: the hand of the Lord made it.

Practice answers

1. An instinct is a complex behavior an animal is born able to do correctly the first time, without being taught. Example: the Sphex wasp stinging a cricket at its three thorax ganglia and dragging it to the burrow.
2. (a) I, (b) L, (c) I, (d) L, (e) I.
3. Their joints still bent, their bodies still worked (they digested and stayed soft and fresh), and some lived on for weeks. They were paralyzed, not dead.
4. The cricket has three separate nerve centers (ganglia) in its thorax controlling its legs, so it needs one sting for each. The beetles Cerceris hunts have their leg ganglia bunched together in one spot, so one sting quiets all the legs.
5. (a) The distance the cricket was moved. (b) 10 + 10 + 9 + 10 = 39 of 40 (97.5%). (c) No. The wasp re-inspected almost every time at every distance, so the distance made little difference;

the moving itself restarted the routine.

6. (a) 12 − 2 = 10 fewer ants per minute. (b) Minute 4. (c) Ants that wandered across the gap laid down new scent, rebuilding the trail so others could follow it again.
7. 4 × 10 = 40 crickets; 40 × 3 = 120 stings.
8. In nature, the check lets the wasp make sure no enemy, parasite or cave-in is waiting inside before it stores food for its young. In Fabre’s test the habit looked foolish because it is a fixed action pattern: moving the cricket restarted the chain, so the wasp repeated a check it had just made instead of reasoning that the burrow was already safe.
9. Raise two groups of wasps from eggs in separate containers. One group is raised completely alone and never sees another wasp; the other group can watch adult wasps hunting. When they become adults, offer each wasp a cricket and record whether it stings and stores it correctly. Independent variable: whether the young wasp could watch others. Dependent variable: whether (or how well) it hunts. Keep the same: species, food, temperature, container size, kind and size of cricket, number of wasps in each group.
10. A wasp’s life combines instinct and learning. The hunting routine (which prey to choose, where to sting, how to drag and store it) is inborn and runs like a fixed program. But each wasp digs its burrow in a new place, so it must learn the landmarks around its own home to find it again. The inborn program even includes the ability to learn the right thing at the right time.

5.2 Spider Webs ★

OBJECTIVES

- Name the parts of an orb web (bridge thread, frame, radii, hub, capture spiral) and describe the order in which a spider builds them.
- Explain what spider silk is made of, how different kinds of silk do different jobs, and what the Skylab spiders showed about instinct.
- Use angles, circumference and scale to make calculations about real webs, and collect and compare web measurements in the field.

Warm-up. Take a piece of sewing thread about 30 cm long and a strip of clear tape the same length, sticky side up. Gently drop a cotton ball onto each one stretched between two chairs. Which catches and holds it? Now imagine you had to build a net that stops a flying insect, holds it fast and never traps *you*. What two kinds of thread would you need?

Video. Coming soon. Garden or orb-weaver spider building a web step by step (time-lapse), and the 1973 Skylab spider experiment with Arabella and Anita; search NASA archives, Smithsonian, Deep Look (KQED), SciShow Kids, BBC Earth style nature footage and Moody Science classics.

KEY TERMS

silk
A strong protein fiber a spider makes in glands in its abdomen. It leaves the body as a liquid and becomes a solid thread as it is pulled out.

spinneret
A small finger-like nozzle near the tip of a spider’s abdomen through which silk comes out. Most spiders have several pairs.

orb web
A round, wheel-shaped web with threads like spokes and a spiral, built by garden spiders and other orb weavers.

radius
One of the straight, dry “spokes” running from the center (hub) of an orb web to its frame. The plural is radii.

capture spiral
The sticky, stretchy spiral thread laid around the radii that catches flying insects.

dragline
The strong safety line a spider trails behind it wherever it goes; the same tough silk forms a web’s frame and radii.

CORE IDEAS

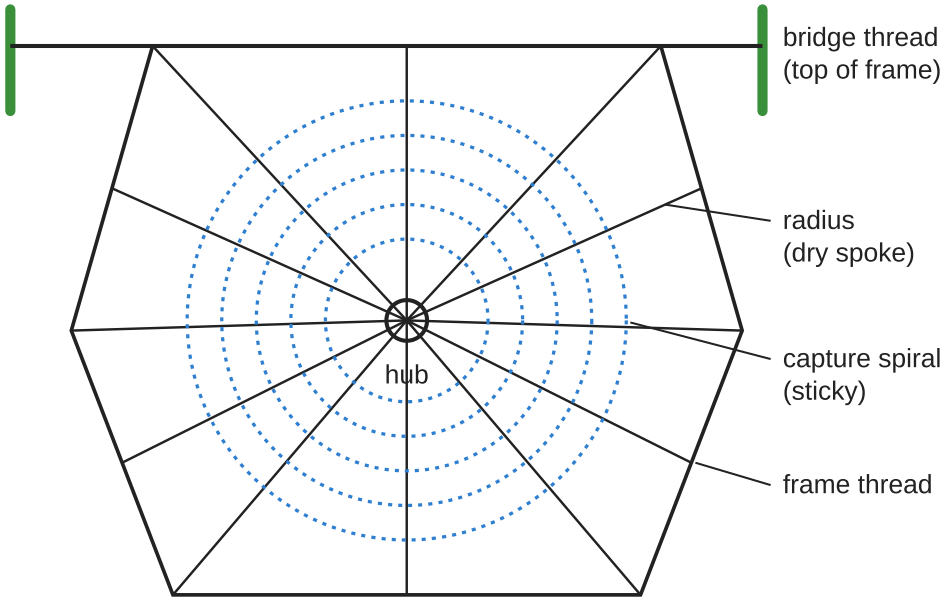
The story. In July 1973, two European garden spiders named Arabella and Anita rode a rocket to *Skylab*, America's first space station. They were there because of a question from Judith Miles, a high school student in Lexington, Massachusetts: could a spider build its web without gravity to tell it which way is down? On Earth, a garden spider uses its own weight to judge its webs. In space, the astronauts released Arabella into a frame and watched. Her first try was a tangled, lopsided mess. But she kept at it, and within a day or two she spun a round orb web that looked much like the webs her kind builds in gardens on Earth. The threads were thinner in places, but the plan was the same. The pattern was inside the spider, not in the gravity around her.

How they figured it out. Naturalists have watched spiders build for centuries, and the order of the work is always the same. First the spider lets out a fine thread on the breeze until it snags on a twig across the gap. This **bridge thread** becomes the top of the web. Next she drops a line from the middle of the bridge to make a Y, and builds the outer **frame**. Then she runs straight **radii** out from the center like the spokes of a wheel, checking the spaces between them with her legs. She lays a temporary, widely spaced spiral to hold everything steady. Finally, starting from the outside, she lays the sticky **capture spiral** round and round toward the center, eating up the temporary spiral as she goes. A garden spider can finish the whole web in about an hour. A young spiderling that has never seen a web builds a correct one on its first try.

The big idea. A spider's silk is a **protein**, made in glands inside her abdomen and pulled out through her **spinnerets**. An orb weaver can make several kinds. The **dragline** silk of the frame and radii is dry and very tough: for its weight it is stronger than steel, and it stretches before it breaks. The capture spiral is softer and much stretchier, beaded with tiny drops of glue. When a fly hits the web, the spiral stretches and soaks up the force of the crash, so the insect sticks instead of bouncing off or tearing through. The spider walks mostly on the dry radii and steps carefully, so she does not get stuck in her own trap. Building the web is an **instinct**: the steps, their order and the kinds of silk are all there from the start.

In the world today. Many orb weavers take down their web every day and eat the old silk, so the protein is recycled into the next web. Scientists measure webs the way you will in this lesson: counting radii, measuring the spacing of the spiral and comparing webs from day to day. Engineers study spider silk because a fiber that is light, strong and stretchy would be useful for ropes, medical stitches and safety gear. Making it in a factory as well as a small spider does in her garden has turned out to be very hard. A spider makes it quietly, at room temperature, out of the insects she eats.

God's handiwork. The Bible notices spiders too. Proverbs 30 lists "four things which are little upon the earth, but they are exceeding wise" (Proverbs 30:24), and one of them is the spider: "The spider taketh hold with her hands, and is in kings' palaces" (Proverbs 30:28). The garden spider did not go to engineering school, yet she builds a net with a frame, spokes and a shock-absorbing spiral, and she builds it right the first time. Her wisdom is real, but it is not her own idea. It is a gift written into her by the Creator.



The parts of an orb web. The radii and frame are dry dragline silk; the capture spiral (dotted) is sticky.

PICTURE STUDY



Arabella's Web Aboard Skylab, NASA astronauts, Skylab 3 mission, 1973 · Color photograph · NASA Marshall Space Flight Center archives (NASA photo MSFC-9513725)

This photograph was taken aboard Skylab in 1973 during the experiment suggested by Judith Miles, the high school student from Lexington, Massachusetts. It shows Arabella, a common cross spider, at the center of a web she spun while weightless, after her first tangled try. The astronauts photographed and filmed her so scientists on the ground could study every step.

It is not a painting, but it is a true natural-history record, made by careful observers who wanted to know whether a spider needs gravity to build. Compare it with the orb webs you find in your own yard.

Look closely

- Find the spider. Where in the web is she sitting?
- Find the radii running out from the hub. Are they straight and evenly spaced?
- Find the rings of the capture spiral. Is one side of the web more complete than the other?
- Find the frame of the cage. Where did Arabella attach her web?

Talk about it

1. Why did the astronauts take photographs instead of just describing the webs in words?
2. What does this web suggest about where the spider's building plan comes from?
3. If you could repeat the experiment, what would you want to photograph or measure?

> **Safety first.** Most spiders are harmless and helpful, but a few, such as black widows and brown recluses, have a dangerous bite. Do not touch spiders or put your hands into dark corners, woodpiles or under ledges. Look with your eyes and a magnifying glass, keep a ruler's length away, and leave the web and spider unharmed. Work with an adult.

EXPERIMENT: WEB SURVEY: MEASURING ORB WEBS IN THE FIELD

Real web scientists measure webs and look for patterns. Question: **Do larger orb webs have more radii?** Write your prediction before you go out.

This is an observation study, so you will not change the webs. What we compare: webs of different sizes. What we keep the same: the time of day, the way we measure and count, and the kind of web (round orb webs only). What we measure: the width of the capture area in centimeters and the number of radii.

You will need

- A spray bottle of water set to a fine mist
- A ruler or tape measure in centimeters
- A magnifying glass
- A flashlight (webs show up well when lit from the side)
- A camera or phone (optional)
- Lab notebook and pencil

Steps

1. Go out in the early morning, when webs are fresh and often beaded with dew. Look in gardens, on fences, porch corners and between shrubs.

2. When you find an orb web, mist it gently from about 1 meter away so the threads show up. Do not soak it.
3. Without touching the web, measure the width of the capture spiral from its outer edge on one side to the outer edge on the other side.
4. Count the radii. Count slowly, starting at the top and going around once, touching nothing. Count twice and record the average.
5. Record each web in a table: Web, Place, Width (cm), Number of radii, Spider seen? (yes/no).
6. Measure at least 5 webs if you can. Then make a scatter graph with width on the bottom axis and number of radii on the side axis.
7. Bonus: visit the same web for three mornings in a row. Is it rebuilt? Does the number of radii stay the same?
8. Write a conclusion: Did your data support your prediction? Give numbers from your table.

Tips

- Light from the side or behind the web makes threads glow. Stand so the sun or flashlight is not behind you.
- Do not blow on the web; the spider may think it has caught something.
- If you find only a few webs, ask a parent to help you search at dusk, when many orb weavers build.

Check your work

- I wrote a prediction before observing.
- I measured and counted at least 5 webs the same way each time.
- I made a table and a scatter graph.
- My conclusion uses numbers from my data.

NATURE NOTEBOOK

1. Draw an orb web in five stages: bridge thread, Y, frame, radii, capture spiral. Number and label each stage.
2. Sketch a real web you found, with its width and number of radii written beside it and the date and place.
3. Draw a spider from above. Label the two body parts (cephalothorax and abdomen), the eight legs and the spinnerets.

> **From history.** In 1948 in Tübingen, Germany, the zoologist Hans Peters had a problem: his garden spiders built their webs in the dark hours before dawn, when he wanted to be asleep. He asked a young pharmacologist named Peter Witt whether a drug might make them build at a more convenient time. The timing did not change, but Witt noticed that spiders given different drugs built webs with odd, measurable changes in their shape. Witt went on to spend decades photographing and measuring thousands of webs, and his

careful counts of radii, angles and spiral spacing showed just how exact and regular a healthy spider's instinctive web is.

WORKED EXAMPLES

Example 1. A garden spider's web has 30 radii spread evenly around the hub. What is the angle between two neighboring radii?

(Use the map or drawing "The radii meet at the hub like the spokes of a wheel." shown earlier in this lesson.)

1. A full turn around the hub is 360°.
2. Divide the full turn by the number of radii: 360° ÷ 30 = 12°.

Answer: 12° between neighboring radii.

Example 2. A web's capture spiral makes 25 turns. Treat each turn as a circle with an average radius of 8 cm. About how long is the whole capture spiral? (Use π ≈ 3.14 and circumference = 2 × π × radius.)

1. Circumference of one average turn: 2 × 3.14 × 8 cm = 50.24 cm.
2. Total length for 25 turns: 50.24 cm × 25 = 1,256 cm.
3. Change to meters: 1,256 cm ÷ 100 = 12.56 m.

Answer: About 12.6 meters of sticky thread, longer than a city bus, laid by a spider in less than an hour.

Example 3. A garden spider's body is 1.5 cm long and its web is 45 cm across. How many body lengths across is the web? If a 1.5 m tall student built a web at the same scale, how wide would it be?

1. Scale factor: 45 cm ÷ 1.5 cm = 30. The web is 30 body lengths across.
2. Student version: 1.5 m × 30 = 45 m.

Answer: 30 body lengths; a 45 m wide web, almost half the length of a football field.

PRACTICE

1. EASY Put these steps of orb-web building in order: capture spiral, bridge thread, radii, frame, temporary spiral.
2. EASY What is spider silk made of, and where does it come out of the spider's body?
3. EASY Why is it helpful to the spider that the radii are dry while the capture spiral is sticky?

4. MEDIUM A web has 24 evenly spaced radii. What is the angle between neighboring radii? Another web has 40 radii. Which web has the smaller gaps?
5. MEDIUM Data reading. A student measured four webs (sample data):
   Web A: width 20 cm, 22 radii
   Web B: width 30 cm, 28 radii
   Web C: width 40 cm, 35 radii
   Web D: width 25 cm, 25 radii
   (a) Which web was largest? (b) As width increased, what happened to the number of radii? (c) Does this data support the hypothesis “Larger webs have more radii”? (d) Why would more webs make the conclusion stronger?
6. MEDIUM Data reading. A naturalist watched 20 orb weavers in a garden one evening and recorded how many had finished webs (sample data): sunset, 0; 1 hour after, 3; 2 hours after, 9; 3 hours after, 15; 4 hours after, 18. (a) How many webs were finished between hour 1 and hour 2? (b) Which one-hour periods were the busiest? (c) What percent of the spiders had finished by hour 4?
7. MEDIUM A small web’s capture spiral has 20 turns with an average radius of 5 cm. About how long is the spiral in meters? ($\pi \approx 3.14$)
8. HARD Many orb weavers eat their old web before building a new one. Explain why this is a wise habit.
9. HARD Experiment design. Design an experiment to test whether a spider must see a web being built in order to build its own. Name the independent variable, the dependent variable and at least two controlled variables.
10. CHALLENGE On Skylab, Arabella’s first web was a tangle, but her later webs were nearly normal. (a) What does this suggest about whether gravity is needed to build an orb web? (b) What control would make the Skylab experiment stronger?

COMMON MISTAKES

- Calling spiders insects. Spiders are arachnids: they have eight legs and two main body parts, while insects have six legs and three body parts.
- Thinking all of a web is sticky. The frame and radii are dry dragline silk; only the capture spiral carries glue.
- Thinking a young spider learns web building by watching its mother. Spiderlings usually never see their mother build, yet they spin correct webs on the first try.

Make it a game · Yarn Orb Web. Between two chairs and a table leg, build a giant orb web with yarn in the true order: bridge thread, frame, radii from a center hub, then a spiral wound from the outside in. Use painter’s tape stuck sticky side out on the spiral turns to make them “sticky.” Take turns tossing cotton-ball “flies” at the web from 2 meters away. Score 1 point for a fly caught on a dry radius and 3 points for one stuck on the capture spiral. Then count your radii and calculate the angle between them.

Scripture. “The spider taketh hold with her hands, and is in kings’ palaces.” (Proverbs 30:28, KJV)

Proverbs 30, the words of Agur, lists the spider among “four things which are little upon the earth” that are “exceeding wise” (Proverbs 30:24). A small spider building in a king’s palace shows that wisdom from God can live in very small packages.

Practice answers

1. Bridge thread, frame, radii, temporary spiral, capture spiral.
2. Protein, made in silk glands in the abdomen; it comes out through the spinnerets near the tip of the abdomen.
3. The spider can walk on the dry radii without getting stuck, while the sticky spiral catches and holds insects.
4. 360° ÷ 24 = 15°. For 40 radii: 360° ÷ 40 = 9°. The 40-radius web has the smaller gaps.
5. (a) Web C (40 cm). (b) The number of radii increased (22, 25, 28, 35 in order of width). (c) Yes, it supports it. (d) Four webs is a small sample; measuring many webs would show whether the pattern is real and not just chance.
6. (a) 9 − 3 = 6 webs. (b) Hour 1 to hour 2 and hour 2 to hour 3 tie, with 6 webs finished in each (the first and last hours had only 3 each). (c) 18 ÷ 20 = 0.90 = 90%.
7. One turn: 2 × 3.14 × 5 = 31.4 cm. Twenty turns: 31.4 × 20 = 628 cm = 6.28 m, about 6.3 m.
8. Silk is made of protein, which takes food and energy to make. Eating the old web lets the spider recycle much of that protein into new silk, so it needs less food to keep rebuilding. A fresh web is also stickier and less damaged.
9. Hatch spiderlings from one egg sac and raise them in separate clear boxes. One group never sees any web or other spider; the other group lives where it can see adult spiders building webs. When they are old enough, give each a frame and record whether it builds a correct orb web and count its radii. Independent variable: whether the spiderling could watch others build. Dependent variable: whether it builds a correct web (and its shape, number of radii). Controls: same species, same egg sac, same food, light, temperature and box size.
10. (a) Gravity helps a spider judge its web, but it is not required: the building plan is in the spider, and she could adjust to weightlessness after a short time. (b) Keep a matching garden spider of the same kind, age and size on Earth in the same kind of frame, feeding and light, and compare its webs with the space webs. Testing more than one or two spiders would also help.

5.3 Beaver Dams

OBJECTIVES

- Describe how a beaver builds a dam and lodge and explain how the pond keeps the family safe and fed through winter.
- Explain what Lars Wilsson's loudspeaker experiments showed about the trigger for dam building, and weigh Lewis Henry Morgan's view that beavers think.
- Calculate pond volumes, building rates and comparisons from data, and test a model dam design with a fair experiment.

Warm-up. Run a thin stream of water from a faucet into the sink and close your eyes. Can you hear it? Now plug the drain partly with a washcloth and listen as the sound changes. Write one sentence: if you were an animal that wanted to stop water from leaking out of a pond, what sense would tell you fastest where the leak is?

Video. Coming soon. Beavers building a dam and lodge, underwater footage of a beaver lodge and winter food cache, and the 1948 Idaho beaver parachute drop; search nature footage channels, US Fish and Wildlife Service, National Park Service, Smithsonian, PBS Nature style documentaries and SciShow Kids.

KEY TERMS

rodent
A mammal with a pair of large front teeth (incisors) in each jaw that keep growing all its life, such as mice, squirrels and beavers.

incisors
The sharp front teeth used for cutting and gnawing. A beaver's are orange on the front because the enamel there contains iron.

dam
A wall of sticks, stones and mud built across a stream to hold back water and make a pond.

lodge
A beaver's home: a dome of sticks and mud with a dry room above the water and entrances that open underwater.

food cache
A pile of branches a beaver stores underwater near its lodge to eat during winter, when the pond is covered with ice.

ecosystem engineer
An animal that changes its surroundings so much that it creates new homes for many other living things.

CORE IDEAS

The story. In the 1850s and 1860s, Lewis Henry Morgan, a lawyer from Rochester, New York, traveled to the forests near Marquette, Michigan, on the south shore of Lake Superior, where he had invested in a railroad that hauled iron ore. Along the new line he found streams crowded with beaver dams, ponds and lodges. Morgan spent his summers there measuring dams, mapping ponds, tracing the canals beavers dug to float logs and sketching the stumps they had gnawed. In 1868 he published *The American Beaver and His Works*, one of the first careful scientific books about the animal. Morgan was so impressed that he argued beavers must think and reason, not merely follow instinct. A dam that fits a stream so well, he believed, could not be built by a blind program.

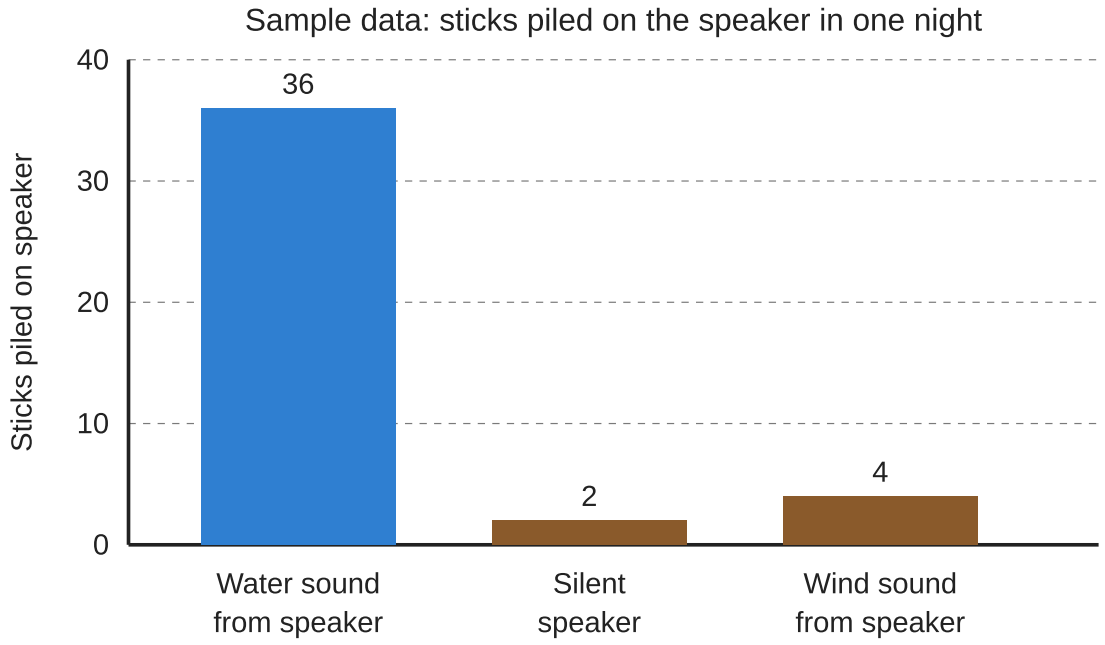
How they figured it out. About a century later, the Swedish zoologist Lars Wilsson tested the question. In the 1960s he raised young beavers in captivity. They had never seen a dam or a beaver building one. Yet when they were old enough, they piled sticks and mud in the right way. Then Wilsson tried a clever test. He set a loudspeaker on dry ground and played the sound of running water. The beavers piled sticks and mud right on top of the speaker, though there was no water to stop at all. When the speaker was silent, they left it alone. The main trigger for dam building was the **stimulus** of the sound of running water. Morgan was right that beavers adjust their work cleverly to each stream, and Wilsson was right that the urge to build and the basic method are inborn. Both are part of the truth.

The big idea. A beaver dam is a home-safety system. The beaver, North America's largest **rodent** (adults usually weigh 15 to 30 kg), cuts trees with its orange **incisors**, which keep growing so they never wear out. It pushes sticks into the streambed, adds stones and packs mud and plants on the upstream side with its front paws. The dam backs up a pond, often 1 to 2 meters deep. In the pond the family builds a **lodge** with a dry room above the waterline and doors that open underwater, where wolves and coyotes cannot follow. The water is deep enough that it does not freeze to the bottom, so all winter the beavers can swim under the ice to their **food cache** of branches stuck in the mud. The beaver is built for the job: valves close its ears and nose underwater, clear eyelids cover its eyes, its lips close behind its front teeth so it can gnaw without swallowing water, its hind feet are webbed and its flat, scaly tail helps it balance and slaps the water to warn the family. It can stay underwater for about 15 minutes.

In the world today. A beaver is an **ecosystem engineer**. Its pond makes a wetland where ducks, frogs, fish, insects, herons and moose find food and shelter. Ponds slow floodwaters after storms and hold water during dry months. Sometimes beavers flood a road or a farm field, and people install pipes called pond levelers through the dam that keep the water at a safe height without removing the beavers. The longest beaver dam known, in Wood Buffalo National Park in northern Canada, is about 850 meters long. It was first spotted in 2007 on satellite images, because it is so remote that few people had ever walked there.

God's handiwork. No one teaches a young beaver to answer the sound of running water by building a wall. The same God who made the water made the animal that listens to it and turns a trickling stream into a pond full of life. Proverbs 30:24 says that some creatures are

“little upon the earth,” yet “they are exceeding wise.” The beaver is one more example of wisdom given, not invented.



Sample data in the style of Wilsson’s loudspeaker test (not his real numbers). The water sound triggers building far more than silence or another sound.

PICTURE STUDY



American Beaver, from The Viviparous Quadrupeds of North America, John James Audubon (with his son John Woodhouse Audubon), text by John Bachman, 1840s · Hand-colored lithograph · Printed in Philadelphia by J. T. Bowen for the Audubons; copies are kept in many libraries, including the New York Public Library

Photo: Free Public Domain Illustrations by rawpixel · CC BY 2.0 (https://creativecommons.org/licenses/by/2.0) · via Wikimedia Commons

After finishing his famous *Birds of America*, John James Audubon set out to paint all the mammals of North America. He worked with his sons and with his friend John Bachman, a Lutheran pastor and naturalist from Charleston, South Carolina, who wrote the descriptions. The beaver was one of the most important animals of the continent at that time, because its fur had drawn trappers and traders across the wilderness for two hundred years.

Audubon painted animals from real specimens and from watching them alive. Look for the details a careful naturalist would want you to notice.

Look closely

- Find the beaver's front teeth. What color are they, and why?
- Look at the tail. How is it different from the tail of a squirrel or a dog?
- Find the sticks. How can you tell they have been gnawed?
- Look at the fur and the feet. Which parts look built for swimming?

Talk about it

1. Which beaver body features from this lesson can you find in the picture? Which ones can you not see?
2. Why would a naturalist paint an animal doing its work instead of just sitting still?
3. If you painted a beaver, what would you put in the background to show its whole home?

> **Safety first.** Do the model dam project outdoors or in a large tub with an adult nearby, and wipe up spills so no one slips. If you visit a real beaver pond, stay with an adult, keep well back from the water's edge and from the animals, never climb on a dam or lodge, and never drink stream or pond water, which can carry germs. Wash your hands after handling mud.

EXPERIMENT: MODEL DAM TEST: DOES MUD MAKE THE DIFFERENCE?

Beavers plaster the upstream side of their dams with mud and plants. Question: **Does packing mud into a stick dam make it hold back more water?** Write your prediction.

What we change: sticks only versus sticks with mud and leaves. What we keep the same: the container, the number and size of sticks, the amount of water and the time we wait. What we measure: how much water leaks past the dam in 2 minutes.

You will need

- A long plastic storage tub, a large baking pan or a section of rain gutter with one end blocked
- About 20 sticks, each about as long as the tub is wide (or a little longer)
- A few small stones
- A bucket of mud (soil mixed with water to a thick paste)
- A handful of leaves or grass

- A measuring cup marked in milliliters and a 1-liter bottle
- A cup or small container to catch leaking water, a timer and a ruler
- Lab notebook

Steps

1. Tilt the tub slightly by putting a book under one end. The high end is “upstream.” Mark the dam line across the middle with a strip of tape.
2. Dam A (sticks only): lay and wedge the 20 sticks and the stones across the dam line, packed as tightly as you can.
3. Pour 1 liter of water slowly into the upstream end. Start the timer.
4. After 2 minutes, measure the depth of water behind the dam with the ruler, then scoop or pour the water that leaked to the downstream side into the measuring cup. Record it in milliliters.
5. Empty the tub, rebuild Dam A the same way and repeat for a total of 3 trials.
6. Dam B (sticks and mud): build the same stick dam, then pack mud and leaves into the gaps on the upstream side, the way a beaver does. Run 3 trials exactly as before.
7. Make a table: Trial, Dam type, Water depth behind dam (cm), Water leaked (mL). Find the average leak for each dam type.
8. Make a bar graph comparing the average leak of Dam A and Dam B, and write a conclusion that uses your numbers.

Tips

- Pour the water the same way every time, slowly and at the same spot, so the test is fair.
- If Dam B holds all the water, try 2 liters or a longer wait to see when it finally leaks.
- Listen while the water leaks. Can you hear where the leak is? That is the sound a beaver listens for.

Check your work

- I wrote a question and a prediction.
- I changed only one thing (mud or no mud) and kept the rest the same.
- I ran 3 trials of each dam and found the averages.
- My conclusion compares the averages and explains what the beaver’s mud is for.

NATURE NOTEBOOK

1. Draw a side view (cross-section) of a beaver pond: the dam, the pond, the lodge with its dry room above water and its underwater entrance, and the food cache under the ice. Label each part.
2. Draw a beaver’s head and label the orange incisors, the nostrils and ears that close underwater and the eyes with their clear eyelids.
3. Make a web of arrows showing at least five animals that benefit from a beaver pond and what each one gets from it.

From history. By the 1800s, trapping for beaver-fur hats had removed beavers from much of North America. In the 1900s, wildlife workers began moving beavers back to places where they had disappeared. In 1948 Elmo Heter of the Idaho Fish and Game Department faced a puzzle: how to carry beavers into roadless mountain valleys. His answer was to drop them by parachute in wooden boxes that opened when they landed. He tested the boxes on a male beaver nicknamed Geronimo, who was dropped again and again until he climbed back into the box as if asking for another ride. That fall, 76 beavers were parachuted into the Idaho backcountry, and all but one landed safely and went on to build new colonies.

WORKED EXAMPLES

Example 1. The longest known beaver dam, in Wood Buffalo National Park, Canada, is about 850 m long. A soccer field is about 100 m long. How many soccer fields long is the dam?

1. Divide the dam length by the field length: 850 m ÷ 100 m = 8.5.

Answer: About 8.5 soccer fields long.

Example 2. A beaver pond is shaped roughly like a rectangle 30 m long and 20 m wide, with an average depth of 1.5 m. What is its volume in cubic meters and in liters? (1 m^3 = 1,000 L)

1. Volume = length × width × depth = 30 m × 20 m × 1.5 m.
2. 30 × 20 = 600; 600 × 1.5 = 900 m^3.
3. Change to liters: 900 × 1,000 = 900,000 L.

Answer: 900 m^3, or 900,000 liters of water held back by a wall of sticks and mud.

Example 3. Read the bar graph of sample data. How many sticks were piled on the speaker playing water sounds, and how many times as many is that as on the silent speaker? Why did the scientist include the wind-sound speaker?

(Use the map or drawing "Sample data for practice." shown earlier in this lesson.)

1. Read the bars: water sound 36 sticks, silent speaker 2 sticks, wind sound 4 sticks.
2. Compare: 36 ÷ 2 = 18.
3. The wind-sound speaker is a control. It shows whether *any* noise makes beavers build, or only the sound of running water.

Answer: 36 sticks, 18 times as many as on the silent speaker. Since the wind sound got only 4 sticks, it is the sound of running water in particular that triggers building.

PRACTICE

1. EASY Give two ways a beaver pond helps a beaver family survive the winter.
2. EASY What is the difference between a beaver dam and a beaver lodge?
3. EASY Name three features of a beaver's body that help it work underwater.
4. MEDIUM A pond is 40 m long, 25 m wide and averages 2 m deep. Find its volume in cubic meters and in liters.
5. MEDIUM Data reading. A naturalist measured the height of a new dam each morning (sample data): night 0, 40 cm; night 1, 45 cm; night 2, 51 cm; night 3, 55 cm; night 4, 60 cm. (a) What was the total growth? (b) What was the average growth per night? (c) If that average continues, what height will the dam reach on night 6?
6. MEDIUM Data reading. Researchers counted kinds of wetland birds at three kinds of places (sample data): a stream with no beavers, 6 kinds; an active beaver pond, 15 kinds; an old beaver meadow where the pond has drained, 9 kinds. Which statement is best supported? (A) Beavers eat birds. (B) The active beaver pond had more than twice as many bird kinds as the stream without beavers. (C) Old beaver meadows have no birds. (D) Birds build beaver dams.
7. MEDIUM A beaver family's dam is 120 m long. Suppose they add 3 m of length per week as the pond spreads. How many weeks until it is 150 m long?
8. HARD Lewis Henry Morgan believed beavers think and reason. Lars Wilsson showed they build when they hear running water, even over a speaker on dry land. Write 3 to 4 sentences explaining what evidence supports each view and how both can be partly right.
9. HARD Experiment design. A scientist wonders whether beavers respond to the *sight* of flowing water or only the *sound*. Design an experiment that separates the two. Name the independent variable, the dependent variable and two controlled variables.
10. CHALLENGE Beavers usually cut trees near the water, and many of those trees fall toward the pond. Some people think this proves beavers aim each tree. Suggest another explanation, and describe what you would measure to test the two ideas.

COMMON MISTAKES

- Thinking beavers eat fish. Beavers are plant eaters: they eat bark, the soft layer just under the bark, leaves, roots and water plants.
- Thinking beavers live inside the dam. The dam holds back the water; the family lives in a separate lodge or a burrow in the bank.
- Thinking beavers carefully aim every tree they cut. Many trees fall toward the water simply because shoreline trees lean toward the open light over the pond.

Make it a game · Find the Leak. One player is the beaver and sits blindfolded in the middle of a room. Another player gently trickles water from a small pitcher into a pan somewhere in the room (or plays a running-water sound on a phone). The beaver points to where the sound is coming from and crawls to "plug the leak" with a towel. Score 1 point for each leak found in under 30 seconds. Then try playing a different sound, such as rustling paper, and see whether the beaver can tell which sound means "leak."

Scripture. "There be four things which are little upon the earth, but they are exceeding wise: The ants are a people not strong, yet they prepare their meat in the summer; The conies are but a feeble folk, yet make they their houses in the rocks;" (Proverbs 30:24–26, KJV)

Like the ant that stores food and the coney that builds its house in the rocks, the beaver prepares a winter food cache and builds a safe home. Small, ordinary animals carry wisdom their Creator gave them.

Practice answers

1. Any two: the deep water does not freeze to the bottom, so beavers can swim under the ice; the food cache of branches is stored underwater where they can reach it; the lodge entrances are underwater, so predators cannot get in.
2. The dam is a wall across the stream that holds back water to make the pond. The lodge is the family's home in or beside the pond, with a dry room above water and underwater entrances.
3. Any three: valves that close the ears and nose; clear eyelids over the eyes; lips that close behind the incisors; webbed hind feet; flat tail for steering and balance; ability to hold its breath about 15 minutes.
4. $40 \times 25 \times 2 = 2{,}000$ m³; $2{,}000 \times 1{,}000 = 2{,}000{,}000$ L.
5. (a) $60 - 40 = 20$ cm. (b) $20 \text{ cm} \div 4 \text{ nights} = 5$ cm per night. (c) $60 + 5 + 5 = 70$ cm.
6. (B). 15 is more than twice 6 ($2 \times 6 = 12$). The others are not supported by the data.
7. $150 - 120 = 30$ m to add; $30 \div 3 = 10$ weeks.
8. Wilsson's evidence: beavers raised without ever seeing a dam still build correctly, and they pile sticks on a speaker playing water sounds where there is no water, so the urge and basic method are inborn and triggered by sound. Morgan's evidence: real dams fit each stream's shape, and beavers dig canals and choose sites in ways that suit local conditions. Both can be true: the building program is instinctive, but beavers adjust it with experience and to the place where they live.

9. Set up four conditions in a beaver enclosure: (1) a hidden speaker playing water sound with no visible water, (2) visible flowing water in a clear sealed channel that makes no sound, (3) both sound and sight, (4) neither. Count the sticks and mud piled at each spot in one night, testing each condition several times. Independent variable: whether sound, sight, both or neither is present. Dependent variable: amount of building (sticks piled). Controls: same beavers, same supply of sticks, same time of night, same distance from the lodge, same speaker volume.
10. Trees on a shore often lean toward the open, sunny side over the water, so they tend to fall that way no matter how the beaver cuts. To test it, measure the lean of many trees before they are cut and record which way each falls. If trees fall in the direction they already leaned, the lean explains it; if they fall toward the water even when leaning away, the beaver may be aiming.

5.4 Who Taught Them? (Job 39)

OBJECTIVES

- Read God's questions to Job in Job 39 and connect each animal named there to an inborn behavior that science has observed.
- Explain how isolation experiments such as Douglas Spalding's hooded chicks separate innate behavior from learned behavior, and tell the difference between a reflex, an instinct and a learned skill.
- Collect and analyze behavior data with percents, averages and a line graph, and design a fair test of an inborn behavior.

Warm-up. Have a partner stand behind you and, without warning, gently tap the back of your knee or clap near your ear. Did you jump or turn? Now think of one thing you can do that you learned in the last year and one thing you could do the day you were born. Write each on a slip of paper. Today's question is an old one, first asked in the Bible: when an animal does something wise that no one showed it, **who taught it?**

Video. Coming soon. Newly hatched chicks pecking, a foal standing within an hour of birth, herring gull chicks pecking at the red spot on the parent's bill, and fall hawk migration at Hawk Mountain; search nature footage channels, Smithsonian, Cornell Lab of Ornithology, Hawk Mountain Sanctuary, SciShow Kids and Moody Science classics.

KEY TERMS

innate behavior
Behavior an animal is born ready to do, without being taught. Instincts and reflexes are innate.

learned behavior
Behavior an animal gains or changes through experience, practice or teaching.

reflex
A quick, automatic response of one part of the body to a stimulus, such as blinking or jerking a hand away from something hot. An instinct is a longer, more complex chain of behavior.

sign stimulus
A simple, specific signal, such as a color, shape or sound, that sets off an instinctive behavior.

imprinting
A special kind of quick learning very early in life, such as a newly hatched chick or duckling learning to follow the first moving object it sees, usually its mother.

isolation experiment
An experiment in which an animal is raised without the chance to learn a behavior from others, to test whether the behavior is innate.

CORE IDEAS

The story. The book of Job tells of a good man who lost nearly everything and asked God why. When God finally answered him "out of the whirlwind," He did not give Job a lecture. He took him on a tour of creation and asked him questions. In Job 39 the questions are about animals: "Knowest thou the time when the wild goats of the rock bring forth?" Who let the wild ass run free? Who gave the ostrich her strange ways and the horse his strength? "Doth the hawk fly by thy wisdom, and stretch her wings toward the south? Doth the eagle mount up at thy command, and make her nest on high?" Job had to answer no. He had not taught any of them. Every one of those questions points to something we now call **instinct**.

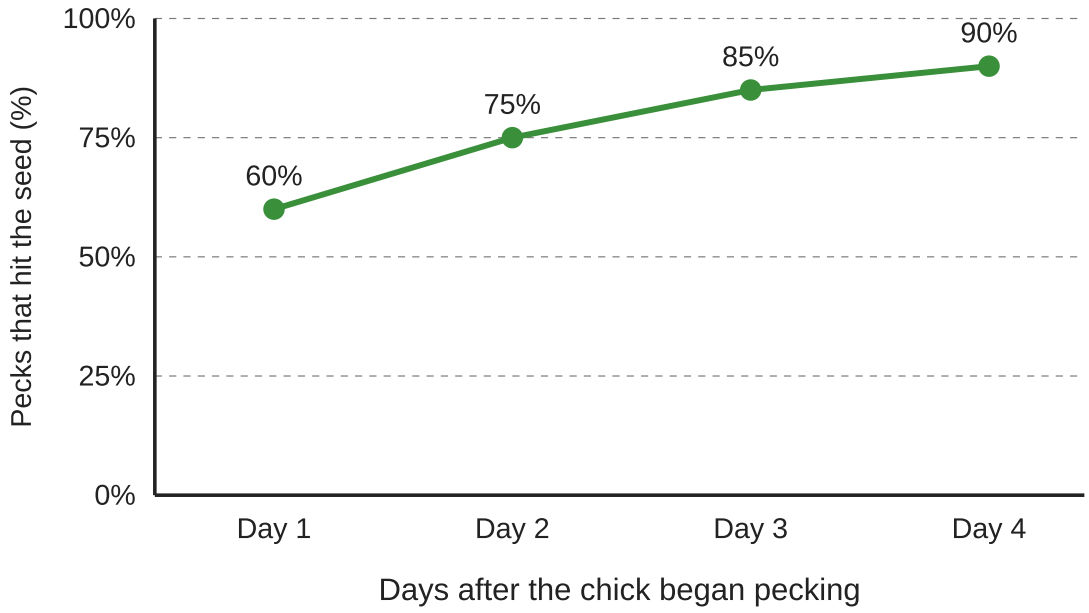
How they figured it out. Scientists test whether a behavior is innate with an **isolation experiment**: raise an animal with no chance to learn the behavior, then see if it does it anyway. One of the first was Douglas Spalding, a young British naturalist, in the early 1870s. He took hen's eggs just as the chicks were breaking out and slipped a little hood over each chick's head, so it could see nothing. After one to three days he took the hoods off. Within minutes, the chicks were following moving insects with their eyes and pecking at them, often hitting them on the first tries. Spalding also sealed some chicks' ears before they hatched; when he opened them, the chicks ran straight toward a hen calling from a hidden box. And he kept young swallows in small cages where they could not flap, then let them go at the age when swallows usually fly. They flew well at once. No one had taught them.

The big idea. Innate behaviors come in two main kinds. A **reflex** is quick and simple, like a blink. An instinct is a longer chain of actions, like a wasp's hunt or a spider's web. Many instincts are set off by a **sign stimulus**. Around 1950 the Dutch scientist Niko Tinbergen showed that a herring gull chick begs for food by pecking at the red spot on its parent's yellow bill. With cardboard models, he found that the chicks pecked far more at a bill with a red spot than at a plain one. But instinct and learning work together. Spalding's chicks began pecking without lessons, and later scientists found that a chick's aim grows more accurate with practice over its first days. Chicks also **imprint**: in their first hours they learn to follow the first moving thing they see. Spalding noticed his unhooded chicks following *him*. The urge to follow is innate; *whom* to follow is learned.

Try it and see. You can see Job 39 in action. A foal usually stands on its wobbly legs within about an hour of birth and soon finds its mother's milk. Young hawks that hatched in the summer fly south in the fall, and at places such as Hawk Mountain in Pennsylvania, watchers count thousands of hawks passing in a single autumn. A young European cuckoo is raised by birds of a different kind, never meets its parents, and still flies alone to Africa for the winter. In this lesson's project, you will test a simple innate behavior in pill bugs and see whether they "know" where to go without being taught.

God's handiwork. Scientists today study how genes help build an animal's nervous system, and how that wiring carries the plan for a web, a dam or a journey south. That is good work, and it tells us *how* an instinct is passed from parent to young. But it leaves Job's question standing. Even the ostrich, whom God says He "hath deprived" of wisdom (Job 39:17), shows that each kind was given its own portion, some more and some less. The wisdom in a hawk's

wings is not the hawk’s, and it is not ours. It belongs to the One who asked Job, and He still invites us to look and wonder.



Sample data: a chick pecks from the start (innate), and its aim improves with practice (learned).

PICTURE STUDY



The Horse Fair, Rosa Bonheur, 1852–1855 · Oil on canvas · The Metropolitan Museum of Art, New York

Rosa Bonheur was a French painter who studied animals the way a scientist does. To paint *The Horse Fair*, she went to the horse market in Paris twice a week for a year and a half, sketching the big draft horses as their handlers showed them off to buyers. The finished

painting is enormous, about 2.4 meters tall and 5 meters wide, so the horses are nearly life-size.

God's description of the horse in Job 39 begins, "Hast thou given the horse strength? hast thou clothed his neck with thunder?" Bonheur's horses look like that verse come to life.

Look closely

- Find the horse that is rearing up. What are its handlers doing?
- Look at the muscles in the horses' necks and legs. Where does the painter show their strength most clearly?
- Find the dust. How does it make the scene feel like it is moving?
- Look at the different colors of horses. How many can you find?

Talk about it

1. Which parts of a horse's behavior in this painting are innate, and which have the horses learned from their handlers?
2. Why do you think Bonheur sketched real horses for so long instead of painting from memory?
3. Read Job 39:19. Which horse in the painting best fits the verse, and why?

> **Safety first.** Handle pill bugs gently with a spoon or a soft paintbrush, keep them out of direct sun and return them to the place you found them within the hour. Wash your hands after the project. Do not pick up other creatures such as centipedes or spiders that may be hiding under the same logs and stones.

EXPERIMENT: PILL BUG CHOICE CHAMBER

Pill bugs (also called roly-polies) are not insects. They are small land crustaceans, cousins of shrimp, that breathe with gill-like parts that must stay damp. Question: **Without being taught, will pill bugs choose damp ground over dry ground?** Write your prediction.

What we change: which side of the chamber is damp. What we keep the same: the light, the temperature, the paper, the number of pill bugs and the timing. What we measure: how many pill bugs are on the damp side and the dry side each minute.

You will need

- 10 pill bugs collected from under a log, stone or flowerpot
- A shoebox lid, baking pan or flat plastic tray
- Two paper towels cut to fit half the tray each
- A spray bottle or a spoon of water
- A spoon or soft paintbrush for moving pill bugs
- A timer
- A piece of cardboard to cover the tray so light is the same on both sides

- Lab notebook

Steps

1. Lay one paper towel on each half of the tray so they touch in the middle. Dampen one side evenly (not dripping); leave the other dry.
2. Gently place all 10 pill bugs along the middle line where the two towels meet. Cover the tray with cardboard and start the timer.
3. Every minute for 10 minutes, lift the cover quickly and count the pill bugs on each side. Record: Minute, Damp side, Dry side.
4. Trial 2: make a fresh tray with the damp side switched to the other end, so you can tell whether the pill bugs prefer dampness or just one end of the tray. Repeat the counts.
5. Trial 3: repeat once more with fresh towels.
6. Find the average number on the damp side at minute 10 across the three trials, and change it to a percent of the 10 pill bugs.
7. Make a line graph of the number on the damp side each minute for one trial.
8. Write a conclusion: Did the pill bugs choose damp ground? Is this behavior innate or learned? How do you know? Then return the pill bugs to their home.

Tips

- Pill bugs may curl into a ball when you move them. Wait a minute; they will unroll and start exploring.
- Count quickly and put the cover right back so light does not change the result.
- Wild pill bugs have lived in damp places all their lives, so a careful scientist would also test pill bugs raised in a jar from birth. Talk about why.

Check your work

- I wrote a prediction and named what I changed, kept the same and measured.
- I switched the damp side in a second trial.
- I averaged my results and turned them into a percent.
- I returned the pill bugs and washed my hands.

NATURE NOTEBOOK

1. Make a page titled “Job 39 Field Guide.” Draw the wild goat, the horse, the ostrich, the hawk and the eagle, and beside each write one innate behavior it shows.
2. Draw Spalding’s hooded chick and, next to it, the same chick pecking at a fly after the hood is removed. Write one sentence explaining what the experiment proved.
3. Draw a herring gull’s head with its yellow bill and red spot. Label the sign stimulus and draw an arrow from the chick’s beak to the spot.

> **From history.** In the early 1930s, hunters gathered each fall on a rocky ridge in eastern Pennsylvania to shoot the hawks that streamed past on their way south. In 1934 a New York woman named Rosalie Edge leased, and later bought, the mountaintop and hired a

warden to stop the shooting. Hawk Mountain Sanctuary became the first refuge in the world set aside for birds of prey. Ever since, volunteers there have counted the hawks, eagles and falcons that fly by each autumn, and their long records are among the best information we have about how hawks still fly south year after year, just as Job 39:26 describes.

WORKED EXAMPLES

Example 1. A student watches a chick on its first day after hatching. It pecks at seeds 20 times and hits the seed 13 times. What percent of its pecks hit?

1. Write the part over the whole: 13 ÷ 20.
2. Divide: 13 ÷ 20 = 0.65.
3. Change to a percent: 0.65 × 100 = 65%.

Answer: 65% of the pecks hit. The chick pecked well without lessons; with practice its aim will improve.

Example 2. Read the line graph of sample data. By how many percentage points did the chick's aim improve from day 1 to day 4? What was the average improvement per day?

(Use the map or drawing "Sample data for practice." shown earlier in this lesson.)

1. Read the graph: day 1 is 60%, day 4 is 90%.
2. Change: 90% − 60% = 30 percentage points.
3. Days between: day 1 to day 4 is 3 days.
4. Average per day: 30 ÷ 3 = 10 percentage points per day.

Answer: 30 percentage points in all, an average of 10 points per day. Pecking itself is innate; the improvement shows learning from practice.

Example 3. In a pill bug choice chamber with 10 pill bugs, the numbers on the damp side at minute 10 were 8 in trial 1, 9 in trial 2 and 7 in trial 3. Find the average and the percent on the damp side. What is the ratio of damp to dry on average?

1. Add the trials: 8 + 9 + 7 = 24.
2. Average: 24 ÷ 3 = 8 pill bugs on the damp side.
3. Percent: 8 ÷ 10 = 0.8 = 80%.
4. On average 10 − 8 = 2 were on the dry side, so damp to dry is 8 : 2, which simplifies to 4 : 1.

Answer: An average of 8 pill bugs (80%) chose the damp side, a ratio of 4 : 1 damp to dry.

PRACTICE

1. EASY Name four animals God asks Job about in Job 39.
2. EASY Sort each as reflex (R), instinct (I) or learned (L): (a) blinking when dust blows at your eye; (b) a hawk flying south in its first autumn; (c) a dog opening a gate latch it has watched you open; (d) a foal standing an hour after birth; (e) pulling your hand off a hot pan.
3. EASY Why did Douglas Spalding put hoods on newly hatched chicks?
4. MEDIUM Explain the difference between a reflex and an instinct, with one example of each.
5. MEDIUM Data reading. A scientist shows herring gull chicks four cardboard bill models for 5 minutes each and counts pecks (sample data): plain yellow bill, 10 pecks; yellow bill with red spot, 40 pecks; yellow bill with black spot, 28 pecks; yellow bill with white spot, 14 pecks. (a) Which model got the most pecks? (b) How many times as many pecks did the red spot get as the plain bill? (c) What does the data suggest about the sign stimulus?
6. MEDIUM Data reading. Pill bug chamber, 10 pill bugs, counts on the damp side (sample data): minute 0, 5; minute 2, 6; minute 4, 7; minute 6, 8; minute 8, 9; minute 10, 9. (a) At minute 0, why were about half on each side? (b) How many moved to the damp side between minute 0 and minute 10? (c) What percent were on the damp side at the end?
7. MEDIUM At a hawk-watching lookout, observers count 1,200 hawks passing one September day. Of these, 900 are broad-winged hawks. What percent are broad-winged hawks?
8. HARD Spalding’s chicks pecked as soon as their hoods came off, and later studies found that a chick’s aim gets better over several days. Does the improvement mean pecking is a learned behavior? Explain.
9. HARD Experiment design. Design an isolation experiment to find out whether a songbird’s song is innate or learned. Name the independent variable, the dependent variable and two controlled variables, and say what result would show the song is learned.
10. CHALLENGE Write a short paragraph (4 to 5 sentences) answering God’s question in Job 39:26, “Doth the hawk fly by thy wisdom, and stretch her wings toward the south?” Use at least two key terms from this lesson.

COMMON MISTAKES

- Thinking an instinctive behavior can never improve. Many instincts start innate and are fine-tuned by practice, like a chick’s pecking aim.
- Thinking reflexes and instincts are the same thing. A reflex is a single quick response; an instinct is a whole chain of behavior.
- Thinking that once science explains how an instinct is passed on through genes, the question of where the wisdom came from has been answered. Science describes how the plan is copied; Job 39 asks who wrote it.

Make it a game · Who Taught You?. Make cards with animal behaviors from this unit and beyond: a wasp stinging a cricket, a spider spinning an orb web, a beaver piling sticks on a speaker, a foal standing, a parrot talking, a dog fetching, a chick following a person, a hawk flying south, a horse pulling a cart on command. Draw a card and act it out silently. The other players guess the animal, then answer "Who taught it?" with Innate, Learned or Both. Score 1 point for the animal and 2 points for the right answer with a reason.

Scripture. "Doth the hawk fly by thy wisdom, and stretch her wings toward the south? Doth the eagle mount up at thy command, and make her nest on high?" (Job 39:26–27, KJV)

God's questions to Job are humble questions for scientists too. We can measure the hawk's route and the eagle's nest, but we did not give them the wisdom to find them. Our study ends where Job's did, in wonder.

Practice answers

1. Any four: the wild goats, the hinds (female deer), the wild ass, the unicorn (wild ox), the peacock, the ostrich, the horse, the hawk, the eagle.
2. (a) R, (b) I, (c) L, (d) I, (e) R.
3. So they could not see anything and therefore could not learn by watching. If they pecked accurately as soon as the hoods came off, pecking had to be innate.
4. A reflex is a quick, simple, automatic response of one body part, such as a blink or a knee jerk. An instinct is a longer, more complex chain of behavior, such as a spider building an orb web or a beaver building a dam.
5. (a) The yellow bill with a red spot. (b) 40 ÷ 10 = 4 times. (c) A spot that stands out against the bill sets off pecking, and a red spot works best; the plain bill hardly does.
6. (a) They had all been placed on the middle line and had not yet had time to choose. (b) 9 − 5 = 4 more pill bugs. (c) 9 ÷ 10 = 90%.
7. 900 ÷ 1,200 = 0.75 = 75%.
8. No. Pecking itself is innate, because the chicks did it with no chance to learn. Practice then sharpened their aim, so the improvement is learned. The behavior is a mix: an innate start that experience fine-tunes.
9. Hatch eggs of one kind of songbird and raise two groups: one hears no adult birds of its kind (isolated in a quiet room), and one hears recordings or a live adult singing the normal song. When the young birds begin to sing, record their songs and compare them with the normal song. Independent variable: whether the young bird heard an adult song. Dependent variable: how closely its song matches the normal song. Controls: same species, same food, light, temperature and cage size, same age when recorded. If the isolated birds sing an incomplete or odd song while the tutored birds sing normally, the song is at least partly learned.
10. Sample answer: No, the hawk does not fly south by my wisdom or by its own. A young hawk makes its first journey south without lessons, which shows the urge to migrate is innate behavior, an instinct. Shortening days and cooling weather are stimuli that set it off. The hawk may learn landmarks and better hunting with experience, but the plan is built in from the start. Its wisdom was given by the Creator who asked Job the question.

Unit 5 review

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

1. (4 pts) Multiple choice. Which best describes an instinct? (A) A behavior an animal learns by watching its parents. (B) A complex behavior an animal does correctly the first time without being taught. (C) Any quick blink or jerk of one body part. (D) A trick taught by a trainer.
2. (6 pts) Describe Fabre’s moved-cricket test. What did Fabre do, what did the wasp do, and what did the test show about instinct?
3. (4 pts) In 20 repeats of the moved-cricket test, a wasp re-inspected its burrow 18 times. What percent of the trials is that? Show your work.
4. (8 pts) Diagram. Draw an orb web hanging between two twigs. Label the bridge thread, the frame, at least one radius, the hub and the capture spiral. Then mark with an S the only part that is sticky, and number the parts 1 to 4 in the order the spider builds them (bridge thread, frame, radii, capture spiral).
5. (4 pts) Multiple choice. Spider silk is made of: (A) sugar, (B) protein, (C) chalk, (D) plant fiber.
6. (5 pts) An orb web has 36 evenly spaced radii. What is the angle between two neighboring radii? If the capture spiral has 10 turns with an average radius of 10 cm, about how long is it in meters? (π ≈ 3.14)
7. (6 pts) Give three ways a beaver’s dam and pond protect the family or help it survive the winter.
8. (6 pts) Data reading. Sample data from a loudspeaker test with beavers: water sound, 30 sticks piled on the speaker; silent speaker, 3 sticks; wind sound, 5 sticks. (a) How many times as many sticks did the water sound get as the silent speaker? (b) Why was the wind sound included? (c) What conclusion does the data support?
9. (5 pts) A beaver pond is about 25 m long, 20 m wide and 2 m deep on average. Find its volume in cubic meters and liters. (1 m³ = 1,000 L)
10. (4 pts) Multiple choice. Douglas Spalding hooded newly hatched chicks and removed the hoods days later. The chicks soon pecked at insects. This showed that: (A) chicks learn pecking from the hen; (B) pecking is innate; (C) chicks cannot see for three days; (D) pecking is a reflex of the eye.
11. (8 pts) (a) In Job 39:26 God asks, “Doth the hawk fly by thy wisdom, and stretch her wings toward the south?” Explain what this question has to do with instinct. (b) Design an isolation experiment to test whether young pill bugs, raised in a jar from birth, still choose damp ground. Name the independent variable, the dependent variable and two controls.

Unit project: my instinct field study

Choose one animal you can watch safely near home: ants on a trail, an orb-weaving spider, a bird building a nest, pill bugs or a pet. Watch it on at least three different days and record

what it does, with dated sketches, measurements and a table of counts. Then run one small fair test of its behavior, change only one thing, and graph the results.

Finish with a one-page report: describe the behavior, classify each part of it as innate, learned or both, and give your evidence. Close with a paragraph connecting your animal to this unit's big question, "Who taught them?", and to God's questions to Job in Job 39. Include a short Scripture verse (KJV) from this unit.

- **Observation**: At least three dated observations with clear, labeled sketches and measurements in metric units.
- **Experiment**: The test has a question, prediction, one changed variable, controls, repeated trials, a data table and a correct graph.
- **Reasoning**: The report correctly uses the terms instinct, learned behavior and stimulus and supports each claim with the student's own data.
- **Care and stewardship**: The notebook is neat and complete, the animal was observed without harm and returned or left undisturbed, and the closing paragraph thoughtfully connects the study to Job 39.

Answer key

1. (B). (A) and (D) are learned behaviors; (C) describes a reflex.
2. When the Sphex left its paralyzed cricket at the burrow entrance and went inside to inspect, Fabre moved the cricket a few centimeters away. The wasp came out, dragged the cricket back to the entrance and went in to inspect again, every time, dozens of times. It showed that the hunt is a fixed action pattern: exact and effective in normal conditions, but rigid; the wasp does not reason that it has already checked the burrow.
3. 18 ÷ 20 = 0.9; 0.9 × 100 = 90%.
4. A correct drawing shows a bridge thread across the top between two twigs, an outer frame, straight radii running from the central hub to the frame and a spiral wound around the radii. The capture spiral is marked S. Order: 1 bridge thread, 2 frame, 3 radii, 4 capture spiral (a temporary spiral comes before the capture spiral and is removed). Scoring: 1 point for each of 5 correct labels, 1 point for the S on the capture spiral, 2 points for the correct order.
5. (B) protein.
6. 360° ÷ 36 = 10°. One turn: 2 × 3.14 × 10 = 62.8 cm; 10 turns: 628 cm = 6.28 m, about 6.3 m.
7. Any three: the lodge entrances are underwater, so predators cannot get in; the deep water does not freeze to the bottom, so beavers can swim under the ice; the food cache of branches is stored underwater within reach all winter; the pond lets beavers travel and float logs by water instead of walking on land where predators hunt.
8. (a) 30 ÷ 3 = 10 times. (b) As a control, to tell whether any noise causes building or only the sound of running water. (c) The sound of running water, in particular, is the stimulus that triggers dam building.
9. 25 × 20 × 2 = 1,000 m^3; 1,000 × 1,000 = 1,000,000 L.
10. (B). The chicks had no chance to learn by watching, yet they pecked, so pecking is innate.
11. (a) Young hawks fly south in their first autumn without being taught; the behavior is innate. Job did not give the hawk that wisdom, and neither did the hawk; the question points to God as the one who gave it. (b) Raise pill bugs from birth in a jar kept evenly damp (they cannot

live long in dry air), so they never experience a choice between damp and dry. Put them in a choice chamber with one damp side and one dry side, switch sides between trials, and count how many are on each side every minute for 10 minutes. Independent variable: which side is damp (or damp versus dry). Dependent variable: number of pill bugs on each side. Controls: same light on both sides (covered), same temperature, same number of pill bugs, same paper and timing. If they still choose damp ground, the preference is innate. Scoring: 3 points for (a), 5 points for (b).

UNIT 6

Social Animals

Some of God's creatures live alone, but many live in families and colonies where each member has a part to play. In this unit you will meet four of the most remarkable animal societies on earth. You will sit beside Karl von Frisch's glass beehive in Austria and learn to read the honeybee's dance. You will watch Arctic wolves at their den with L. David Mech and discover that a wolf pack is a family. You will follow Cynthia Moss among the elephants of Amboseli, where the oldest grandmother leads the way. And you will dig into a leafcutter ant nest with Thomas Belt in Nicaragua and find a farm underground.

In every lesson you will ask the same scientific questions: **Who leads? How are the jobs divided? How do the members send messages?** You will measure and calculate as real field biologists do: decoding the angle and length of a bee's dance, working out wolf densities and predator-to-prey ratios, finding the wavelength of an elephant's rumble and timing an ant on her trail. You will run small experiments at home on cell shapes, scent marks, sound through the floor and the food choices of real ants.

Along the way you will see that good order in these societies does not come from a ruler shouting commands. The queen bee and the queen ant give no orders, yet the work gets done; wolf and elephant families are led by parents and grandmothers who care for the young. Solomon told us to "go to the ant" and learn (Proverbs 6:6), and this unit is an invitation to do just that.

BEFORE YOU BEGIN

- Can measure angles with a protractor and read compass bearings (north 0°, east 90°, south 180°, west 270°)
- Can divide, find a percent and convert metric units (mm, cm, m, km; mg, g, kg)
- Can make a data table and a bar or line graph
- Knows the parts of a fair test from earlier units: question, prediction, variables, control and conclusion

MASTERY CHECKLIST

- I can describe the castes of a honeybee colony and decode a waggle dance into a direction and distance.
- I can explain why a wild wolf pack is a family and how wolves cooperate to raise pups, hunt and hold a territory.
- I can explain how an elephant matriarch's experience helps her family, and what infrasound is.
- I can explain how leafcutter ants farm fungus and give examples of mutualism.
- I can calculate rates, ratios and percents from animal data and read data tables in science-reasoning questions.
- I can design a fair test with a control to study animal behavior.

OPTIONAL BOOKS AND RESOURCES

- ***The Naturalist in Nicaragua* by Thomas Belt (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/search/?query=naturalist+in+nicaragua): Free. Read aloud Belt's own description of the leafcutter ants and their fungus gardens (Lesson 6.4). The book is long and written for adults, so a parent may choose the passages.
- **Isle Royale National Park, National Park Service** (https://www.nps.gov/isro/): Free. The park's pages on wolves and moose explain the long-running winter study and the newer wolves brought to the island (Lesson 6.2).
- **Biodiversity Heritage Library** (https://www.biodiversitylibrary.org/): Free. Search for Maria Sibylla Merian's *Metamorphosis insectorum Surinamensium* to page through her plates, including the ants on the guava branch (Lesson 6.4), and for old natural history books on bees and elephants.

6.1 Honeybee Hives: The Dance Language ★

OBJECTIVES

- Describe the three kinds of honeybees in a colony (queen, workers and drones) and explain how workers divide their jobs by age.
- Explain how Karl von Frisch decoded the waggle dance, and use a dance's angle and length to find the direction and distance of a flower patch.
- Calculate why a six-sided (hexagonal) honeycomb cell uses less wax than a square cell of the same area.

Warm-up. Take a sheet of paper and a pencil. Without using any words, numbers or pointing, try to tell a family member where the cookie jar is in your kitchen, using only how you move your body on one spot. Give yourself one minute. Did they find it? Now imagine doing the same thing in a pitch-dark room, on a wall, with sisters who can only feel you move. That is the problem a honeybee solves every day.

Video. Coming soon. Honeybee waggle dance in an observation hive, Karl von Frisch, and how honeycomb is built; search Smithsonian, university entomology and extension channels, beekeeping association channels, nature footage of hives, and Homeschool Pop (Alternate) or SciShow Kids for bee basics.

KEY TERMS

colony
A group of animals of one kind that live together and depend on each other. A honeybee colony has one queen, thousands of workers and, in summer, some drones.

caste
A group within a social insect colony that has a certain body type and job. Honeybee castes are queen, worker and drone.

division of labor
Splitting the work of a group so that different members do different jobs. In a hive, young workers do inside jobs and older workers fly out to gather food.

waggle dance
A figure-eight dance a forager bee does on the comb. The angle of the straight waggle run tells the direction of the food compared with the sun, and the length of the waggle run tells how far away it is.

pheromone
A chemical an animal gives off that carries a message to others of its kind, such as the queen's scent that tells the hive she is present.

forager
An older worker bee that flies out of the hive to collect nectar, pollen, water or plant resin.

CORE IDEAS

The story. In the summer of 1944, while war raged across Europe, an Austrian scientist named Karl von Frisch sat beside a glass-walled beehive at his family's country house in Brunnwinkl, on the shore of the Wolfgangsee in Austria. He had been studying bees for more than thirty years. He already knew that a bee who found good food came home and danced on the comb, and that her sisters then flew out and found the same flowers. But how did they know where to go? That summer, watching bees he had marked with tiny dots of paint, von Frisch saw something astonishing: the dance was a *map*. In 1973 he shared the Nobel Prize for his work on animal behavior.

How they figured it out. Von Frisch set out small dishes of sugar water at measured distances and in known directions from the hive. He marked each bee that fed at a dish, then hurried back to watch her dance. When the dish was close, the forager ran in a little circle, which he called the round dance. When the dish was farther away, she did a **waggle dance**: a straight run while shaking her body from side to side, then a loop back around to the start, then another straight run, making a figure eight. When he moved the dish farther away, the waggle runs grew longer. When he moved it to a new direction, the angle of the run changed. On the dark, upright comb, "straight up" stands for the direction of the sun. If the waggle run points 40° to the right of straight up, the food lies 40° to the right of the sun. The sisters crowd close, feel the dance with their antennae, taste the nectar she brings and fly off on the right bearing.

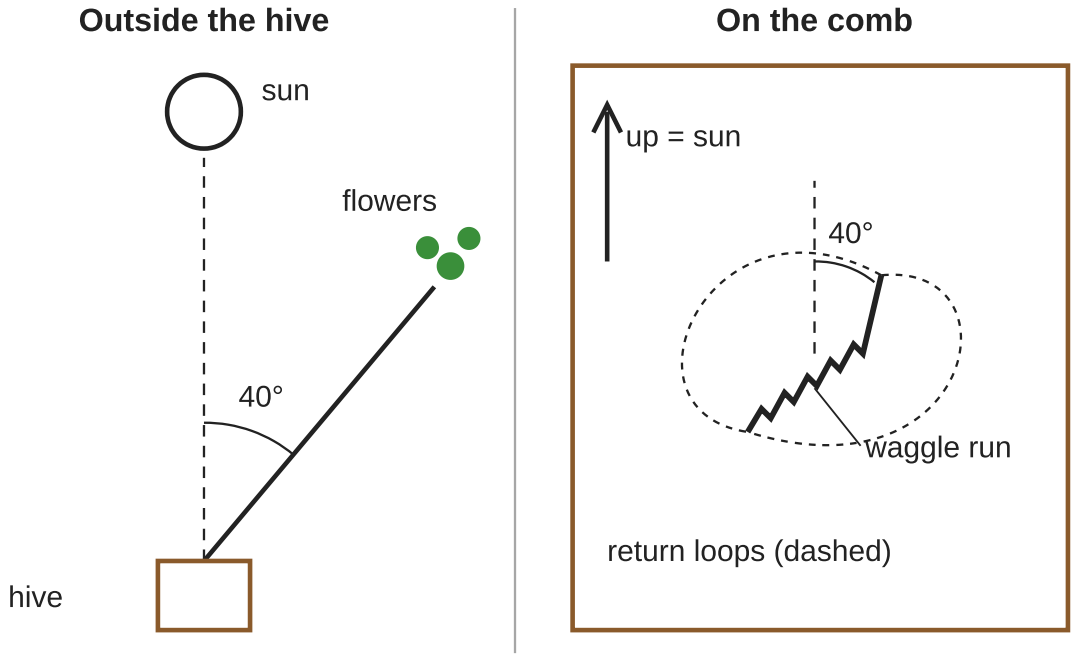
The big idea. A honeybee colony works almost like one great body. There is one **queen**, a female whose job is to lay eggs, as many as 1,500 or more in a day in early summer. There are tens of thousands of **workers**, all female, who do every other job. In summer there are a few hundred **drones**, the males, whose only job is to mate with a young queen from another hive. The queen does not give orders. Her **pheromones** tell the workers that she is alive and well, and the work is shared out by **division of labor**. A summer worker lives only about five or six weeks. In her first days she cleans cells; then she becomes a nurse feeding larvae; then she builds wax comb and stores food; then she guards the entrance; and in her last two or three weeks she becomes a **forager**. The plan bends when the hive needs it: if foragers are lost, young bees can start foraging early.

Built from wax. Workers make wax from glands on the underside of the abdomen, and it is costly: bees must eat several kilograms of honey to make one kilogram of wax. So it matters that the comb is built of hexagons, six-sided cells. Only three regular shapes fit together with no gaps (triangles, squares and hexagons), and of those, the hexagon holds the most space for the least wall. People suspected this for about two thousand years, and the mathematician Thomas Hales finally proved it in 1999. The bees build the same shape in every hive in the world, in the dark, with no ruler.

In the world today. Each year in late winter, beekeepers load more than a million hives onto trucks and drive them to the almond orchards of California, because almond flowers need bees to carry pollen from tree to tree. Apples, blueberries, cherries and many other crops are helped by bees in the same way. Scientists still use von Frisch's method: they film

dances in observation hives, measure the angle and length of each waggle run, and plot where the colony is feeding.

God’s handiwork. A bee’s brain is smaller than a grain of rice, yet she can find a patch of clover kilometers away, come home, and pass its position to her sisters by dancing in the dark. Honey has been a picture of good things since Bible times. The psalmist said God’s judgments are “sweeter also than honey and the honeycomb” (Psalm 19:10), and the more we learn about how the comb is made, the more that sweetness is matched by wisdom.



The waggle dance: on the upright comb, straight up stands for the sun. A waggle run 40° right of up means the food is 40° right of the sun.

PICTURE STUDY



The Beekeepers, Pieter Bruegel the Elder, about 1568 · Pen and brown ink on paper · Kupferstichkabinett (Museum of Prints and Drawings), Staatliche Museen zu Berlin

Pieter Bruegel the Elder was a Flemish artist of the 1500s who loved to draw and paint ordinary country people at work. In this drawing, made near the end of his life, he shows beekeepers of his day. Before wooden hive boxes were invented, bees were often kept in skeps, dome-shaped baskets of coiled straw. To protect their faces from stings, the beekeepers wear masks of woven wicker.

Bruegel does not show us anyone’s face. Look at how he tells the story with bodies and hands instead, and think about what these men knew about bees, and what they did not yet know.

Look closely

- Find the straw hives. How are the beekeepers carrying or handling them?
- Look at the masks and long clothing. Why might beekeepers have dressed this way?
- Find the boy in the tree. What might he be doing up there?
- Bruegel used only brown ink. How does he show light, shadow and texture without color?

Talk about it

1. These beekeepers knew how to keep bees, but no one yet knew about the waggle dance. What would you most like to tell them about their bees?
2. Why do you think honey was so valuable in a time before sugar was cheap?
3. What does this drawing tell you about country life in Bruegel’s time?

> **Safety first.** Bees and wasps can sting, and some people are seriously allergic. Watch bees only from at least 2 meters away, never swat at them, and never open or bump a hive. If you know you are allergic to stings, stay indoors for the bee-watching part and tell an adult. The project uses scissors; cut carefully.

EXPERIMENT: WHY HEXAGONS? THE WALL-LENGTH EXPERIMENT

Bees spend precious honey to make wax, so the best cell shape holds the most space for the least wall. In this experiment you will bend paper strips of the same length into different shapes and measure how much area each one encloses. You will be testing the same question the mathematicians argued about for two thousand years.

You will need

- Five strips of stiff paper or card, each exactly 12 cm long and about 2 cm wide
- Centimeter grid paper (or plain paper with a 1 cm grid you draw with a ruler)
- Ruler, pencil, tape and scissors
- Lab notebook
- Optional: a calculator

Steps

1. **Question:** When the wall length is the same, which shape encloses the most area: a triangle, a square, a hexagon or a circle? Write the question in your notebook.
2. **Prediction:** Write which shape you think will win and why.
3. **Variables:** What you change is the shape. What you keep the same is the wall length (12 cm). What you measure is the area inside, in square centimeters.
4. Fold one strip into an equilateral triangle (three sides of 4 cm), one into a square (four sides of 3 cm) and one into a regular hexagon (six sides of 2 cm). Bend one strip into a circle. Tape each closed where the ends meet.
5. Stand each shape on the grid paper and trace around the inside. Count the whole squares inside, then add half-squares as one-half each. Record each area in a table with columns: Shape, Wall length (cm), Area (cm^2).
6. Check your counts with the formulas: triangle with side 4 cm is about 6.9 cm^2; square with side 3 cm is 9 cm^2; hexagon with side 2 cm is about 10.4 cm^2; circle with a 12 cm rim is about 11.5 cm^2.
7. Now trace six copies of each shape side by side on grid paper as if building a comb. Which shapes fit together with no gaps? Shade any gaps.
8. **Conclusion:** Write two or three sentences: Which shape held the most area? Which shape is the best choice when the cells must also fit together with no wasted space?

Tips

- Crease the corners sharply so the sides stay straight and equal.

- The circle wins on area, but look at what happens between circles when you pack them together. Bees cannot afford wasted space or extra walls to fill it.
- Do it at home: if your family keeps bees or knows a beekeeper, ask to see a frame of empty comb up close (with the beekeeper's permission and protective gear).

Check your work

- I kept the wall length the same for every shape.
- My table shows the area for each shape, and my counts are close to the formula values.
- I can explain why the hexagon is the best shape for a comb, even though the circle encloses a little more area.

NATURE NOTEBOOK

1. Draw a worker bee in side view and label the head, thorax, abdomen, antennae, two pairs of wings, six legs and the pollen basket on the hind leg.
2. Draw a timeline of a summer worker bee's life from day 1 to about day 42, marking each job she does.
3. From at least 2 meters away, watch bees on flowers for 5 minutes. Record the date, time, weather, the kind and color of flower, and how many bees you see. Note whether any bee has yellow or orange pollen on her legs.

> **From history.** In 1851 the Reverend Lorenzo Langstroth, a minister and beekeeper in Philadelphia, noticed that bees leave a gap of about one centimeter or a little less between combs and between comb and hive wall. They fill smaller gaps with sticky resin and larger gaps with wax, but they leave this "bee space" open as a walkway. Langstroth built a wooden hive with frames hanging exactly one bee space apart, so each frame could be lifted out without tearing the comb. He patented it in 1852, and most beehives in the world today still follow his design.

WORKED EXAMPLES

Example 1. A forager dances on the upright comb. Her waggle run points 60° to the *left* of straight up. At that hour the sun is due south (a compass bearing of 180°). On what compass bearing should her sisters fly?

1. On the comb, straight up stands for the direction of the sun. So the food is 60° to the left of the sun's direction.
2. Facing the sun, "left" means turning counterclockwise, which makes the compass bearing smaller.
3. Bearing of food = 180° − 60° = 120°.
4. A bearing of 90° is east and 180° is south, so 120° is between east and south, a little closer to east.

Answer: A bearing of 120°, which is east-southeast of the hive.

Example 2. In one colony, scientists found that each second of waggle run stands for about 1 kilometer of flight. A forager's waggle runs last 2 seconds. Worker bees fly about 24 km per hour. How far away is the food, and about how long will the one-way flight take?

1. Distance: 2 seconds × 1 km per second = 2 km.
2. Time = distance ÷ speed = 2 km ÷ 24 km per hour = 0.083 hour.
3. Convert to minutes: 0.083 hour × 60 minutes per hour = 5 minutes.

Answer: The food is about 2 km away, and the flight takes about 5 minutes each way.

Example 3. A worker cell is a regular hexagon with sides of 3 mm. Its area is about 23.4 mm². How much wall does it need, and how much wall would a square cell with the same area need? (Hint: the side of the square is the square root of the area.)

1. Hexagon wall length: 6 sides × 3 mm = 18 mm.
2. Square side: √23.4 ≈ 4.84 mm.
3. Square wall length: 4 sides × 4.84 mm ≈ 19.4 mm.
4. Wax saved: 19.4 − 18 = 1.4 mm of wall per cell. As a percent of the square's wall: 1.4 ÷ 19.4 ≈ 0.07, or about 7%.

Answer: The hexagon needs 18 mm of wall; the square needs about 19.4 mm. The hexagon saves about 7% of the wall for every cell, which adds up over tens of thousands of cells.

PRACTICE

1. EASY Name the three castes of honeybees and tell whether each is male or female.
2. EASY In the waggle dance, what does the *angle* of the waggle run tell the other bees? What does the *length* of the waggle run tell them?
3. EASY Which does a forager collect to make honey, nectar or pollen? What is the other one used for?
4. MEDIUM A forager's waggle run points straight down the comb. Where is the food?
5. MEDIUM A queen lays 1,500 eggs a day for 30 days in early summer. How many eggs is that? If a worker takes 21 days to grow from egg to adult, on about what day will the first of these eggs become adult bees?
6. MEDIUM **Data reading.** A beekeeping guide gives this typical schedule for a summer worker: Days 1–2, cleaning cells. Days 3–11, nursing larvae. Days 12–17, building comb and storing food. Days 18–21, guarding the entrance. Days 22–42, foraging. (a) What job is a 15-day-old worker most likely doing? (b) What fraction of her 42-day life is spent foraging? (c) A guide says the schedule can change. Which observation from the lesson supports that?
7. MEDIUM **Data reading.** A class measured waggle runs for feeders placed at different distances: 0.25 km, 0.4 s; 0.5 km, 0.7 s; 1.0 km, 1.2 s; 2.0 km, 2.2 s. (a) Describe the relationship between distance and waggle time. (b) A dancer's waggle runs last 1.7 s. Estimate the distance to the food. (c) Would it be safe to use this table to predict the distance for a 6-second waggle run? Explain.
8. HARD Triangles and squares also fit together with no gaps. Why are hexagons a better choice for a bee? Why not circles?
9. CHALLENGE **Experiment design.** Von Frisch wanted to know whether bees can see color, or only light and dark. Design an experiment using sugar water, a blue card and cards in many shades of gray. Name what you change, what you keep the same and what you measure, and explain how you would know the bees really see blue.
10. HARD In three or four sentences, explain how a honeybee colony is like one body, even though it is made of thousands of separate bees.

COMMON MISTAKES

- Thinking the queen rules the hive. She lays the eggs and her scent holds the colony together, but she gives no orders; the workers' jobs are shared out by age and need.
- Thinking bees make honey from pollen. Honey is made from nectar, which the bees thicken by evaporating water. Pollen is the protein food for larvae.
- Thinking all bees live in hives. Most kinds of bees, such as many mason bees and leafcutter bees, live alone. Honeybees and bumblebees are among the few that live in colonies.

Make it a game · Waggle Dance Treasure Hunt. Choose a "sun": a lamp or a sign taped to one wall. One player hides a small treat in the room, then stands in the middle and "dances" by walking a short straight line while wiggling, pointing at the correct angle

from the direction of the sun, and making the run longer for farther hiding places. No pointing with hands or talking! The other players must find the treat from the dance alone. Take turns being the forager. For a harder round, dance on a vertical sheet of paper taped to the wall, where straight up stands for the sun.

Scripture. “More to be desired are they than gold, yea, than much fine gold: sweeter also than honey and the honeycomb.” (Psalm 19:10, KJV)

David compared God’s words to the sweetest thing he knew. Honey is the product of thousands of bees each doing her small part in order, and the comb that holds it is built with perfect thrift. Both show the care of the One who made them.

Practice answers

1. Queen (female), worker (female) and drone (male).
2. The angle tells the direction of the food compared with the direction of the sun. The length (how long the waggle run lasts) tells how far away the food is.
3. Honey is made from nectar. Pollen is protein food, mostly fed to the growing larvae.
4. Straight down stands for the direction opposite the sun, so the food is directly away from the sun.
5. 1,500 × 30 = 45,000 eggs. The first eggs become adult workers on about day 21 after they were laid.
6. (a) Building comb and storing food. (b) Days 22 to 42 is 21 days; 21 ÷ 42 = 1/2, so about half her life. (c) If many foragers are lost, younger bees can begin foraging early, so the jobs follow the hive’s needs, not a fixed clock.
7. (a) As the distance increases, the waggle run gets longer. (b) 1.7 s is halfway between 1.2 s and 2.2 s, so the food is about halfway between 1.0 and 2.0 km, about 1.5 km. (c) Not very safe: 6 s is far outside the measured data, so the pattern might change; we would be guessing beyond our data (extrapolating).
8. Of the three shapes that tile with no gaps, the hexagon encloses the most area for the least wall, so it saves wax. Circles enclose a little more area, but packed circles leave gaps between them, wasting space or needing extra wax to fill.
9. Sample answer: Put a dish of sugar water on a blue card among many gray cards of every shade from white to black, each with an empty dish. Let bees feed for a while so they learn to visit the blue card. Then switch to clean, empty dishes on every card (so there is no scent of sugar) and move the cards to new places. Count how many bees land on each card. Keep the dishes, card sizes and spacing the same. If the bees still go to the blue card and not to any gray of the same brightness, they must be seeing its color. (Von Frisch did this in 1914. Repeating it with red, bees confused red with dark gray, because bees cannot see red, though they can see ultraviolet.)
10. Sample answer: No single bee can survive alone for long, just as a single cell of the body cannot. Different bees do different jobs, like different organs: the queen makes new members, nurses feed the young, builders make the comb and foragers bring in food. Messages travel through the colony by dances and pheromones, somewhat like signals in a body. Together the colony keeps itself fed, warm and defended, and even reproduces by swarming.

6.2 Wolves: The Family Pack

OBJECTIVES

- Describe a wild wolf pack as a family led by a breeding pair, and explain how L. David Mech's observations corrected the older "alpha wolf" picture.
- Explain how wolves cooperate to raise pups, hunt large prey and hold a territory using howls, scent marks and body language.
- Calculate population density, predator-to-prey ratios and hunting success rates from wolf and moose data.

Warm-up. Make a quick list of every job it takes to keep your household running for one week: cooking, shopping, cleaning, caring for little ones, fixing things, earning money. Next to each job, write who usually does it. Could one person do all of them alone? Keep your list: in this lesson you will compare it with the jobs in a wolf family.

Video. Coming soon. Gray wolf pack family life, pups at the den, howling and the Isle Royale wolf and moose study; search National Park Service (Isle Royale and Yellowstone), Smithsonian, wildlife biologist talks by L. David Mech, nature footage of Arctic wolves, and Homeschool Pop (Alternate) or SciShow Kids for wolf basics.

KEY TERMS

pack
A group of wolves that live, travel and hunt together. Most wild packs are families: a mother, a father and their young of the last one to three years.

breeding pair
The mother and father wolf of a pack, the only wolves in most packs that have pups. Older books called them the "alpha" wolves.

territory
An area that an animal or group lives in and defends against others of its kind.

dispersal
When a young animal leaves the group it was born into to find a mate and a home of its own.

scent marking
Leaving urine or other scent on trees, rocks or snow as a message to other animals, such as "this territory is taken."

predator and prey
A predator is an animal that hunts and eats other animals; the animals it eats are its prey. Wolves are predators; moose, elk and deer are among their prey.

CORE IDEAS

The story. In the summer of 1986, the wildlife biologist L. David Mech traveled to Ellesmere Island in the far north of Canada, about 80° north latitude, where the summer sun never sets. There he found something few scientists had ever had: a pack of white Arctic wolves that had almost never seen people and were not afraid of him. He could sit a few meters from their den and watch for hours as the adults came and went and the pups tumbled over each other. He returned summer after summer. What he saw changed the way scientists described wolves.

How they figured it out. Earlier, in the 1940s, a Swiss scientist named Rudolph Schenkel had studied wolves in a zoo in Basel. Those wolves were unrelated adults put together in one pen, and they fought over rank. Schenkel called the top male and female the "alpha" wolves, and the word spread into books, including one Mech himself wrote in 1970. But in the wild, Mech saw that the "alpha" pair were simply the *mother and father*, and the rest of the pack were their own sons and daughters. Nobody fought to become the leader; the parents led because they were the parents. In 1999 Mech published a paper explaining the mistake, and he has spent years asking people to stop using the old picture. It is a good lesson in science: watch animals in their natural setting before drawing conclusions, and be willing to correct even your own earlier work.

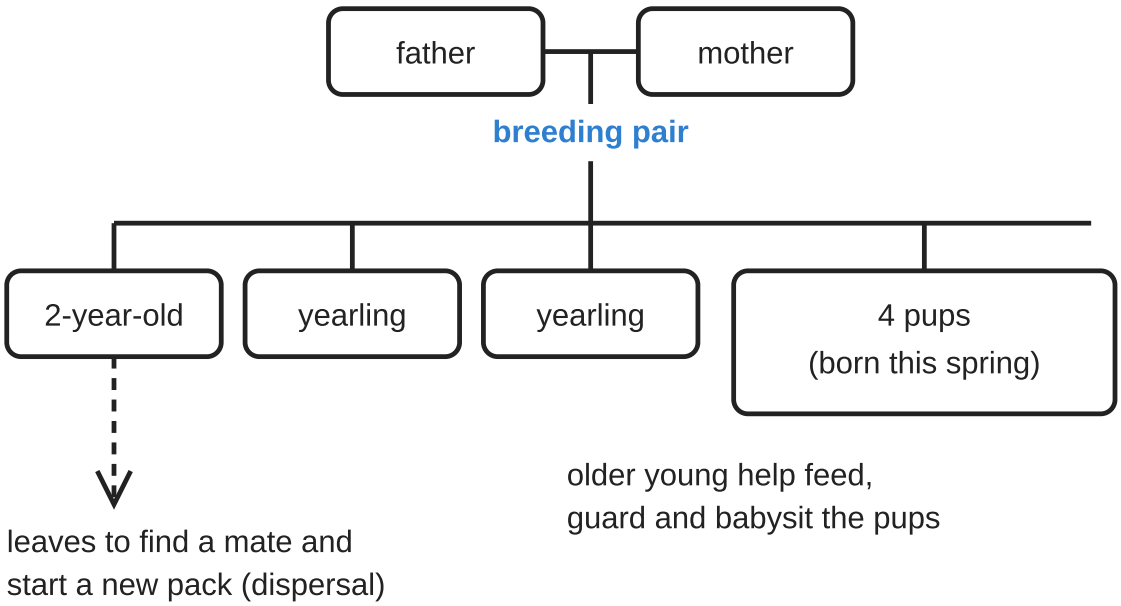
The big idea. A wild wolf **pack** is a family. The **breeding pair** usually has one litter a year, often four to six pups, born blind and deaf in a den in spring. The whole family helps raise them. Yearlings and older brothers and sisters bring meat home in their stomachs and bring it back up for the pups, and they babysit while the parents hunt. When young wolves are one to three years old, most leave in **dispersal**, sometimes traveling hundreds of kilometers to find a mate and an empty territory and start a family of their own. Most packs have about five to ten wolves, though some grow larger.

Working together. Wolves hunt prey much larger than themselves. A gray wolf weighs about 30 to 60 kilograms, while an adult moose can weigh 400 kilograms or more. A single wolf could rarely bring one down, but a family working together can. They trot for hours across their range, test herds by chasing them, and look for an animal that is young, old, sick or stuck in deep snow. Most chases fail, and a healthy moose that stands its ground is usually left alone. Wolves also hold a **territory**, often hundreds of square kilometers, and they guard it with signals. A howl can carry up to about 10 kilometers on a still night; it gathers scattered family members and warns other packs away. **Scent marks** along trails and at the edges of the territory say the same thing in smell. Within the pack, tails, ears and faces carry messages: a raised tail and steady stare show confidence, while a low tail and licking at a parent's mouth say "I am your youngster."

In the world today. On Isle Royale, an island in Lake Superior, wolves crossed an ice bridge from Canada in the late 1940s. In 1958 Durward Allen of Purdue University began counting the wolves and moose there each winter from a small airplane, with young David Mech as his first student. The study has gone on ever since, the longest-running study of a predator and

its prey in the world. It shows how the numbers of wolves and moose rise and fall, each affected by the other and by hard winters, disease and food.

God's handiwork. The dog asleep on your floor and the wolf on Ellesmere Island are the same kind of animal. They can interbreed, and every breed from the tiny Chihuahua to the Great Dane came from that one kind by variation. Genesis says God made "the beast of the earth after his kind" (Genesis 1:25), and in the wolf family we see one of His gifts to that kind: a home where the young are fed, guarded and taught by their own parents.



A typical wild wolf pack is a family: the breeding pair and their young of the last few years.

PICTURE STUDY



White American Wolf, from The Viviparous Quadrupeds of North America, John James Audubon and his son John Woodhouse Audubon (lithograph printed by J. T. Bowen), 1845–1848 (published in parts) · Hand-colored lithograph · Prints of the plates are in many libraries and museums, including the Library of Congress.

Photo: Free Public Domain Illustrations by rawpixel · CC BY 2.0 (https://creativecommons.org/licenses/by/2.0) · via Wikimedia Commons

After finishing *The Birds of America*, John James Audubon began a second great book on the mammals of North America, working with his sons and with the naturalist and Lutheran minister John Bachman, who wrote most of the text. Audubon's eyesight failed before the work was done, and his son John Woodhouse Audubon painted many of the later animals. The plates were printed as lithographs in Philadelphia and colored by hand.

In the 1840s, wolves still roamed most of North America, and the pale wolves of the northern plains and the far north were called "white wolves." As you look, ask which features of this animal would help it travel far and hunt with its family in the cold.

Look closely

- Study the coat. How thick does it look? What color is it, and where might that color be useful?
- Look at the legs and feet. Are they long or short compared with the body? Why would long legs help a wolf that trots for hours?
- Find the ears, eyes and nose. Which senses do you think a wolf depends on most?
- What has the artist put in the background? Does the setting help tell where this wolf lives?

Talk about it

1. Audubon showed one wolf alone. How would you change the picture to show what you now know about wolf packs?
2. Why do you think artists of Audubon's time worked from specimens, while scientists like Mech watched living animals for years?

> **Safety first.** Never approach a wild wolf, coyote, fox or an unfamiliar dog, and never feed wild animals. In the project, sniff only the vanilla and water samples your parent prepares, and waft the smell toward your nose with your hand instead of sniffing hard.

EXPERIMENT: HOW LONG DOES A SCENT MARK LAST?

Wolves "write" messages in scent at the edges of their territory. A message is only useful if it lasts long enough for a neighbor to find it. In this experiment you will make scent marks with vanilla extract and test how long a sniffer can still detect them.

You will need

- Vanilla extract and plain water
- Eight cotton balls and eight small paper cups, numbered on the bottom
- Dropper or measuring spoon
- A clock or timer
- A family member to be the "sniffer" and one to be the "marker"
- Lab notebook

Steps

1. **Question:** How many hours does a scent mark of vanilla stay strong enough to detect? Write the question in your notebook.
2. **Prediction:** Write how many hours you think it will last, and whether a mark kept outdoors will fade faster or slower than one kept indoors.
3. **Variables:** What you change is the time since marking (and, for a second test, indoors versus outdoors). What you keep the same is the amount of vanilla (5 drops), the kind of cotton ball and cup, and the sniffer. What you measure is the smell strength rating.
4. The marker puts 5 drops of vanilla on each of four cotton balls and 5 drops of plain water on four more (the controls). Place one vanilla ball and one water ball in each cup. Set two pairs on a windowsill indoors and two pairs outside in a sheltered spot.
5. At 0, 1, 3, 6 and 24 hours, the sniffer, without knowing which cup is which, wafts each cup and rates it: 0 = no smell, 1 = faint, 2 = clear, 3 = strong.
6. Record the ratings in a table with columns: Time (hours), Indoor vanilla, Indoor water, Outdoor vanilla, Outdoor water.
7. Draw a line graph with time on the x-axis and smell rating on the y-axis, one line for indoor vanilla and one for outdoor vanilla.
8. **Conclusion:** How long did the mark last? Did wind, sun or temperature seem to matter? Why might a wolf need to renew its marks often?

Tips

- The water cups are the control. If the sniffer rates a water cup above 0, the test is not blind enough: shuffle the cups so the sniffer cannot guess.
- A wolf's nose is far more sensitive than yours, so real scent marks last much longer for wolves than vanilla does for you. Your experiment shows the *pattern* of fading, not the wolf's exact time.

Check your work

- I used the same amount of vanilla on every mark and included water controls.
- My sniffer did not know which cup was which.
- My graph shows how the smell rating changed over time, and I explained what the result means for scent marking.

NATURE NOTEBOOK

1. Draw the wolf family tree from the lesson, then add a short note beside each wolf telling one job it does for the pack.
2. Draw three sketches of a dog or wolf showing three different moods using only the tail, ears and posture: confident, playful and afraid. Label each part that carries a message.
3. If you have a dog, watch it for 10 minutes. Record every signal it gives (tail, ears, sounds, sniffing or marking) and what you think each one means.

> **From history.** Isle Royale was chosen as a natural laboratory because it is an island about 70 kilometers long in Lake Superior, with only one large predator (the wolf) and one main large prey animal (the moose). Moose probably swam or crossed the ice to the island in the early 1900s, and wolves arrived across an ice bridge from Ontario in the late 1940s. When Durward Allen began the winter counts in 1958, he expected the study to last about ten years. Instead it has continued for more than six decades, and when the wolves dwindled to only two in the late 2010s, the National Park Service brought new wolves to the island from Minnesota and Ontario.

WORKED EXAMPLES

Example 1. A pack of 6 wolves holds a territory of 300 km². How many square kilometers are there per wolf? What is the wolf density in wolves per 1,000 km²?

1. Area per wolf = 300 km² ÷ 6 wolves = 50 km² per wolf.
2. Density = wolves ÷ area = 6 ÷ 300 km² = 0.02 wolves per km².
3. Per 1,000 km²: 0.02 × 1,000 = 20 wolves.

Answer: 50 km² per wolf, or a density of 20 wolves per 1,000 km².

Example 2. Here are simplified counts for an island like Isle Royale. Year A: 25 wolves and 1,000 moose. Year B: 50 wolves and 700 moose. Find the number of moose per wolf in each year. In which year was each wolf’s food supply tighter?

1. Year A: 1,000 moose ÷ 25 wolves = 40 moose per wolf.
2. Year B: 700 moose ÷ 50 wolves = 14 moose per wolf.
3. Fewer moose per wolf means less food for each wolf.

Answer: Year A: 40 moose per wolf; Year B: 14 moose per wolf. Food was much tighter in Year B, so we might expect the wolf numbers to fall in the years after.

Example 3. Suppose a team watching from an airplane saw a wolf pack test 120 moose over one winter and kill 9 of them. What was the success rate as a percent? About how many moose did the pack have to test for each one it caught?

1. Success rate = 9 ÷ 120 = 0.075.
2. As a percent: 0.075 × 100 = 7.5%.
3. Moose tested per kill = 120 ÷ 9 ≈ 13.3.

Answer: A success rate of 7.5%; the pack tested about 13 moose for every one it caught. Most chases fail, which is why wolves cover so much ground.

PRACTICE

1. EASY Who are the members of a typical wild wolf pack?
2. EASY Name three ways wolves send messages to each other or to other packs.
3. EASY What is dispersal, and why is it important for wolves?
4. MEDIUM Why did Rudolph Schenkel’s zoo wolves give a wrong picture of wild packs?
5. MEDIUM A territory is 800 km² and holds a pack of 10 wolves. Find the area per wolf and the density in wolves per 1,000 km².
6. MEDIUM **Data reading.** Simplified island counts: Year 1: 20 wolves, 1,200 moose. Year 3: 30 wolves, 1,100 moose. Year 5: 45 wolves, 800 moose. Year 7: 25 wolves, 750 moose. Year 9: 18 wolves, 1,000 moose. (a) In which year were wolves most numerous? (b) What happened to the moose while the wolves were increasing? (c) What happened to the wolves after the moose fell? (d) Give one reason other than wolves that could make moose numbers drop.
7. HARD **Data reading.** In a made-up study, researchers recorded how many pups survived to 1 year old in packs with different numbers of helpers (older offspring): 0 helpers, 1.5 pups per litter; 2 helpers, 2.5 pups; 4 helpers, 3.5 pups; 6 helpers, 3.6 pups. (a) Describe the trend. (b) Does adding helpers keep making the same difference? (c) Suggest one reason helpers might raise pup survival.

8. MEDIUM Wolves often chase a herd and then single out one animal. Which animals are they most likely to catch, and why?
9. CHALLENGE **Experiment design.** Design an experiment to find out whether a pet dog can tell its own family's scent from a stranger's scent. Name what you change, what you keep the same, what you measure and your control.
10. HARD In three or four sentences, explain how Mech's Ellesmere Island work shows a good habit of scientists.

COMMON MISTAKES

- Thinking a pack is a gang of unrelated wolves that fight to become "alpha." Wild packs are families, and the parents lead.
- Thinking wolves howl at the moon. Wolves howl to gather the family and to warn other packs away. They point their noses up because the sound carries farther, and they howl on moonless nights too.
- Thinking predators always win. Most wolf hunts fail, and wolves usually catch the weak, young, old or sick.

Make it a game · Pack Signals Charades. Write wolf messages on slips of paper: "I am your pup, please feed me," "Danger, gather close," "Let's play," "This is our territory," "I am the confident parent," "Come home, the hunt is over." Players take turns drawing a slip and acting it out using only tail (a scarf tucked in a belt), ears (hands on head), posture, face and wolf sounds, no words. The first player to guess the message scores a point. Bonus point for naming the real signal a wolf would use.

Scripture. "The wolf also shall dwell with the lamb, and the leopard shall lie down with the kid; and the calf and the young lion and the fatling together; and a little child shall lead them." (Isaiah 11:6, KJV)

In this world wolves are hunters, and the shepherds of the Bible guarded their flocks against them. Isaiah looks ahead to the peace of the Messiah's kingdom, when even the wolf and the lamb will be at rest together. Wolves remind us both of the order God built into nature now and of the peace He has promised.

Practice answers

1. A mother and father (the breeding pair) and their offspring of the past one to three years: this year's pups and older brothers and sisters.
2. Any three: howling, scent marking, body language (tail, ears, posture, face), growls, whimpers or barks.
3. Dispersal is when a young wolf leaves its family to find a mate and a territory of its own. It is how new packs are started and how wolves spread to new areas.
4. His zoo wolves were unrelated adults forced together in a pen, so they fought over rank. In the wild, packs are families, and the parents lead naturally without fighting for the top place.
5. 800 ÷ 10 = 80 km² per wolf. Density = 10 ÷ 800 = 0.0125 per km², which is 12.5 wolves per 1,000 km².

6. (a) Year 5 (45 wolves). (b) The moose went down, from 1,200 to 800. (c) The wolves fell, from 45 to 25 and then 18, because there was less food. (d) Any reasonable answer: a very hard winter with deep snow, a shortage of food plants, ticks or disease.
7. (a) More helpers, more surviving pups. (b) No: from 0 to 4 helpers survival rises by about 0.5 pup for every 2 helpers, but from 4 to 6 helpers it barely changes (3.5 to 3.6), so the benefit levels off. (c) Helpers bring food to the den, babysit and guard the pups while the parents hunt.
8. Young, old, sick or injured animals, or animals floundering in deep snow, because they are slower or weaker. A healthy adult moose that stands its ground is usually too dangerous to attack.
9. Sample answer: Rub three clean cotton cloths: one on a family member’s hand, one on a visitor’s hand (with permission) and one left unrubbed (the control). Place each cloth in an identical box with holes, in random order, and let the dog sniff. Change only whose scent is on the cloth. Keep the boxes, cloth size, rubbing time and room the same. Measure the number of seconds the dog spends sniffing each box. Repeat on several days, shuffling positions. If the dog spends clearly different time on the family cloth than on the stranger’s, and little time on the blank, it can tell them apart.
10. Sample answer: Mech watched wild wolves living naturally for many summers instead of relying on zoo animals in an unnatural group. What he saw did not fit the “alpha” idea, even though he had used it himself. He published a correction and urged others to drop the old picture. Good scientists test ideas against careful observation and are willing to change their minds when the evidence shows they were wrong.

6.3 Elephants: The Matriarch's Memory

OBJECTIVES

- Describe an elephant family unit led by a matriarch, and explain how Cynthia Moss and Karen McComb showed that an older matriarch's knowledge helps her family survive.
- Explain how elephants communicate with low rumbles, including infrasound below the range of human hearing.
- Calculate elephant food needs, mass ratios and the travel time and wavelength of low sounds using metric units.

Warm-up. Ask the oldest person in your family two questions: "What is something you know from experience that I don't know yet?" and "Was there ever a time when remembering something from long ago helped you?" Write down their answers. Then put your hand flat on a table while someone taps the far end gently with a spoon. Can you feel it as well as hear it?

Video. Coming soon. African elephant families, matriarchs and low-frequency rumbles; search Smithsonian, Amboseli Trust for Elephants talks by Cynthia Moss, Cornell Lab of Ornithology Elephant Listening Project (Katy Payne), nature footage of Amboseli elephants, and Homeschool Pop (Alternate) or SciShow Kids for elephant basics.

KEY TERMS

matriarch
The female leader of an elephant family, usually the oldest and most experienced female.

family unit
A close group of related female elephants (mothers, daughters, sisters and aunts) and their young, who live and travel together.

bull
An adult male elephant. Young males leave their family when they are about 12 to 15 years old and live on their own or in loose groups of males.

allomother
A family member other than the mother, often a young female, who helps care for a calf.

infrasound
Sound with a frequency below 20 hertz (20 vibrations per second), too low for people to hear. Elephants use it in their rumbles.

playback experiment
An experiment in which scientists play recorded animal sounds through a loudspeaker and watch how wild animals respond.

CORE IDEAS

The story. In 1972, an American writer named Cynthia Moss set up a small tent camp in Amboseli National Park in Kenya, in the shadow of Mount Kilimanjaro. She began to learn the elephants one by one. No two elephants have the same ears: each has its own pattern of notches, holes and tears around the edge, and its own tusk shape. Moss photographed every elephant, gave each family a letter code and each elephant a name, and kept careful records of births, deaths and who traveled with whom. One family, the EB family, was led by a matriarch named Echo, whom Moss watched from 1973 until Echo died in 2009. The study Moss began, the Amboseli Elephant Research Project, has now followed more than three thousand elephants and is the longest study of wild elephants in the world.

How they figured it out. Moss's long records let other scientists ask sharp questions. In the 1990s, Karen McComb of the University of Sussex, working with Moss, recorded the "contact calls" of many Amboseli families. Then she did a **playback experiment**: she hid a loudspeaker and played a call to a family resting in the open. Sometimes it was the voice of a family they met often; sometimes it was the voice of a family they rarely or never met. If the elephants felt threatened, they bunched together around the calves. McComb found, in a study published in 2001, that families led by *older* matriarchs were better at telling friends from strangers. They stayed calm for familiar voices and bunched up only for strangers, while families with younger matriarchs often got upset for nothing. Those families with older matriarchs also raised more calves. The matriarch's long memory was a treasure for her whole family.

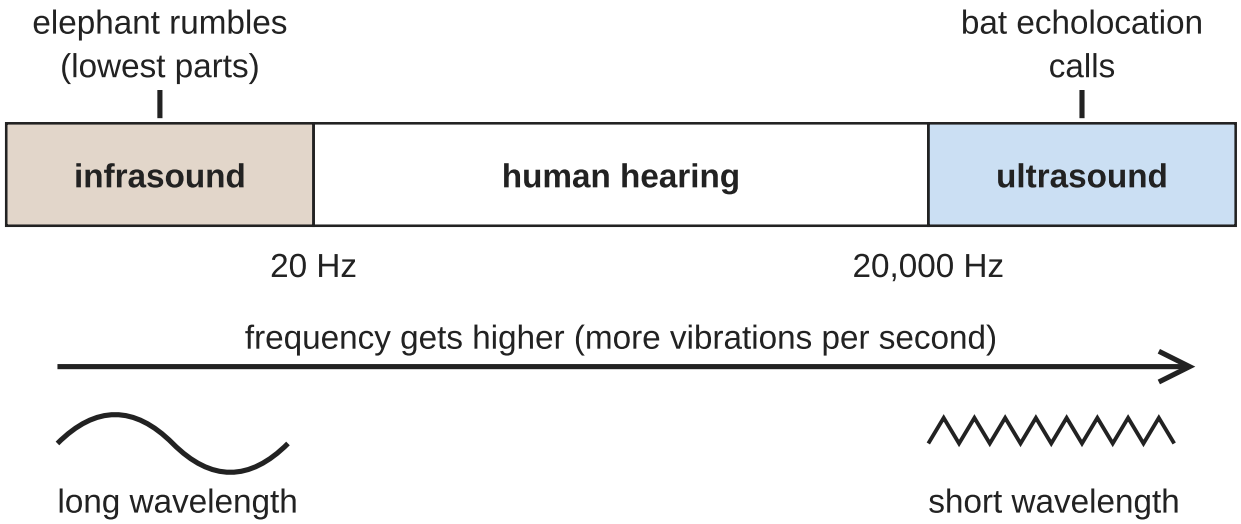
The big idea. An elephant **family unit** is made of related females and their young, often about ten elephants, led by a **matriarch**, usually the oldest female. She decides when to move, leads the way to water and food, and leads the defense against lions. Young females are **allomothers**: they babysit, rescue a calf stuck in mud and stand close when danger comes. A calf weighs about 100 kilograms at birth, after a pregnancy of about 22 months, the longest of any land animal. Young males leave their families in their early teens and grow into **bulls** that roam more widely. The family keeps in touch with other related families nearby, and greetings between them can be noisy celebrations of rumbles, trumpets and flapping ears.

Hearing what we cannot hear. In 1984 the biologist Katy Payne stood beside the elephant pens at a zoo in Portland, Oregon, and felt a throbbing in the air, like the deep notes of a pipe organ, though she heard almost nothing. She suspected the elephants were calling below the range of human hearing. With recording equipment she proved it: many elephant rumbles include **infrasound**, below 20 hertz. Low sounds have long wavelengths and lose less energy as they travel, so on a calm evening a rumble can carry several kilometers. Elephants may also feel rumbles through the ground with their sensitive feet and trunks. Families spread out across the savanna can keep in touch over distances where they cannot see one another.

Built for the work. An African savanna elephant is the largest land animal. An adult female weighs about 3,000 kilograms, and a big bull twice that or more. To fuel that body, an

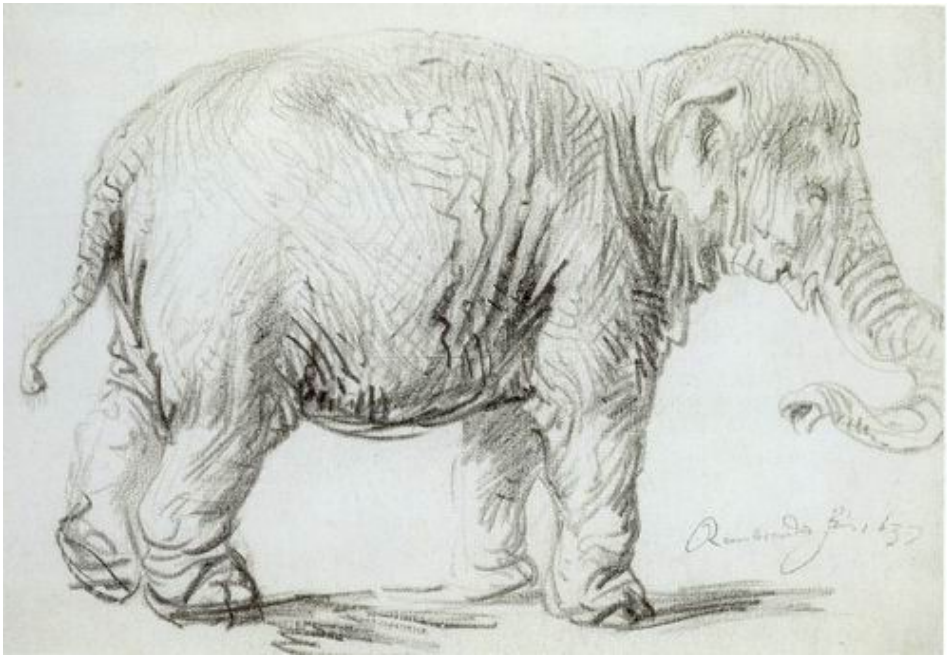
elephant eats around 150 kilograms of grass, leaves, bark and fruit a day and drinks 100 liters of water or more. Its trunk, a nose and upper lip joined together, has tens of thousands of small muscle bundles and no bones; it can pull up a small tree or pick up a single peanut. Elephants can live 60 years or more, which gives an old matriarch decades of experience to draw on.

God's handiwork. In elephant families, the oldest members are not left behind; they are the leaders, because they remember droughts, dangers and distant water holes that the young have never seen. Job said, "With the ancient is wisdom; and in length of days understanding" (Job 12:12). The elephants show us a picture of a truth God built into families: experience gathered over a long life is a gift to the young.



Sounds too low for us (infrasound) and too high for us (ultrasound). Elephants use the low end; bats, from Unit 3, use the high end. (Not to scale.)

PICTURE STUDY



An Elephant (Hansken), Rembrandt van Rijn, 1637 · Black chalk on paper · Albertina, Vienna

In the 1630s a young female Asian elephant named Hansken was brought from Ceylon to the Netherlands and toured the cities of Europe, where crowds paid to watch her do tricks. Most Dutch people had never seen an elephant. The great Dutch painter Rembrandt van Rijn saw her in Amsterdam and drew her several times in black chalk. He was fascinated by her wrinkled skin and her great weight.

Rembrandt was not making a scientific plate, but he drew like a naturalist: from life, with close attention to how her body really looked. Compare his drawing with the African elephants of Amboseli. Hansken was an Asian elephant, a different kind, with smaller ears and a rounder back.

Look closely

- Look at the skin. How did Rembrandt show wrinkles and folds with only chalk lines?
- Find the trunk. What is it doing? Does it look stiff or flexible?
- Find the ear. Is it large or small compared with the head? How would an African elephant’s ear be different?
- Where are the darkest lines in the drawing? How do they make the elephant look heavy?

Talk about it

1. Hansken lived her whole life away from other elephants. From what you learned in this lesson, what did she miss?
2. Why might a quick drawing from life teach a scientist more than a careful copy of another artist’s picture?

EXPERIMENT: CAN YOU FEEL IT? SOUND THROUGH THE FLOOR AND THROUGH THE AIR

Elephants may sense rumbles through the ground as well as through the air. In this experiment you will test whether a gentle tap is easier to detect through a solid floor or through the air, at different distances.

You will need

- A long hard floor (wood, tile or concrete), a long hallway or a long table
- A metal spoon
- Meter stick or tape measure and masking tape
- A blindfold or a sleep mask
- A partner
- Lab notebook

Steps

1. **Question:** Is a gentle tap easier to detect through a solid floor or through the air? Write the question.
2. **Prediction:** Write which you think will work better at long distances, and why.
3. **Variables:** What you change is how the listener receives the sound (ear pressed to the floor, or sitting up with head in the air) and the distance. What you keep the same is the spoon, the tapper and how hard each tap is. What you measure is how many of 10 taps the listener detects.
4. Mark distances of 1, 2, 4 and 6 meters from the listener’s spot with masking tape.
5. The listener wears the blindfold and lies with one ear pressed to the floor. At each distance the tapper gives 10 gentle taps, each the same small drop of the spoon (for example, lifting it 2 cm and letting it fall), with random pauses so the listener cannot guess the rhythm. The listener raises a hand each time a tap is detected. Record the count.
6. Repeat with the listener sitting up, head in the air, at the same distances.
7. Record a table with columns: Distance (m), Taps detected with ear on floor (out of 10), Taps detected with head in air (out of 10). Make a double bar graph.
8. **Conclusion:** Which way detected more taps at the longest distance? How might an elephant use the ground to stay in touch with its family?

Tips

- Keep the house quiet and do the two conditions in the same session so the background noise is the same.
- Make the taps very gentle; a loud tap will be heard either way and the test will not show a difference.
- Swap jobs and repeat so you have two listeners. Do the results agree?

Check your work

- I kept the taps the same strength and changed only the listening position and distance.
- My table and double bar graph show the counts for both conditions at every distance.
- I explained my result and connected it to how elephants sense rumbles.

NATURE NOTEBOOK

1. Draw the outline of an elephant's ear and invent a pattern of notches and holes. Then draw a second ear with a different pattern. Explain how Moss used ear patterns to tell elephants apart.
2. Make a family chart for an imaginary elephant family: a matriarch, her two grown daughters, their calves and one teenage male about to leave. Write each elephant's name and age.
3. Draw a side-by-side comparison of an African and an Asian elephant. Label at least three differences, such as ear size and shape, back shape and head shape.

> **From history.** Katy Payne had spent years recording the songs of humpback whales with her husband, Roger Payne, before she turned to elephants. After her discovery at the Portland zoo in 1984, she took recording equipment to Amboseli to work alongside Cynthia Moss's team, and later to Namibia, and showed that wild elephants use infrasound to keep in touch over long distances. Her work grew into the Elephant Listening Project at Cornell University, which uses hidden recorders in the forests of central Africa to count forest elephants by their calls, since they are hard to see in thick trees.

WORKED EXAMPLES

Example 1. An elephant mother has a mass of 3,000 kg, and her newborn calf has a mass of 100 kg. A human mother has a mass of 60 kg, and her newborn baby has a mass of 3.4 kg. For each, what percent of the mother's mass is the newborn?

1. Elephant: 100 ÷ 3,000 = 0.033, which is about 3.3%.
2. Human: 3.4 ÷ 60 = 0.057, which is about 5.7%.
3. Compare: 5.7 ÷ 3.3 ≈ 1.7.

Answer: The elephant calf is about 3.3% of its mother's mass; the human baby is about 5.7%. Compared with its mother, a human baby is about 1.7 times as heavy as an elephant calf, even though the calf is about 30 times heavier in kilograms.

Example 2. An adult female elephant of 3,000 kg eats about 150 kg of plants a day. What percent of her body mass does she eat each day? How many kilograms does she eat in one year (365 days)? Give the answer in metric tonnes (1 tonne = 1,000 kg).

1. Percent per day: 150 ÷ 3,000 = 0.05, which is 5%.
2. Food per year: 150 kg × 365 = 54,750 kg.
3. In tonnes: 54,750 ÷ 1,000 = 54.75 tonnes, about 55 tonnes.

Answer: She eats 5% of her body mass a day, about 54,750 kg (about 55 tonnes) of plants in a year, more than 18 times her own mass.

Example 3. Sound travels through air at about 343 meters per second. (a) How long does an elephant's rumble take to reach a family 5 km away? (b) The wavelength of a sound equals its speed divided by its frequency. Find the wavelength of a 15 Hz rumble and of a 200 Hz human voice.

1. (a) 5 km = 5,000 m. Time = 5,000 m ÷ 343 m/s ≈ 14.6 s.
2. (b) Rumble: 343 ÷ 15 ≈ 22.9 m.
3. Human voice: 343 ÷ 200 ≈ 1.7 m.

Answer: (a) About 15 seconds. (b) The rumble's wavelength is about 23 m, about as long as three or four elephants standing trunk to tail; the human voice's is about 1.7 m. Long waves pass around trees and hills and fade more slowly, which helps rumbles travel far.

PRACTICE

1. EASY Who leads an elephant family unit, and who are its members?
2. EASY What is infrasound? Can people hear it?
3. EASY How did Cynthia Moss tell individual elephants apart?
4. MEDIUM An elephant drinks 150 liters of water a day. How many liters is that in a 30-day month? A bathtub holds about 150 liters; how many bathtubs is that?
5. MEDIUM A rumble travels 8 km at 343 m/s. How long does it take, to the nearest second?
6. MEDIUM **Data reading.** Made-up results patterned after the 2001 Amboseli study: when a familiar family's call was played, the percent of trials in which the family wrongly bunched up in alarm was: matriarch age 20 years, 60%; age 35 years, 35%; age 50 years, 15%; age 60 years, 10%. (a) Describe the trend. (b) Which family wasted the most time and energy on false alarms? (c) Why might false alarms be costly for an elephant family?
7. HARD **Data reading.** A student recorded how many of 10 gentle taps were detected in the floor experiment: 1 m, floor 10, air 10; 2 m, floor 10, air 8; 4 m, floor 9, air 4; 6 m, floor 7, air 1. (a) At which distance did the two methods first differ? (b) At 6 m, how

many times more taps were detected through the floor than through the air? (c) Write a one-sentence conclusion.

8. MEDIUM Why do young male elephants leave their families? What do they become?
9. CHALLENGE **Experiment design.** You want to know whether elephants recognize the voice of a family member that has been away for a long time. Design a playback experiment. Include what you change, what you keep the same, what you measure and a control.
10. HARD In three or four sentences, explain why an older matriarch is valuable to her family. Use evidence from the lesson.

COMMON MISTAKES

- Thinking the biggest bull leads the herd. Elephant families are led by an old female, the matriarch; adult bulls live apart.
- Thinking elephants drink through their trunks like a straw. An elephant sucks water partway up its trunk, then curls the trunk and squirts the water into its mouth.
- Thinking infrasound is silence or something mysterious. It is ordinary sound, just lower than human ears can hear, and it is measured with microphones like any other sound.

Make it a game · Matriarch, Lead Us Home. Hide five “water holes” (cups or paper circles) around the house or yard. Only the oldest player (the matriarch) is shown where they are. The rest of the family must follow the matriarch with eyes closed or looking only at the ground, guided only by low hums (“rumbles”) and gentle touches on the shoulder, no words. Count how many water holes the family reaches in three minutes. Then let a younger player who has *not* seen the hiding places try to lead. Which family found more water?

Scripture. “With the ancient is wisdom; and in length of days understanding.” (Job 12:12, KJV)

Job knew that long experience brings understanding. An elephant family that follows its oldest member finds water in drought and safety from danger. God means for the young to learn from the old, in families of people as well as of elephants.

Practice answers

1. The matriarch, usually the oldest female, leads. The members are related females (her daughters, sisters, nieces and granddaughters) and their young calves.
2. Sound below 20 hertz (20 vibrations per second). It is too low for people to hear, though very strong infrasound can sometimes be felt.
3. By the patterns of notches, holes and tears in their ears and by the shape of their tusks, recorded in photographs.
4. 150 × 30 = 4,500 liters, which is 4,500 ÷ 150 = 30 bathtubs.
5. 8,000 ÷ 343 ≈ 23.3, about 23 seconds.
6. (a) The older the matriarch, the fewer false alarms. (b) The family with the 20-year-old matriarch (60% of trials). (c) Every false alarm stops feeding and resting, uses energy and stresses the calves; over a year that can mean less food and fewer healthy calves.

7. (a) At 2 m (10 versus 8). (b) 7 ÷ 1 = 7 times as many. (c) Gentle taps were detected much better through the solid floor than through the air, and the difference grew with distance.
8. As they grow into their teens they become more independent and are gradually pushed out by the family; leaving also keeps them from mating with close relatives. They become bulls that live alone or in loose groups of males and visit families only for a time.
9. Sample answer: Record the contact calls of several elephants. Play each family two kinds of calls from a hidden speaker: a call from their own absent relative and a call from an unrelated elephant of similar age (the control). Change only whose voice is played. Keep the volume, distance to the speaker, time of day and length of call the same, and play the calls in random order on different days. Measure responses such as whether the elephants answer with rumbles, raise their heads and ears, or walk toward the speaker, and how quickly. If they respond much more strongly to the relative, they recognize the voice.
10. Sample answer: An older matriarch has decades of memories of friends, enemies, water holes and dangers. McComb’s playback study showed that families with older matriarchs told familiar and strange voices apart better, so they had fewer false alarms. Those families also raised more calves. Her experience guides the family to food and water and keeps them safe without wasting energy.

6.4 Ants That Farm: Leafcutters and Their Gardens

OBJECTIVES

- Tell how Thomas Belt discovered that leafcutter ants do not eat leaves but use them to grow a fungus garden, and describe the jobs of the different worker sizes.
- Explain mutualism using leafcutter ants and their fungus, and ants that tend aphids for honeydew.
- Calculate load ratios, travel times and traffic rates from ant data, and design a fair test of ant food choices.

Warm-up. Put a few crumbs of bread on a plate and leave it on a windowsill or porch step for a day if your parent allows. Meanwhile, think: if you had to grow all your food in a dark basement with no sunlight, what could you grow? Write your answer. (Hint: think of what grows on old bread, or what grows in the dark at a mushroom farm.)

Video. Coming soon. Leafcutter ant fungus gardens, worker sizes and trails, plus ants tending aphids; search Smithsonian and American Museum of Natural History clips, natural history museum channels, university entomology channels, nature footage of rain forest ants, and Homeschool Pop (Alternate) or SciShow Kids for ant basics.

KEY TERMS

fungus
A living thing, such as a mushroom, mold or yeast, that cannot make its own food from sunlight and instead feeds by breaking down other material. Plural: fungi.

fungus garden
A spongy mass of chewed leaves inside a leafcutter ant nest, on which the ants grow the fungus they eat.

mutualism
A partnership between two different kinds of living things in which both are helped, like leafcutter ants and their fungus, or ants and aphids.

honeydew
The sugary liquid that aphids and some other sap-sucking insects give off. Many ants collect it as food.

mating flight
The flight in which winged young queens and males leave the nest to mate. Afterward each new queen sheds her wings and tries to start a colony.

antibiotic
A substance made by one living thing that kills or stops the growth of germs such as bacteria or harmful molds.

CORE IDEAS

The story. From 1868 to 1872, an English mining engineer named Thomas Belt managed gold mines at Chontales in Nicaragua. In his spare hours he was a keen naturalist, and he could not stop watching the leafcutter ants. Day and night, long columns of reddish ants marched along cleared trails, each carrying a piece of leaf held high over its head like a green flag. They stripped whole trees and even raided gardens. Everyone assumed they ate the leaves. Belt was not so sure. In 1874 he published his book *The Naturalist in Nicaragua*, and in it he made a bold suggestion: the ants were not leaf eaters at all, but farmers.

How they figured it out. Belt dug into the nests. Deep underground he found chambers filled with a gray, spongy mass made of chewed-up leaf pieces, threaded through with a fine white fungus. He never saw the ants eat the leaves, and he found their young lying among the fungus. The naturalist Henry Walter Bates had guessed the leaves were used to thatch the nest. Belt reasoned instead that the ants used the leaves as compost to grow their food, and that the fungus was their real crop. In 1893 Alfred Möller, working in southern Brazil, proved it: he grew the fungus himself and showed that it forms tiny swollen tips, like little knobs of food, which the ants harvest and eat. Belt had been right.

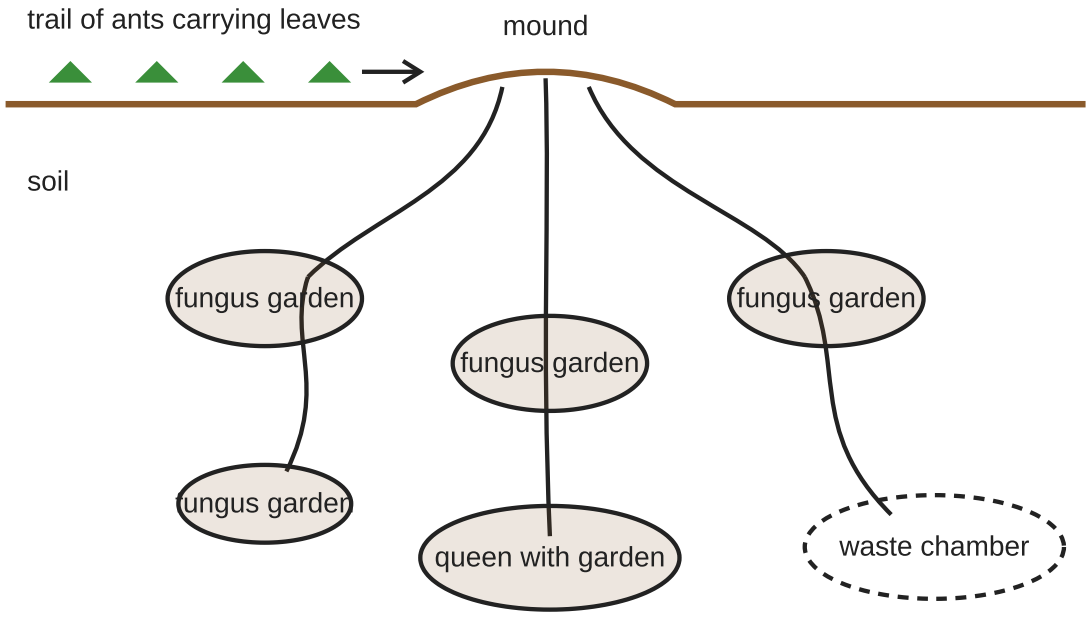
The big idea. Leafcutter ants practice true farming. Workers cut leaves and carry them home; smaller workers lick them clean, chew them into pulp and plant bits of fungus on them in the **fungus garden**; the tiniest workers tend the garden and pull out invading molds; and still other workers carry old, used material away to a separate waste chamber. The workers come in very different sizes, each fitted to its job. The smallest tend the garden and even ride on the leaves carried by larger sisters, guarding them against tiny parasite flies. Middle-sized workers cut and carry. The largest workers, with huge heads and jaws, defend the colony. A big colony can have millions of workers, all daughters of one queen. Both partners gain: the fungus is fed, protected and spread, and the ants get food. That is **mutualism**. Ants even fight crop disease. In 1999 the scientist Cameron Currie and his team showed that leafcutters carry helpful bacteria on their bodies that make an **antibiotic** against a mold that attacks their gardens.

Seed, herd and harvest. When a young queen leaves on her **mating flight**, she carries a small pellet of the fungus in a pocket inside her mouth. After mating, she digs a new nest, spits out the pellet and starts a fresh garden, tending it herself until her first daughters grow up. Other ants are herders. Many kinds guard aphids, small sap-sucking insects, protecting them from ladybugs and other enemies and stroking them with their antennae to collect sweet **honeydew**. Some even carry aphid eggs into their nests for the winter and set the young aphids back on plant roots in spring. Still others, the harvester ants of dry lands, gather seeds and store them in underground granaries.

In the world today. Leafcutter ants are among the most important plant eaters of the American tropics; a single large colony can cut a great deal of leaf material in a year, which makes them a pest on farms but also a great recycler in the forest. Scientists study the ants' antibiotic bacteria for clues to new medicines. Several zoos and science museums, including

the American Museum of Natural History in New York, keep living leafcutter colonies behind glass so visitors can watch the trails and gardens.

God's handiwork. Solomon wrote, "Go to the ant, thou sluggard; consider her ways, and be wise" (Proverbs 6:6), and he noticed that the ant works with "no guide, overseer, or ruler." Science agrees: the queen gives no orders, yet millions of workers plant, weed, harvest and defend in good order. Each ant follows the simple ways God built into her, and together they keep a garden underground.



Inside a leafcutter nest: leaves come in from the trail, are turned into fungus gardens, and used material goes to a separate waste chamber. (Simplified, not to scale; big nests have hundreds of chambers.)

PICTURE STUDY



Spiders, Ants and a Hummingbird on a Guava Branch (Plate 18, Metamorphosis insectorum Surinamensium), Maria Sibylla Merian, 1705 · Hand-colored engraving after Merian's watercolor · This copy: British Library, London. Hand-colored copies are kept in many libraries, and scans of the whole book are free online.

Maria Sibylla Merian was a German-born naturalist and artist who raised caterpillars and drew them from life. In 1699, when she was about 52 years old, she sailed with her daughter to the Dutch colony of Suriname in South America to study tropical insects where they lived. Back in Amsterdam, she published her great book, *Metamorphosis insectorum Surinamensium* (Latin for *The Metamorphosis of the Insects of Suriname*), in 1705.

In this plate Merian packed a crowd of rain forest life onto one guava branch, including swarms of ants. In her text she described tropical ants that work together in huge numbers and can even link their bodies to make a bridge. As you look, notice how many small creatures she placed in one picture.

Look closely

- Find the ants. How many can you count? Where are they going?
- Find the big spider and the small bird. Why do you think this part of the picture startled readers in Europe?
- Look at the leaves and fruit. How did Merian show which leaves have been chewed or damaged?
- Merian drew from living animals. What details show she looked closely?

Talk about it

1. Merian showed ants as part of a whole community of living things. What other living things in the picture might ants depend on, or be eaten by?

2. Merian traveled across an ocean to see insects for herself. Why is seeing a living animal in its home better than studying a dead specimen?

> **Safety first.** Some ants bite or sting, and fire ants (small reddish ants that build loose dirt mounds) can sting many times and cause serious reactions. Have an adult check the ants before you start, keep your hands away from the nest and the bait cards, wear closed shoes, and never disturb a mound. Wash your hands when you finish.

EXPERIMENT: WHAT DO ANTS CHOOSE? A FAIR BAIT TEST

Different ants farm different foods: leafcutters grow fungus, many others collect sweet honeydew, and harvester ants store seeds. Which foods do the ants near your home prefer? In this experiment you will set out small baits on cards and count the ants that come.

You will need

- Five white index cards
- Five baits, each about the size of a pea: a drop of sugar water, a dab of honey, a dab of peanut butter (skip if anyone nearby has a nut allergy), a few crumbs of plain cracker, and a drop of plain water (the control)
- A pencil, a watch or timer, and a hand lens if you have one
- Lab notebook

Steps

1. **Question:** Which food will the ants near my home visit most? Write the question.
2. **Prediction:** Rank the baits from most visited to least, and explain your guess.
3. **Variables:** What you change is the kind of bait. What you keep the same is the size of each bait, the cards, the distance from the ant trail (about 30 cm) and the time of day. What you measure is the number of ants on each card. The plain water card is the control.
4. Find an ant trail on a sidewalk, patio or path with an adult. Label each card and place the five cards in a row about 30 cm from the trail, 15 cm apart.
5. Count the ants on each card at 5, 10, 15 and 20 minutes. Do not move or touch the cards. Record a table with columns: Bait, 5 min, 10 min, 15 min, 20 min.
6. Repeat on a second day with the cards in a different order, so position is not the reason for your result.
7. Make a bar graph of the number of ants on each bait at 20 minutes (use the average of the two days).
8. **Conclusion:** Which bait won? Did the ants seem to recruit sisters, with numbers rising quickly after the first ant found the bait? What does your result suggest about what these ants eat?

Tips

- Use a hand lens to watch ants at the bait. Do they drink, or carry pieces away? Do returning ants touch antennae with ants on the trail?
- When you finish, pick up and throw away all the cards and baits so you do not draw ants into the house.
- Do it at home: ants that tend aphids are easy to spot on garden plants such as roses, milkweed or beans in summer.

Check your work

- Every bait was the same size and the same distance from the trail, and I included a plain water control.
- I repeated the test on a second day with the cards in a new order.
- My table and bar graph match, and my conclusion is based on my counts.

NATURE NOTEBOOK

1. Draw three leafcutter workers side by side, small, medium and large, and label the job of each: garden tender and leaf rider, cutter and carrier, defender.
2. Find an ant trail outdoors and watch it for 5 minutes. Draw a map of the trail and count how many ants pass one spot in one minute, going each way. Record the date, time and temperature.
3. Draw an ant stroking an aphid on a plant stem. Label the ant, the aphid and the drop of honeydew, and write one sentence explaining how each partner benefits.

> **From history.** For centuries readers wondered about Proverbs 6:8, which says the ant “gathereth her food in the harvest,” and some European naturalists of the 1800s said Solomon must have been mistaken, because the ants they knew in northern Europe did not store seeds. In 1873 a young English naturalist, J. Traherne Moggridge, who was living for his health at Menton on the Mediterranean coast of France, dug into the nests of harvester ants there. He found underground granaries full of seeds, watched the ants carry seeds in and bring sprouting ones out to dry, and published his findings in *Harvesting Ants and Trap-door Spiders*. The ants of the warm Mediterranean lands, like those of Solomon’s country, really do harvest.

WORKED EXAMPLES

Example 1. A leafcutter worker with a mass of 5 mg carries a leaf piece with a mass of 20 mg. How many times her own mass is she carrying? If a 40 kg student could carry the same multiple of his or her own mass, how much would that be?

1. Load ratio = 20 mg ÷ 5 mg = 4. She carries 4 times her own mass.
2. Student: 4 × 40 kg = 160 kg.

Answer: She carries 4 times her own mass. For a 40 kg student, that would be 160 kg, about the mass of two grown men.

Example 2. A loaded leafcutter walks at about 1.5 cm per second. The cutting tree is 60 m from the nest along the trail. How long does one trip home take, in minutes?

1. Convert the distance to centimeters: 60 m × 100 cm/m = 6,000 cm.
2. Time = distance ÷ speed = 6,000 cm ÷ 1.5 cm/s = 4,000 s.
3. Convert to minutes: 4,000 s ÷ 60 s/min ≈ 66.7 minutes.

Answer: About 67 minutes, a little over an hour, for one trip home with a single leaf piece.

Example 3. A student counted loaded ants passing one spot on a trail for five separate minutes: 42, 38, 45, 40 and 35. Find the mean number per minute. At that rate, how many leaf pieces pass in one hour? In 10 hours of work?

1. Sum: 42 + 38 + 45 + 40 + 35 = 200.
2. Mean: 200 ÷ 5 = 40 ants per minute.
3. One hour: 40 × 60 = 2,400 leaf pieces.
4. Ten hours: 2,400 × 10 = 24,000 leaf pieces.

Answer: A mean of 40 per minute, 2,400 leaf pieces an hour and 24,000 in 10 hours, from just one trail.

PRACTICE

1. EASY What do leafcutter ants actually eat?
2. EASY What is mutualism? Give one example from this lesson.
3. EASY How does a new leafcutter queen start a garden in her new nest?
4. MEDIUM What did Henry Walter Bates think the leaves were for, and what did Thomas Belt think? Who was proved right, and by whom?

5. MEDIUM A 2 mg worker carries a 13 mg leaf piece. What is her load ratio? Round to one decimal place.
6. MEDIUM **Data reading.** Made-up trail counts (loaded ants passing per minute) for one leafcutter colony: 6 a.m., 10; 10 a.m., 35; 2 p.m., 8; 6 p.m., 40; 10 p.m., 50; 2 a.m., 30. (a) At what time was traffic highest? (b) At what time was it lowest? (c) Suggest a reason for the low count at that time. (d) Are leafcutters only active in the daytime?
7. HARD **Data reading.** Results of a bait test (ants on each card at 20 minutes, average of two days): sugar water 34, honey 28, peanut butter 12, cracker 5, plain water 0. (a) Which bait was most visited? (b) Why is the plain water result important? (c) A student concludes, “All ants like sugar best.” What is wrong with that conclusion?
8. MEDIUM Why do the smallest leafcutter workers ride on top of the leaf pieces carried by their larger sisters?
9. CHALLENGE **Experiment design.** Ants leave a scent trail for their sisters to follow. Design an experiment to test whether ants follow a scent trail rather than following the ant in front. Name what you change, what you keep the same, what you measure and a control.
10. HARD In three or four sentences, explain why leafcutter ant farming is called “true farming.” Name at least three farming jobs the ants do.

COMMON MISTAKES

- Thinking leafcutter ants eat leaves. They use the leaves to grow fungus, and the fungus is their food.
- Thinking the queen is the boss who gives orders. She lays the eggs, but no ant commands the colony; each worker responds to signals such as scent trails and the needs she meets.
- Thinking all ants in a colony are the same. Leafcutter workers come in many sizes with different jobs, and ant species differ widely in what they eat.

Make it a game · Leafcutter Relay. Set up a “tree” (a pile of paper leaf shapes) at one end of the yard and a “nest” (a basket) at the other. Each team has cutters, carriers and riders. Cutters tear a leaf shape in half; carriers carry the pieces to the nest on top of their heads; a rider (a small paper ant) must stay on top of each leaf piece the whole way. If the rider falls off, a “parasite fly” (one player with a feather) can tag the carrier, who must return to the tree. The team with the most leaf pieces in the nest after three minutes wins the harvest.

Scripture. “Go to the ant, thou sluggard; consider her ways, and be wise: Which having no guide, overseer, or ruler, Provideth her meat in the summer, and gathereth her food in the harvest.” (Proverbs 6:6–8, KJV)

Solomon told the lazy person to study the ant, and he noticed something scientists confirmed thousands of years later: no ant stands over the others giving orders, yet the work gets done in season. Diligence, planning ahead and faithful work at small tasks are lessons the ant teaches without a word.

Practice answers

1. A fungus that they grow on chewed-up leaves in their underground gardens. They do not eat the leaves themselves.
2. A partnership in which both kinds of living things benefit. Examples: leafcutter ants and their fungus (food for the ants; food, care and spreading for the fungus), or ants and aphids (honeydew for the ants; protection for the aphids).
3. She carries a small pellet of fungus in a pocket in her mouth on her mating flight, then spits it out in her new nest and tends it until her first workers grow up.
4. Bates thought the ants used the leaves to thatch their nests. Belt thought they used the leaves to grow fungus for food. Belt was right; Alfred Möller proved it in 1893 by growing the fungus and showing the food knobs the ants eat.
5. 13 ÷ 2 = 6.5 times her own mass.
6. (a) 10 p.m. (50 per minute). (b) 2 p.m. (8 per minute). (c) The middle of the afternoon is the hottest, driest part of the day, which can be hard on small ants (also, parasite flies may be more active). (d) No; traffic was high at night (10 p.m. and 2 a.m.), so this colony worked day and night, with peaks in the evening.
7. (a) Sugar water (34 ants). (b) It is the control: zero ants on plain water shows the ants were coming for the food, not just the card or the moisture. (c) The test only used one kind of ant in one place at one time; other kinds of ants (such as seed-gathering harvesters or meat-eating ants) might prefer other foods, and a colony's needs may change with the season.
8. To guard them against tiny parasite flies that try to lay eggs on the carrying ants; the little riders chase the flies away.
9. Sample answer: Find a busy trail on a sidewalk. Wait until no ants are passing one short section, then rub a finger firmly across the trail to wipe away the scent (on another section, just touch the ground lightly without rubbing, as a control). Change only whether the scent is wiped away. Keep the place, time and the amount of pressure on the control the same. Measure how many ants stop, turn back or wander at each section in 2 minutes, and how long until the trail is used normally again. If ants become confused only where the scent was wiped away, they are following a scent trail.
10. Sample answer: Leafcutters do the same jobs a human farmer does. They gather material to feed their crop (cutting and carrying leaves as compost), plant the fungus on fresh leaf pulp, weed out invading molds, protect the crop from disease with antibiotic-making bacteria, and harvest the fungus knobs for food. They even carry "seed" fungus to start new gardens. Because they plant, tend and harvest a crop over and over, it is real farming, done by instinct.

Unit 6 review

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

1. (4 pts) Multiple choice. Which honeybees are female? (a) only the queen (b) the queen and the workers (c) the workers and the drones (d) all three castes
2. (6 pts) A forager's waggle runs point 30° to the right of straight up on the comb and last about 1.5 seconds. The sun is at a compass bearing of 150°. In this colony, 1 second of waggling means about 1 km. On what bearing is the food, and how far away is it?
3. (8 pts) **Diagram.** Draw a rectangle to stand for an upright honeycomb. Mark "up = sun" with an arrow. Then draw the figure-eight waggle dance a bee would do if the food were 50° to the *left* of the sun. Label the waggle run, the return loops and the 50° angle.
4. (5 pts) Explain why bees build hexagonal cells instead of round or square ones.
5. (4 pts) Multiple choice. A typical wild wolf pack is (a) unrelated adults who fight for the alpha position (b) a mother, a father and their offspring (c) only male wolves (d) a group of several unrelated breeding pairs
6. (6 pts) One winter an island has 30 wolves and 900 moose. Five years later it has 15 wolves and 1,200 moose. Find the moose per wolf in each year. In which year did each wolf have more food available?
7. (5 pts) Name two ways wolves defend their territory without fighting, and explain what dispersal is.
8. (4 pts) Multiple choice. Elephant rumbles can travel several kilometers mainly because (a) they are very high-pitched (b) their low frequencies have long wavelengths that fade slowly (c) elephants shout louder than any other animal (d) sound travels faster in hot air
9. (6 pts) Sound travels about 343 m/s in air. (a) How long does a rumble take to travel 6 km? (b) What is the wavelength of a 14 Hz rumble? Round both answers to one decimal place.
10. (6 pts) Describe Karen McComb's playback experiment in Amboseli and what it showed about matriarchs.
11. (6 pts) What did Thomas Belt discover about leafcutter ants? Explain why their relationship with their fungus is called mutualism, and name one job done by the smallest workers.

Unit project: field guide to four animal societies

Make a four-page illustrated field guide, one page each for the honeybee colony, the wolf pack, the elephant family and the leafcutter ant colony. On each page draw the members (with labels), answer the three unit questions (Who leads? How are the jobs divided? How do members send messages?) and include one calculation from the lesson with the work shown. Finish with a comparison table of all four societies and add the full record (question,

prediction, variables, data table, graph and conclusion) of one experiment you did in this unit.

- **Accuracy**: Facts about leaders, castes or family members, jobs and communication are correct for each animal, and the drawings are labeled correctly.
- **Calculations**: Each page has a worked calculation with units, clear steps and a correct answer.
- **Experiment record**: The experiment includes a question, prediction, variables, a control, a neat data table, a correctly labeled graph and a conclusion based on the data.
- **Comparison and care**: The comparison table shows thoughtful likenesses and differences, and the whole guide is neat, colorful and easy to read.

Answer key

1. (b) The queen and the workers are female; drones are male.
2. Right of up means clockwise from the sun's direction: 150° + 30° = 180°, due south. Distance: 1.5 s × 1 km/s = about 1.5 km.
3. Full credit: the straight waggle run is tilted 50° counterclockwise (to the left) from a vertical reference line; two curved return loops (one on each side) join the ends to form a figure eight; the waggle run, return loops, the 50° angle and the up = sun arrow are labeled. (2 points each: up arrow, correct direction of tilt, correct angle marked, loops and labels.)
4. Wax is costly to make. Of the shapes that fit together with no gaps (triangles, squares and hexagons), the hexagon encloses the most space for the least wall, so it saves wax. Circles leave wasted gaps between them.
5. (b) A mother, a father and their offspring.
6. First year: 900 ÷ 30 = 30 moose per wolf. Five years later: 1,200 ÷ 15 = 80 moose per wolf. Each wolf had more food available in the later year.
7. Howling (which warns other packs away and gathers the family) and scent marking along trails and territory edges. Dispersal is when a young wolf, usually one to three years old, leaves its family to find a mate and a territory of its own.
8. (b) Their low frequencies have long wavelengths that fade slowly.
9. (a) 6,000 m ÷ 343 m/s ≈ 17.5 s. (b) 343 ÷ 14 = 24.5 m.
10. She played recorded contact calls of familiar and unfamiliar elephant families from a hidden loudspeaker and watched whether the listening family bunched together in alarm. Families led by older matriarchs were better at telling friends from strangers, so they had fewer false alarms, and they also raised more calves. An older matriarch's knowledge helps her whole family.
11. Belt discovered that leafcutter ants do not eat the leaves they cut but use them to grow a fungus, which is their food. It is mutualism because both benefit: the ants get food, and the fungus is fed, protected from molds and carried to new nests. The smallest workers tend and weed the garden, or ride on carried leaves to guard against parasite flies.

UNIT 7

Giants: Whales and Dinosaurs

What is the largest animal God ever made, and how could any creature grow so big? In this unit you will meet the giants: the blue whale, the heaviest animal known for certain, and the sauropods, the long-necked dinosaurs that were the largest animals ever to walk on land. You will ask the questions an engineer would ask. How does a heart push blood up a neck many meters high? How do bones carry tens of tonnes? Why can a whale be heavier than any dinosaur? And how do scientists weigh an animal no one has ever seen alive?

You will ride along in 2018 as scientists stick a heart-rate tag on a blue whale in Monterey Bay, and dig in Colorado in 1900 with Elmer Riggs as he finds an arm bone so long he first mistook it for a thigh bone. You will follow a rancher in Argentina who found a “petrified log” that turned out to be one of the largest leg bones ever found, and watch Andrew Carnegie’s *Diplodocus* go from a Wyoming hillside to the great hall of a London museum. Along the way you will use blood pressure, the **square-cube law**, scale models and the lever rule to understand why giants are built the way they are.

Because sauropods appear on museum signs with words like “Jurassic” and “Cretaceous,” each dinosaur lesson includes a ⏳ **Thinking About Time** box. It separates what the sign says from what we actually observe in the rocks and bones, and shows how Christians who read Genesis as history understand the same evidence. The lesson of the whole unit is the one God gave Job: the Maker of Behemoth, whose “bones are like bars of iron,” is greater than His greatest creatures.

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and decimals, and find an average and a range
- Can work with metric units of length, mass and volume (m, cm, kg, tonnes, mL, L)
- Can read a line graph and a data table
- Knows that the heart pumps blood through blood vessels to the whole body

MASTERY CHECKLIST

- I can explain why the blue whale is a mammal, how it feeds with baleen, and how its heart slows during a dive.
- I can calculate the blood pressure a tall animal needs to lift blood to its head and explain why sauropod neck posture is debated.
- I can use the square-cube law to explain why giants need thick bones and why there are limits to size.
- I can estimate an animal’s mass from a scale model and explain why dinosaur masses are estimates.
- I can use the lever rule and pressure per area to explain how a sauropod was engineered to carry its weight.

- I can tell the difference between what a museum sign says about time and what we actually observe in the rocks and bones.

OPTIONAL BOOKS AND RESOURCES

- **NOAA Fisheries: Blue Whale** (https://www.fisheries.noaa.gov/species/blue-whale): Free. The U.S. government's fact page on the blue whale: size, feeding, range, calls and how the species is protected. Good for checking the numbers in Lesson 7.1.
- **Dinosaur National Monument (National Park Service)** (https://www.nps.gov/dino/index.htm): Free. Photographs and information about the Quarry Exhibit Hall wall of about 1,500 dinosaur bones, including sauropods, on the Utah–Colorado border. Use it with the ⏳ box in Lesson 7.4, or plan a family visit.
- **Smithsonian Ocean** (https://ocean.si.edu/): Free. Articles, photographs and videos about whales and other ocean life from the Smithsonian Institution. Search for "blue whale" and "baleen."

7.1 The Blue Whale: Largest Animal Known ★

OBJECTIVES

- Describe the blue whale's size, body plan and lunge feeding, and explain why a whale is a mammal and not a fish.
- Read heart-rate data from a diving blue whale and explain how slowing the heart helps it stay underwater.
- Use scale, rates and ratios to compare a blue whale with familiar objects and to calculate how fast a calf grows.

Warm-up. Measure your height in meters with a tape measure. A large blue whale is about 30 m long. Predict how many of you, lying head to toe, would stretch the length of one whale, then calculate it. Next, count your pulse for 15 seconds and multiply by 4 to get beats per minute. A diving blue whale's heart can slow to about 2 beats per minute. How many times does your heart beat while the whale's heart beats once?

Video. Coming soon. Blue whale lunge feeding, baleen and the Stanford heart-rate tag study in Monterey Bay, with drone footage of blue whales feeding; search NOAA Fisheries, Smithsonian Ocean, Monterey Bay Aquarium, SciShow Kids, Homeschool Pop (Alternate) and nature footage channels.

KEY TERMS

mammal
An animal that breathes air with lungs, is warm-blooded, has hair at some stage of life, and feeds its young on milk. Whales are mammals, not fish.

baleen
Long plates of keratin (the same material as your fingernails) that hang from the upper jaw of some whales. Their frayed inner edges form a mat that strains small food out of seawater.

krill
Small, shrimp-like animals, most about as long as your little finger or shorter, that swim in huge swarms. Krill are the main food of the blue whale.

lunge feeding
The way a blue whale eats: it speeds forward, opens its mouth wide, swallows a huge gulp of water and krill, then pushes the water out through its baleen and swallows the krill.

dive response
The changes in a diving mammal's body when it goes underwater: the heart slows and blood is sent mainly to the brain and heart, so stored oxygen lasts longer.

blowhole
The nostrils of a whale, placed on top of the head. A blue whale has two side by side, and its spout of breath can rise about 9 m into the air.

CORE IDEAS

The story. In August 2018, on Monterey Bay off the coast of California, a team of scientists led by Jeremy Goldbogen of Stanford University was chasing a blue whale in a small inflatable boat. Each time the whale rose to breathe, one of them reached out with a long pole and tried to stick a tag to its back with suction cups. This was not easy. Whale skin is smooth and slippery, the whale keeps moving, and the tag had to end up close enough to the heart to pick up its beat. The team had tried for years. This time it worked, and the tag rode on the largest animal in the world for about eight and a half hours.

How they figured it out. Every heartbeat makes a small electrical signal, the same signal a doctor records with stickers on your chest. The tag recorded those signals along with the whale's depth. When the scientists read the record, they found something astonishing. At the surface, taking breaths, the whale's heart beat more than 30 times a minute. As it dove, the heart slowed to about 4 to 8 beats a minute, and at its slowest it beat only about **2 times a minute**. This is the **dive response**, and you have a small version of it too: cold water on your face slows your heart a little. By slowing its heart, the whale sends its stored oxygen mainly to the brain and heart, so a single breath lasts through a long dive. The scientists published their results in 2019. They also suggested that the whale's heart was already working near its limits, which may be one reason no animal grows much bigger than a blue whale.

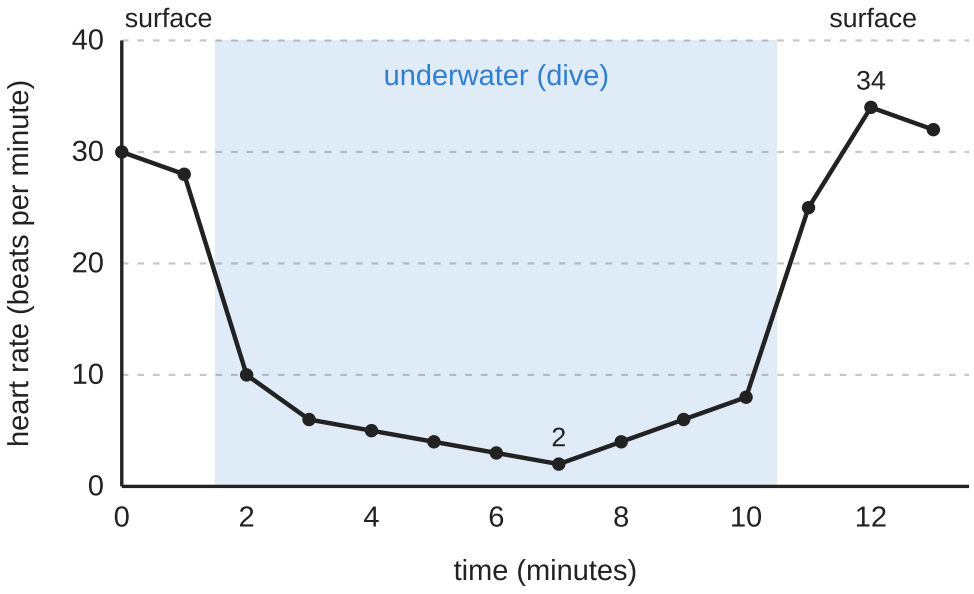
The big idea. A large adult blue whale is about 30 m long, longer than two school buses parked end to end, and can weigh about 150 tonnes (1 tonne is 1,000 kg). The longest ones ever measured were over 33 m. It is the heaviest animal known for certain ever to have lived, heavier than any dinosaur whose bones we have found. Yet it is a **mammal**, like a dog or a horse. It breathes air through two **blowholes**, it is warm-blooded, it has a few hairs on its head as a young calf, and the mother feeds her calf rich milk. A newborn calf is about 7 m long, and on its mother's milk it gains about 90 kg every day. In 2014 scientists from the Royal Ontario Museum in Toronto preserved the heart of a blue whale that washed ashore in Newfoundland. It weighed about 180 kg and stood about 1.5 m tall: enormous, but not the size of a car, as many books used to say.

Try it and see. The largest animal eats some of the smallest. A blue whale has no teeth. Instead, 260 to 400 plates of **baleen** hang from each side of its upper jaw. To eat, it uses **lunge feeding**. It speeds toward a swarm of **krill**, opens its mouth almost to a right angle, and the pleated skin of its throat stretches like an accordion until it holds a gulp of water and krill roughly as heavy as the whale itself. Then it closes its mouth, pushes the water out through the baleen with its tongue and throat, and swallows the krill left behind. NOAA scientists report that in feeding season one blue whale can eat about 3.6 tonnes of krill a day. In this lesson's project you will build your own baleen filters and test which one catches the most "krill."

In the world today. Why can a whale be so much heavier than any land animal? Water holds it up. The push of water on a floating body, called buoyancy, carries most of its weight, so its bones do not have to hold up 150 tonnes the way legs would on land. Its real limits are food

and oxygen, not weight. Blue whales were once hunted so heavily that very few were left. In 1966 hunting them was banned worldwide, and since then their numbers have been slowly growing in many oceans. Today scientists count them by photographing the gray, mottled pattern on each whale's skin, which is different for every whale, like a fingerprint. That is good dominion: knowing a creature and caring for it.

God's handiwork. On the fifth day of creation, Genesis says, "God created great whales." The blue whale shows the same care in design as the smallest creature: a heart that can slow almost to a stop and speed up again, a mouth that can swallow a swimming pool's worth of water, and baleen fine enough to catch animals the size of your finger. Large and small, God saw that it was good.



Heart rate of a blue whale during one dive (sample data, simplified from the 2018 tag record). The shaded part is underwater.

PICTURE STUDY



Whalers, Joseph Mallord William Turner, about 1845 · Oil on canvas · Tate, London

J. M. W. Turner was an English painter famous for light, storms and sea spray. In 1845, when he was about seventy, he showed several paintings of whaling at the Royal Academy in London. He had read a book on sperm whaling by Thomas Beale, a ship’s surgeon who had sailed on whaling voyages, and he tried to paint the danger and confusion of a whale hunt in the open sea.

The whalers of Turner’s day rowed small boats out from a sailing ship and threw harpoons by hand. They hunted sperm whales and right whales. The blue whale was safe from them: it was too fast to catch by rowing, and it usually sank when killed. That changed only when steam ships and harpoon cannons came, as you will read in the history note.

Look closely

- Find the whale. How much of its body can you actually see? What hides the rest?
- Find the small boats and the ship in the background. How big do the people look compared with the sea?
- Turner painted with loose, swirling strokes. Where is the brightest light, and where does your eye go first?
- Look at the water and sky. Can you tell where one ends and the other begins?

Talk about it

1. Why do you think Turner painted the scene so misty instead of sharp and clear?
2. How would a painting of a blue whale feeding look different from this hunting scene?
3. What does this painting make you feel about the size and power of whales?

> **Safety first.** Do the project on a table you can wipe, or outdoors, and clean up spills at once so no one slips. Do not drink the test water.

EXPERIMENT: THE BALEEN TEST: WHICH FILTER CATCHES THE MOST KRILL?

A blue whale's baleen must let water out quickly but keep krill in. In this experiment you will pour "krill" (grains of rice) in water through three different filters and count how many grains each one catches.

Question: Does the spacing of the bristles or teeth in a filter change how much krill it catches? **What we change:** the filter. **What we keep the same:** the amount of water, the number of rice grains, the height and speed of the pour, and the angle of the filter. **What we measure:** the number of grains caught, out of 50.

You will need

- A pitcher or large measuring cup
- Water (500 mL for each trial)
- Uncooked rice: count out 50 grains for each trial
- Three filters: a dinner fork, a wide-tooth comb and a fine-tooth comb
- A large bowl or baking dish to catch the water
- A ruler, a pencil and your lab notebook

Steps

1. Write your prediction: which filter will catch the most rice, and why?
2. Draw a data table with columns for Filter, Trial 1, Trial 2, Trial 3 and Average.
3. Put 500 mL of water and 50 grains of rice into the pitcher. Stir so the rice is moving.
4. Hold the first filter flat across the bowl, teeth pointing the same way each time. Pour the whole pitcher across it from a height of about 10 cm, at a steady speed.
5. Count the grains left on the filter. Record the number.
6. Repeat for three trials with each filter. Use fresh water and a fresh 50 grains each time.
7. Find the average for each filter: add the three trials and divide by 3.
8. Make a bar graph of your averages and write a conclusion: was your prediction right? What does the result tell you about why baleen has a fine, hairy fringe?

Tips

- Keep the pour the same. If you pour faster in one trial, the water may wash the rice over the filter and spoil the fair test.
- Real baleen plates are close together, and their frayed inner edges tangle into a mat that works like your fine-tooth comb, only better.
- If counting grains is slow, have one person pour and another count.

Check your work

- I changed only one thing (the filter) and kept the rest the same.
- I did three trials for each filter and found averages.
- I can explain how the result connects to a blue whale’s baleen.

NATURE NOTEBOOK

1. Draw a blue whale from the side and label the blowholes, baleen, throat pleats, flippers, small dorsal fin and tail flukes. Add a scale bar showing 5 m.
2. Draw one krill as large as your page allows and label its eyes, legs and antennae. Beside it, write how many grams of krill a whale eats in a day (3.6 tonnes = 3,600,000 g).
3. Copy the heart-rate graph into your notebook. Mark the point where the heart beats slowest and write one sentence explaining why it slows.

> **From history.** For most of history the blue whale was too fast for whalers to catch, and it usually sank when killed. In the 1860s and 1870s the Norwegian whaler Svend Foyn developed a harpoon fired from a cannon on the bow of a fast steam boat, with a head that exploded inside the whale. With his invention, and later with large factory ships, blue whales were hunted in great numbers, especially in the cold southern oceans. In 1966 the International Whaling Commission protected them from hunting worldwide. Since then, careful counts using photographs of each whale’s skin pattern show blue whales slowly returning in many waters.

WORKED EXAMPLES

Example 1. A large blue whale is 30 m long. A school bus is about 12 m long, and a sixth grader is about 1.5 m tall. How many school buses long is the whale? How many sixth graders lying head to toe?

1. To compare sizes, divide the larger length by the smaller one.
2. Buses: 30 m ÷ 12 m = 2.5.
3. Students: 30 m ÷ 1.5 m = 20.

Answer: The whale is 2.5 school buses long, or about 20 sixth graders lying head to toe.

Example 2. Use the heart-rate graph. What is the highest heart rate shown, and the lowest? How many times faster does the heart beat at its highest than at its lowest?

(Use the map or drawing "Read the highest and lowest points of the line." shown earlier in this lesson.)

1. Find the highest point: just after the whale surfaces, at 12 minutes, the line reaches 34 beats per minute.
2. Find the lowest point: in the middle of the dive, at 7 minutes, the line is at 2 beats per minute.
3. Divide to compare: 34 ÷ 2 = 17.

Answer: Highest 34 beats per minute, lowest 2 beats per minute; the heart beats 17 times faster at its highest.

Example 3. A blue whale calf is born with a mass of about 2,500 kg and gains about 90 kg a day on its mother's milk. What is its mass after 30 days? About how much does it gain each hour?

1. Gain in 30 days: 90 kg/day × 30 days = 2,700 kg.
2. Add the birth mass: 2,500 kg + 2,700 kg = 5,200 kg.
3. Gain per hour: there are 24 hours in a day, so 90 kg ÷ 24 h = 3.75 kg per hour.

Answer: About 5,200 kg after 30 days, gaining about 3.75 kg every hour (more than the mass of a newborn human baby).

PRACTICE

1. EASY Give three features that show a blue whale is a mammal and not a fish.
2. EASY What is baleen made of, and what does it do?
3. EASY Describe the four steps of lunge feeding.
4. MEDIUM A blue whale eats about 3.6 tonnes (3,600 kg) of krill a day during feeding season. How many kilograms does it eat in 30 days? How many tonnes is that?
5. MEDIUM Data reading. Use the heart-rate graph. (a) During which minutes was the heart rate below 5 beats per minute? (b) Was the whale at the surface or deep in its dive then?
   (Use the map or drawing "Use the graph for practice item 5." shown earlier in this lesson.)
6. MEDIUM Data reading. The table shows typical resting heart rates.
   Mouse (0.02 kg): about 600 beats/min
   Cat (4 kg): about 150 beats/min
   Human adult (70 kg): about 70 beats/min
   Horse (500 kg): about 35 beats/min
   Elephant (5,000 kg): about 30 beats/min
   Which conclusion is best supported by the data? (A) Heavier animals have faster heart

rates. (B) Heavier animals tend to have slower heart rates. (C) Heart rate does not depend on size. (D) Every animal's heart rate is half of the next smaller one.

7. HARD You make a scale drawing of a blue whale family with 1 cm = 2 m. The mother is 30 m long and her calf is 7 m long. How long should each be on the paper?
8. HARD Blue whale calls are very low and loud, and sound travels about 1,500 m/s in seawater. How long does a call take to reach another whale 300 km away? Give your answer in seconds and in minutes and seconds.
9. CHALLENGE Write a short explanation (3–4 sentences): why can a blue whale grow heavier than any land animal, and why would a stranded whale on a beach be in danger even if it could still breathe?
10. CHALLENGE Experiment design. People have a small dive response too. Design a safe experiment to test whether holding your breath with your face in cool water slows your heart more than holding your breath in air. Name the independent variable, the dependent variable, two things you keep the same, and how many trials you would do.

COMMON MISTAKES

- Thinking whales are fish because they live in water. Whales breathe air, are warm-blooded and feed their young milk; they are mammals.
- Thinking the biggest animal must eat the biggest food. The blue whale eats krill, some of the smallest animals in the sea, by the tonne.
- Repeating that a blue whale's heart is "the size of a car." A real preserved heart weighed about 180 kg and stood about 1.5 m tall: huge, but much smaller than a car.

> **Make it a game · Lunge or Stay.** A parent reads true-or-false statements about blue whales (for example, "A blue whale has teeth," or "A calf drinks milk"). If the statement is true, players lunge forward with arms opened wide like a feeding whale's mouth, then "strain" by closing their arms. If it is false, they stay perfectly still. Anyone who lunges at a false statement must correct it to stay in. For a bonus round, the parent calls out a size (a bus, a giraffe, a krill) and players say whether it is bigger or smaller than a blue whale's heart.

> **Scripture.** "And God created great whales, and every living creature that moveth, which the waters brought forth abundantly, after their kind, and every winged fowl after his kind: and God saw that it was good." (Genesis 1:21, KJV)

The very first animals named in the Bible's account of creation are the "great whales." The largest creature known still lives in the sea, and its design, from its slowing heart to its fine baleen, shows the wisdom of the One who made it.

Practice answers

1. Any three: it breathes air with lungs (through blowholes); it is warm-blooded; it has hair at some stage of life; it gives birth to live young; the mother feeds her calf milk.

2. Baleen is made of keratin, the same material as fingernails. It hangs from the upper jaw in plates and strains krill out of the water while letting the water out.
3. The whale speeds toward a swarm of krill; opens its mouth wide while its pleated throat stretches to take in a huge gulp of water and krill; closes its mouth and pushes the water out through the baleen; swallows the krill left inside.
4. 3,600 kg × 30 = 108,000 kg, which is 108 tonnes (nearly three-quarters of the whale’s own mass).
5. (a) From just after minute 4 to just after minute 8 (the points at 5, 6, 7 and 8 minutes show 4, 3, 2 and 4 beats per minute). (b) Deep in its dive, in the middle of the shaded part.
6. (B). As body mass goes up from mouse to elephant, the resting heart rate goes down. (D) is wrong because the drops are not all by half; for example, the horse and elephant are close.
7. Mother: 30 ÷ 2 = 15 cm. Calf: 7 ÷ 2 = 3.5 cm.
8. 300 km = 300,000 m. 300,000 ÷ 1,500 = 200 seconds, which is 3 minutes 20 seconds.
9. In water, buoyancy holds up most of the whale’s weight, so its skeleton does not have to carry 150 tonnes. Its size is limited more by food and oxygen than by weight. On a beach, nothing holds the body up, so the whale’s own weight presses on its chest and organs, making breathing hard and harming its body. Its bones and muscles were made for life in water, not for carrying its full weight on land.
10. Independent variable: face in cool water or not (in air). Dependent variable: heart rate in beats per minute, counted by pulse. Keep the same: the same person, the same breath-hold time (for example 15 seconds), the same position (sitting), and resting the same time before each trial; use cool tap water, not icy water, with an adult present. Take the pulse at rest first, then during or right after each breath-hold, and do at least three trials of each kind, then compare averages.

7.2 Sauropod Necks and Hearts

OBJECTIVES

- Tell how Elmer Riggs's team found *Brachiosaurus* in 1900 and describe the main features of a sauropod skeleton.
- Explain why a tall animal needs high blood pressure, and calculate the pressure a heart must make to lift blood to the head.
- Describe how air-filled bones and bird-like air sacs helped make a long neck possible, and explain why scientists still debate how sauropods held their necks.

Warm-up. Put a drinking straw in a glass of water and sip. Now tape two or three straws together end to end, making one long straw, and sip again from the same glass. Which took more effort? Where in a tall animal's body would the same problem show up?

Video. Coming soon. Sauropod neck posture, air-filled vertebrae and how a giraffe's heart pumps blood up its long neck; search Smithsonian National Museum of Natural History, Field Museum, PBS Eons (preview first), SciShow Kids, Homeschool Pop (Alternate) and giraffe nature footage.

KEY TERMS

sauropod
A group of huge, plant-eating dinosaurs with a small head, a long neck, a long tail and four pillar-like legs. *Brachiosaurus*, *Diplodocus* and *Argentinosaurus* are sauropods.

vertebra
One of the bones that make up the backbone (plural: vertebrae). You and a giraffe each have 7 neck vertebrae; sauropods had from about 12 to 19.

blood pressure
The push of blood against the walls of the blood vessels, made by the heart. It is measured in millimeters of mercury (mmHg). A healthy resting person's top number is about 120 mmHg.

pneumatic bone
A bone with hollow spaces filled with air, connected to the lungs. Birds have them today, and sauropod neck bones were full of them.

air sac
A thin, balloon-like bag connected to the lungs that stores and moves air. Birds use air sacs to keep fresh air flowing one way through their lungs.

trackway
A line of fossil footprints made by one animal walking. Trackways show how an animal stood and moved.

CORE IDEAS

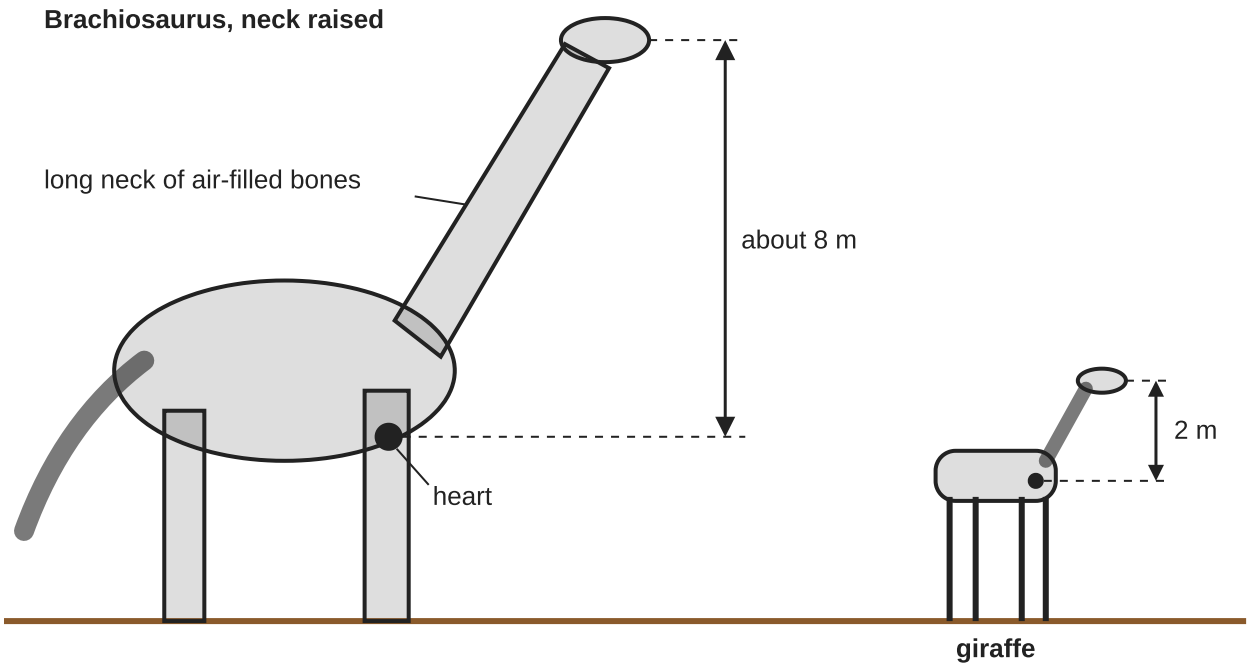
The story. In July 1900, a fossil-hunting team from the Field Columbian Museum in Chicago was searching the dry hills near Grand Junction, Colorado. The leader was Elmer Riggs, and it was his assistant, Harold Menke, who spotted a giant bone weathering out of the rock. As they dug, the team found more: backbones, ribs, part of a hip, and a huge limb bone more than 2 m long. Riggs at first took that limb bone for a thigh bone, because it seemed far too long to be an upper arm. It turned out to be the arm bone, the humerus. This dinosaur's front legs were longer than its back legs. In 1903 Riggs named it *Brachiosaurus altithorax*, which means "arm lizard with a deep chest."

How they figured it out. A long front leg means high shoulders, and high shoulders mean the neck rose up from the body like a crane. Later, a German team digging at Tendaguru in East Africa found more complete skeletons of a very close cousin, and the skeleton mounted in Berlin stands about 13 m tall, as high as a four-story building. Sauropod necks are a marvel of design. Where a giraffe has 7 neck vertebrae, as you do, sauropods had from about 12 to 19, each one long. Yet the bones were surprisingly light. They were **pneumatic bones**: hollowed out by air spaces, with thin bony walls and plates between them. In some neck bones more than half the volume was air. In birds, pneumatic bones are connected to **air sacs** that keep fresh air moving one way through the lungs. Sauropod bones show the same kind of openings, so most scientists think sauropods breathed in this bird-like way. That would have solved another problem: a windpipe many meters long holds a lot of stale air, and flow-through breathing gets fresh air to the lungs anyway.

The big idea. A tall animal has a plumbing problem. The heart must push blood all the way up to the brain, and every meter of height takes more push. Blood pressure needed rises by close to **80 mmHg for every meter** that the head is above the heart. Your head is only about 0.3 m above your heart, and your heart makes about 120 mmHg. A giraffe's head is about 2 m above its heart, and a giraffe's blood pressure is about twice yours, made by a heart with very thick, strong walls. Now picture *Brachiosaurus* with its head raised 8 m above its heart. If its brain needed about 100 mmHg, its heart would have to make about 100 + 8 × 80 = **740 mmHg**, more than six times your blood pressure. That would require a huge, thick-walled heart.

Try it and see. Did sauropods really hold their heads that high? Scientists disagree, and this is a good place to watch how science works. Some built computer models of the neck bones in the 1990s and argued that *Diplodocus* held its neck out more level, like a long bridge, which would need far less blood pressure. Others pointed out that living animals with long necks, from giraffes to swans, usually hold their necks raised, and that a *Brachiosaurus*, with its high shoulders, was built to reach up. No one has ever found a fossil sauropod heart, so the debate is settled by reasoning from bones, from living animals and from physics. Some people have suggested sauropods had several hearts along the neck, but no animal living today is built that way and there is no fossil evidence for it. In this lesson's project you will measure how the height of a water column changes the push at the bottom, the same physics a sauropod heart had to overcome.

God’s handiwork. A long neck is not just a short neck stretched out. It needed light, air-filled bones, strong ligaments, a breathing system that could move air through a long windpipe, and a heart and blood vessels able to handle great pressure. All of these parts had to work together for the animal to live at all. The scientists who study sauropods often say these animals had no living equal. We can say more: they show the wisdom of the One who made the beasts of the earth after their kind.



The heart must lift blood from the heart up to the head. Dots mark the hearts. The higher the head, the higher the blood pressure needed (about 80 mmHg for each meter).

⏳ Thinking About Time

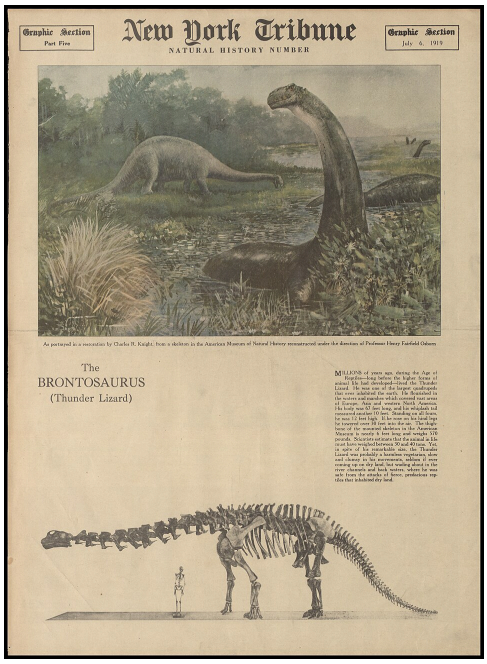
What the sign says. What the sign says: museum signs and textbooks call *Brachiosaurus* a Late Jurassic dinosaur and say it lived about 150 million years ago, long before any people.

What we observe. What we observe: Riggs’s bones lay in layers of sandstone and mudstone that geologists call the Morrison Formation, which covers parts of several western states. The bones are heavy and mineral-filled, and they lie with the bones of other sauropods and dinosaurs. No label or date is found with them; the age comes from how scientists interpret the rock layers.

How Christians read it. How Christians read it: many Christians read Genesis to mean that land animals, sauropods among them, were made on the sixth day along with people, only thousands of years ago. They see layers like the Morrison Formation as laid down quickly in the worldwide Flood of Noah’s day, when great numbers of animals were buried in mud and sand that hardened into rock.

> **Try it.** On a map of the United States, find Grand Junction, Colorado, where Riggs dug, and Dinosaur National Monument nearby on the Utah–Colorado border.
>
> *Genesis 1:24–25*

PICTURE STUDY



Brontosaurus, Charles R. Knight, 1897 · Watercolor · American Museum of Natural History, New York

Charles R. Knight was an American artist who loved to draw animals at the zoo. In the 1890s scientists at the American Museum of Natural History asked him to paint dinosaurs as living animals, and his pictures became the way most people imagined dinosaurs for the next fifty years. He studied the skeletons closely and worked with the scientists so that the muscles and poses would fit the bones.

In 1897 most scientists thought sauropods were too heavy to walk well on land, so Knight painted them wading in water that would help hold them up. Later evidence changed that idea, as you will see in the history note. The painting is a good reminder that a picture of a dinosaur is only as good as the science behind it.

Look closely

- Where are the sauropods standing? What did the artist believe about how they lived?
- Look at the necks. Are they held up high, held level or hanging down?
- Compare the size of the heads with the size of the bodies. What do you notice?
- What did Knight have to guess, since no one had seen a living sauropod?

Talk about it

1. If a sauropod stood in deep water with its head up to breathe, the water would press hard on its chest. Why would that make breathing difficult?
2. How would you change this painting to show what scientists think today?
3. Why is it wise to ask “What is the evidence?” when you look at any picture of an extinct animal?

> **Safety first.** An adult should make the holes in the bottle with a pushpin or small nail, since sharp points can slip. Do the experiment outdoors or over a tub, and wipe up spilled water so no one slips.

EXPERIMENT: THE WATER TOWER TEST: HOW DOES HEIGHT CHANGE PRESSURE?

A sauropod’s heart sat at the bottom of a tall column of blood. In this experiment you will make three holes at different heights in a bottle of water and see how hard water squirts from each one. The farther a jet shoots, the greater the pressure pushing it out.

Question: Does a hole with more water above it squirt harder? **Prediction:** write yours before you start. **What we change:** the height of the hole. **What we keep the same:** the water level in the bottle (always filled to the same line), the size of the holes and the place the bottle stands. **What we measure:** how far each jet lands from the bottle, in centimeters.

You will need

- An empty 2-liter plastic bottle with straight sides, label removed
- A pushpin or small nail (adult use) and a marker
- Waterproof tape, such as duct tape or electrical tape
- A ruler and a tape measure
- A pitcher of water
- An outdoor step, wall or picnic table about 1 m high, with ground below where the water can land
- Your lab notebook

Steps

1. Measure up the side of the bottle and mark three dots in a straight vertical line, 5 cm, 12 cm and 20 cm above the bottom. Draw a fill line 30 cm above the bottom (or as high as the straight part of your bottle goes, and use that line every time).
2. Have an adult push the pin through each dot to make three holes the same size. Cover each hole with its own small strip of tape.
3. Set the bottle at the edge of the step or table, with the holes facing out over the ground.
4. Fill the bottle to the fill line. Pull off the tape from the 5 cm hole only. Have a helper mark where the jet first lands on the ground, then cover the hole again. Measure the distance from the base of the step to the mark.
5. Refill to the fill line and repeat for the 12 cm hole, then for the 20 cm hole.

6. Do three trials for each hole and find the averages.
7. Make a bar graph: height of hole on the bottom, distance of jet up the side.
8. Write a conclusion that answers the question and connects it to a sauropod or giraffe heart.

Tips

- Refilling to the same line every time is the key to a fair test. As the water level drops, every jet gets weaker.
- The lowest hole is also a little closer to the ground, so its jet has less distance to fall. If it still lands farthest, that is strong evidence that the deeper water pushes harder.
- Measure where the jet lands in the first second after you pull the tape, before the level drops.

Check your work

- I changed only the height of the hole and kept the water level the same each time.
- I recorded three trials for each hole and found averages.
- I can explain why a heart far below the head must pump with high pressure.

NATURE NOTEBOOK

1. Draw a sauropod neck vertebra as a cutaway, showing thin bony walls, plates and air spaces. Beside it, draw a solid bone of the same size and write which one you would rather carry up high.
2. Draw a giraffe and a *Brachiosaurus* side by side to the same scale (1 cm = 1 m). Mark each heart with a dot and draw an arrow from the heart to the head with its height in meters.
3. Write a paragraph titled “Head High or Head Level?” giving one piece of evidence for each side of the sauropod neck debate.

From history. In 1938 Roland T. Bird, a fossil hunter for the American Museum of Natural History, followed reports of giant footprints to the Paluxy River near Glen Rose, Texas. In the limestone of the riverbed he found long trackways of sauropod footprints, each big enough for a child to sit in, and beside them the three-toed prints of a meat-eating dinosaur. The trackways showed sauropods walking across the mud on all four feet, their bodies held up on straight legs, and trackways like these later helped convince scientists that sauropods were not swamp-bound. Bird’s crew cut out a section of the trackway, and it was set up in the museum behind the great sauropod skeleton, where visitors could see the footprints and the bones together.

WORKED EXAMPLES

Example 1. A giraffe's head is about 2 m above its heart. Suppose its brain needs about 100 mmHg of blood pressure, and each meter of height adds about 80 mmHg. What pressure must the heart make? How does that compare with a person's 120 mmHg?

1. Extra pressure to lift the blood: 2 m × 80 mmHg per m = 160 mmHg.
2. Add what the brain needs: 100 + 160 = 260 mmHg.
3. Compare: 260 ÷ 120 ≈ 2.2.

Answer: About 260 mmHg, a little more than twice a person's blood pressure, which matches what has been measured in giraffes.

Example 2. Use the same rule for *Brachiosaurus*. (a) With its head raised 8 m above its heart, what pressure must its heart make? (b) If it held its neck level, with its head only about 1 m above its heart, what pressure would be needed? (c) What is the difference?

(Use the map or drawing "Height from heart to head sets the blood pressure needed." shown earlier in this lesson.)

1. (a) 8 m × 80 = 640 mmHg; 640 + 100 = 740 mmHg.
2. (b) 1 m × 80 = 80 mmHg; 80 + 100 = 180 mmHg.
3. (c) 740 − 180 = 560 mmHg.

Answer: (a) About 740 mmHg. (b) About 180 mmHg. (c) Raising the head would need about 560 mmHg more, which is why neck posture matters so much to the heart question.

Example 3. Suppose a sauropod neck vertebra would weigh 120 kg if it were solid bone, but 60% of its volume is air spaces. About how much does it weigh? If the neck has 13 such vertebrae, how much weight is saved in all?

1. If 60% is air, then 100% − 60% = 40% is bone.
2. 40% of 120 kg: 0.40 × 120 = 48 kg.
3. Saved per vertebra: 120 − 48 = 72 kg.
4. Saved for 13 vertebrae: 13 × 72 = 936 kg.

Answer: Each vertebra weighs about 48 kg, and the air spaces save about 936 kg, nearly a tonne, along the neck.

PRACTICE

1. EASY How many neck vertebrae does a person have? A giraffe? About how many did sauropods have?

2. EASY What does the name *Brachiosaurus* mean, and what discovery gave it that name?
3. EASY What is a pneumatic bone, and what living animals have them?
4. MEDIUM Using the rule (100 mmHg for the brain plus 80 mmHg for each meter), what pressure would a sauropod need with its head 5 m above its heart?
5. MEDIUM Data reading. The table shows the height of the head above the heart and the blood pressure the heart makes.
   Person: 0.3 m, about 120 mmHg (measured)
   Giraffe: 2 m, about 250 mmHg (measured)
   Brachiosaurus, head raised: 8 m, about 740 mmHg (calculated)
   (a) Which statement best fits the data? (A) Pressure goes down as height goes up. (B) Pressure goes up as height goes up. (C) Pressure is the same for all. (b) Why is the *Brachiosaurus* number marked “calculated” instead of “measured”?
6. MEDIUM Data reading. A student ran the Water Tower Test with the bottle filled to 30 cm each time. Average results: hole at 5 cm, jet landed 100 cm away; hole at 12 cm, 90 cm; hole at 20 cm, 70 cm. (a) What was the independent variable? (b) What was the dependent variable? (c) Predict about how far a jet from a hole at 25 cm would go: more than 100 cm, between 70 and 90 cm, or less than 70 cm?
7. HARD In Knight’s day, many scientists thought sauropods lived in deep water. Give two pieces of evidence or reasoning against that idea.
8. HARD Explain why a very long windpipe makes breathing harder, and how bird-like air sacs may have helped sauropods.
9. CHALLENGE Experiment design. A giraffe’s body has special ways to keep blood from rushing to its head when it lowers it to drink. Design an experiment on yourself to test whether body position (lying down or standing) changes your pulse rate. Name the independent and dependent variables, two things you keep the same, and how you would make the result reliable.
10. CHALLENGE A *Brachiosaurus* with its head raised would need about 740 mmHg. How many times a person’s 120 mmHg is that? Then explain in two or three sentences why “sauropods had many hearts” is not a good scientific conclusion.

COMMON MISTAKES

- Thinking a longer neck must have many more bones in every animal. A giraffe has the same 7 neck vertebrae as a mouse and a person; its bones are just longer.
- Picturing sauropods living in swamps to hold up their weight. Trackways and leg bones show they walked on land.
- Thinking heavy bones are the strongest design. Sauropod neck bones were light and air-filled, and that is what made a long neck possible.

> **Make it a game · Pump It Up.** A parent calls out a height in meters (for example, 3 m). Players race to say the blood pressure needed using the rule “100 plus 80 for every meter” (3 m: 100 + 240 = 340 mmHg). The first correct answer wins a point and gets to stretch their arms high like a sauropod neck. Mix in animals: “person, 0.3 m,” “giraffe, 2 m,” “*Brachiosaurus*, 8 m.” First to five points wins.

> **Scripture.** “Behold now behemoth, which I made with thee; he eateth grass as an ox.” (Job 40:15, KJV)

God points Job to a great plant-eating beast He made, and later says “he moveth his tail like a cedar” (Job 40:17). Some Bible readers think Behemoth may describe a sauropod; others think of the hippopotamus or elephant. Either way, the point is the same: the Maker of the greatest beasts is greater still.

Practice answers

1. A person has 7 and a giraffe has 7. Sauropods had from about 12 to 19.
2. It means “arm lizard.” Riggs’s team found that its arm bone (humerus) was so long it was at first mistaken for a thigh bone; the front legs were longer than the back legs.
3. A bone with air-filled hollow spaces connected to the lungs and air sacs. Birds have them today.
4. 5 × 80 = 400; 400 + 100 = 500 mmHg.
5. (a) (B). (b) No one can measure the blood pressure of an extinct animal; the number comes from applying the physics of fluid columns to the height of the neck.
6. (a) The height of the hole. (b) The distance the jet landed from the bottle. (c) Less than 70 cm, because a hole at 25 cm has even less water above it pushing down.
7. Any two: fossil trackways show sauropods walking on land with their bodies held up on straight legs; water pressure on the chest deep underwater would make it very hard to breathe through a long neck held up to the surface; their feet and legs were built like an elephant’s for carrying weight on land; their teeth and neck suit eating plants from trees and the ground, not water plants only.
8. A long windpipe holds a large amount of stale air. When an animal breathes in and out like we do, much of each breath is just the old air from the windpipe moving back and forth. Bird-like air sacs move air one way through the lungs, so fresh air keeps flowing past the lung surfaces, making each breath more useful.
9. Independent variable: body position (lying down or standing). Dependent variable: pulse in beats per minute. Keep the same: the same person, the same time spent resting in each position before measuring (for example 2 minutes), the same way of counting (30 seconds × 2), no exercise beforehand. Reliability: do at least three trials in each position, perhaps alternating the order, and compare averages.
10. 740 ÷ 120 ≈ 6.2, so about six times. It is not a good conclusion because no fossil hearts have been found and no living animal has hearts spaced along the neck; a claim needs evidence, and the bones and living animals only show us a single heart system. Scientists instead test ideas like neck posture and heart size that the evidence can speak to.

7.3 How Big Could a Dinosaur Get?

OBJECTIVES

- Tell how *Argentinosaurus* was discovered and explain how scientists estimate the size of a giant from only a few bones.
- Use the square-cube law to show how surface area, volume and mass change when an animal is scaled up.
- Estimate an animal's mass from a scale model using water displacement, and explain why different estimates disagree.

Warm-up. Take 8 sugar cubes, dice or small building blocks. Count the faces you can see on one cube (6). Now build a bigger cube 2 wide, 2 long and 2 tall. How many small cubes did it take? Count the small square faces on the outside of the big cube. The big cube is twice as wide. Did the inside grow by the same amount as the outside?

Video. Coming soon. Titanosaur discoveries in Argentina (Argentinosaurus, Patagotitan) and how scientists estimate dinosaur weight, plus the square-cube law explained for students; search American Museum of Natural History, Field Museum, Smithsonian, SciShow Kids, Science Max and Homeschool Pop (Alternate).

KEY TERMS

scale factor
The number you multiply every length by when you make something bigger or smaller. A model at 1:100 has a scale factor of 100 to reach the real size.

surface area
The total area of the outside of an object, measured in square units such as cm^2 or m^2.

volume
The amount of space an object takes up, measured in cubic units such as cm^3 or m^3, or in milliliters and liters (1 mL = 1 cm^3).

square-cube law
When an object is scaled up by a factor, its areas grow by the factor squared and its volume and mass grow by the factor cubed. Double the size: area × 4, volume × 8.

femur
The thigh bone, the upper bone of the back leg. Its length and thickness help scientists estimate an animal's size.

titanosaur
A group of sauropods that includes the largest known land animals, such as *Argentinosaurus* and *Patagotitan*. Many have been found in South America.

CORE IDEAS

The story. In 1987, on his ranch near the town of Plaza Huincul in Neuquén Province, Argentina, a rancher named Guillermo Heredia found what he thought was a huge piece of petrified wood. Scientists from the town museum came to look. It was not wood at all. It was a leg bone. Digging turned up a few more giant bones: backbones taller than a sixth grader, part of a femur, a shin bone and some ribs. In 1993 the Argentine paleontologists José Bonaparte and Rodolfo Coria named the animal *Argentinosaurus*, "Argentina lizard." From those few bones it seemed to be one of the largest land animals ever found.

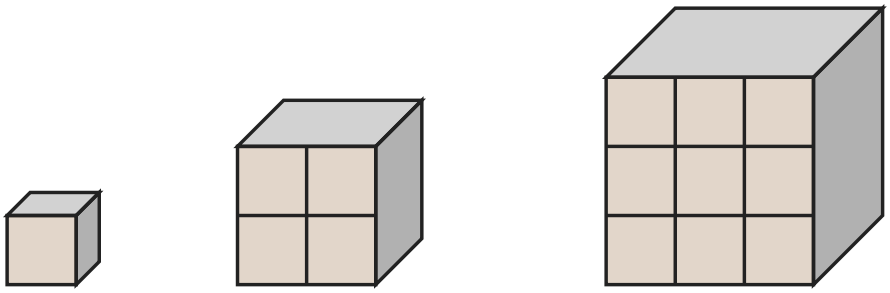
How they figured it out. How do you weigh an animal when you have only a few of its bones? Scientists use several methods and compare the answers. First, they compare the bones with those of more complete relatives and work out how long the whole animal probably was. For *Argentinosaurus* most estimates give a length of about 30 to 35 m. Second, they make an accurate scale model and measure its volume, then scale it up. Edwin Colbert of the American Museum of Natural History did this in 1962, lowering dinosaur models into water and sand to measure how much they displaced. Third, they measure the thickness of the leg bones, because in living animals the thicker the upper arm and thigh bones, the heavier the body they carry. Using these different methods, scientists have estimated *Argentinosaurus* at anywhere from about 60 to 100 tonnes. Those numbers are estimates, not weighings, and that is why they disagree.

The big idea. Why can't an animal just keep getting bigger? The answer is the **square-cube law**. If you make an animal twice as long, twice as wide and twice as tall, its **surface area** grows $2 \times 2 = 4$ times, but its **volume**, and so its mass, grows $2 \times 2 \times 2 = 8$ times. The strength of a leg bone depends on the area of its cross-section, which only grows 4 times. So the doubled animal puts twice as much load on every square centimeter of bone. To carry it safely, the bones must become much thicker for their length. Galileo explained this in 1638 and drew a small bone beside a bone three times longer for a giant, which had to be far thicker. That is why an elephant has stout, pillar-like legs while a gazelle has slender ones, and why the giant titanosaurs had thighs as thick as tree trunks. *Patagotitan*, found in Argentina in the 2010s, had a femur about 2.4 m long.

Try it and see. Size brings other problems too. A huge body must find enormous amounts of food. It must also get rid of heat: heat leaves through the surface, and a big animal has much less surface for each kilogram of body, so it holds its heat well but can overheat. Even eggs set a limit. A sauropod egg could not grow very large, because a thicker shell would keep the baby from getting air and from breaking out. Fossil titanosaur eggs found in Argentina are only about 15 cm across, not much bigger than a grapefruit, so each giant began small and grew fast. The blue whale escapes the weight problem because water holds it up, and so it remains heavier than any dinosaur whose bones we have actually found, though some sauropods may have been longer. In this lesson's project you will estimate the mass of a sauropod the way Colbert did.

God's handiwork. The square-cube law is part of the order God built into the world, and every creature is made to fit it. A spider's thin legs would snap under an elephant, and an

elephant’s heavy legs would be useless to a spider. The giants of the earth were not simply small animals made large. Their bones, hearts, lungs and eggs were all suited to their size.



side 1 cm	side 2 cm	side 3 cm
area 6 cm²	area 24 cm²	area 54 cm²
volume 1 cm³	volume 8 cm³	volume 27 cm³
ratio 6 : 1	ratio 3 : 1	ratio 2 : 1

Double the side: area × 4, volume × 8.

The square-cube law. As the side grows, the volume grows much faster than the surface area.

⏳ Thinking About Time

What the sign says. What the sign says: museums and textbooks place *Argentinosaurus* in the Late Cretaceous and say it lived about 95 million years ago.

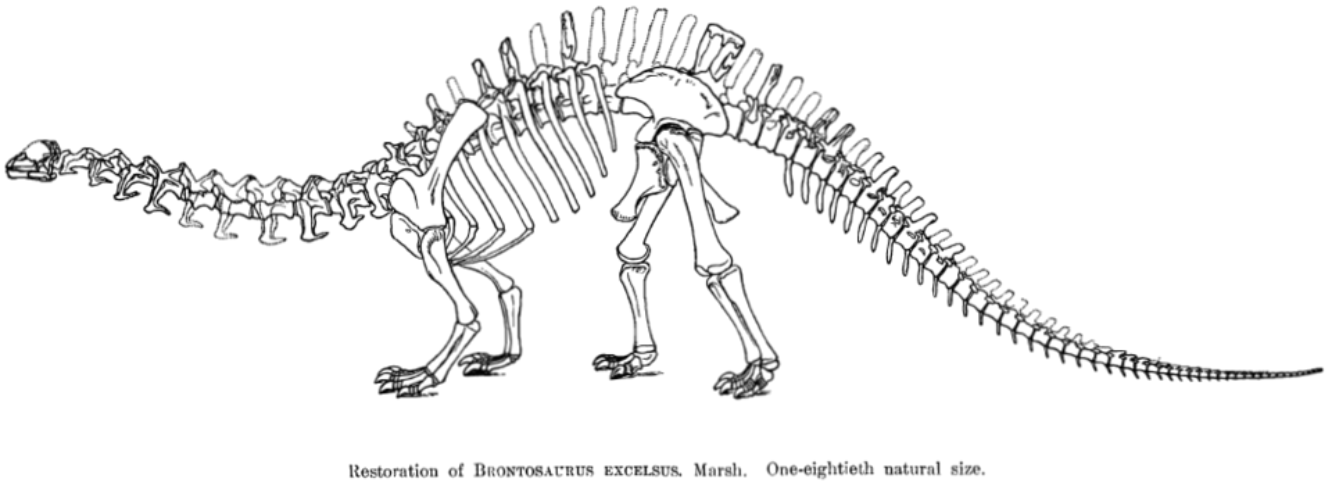
What we observe. What we observe: a small number of very large, mineralized bones buried in layers of sandstone and mudstone in Neuquén Province, Argentina. Bones this large are only preserved when they are buried before they rot, scatter or weather away, so they must have been covered by sediment quickly.

How Christians read it. How Christians read it: young-earth Christians see the rapid burial of giant animals in thick layers of water-laid sediment as fitting the great Flood of Genesis 6–9. They read the Bible to teach that the sauropods were created with the other land animals only thousands of years ago, and that the date on the sign is an interpretation of the rocks, not something written on the bones.

Try it. Ask: what would have to happen to a 70-tonne animal’s body for its bones to survive as fossils instead of being scattered and rotting away?

Genesis 7:11

PICTURE STUDY



Restoration of Brontosaurus excelsus, Othniel Charles Marsh (drawn under his direction), 1883 · Printed plate (engraving) published in the *American Journal of Science* · Published in New Haven, Connecticut; copies in many libraries, and the bones at the Yale Peabody Museum

Othniel Charles Marsh was a professor at Yale College and one of the great fossil hunters of the American West. His crews dug many sauropod bones at Como Bluff in Wyoming. In 1883 he published this drawing, one of the very first pictures of a whole sauropod skeleton, to show the world what a “thunder lizard” looked like.

Marsh did not have every bone. Some parts, including the head, were filled in from other skeletons or by careful guessing, and the true head shape of this kind of sauropod was not settled until the 1970s. That is exactly the problem you studied in this lesson: scientists must estimate the size and shape of a giant from the bones they have.

Look closely

- Compare the size of the skull with the size of the rib cage. What does that tell you about where the animal’s weight was?
- Look at the legs. Are they bent out to the sides like a lizard’s, or straight under the body like an elephant’s?
- Follow the tail. How does it end, and do you think it dragged on the ground?
- Which bones look thickest? Why would those bones need to be thick?

Talk about it

1. If you had only the bones of one leg, how could you use this drawing to guess the length of the whole animal?
2. Why might a scientist’s first restoration of a new animal be wrong in some places?
3. What new evidence could change a drawing like this?

> **Safety first.** Work over a tray or towel to catch spilled water, and keep the kitchen scale dry. Wash hands after handling modeling clay.

EXPERIMENT: WEIGH A DINOSAUR WITH WATER

You will make a 1:100 scale model of a sauropod 20 m long and use water to find its volume, just as Edwin Colbert did. At a scale of 1:100, every 1 mL of model volume stands for 1 m^3 of real dinosaur, and 1 m^3 of animal has a mass of roughly 1 tonne. So the number of milliliters is your estimate in tonnes.

Question: Do different people's models of the same dinosaur give the same mass estimate? **What we change:** the person who builds the model. **What we keep the same:** the scale (1:100), the length (20 cm), the clay, the method of measuring. **What we measure:** the volume of each model in milliliters.

You will need

- Oil-based modeling clay (not play dough, which softens in water)
- A sauropod skeleton or side-view picture to copy, from a book or museum website
- A ruler
- A kitchen scale that reads in grams
- A cup or bowl of water deep enough to cover the model
- A toothpick or thin skewer
- A tray or towel, and your lab notebook

Steps

1. Each builder makes a sauropod model exactly 20 cm long from nose to tail tip, copying the same picture as carefully as possible. Give it a full body, not a thin stick figure.
2. Write a prediction: how close will the estimates be?
3. Set the cup of water on the scale and press zero (tare), so the scale reads 0 g.
4. Push a toothpick into the model's back. Holding the toothpick, lower the model into the water until it is just covered. It must not touch the bottom or sides of the cup.
5. Read the scale. The number of grams equals the volume of the model in milliliters, because each milliliter of water the model pushes aside presses down with a mass of 1 gram.
6. Record each builder's result. Repeat each measurement twice and average.
7. Convert: at 1:100, the real volume is the model volume × 100 × 100 × 100 = model volume × 1,000,000. For example, 20 mL becomes 20,000,000 mL, which is 20 m^3, or about 20 tonnes.
8. Find the average and the range (largest minus smallest) of the family's estimates. Write a conclusion about why scientists' estimates of giant dinosaurs disagree.

Tips

- Wiggle out any trapped air bubbles before reading the scale.
- Sauropods had air sacs and air-filled bones, so they were probably a little lighter than water for their size. Some scientists multiply by about 0.8 or 0.9 to allow for that. Try it and see how much your estimate changes.

- A thick tail or fat belly changes the answer a lot. Notice which body parts cause the biggest differences between models.

Check your work

- I measured each model's volume in the same careful way.
- I used the scale factor cubed (1,000,000) to change model volume into real volume.
- I can explain why mass estimates for *Argentinosaurus* range from about 60 to 100 tonnes.

NATURE NOTEBOOK

1. Draw the three cubes from the figure and write each one's surface area and volume. Add a fourth cube with a side of 4 cm and work out its numbers.
2. Copy Galileo's idea: draw a small bone, then a bone three times as long that is thick enough to hold a giant. Label which grew more, the length or the thickness.
3. Draw a sauropod egg at real size (a circle about 15 cm across) and, on the same page, a tiny sketch of an adult *Argentinosaurus*. Write one sentence about how much the animal had to grow.

> **From history.** In 1878 the American paleontologist Edward Drinker Cope described a single sauropod vertebra from Colorado that he named *Amphicoelias fragillimus*. Even the incomplete bone he described was about 1.5 m tall, and he estimated the whole bone at well over 2 m. The bone was fragile, and at some point it crumbled or was lost; it has never been found. Some writers have used Cope's numbers to claim a sauropod far larger than any other. Most scientists today are cautious, because one lost bone cannot be checked, and a famous record built on missing evidence is only a guess.

WORKED EXAMPLES

Example 1. A cube 1 cm on each side has a surface area of 6 cm^2 and a volume of 1 cm^3. Find the surface area and volume for cubes with sides of 2 cm and 3 cm. By what factor does each grow?

(Use the map or drawing "Check your work against the figure." shown earlier in this lesson.)

1. Surface area = 6 × side × side. Side 2: 6 × 2 × 2 = 24 cm^2. Side 3: 6 × 3 × 3 = 54 cm^2.
2. Volume = side × side × side. Side 2: 2 × 2 × 2 = 8 cm^3. Side 3: 3 × 3 × 3 = 27 cm^3.
3. Growth: doubling the side multiplies area by 24 ÷ 6 = 4 and volume by 8 ÷ 1 = 8. Tripling the side multiplies area by 54 ÷ 6 = 9 and volume by 27.

Answer: Side 2: 24 cm^2 and 8 cm^3 (area × 4, volume × 8). Side 3: 54 cm^2 and 27 cm^3 (area × 9, volume × 27). Volume grows faster than area.

Example 2. A careful 1:40 model of a sauropod displaces 600 mL of water. Estimate the real animal's volume and mass, using 1,000 kg for each cubic meter. Then estimate again using 800 kg per cubic meter to allow for air sacs.

1. Scale factor cubed: 40 × 40 × 40 = 64,000.
2. Real volume: 600 mL × 64,000 = 38,400,000 mL. Since 1,000,000 mL = 1 m^3, that is 38.4 m^3.
3. Mass at 1,000 kg/m^3: 38.4 × 1,000 = 38,400 kg, about 38 tonnes.
4. Mass at 800 kg/m^3: 38.4 × 800 = 30,720 kg, about 31 tonnes.

Answer: About 38.4 m^3, giving a mass of about 38 tonnes, or about 31 tonnes if the body was lightened by air. The choice of density alone changes the answer by almost 8 tonnes.

Example 3. An animal of 10 tonnes is scaled up so every length doubles. What is its new mass? By what factor does the cross-section area of its leg bones grow if they keep the same shape? How does the load on each square centimeter of bone change?

1. Mass grows by 2 × 2 × 2 = 8, so 10 t × 8 = 80 t.
2. Bone cross-section area grows by 2 × 2 = 4.
3. Load per square centimeter = mass ÷ area, so it grows by 8 ÷ 4 = 2.

Answer: The new animal is 80 tonnes, its bone area is only 4 times larger, and every square centimeter of bone carries twice the load. To be safe, the giant needs bones much thicker for their length.

PRACTICE

1. EASY State the square-cube law in your own words.
2. EASY Who found the first bone of *Argentinosaurus*, and what did he first think it was?
3. EASY Name three methods scientists use to estimate the mass of a dinosaur known from bones.
4. MEDIUM A toy dinosaur is scaled up by a factor of 4 in every direction. By what factor do its surface area and its volume grow?
5. MEDIUM A 1:50 model displaces 200 mL. What is the real animal's volume in cubic meters, and its approximate mass at 1,000 kg per cubic meter?
6. MEDIUM Data reading. Rounded size estimates (the sauropods are known only from partial skeletons):
   Blue whale: 30 m, 150 t
   Patagotitan: 37 m, 60 t
   Argentinosaurus: 35 m, 70 t
   Diplodocus: 26 m, 14 t
   African elephant: 7 m, 6 t

(a) Which is longest? (b) Which is heaviest? (c) Is length alone a good way to predict mass? Use two animals from the table to explain.

7. MEDIUM Data reading. Four people made 1:100 models of the same sauropod. Their volumes were 22 mL, 18 mL, 25 mL and 19 mL. (a) What is the average estimate in tonnes? (b) What is the range? (c) Which conclusion is best supported? (A) The sauropod weighed exactly 21 tonnes. (B) The method gives a rough estimate, about 18 to 25 tonnes. (C) The method does not work.
8. HARD Find the surface area, volume and area-to-volume ratio of a cube 4 cm on each side. Use the pattern to explain why a giant animal holds heat better than a small one.
9. CHALLENGE Experiment design. Design an experiment with uncooked spaghetti to test whether a thicker “leg” holds more weight. Name the independent variable, dependent variable, at least three controlled variables and how you would record results.
10. CHALLENGE In 1878 Edward Drinker Cope described a single, enormous sauropod backbone from Colorado. The bone was later lost, leaving only his drawing and measurements. Some people have called it the biggest dinosaur ever. Write three or four sentences explaining how a careful scientist should treat this claim.

COMMON MISTAKES

- Thinking a giant is just a small animal made bigger. Because of the square-cube law, a giant needs much thicker bones, stronger hearts and different body proportions.
- Thinking a dinosaur’s mass is weighed or known exactly. Every dinosaur mass is an estimate, and different methods can give answers tens of tonnes apart.
- Thinking the biggest dinosaurs were heavier than the blue whale. The blue whale is the heaviest animal known for certain; some sauropods may have been longer, but probably not heavier.

> **Make it a game · Scale It Up!.** A parent calls out a scale factor, such as “3!” Players race to shout the area factor and then the volume factor (“9 and 27!”). The first correct pair wins a point. For harder rounds the parent names an animal and a mass, such as “a 2-tonne dinosaur, scale factor 2,” and players must give the new mass (16 tonnes). First to seven points is the Titanosaur Champion.

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

No one was there to weigh a living *Argentinosaurus*. We study the bones carefully and make our best estimates, but God’s question to Job reminds us to be humble about what we can know of the past, and to stand in awe of the One who saw it all.

Practice answers

1. When something is scaled up, its area grows by the scale factor squared, but its volume (and mass) grows by the scale factor cubed, so volume and weight grow faster than area and strength.

2. The rancher Guillermo Heredia, on his land near Plaza Huincul, Argentina, in 1987. He thought it was a piece of petrified wood.
3. Comparing its bones with more complete relatives and scaling up; measuring the volume of a scale model (water displacement) and multiplying; using the thickness of the leg bones, which in living animals goes with body mass.
4. Area: 4 × 4 = 16 times. Volume: 4 × 4 × 4 = 64 times.
5. 50 × 50 × 50 = 125,000. 200 mL × 125,000 = 25,000,000 mL = 25 m^3. Mass about 25,000 kg, or 25 tonnes.
6. (a) *Patagotitan*, 37 m. (b) The blue whale, 150 t. (c) No. *Diplodocus* is 26 m long but only about 14 t because it was slender with a thin neck and whip-like tail, while the blue whale is only 4 m longer but more than ten times heavier because its body is thick all the way along.
7. (a) (22 + 18 + 25 + 19) ÷ 4 = 84 ÷ 4 = 21 mL, so about 21 tonnes. (b) 25 − 18 = 7 tonnes. (c) (B). Every model gave a similar answer, but small differences in body shape change the result, so it is an estimate, not an exact weight.
8. Area: 6 × 4 × 4 = 96 cm^2. Volume: 4 × 4 × 4 = 64 cm^3. Ratio: 96 ÷ 64 = 1.5 to 1 (compared with 6 to 1 for a 1 cm cube). Heat is made inside the whole volume but escapes through the surface. A giant has much less surface for each unit of volume, so heat escapes more slowly; it stays warm easily but must take care not to overheat.
9. Independent variable: the number of spaghetti strands bundled together (for example 1, 2, 4 and 8) as a stand-in for leg thickness. Dependent variable: the mass (or number of coins) the bundle holds before it breaks or buckles. Controls: the same brand and kind of spaghetti, the same length of bundle, the same way of loading (coins added one at a time to the same cup), the same support at the bottom. Do three trials for each bundle, record in a table, find averages, and graph mass held against number of strands.
10. A careful scientist would say the claim is possible but not proven. One partial bone, now lost, cannot be measured again or checked by others, and Cope’s measurement or drawing might contain errors. Size estimates scaled up from one bone depend on assuming the animal was shaped like its relatives. The claim should be held loosely until new, well-preserved bones are found and studied.

7.4 Engineering a Giant

OBJECTIVES

- Tell the story of Andrew Carnegie's *Diplodocus* and explain how new evidence changed the way its skeleton was mounted.
- Explain how column legs, hollow bones, ligaments and a balanced neck and tail let a sauropod carry its great weight.
- Use the lever rule and weight-per-area calculations to analyze a sauropod's body, and test paper columns in a fair experiment.

Warm-up. Lay a ruler across a round pencil like a seesaw, with the 15 cm mark on the pencil. Stack 2 coins on the ruler 12 cm from the pencil on one side. Predict where you must put a stack of 3 coins on the other side to balance it. Try it. A sauropod's neck and tail balanced over its legs in the same way.

Video. Coming soon. Mounting the Diplodocus skeleton (Carnegie Museum and "Dippy" at the Natural History Museum, London), sauropod trackways and how columns and I-beams carry loads; search Carnegie Museum of Natural History, Natural History Museum London, Smithsonian, Science Max, SciShow Kids and engineering explainer channels for students.

KEY TERMS

column
An upright support that carries weight straight down, like a pillar. Straight legs under the body work as columns.

center of mass
The balance point of an object, where its weight acts as if it were all gathered in one spot. An animal is stable when its center of mass is over its feet.

lever rule
A seesaw balances when mass × distance on one side equals mass × distance on the other side of the pivot.

cantilever
A beam held up at only one end or in the middle, sticking out into the air, like a diving board or a crane's arm. A sauropod's neck and tail were living cantilevers.

ligament
A tough band of tissue that connects bone to bone. A strong ligament along the top of a sauropod's backbone helped hold up its neck and tail like a cable.

hollow tube
A shape with its material spread out around an empty middle, like a bicycle frame or a bone. A tube is much stiffer than a solid rod made of the same amount of material.

CORE IDEAS

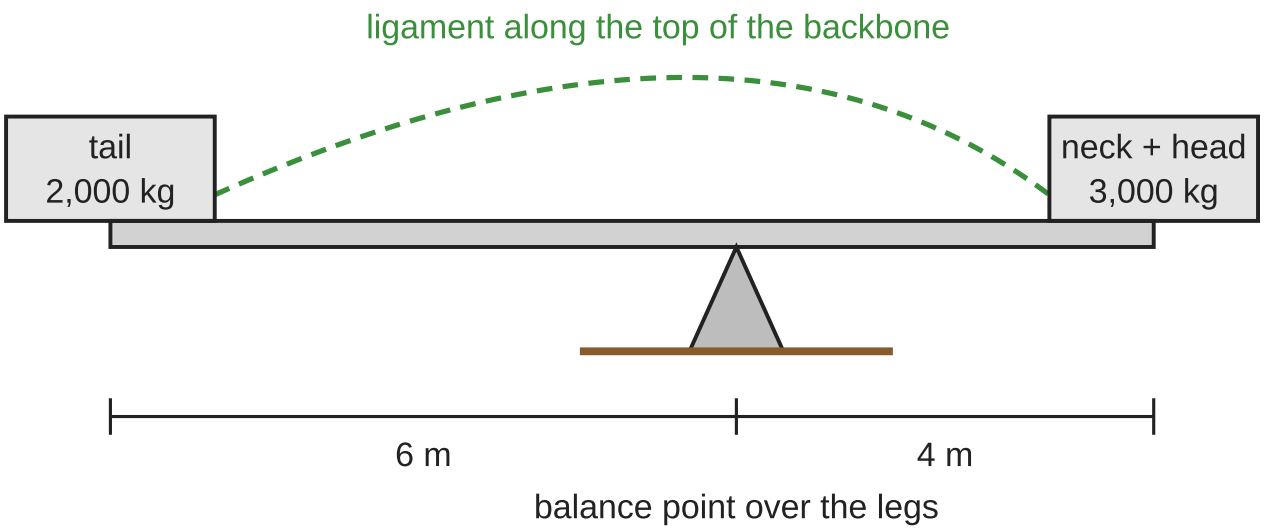
The story. In 1898 the Pittsburgh steel maker Andrew Carnegie read a newspaper story about a giant dinosaur and decided his new museum must have one. He paid for fossil hunters to search the West. On July 4, 1899, at Sheep Creek in Wyoming, his team found the bones of a long, slender sauropod. In 1901 the paleontologist John Bell Hatcher named it *Diplodocus carnegii* in Carnegie's honor. The skeleton was about 26 m long. When King Edward VII of Britain saw a drawing of it, the story goes, he asked for one too, so Carnegie had plaster casts made of every bone. On May 12, 1905, a complete cast of *Diplodocus* was unveiled at the Natural History Museum in London. The British public called it "Dippy."

How they figured it out. Putting a giant skeleton together is an engineering problem. The museum preparator Arthur Coggeshall designed a steel frame to hold hundreds of bones in a standing pose. In 1905 the scientists posed Dippy with its tail dragging on the floor, the way people then pictured sauropods, like giant lizards. But evidence piled up against that pose. Sauropod trackways show the footprints of all four feet and almost never any groove from a dragging tail. The joints of the tail bones also fit best with the tail held out straight behind. So in 1993 the London museum remounted Dippy with its tail lifted high in the air. A better pose came from better evidence.

The big idea. A sauropod body uses the same ideas engineers use. First, its legs were **columns**. They stood straight under the body, like an elephant's or the pillars of a building, so the weight pressed straight down along the bones instead of bending them. The feet had thick, fleshy pads, as trackways show, which spread the weight over a large area. Second, the long neck and tail were **cantilevers**, sticking out from the body and balanced over the legs like the arm and counterweight of a crane. Using the **lever rule**, a heavy tail far behind the hips could balance a neck in front. A strong **ligament** along the top of the backbone held them up the way cables hold up a bridge, so the muscles did not have to work all the time. Third, the backbones were not solid lumps. They were built of thin bony plates and hollow, air-filled spaces, like steel I-beams and tubes: strong where strength was needed and light everywhere else.

Try it and see. A fourth design trick was a small, light head. *Diplodocus* did not chew. It stripped leaves with its peg-like front teeth and swallowed them whole, leaving the slow work of digestion to its huge gut. A heavy jaw full of grinding teeth on the end of a 7 m neck would have been far harder to hold up. Engineers today use the same ideas: tubes for bicycle frames and scaffolding, I-beams for skyscrapers, counterweights for cranes, cables for long bridges. In this lesson's project you will test whether a sheet of paper makes a stronger column as a solid rod or as a hollow tube, and you may be surprised how much weight one sheet can hold.

God's handiwork. When God answered Job out of the whirlwind, He described Behemoth: "His bones are as strong pieces of brass; his bones are like bars of iron." A sauropod carried tens of tonnes on four legs, swung a neck many meters long and held its tail aloft on living cables, all with bones that were partly air. Human engineers needed centuries to learn these principles. The Designer built them into His creatures from the beginning.



2,000 kg × 6 m = 3,000 kg × 4 m

A simplified model: the neck and tail balance over the legs like a seesaw. 2,000 kg × 6 m = 3,000 kg × 4 m.

⏳ Thinking About Time

What the sign says. What the sign says: museum signs and textbooks place *Diplodocus* in the Late Jurassic and say it lived about 150 million years ago.

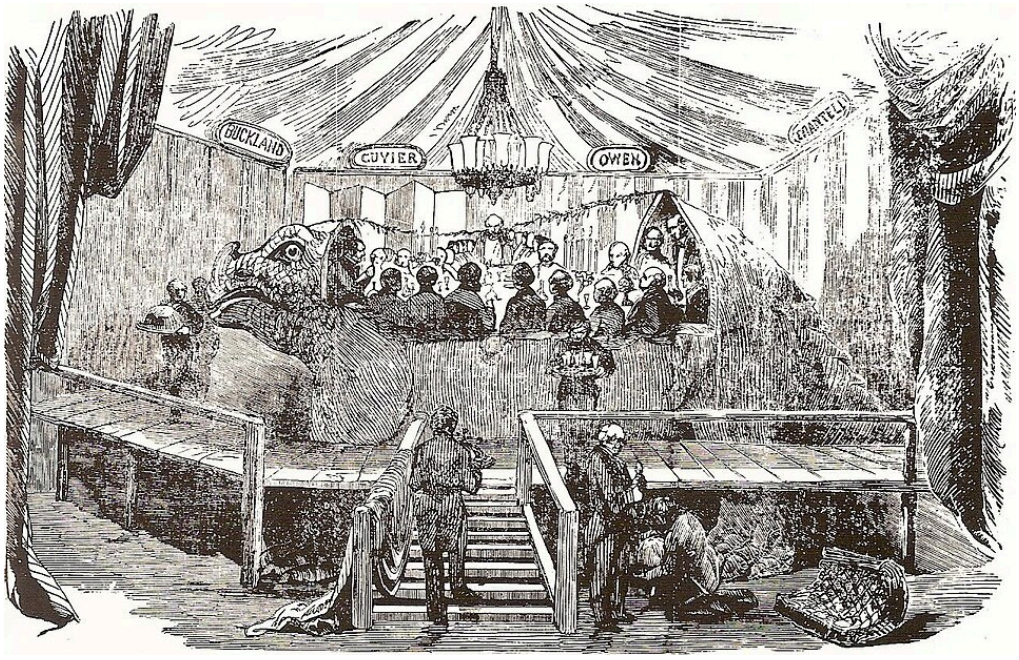
What we observe. What we observe: *Diplodocus* bones are found in the Morrison Formation, layers of sandstone and mudstone that stretch across parts of several western states. At the quarry Earl Douglass opened for the Carnegie Museum in 1909, now Dinosaur National Monument, a single tilted sandstone layer holds about 1,500 bones of many kinds of dinosaurs, jumbled together, some still joined and many scattered, as if swept along by moving water and buried.

How Christians read it. How Christians read it: young-earth Christians read Genesis to teach a recent creation and see huge bone beds like this one, and the wide Morrison layers, as the work of the year-long Flood, when the waters covered the earth and buried animals by the thousands in sediment that later hardened. The number on the sign is an interpretation of the layers, while the jumbled bones in rock are what we can see.

Try it. Look at photographs of the Quarry Exhibit Hall wall at Dinosaur National Monument on the National Park Service website and count how many bones you can see in one small square of the wall.

Genesis 7:19

PICTURE STUDY



Dinner in the Iguanodon Model at the Crystal Palace, Sydenham, Engraver for *The Illustrated London News*, Published January 7, 1854 (the dinner was held on December 31, 1853) · Wood engraving · *The Illustrated London News*; the sculptures still stand in Crystal Palace Park, London

In 1852 and 1853 the sculptor Benjamin Waterhouse Hawkins built the first life-size models of dinosaurs in the world, for the park of the Crystal Palace in south London. He worked with the scientist Richard Owen, who had invented the word “dinosaur” in 1842. Each model was a real engineering job: a frame of iron, with brick, tiles and cement built up around it, and an outer skin of sculpted stucco. To celebrate, Hawkins held a New Year’s Eve dinner for scientists and friends inside the half-built mold of his *Iguanodon*, and this engraving of the party appeared in the newspaper a week later.

Hawkins and Owen made their best guesses from only a few bones. They gave *Iguanodon* four heavy legs like a rhinoceros and a horn on its nose. When many complete skeletons were found in a Belgian coal mine at Bernissart in 1878, scientists learned that the “horn” was really a spike on its thumb. The models in the park still show the old ideas, and they have become a lesson in how science corrects itself.

Look closely

- Find the dinosaur. How many people fit inside or around it? What does that tell you about its size?
- Look at the shape of the model’s body and legs. Which living animal does it remind you of?
- Look for banners, flags and the tent overhead. How did the artist show this was a grand celebration?
- What tools or building materials would Hawkins have needed to make a model this big?

Talk about it

1. Hawkins built a giant out of iron, brick and cement. How is that like the way a living giant's skeleton holds up its body?
2. What did Hawkins get wrong about *Iguanodon*, and what new evidence corrected it?
3. Why do you think so many people wanted to see these models in 1854?

> **Safety first.** Stand back as the books get high, keep feet and fingers out from under the cardboard, and use only books an adult says may fall to the floor.

EXPERIMENT: PAPER PILLARS: TUBE OR ROD?

Sauropod leg bones and backbones were built like tubes and beams, not solid rods. In this experiment you will roll identical sheets of paper into three kinds of column and find out which shape holds the most weight.

Question: Does the shape of a paper column change how much weight it can hold? **Prediction:** write yours first. **What we change:** the shape: a wide hollow tube, a narrow hollow tube, or a tightly rolled solid rod. **What we keep the same:** the kind and size of paper (one sheet per column), the height of the columns, three columns per test, and the way books are added. **What we measure:** the number of books held before the columns buckle.

You will need

- At least 18 sheets of the same printer paper (8.5 × 11 in or A4)
- Clear tape
- A marker or thick pen to roll paper around, and a soup can
- A piece of stiff cardboard about 30 cm square
- A stack of books of about the same size (or bags of rice of equal mass and a kitchen scale)
- A ruler and your lab notebook

Steps

1. Make three wide tubes: roll each sheet around a soup can, the short way so the tube is about 22 cm tall (21 cm for A4), tape the seam, and slide out the can.
2. Make three narrow tubes the same height by rolling each sheet around a marker, taping it, and sliding out the marker.
3. Make three solid rods the same height by rolling each sheet as tightly as you can with no hole in the middle, then taping it.
4. Stand the three wide tubes upright in a triangle on a hard floor, set the cardboard on top, and add books one at a time, gently, in the center. Count the books held before the columns crumple. Record.
5. Repeat with the narrow tubes and with the solid rods.

6. Make new columns and repeat the whole test a second time. Find the average for each shape.
7. Make a bar graph and write a conclusion. Which shape held the most? Every column used the same amount of paper, so what made the difference?

Tips

- Place each book gently. Dropping a book tests impact, not steady weight, and makes the test unfair.
- Keep the column ends flat and even. A crooked column fails early.
- If the wide tubes hold all your books, weigh the stack on a bathroom scale instead of counting.

Check your work

- I used the same paper, height and number of columns for every shape.
- I ran two complete tests and found averages.
- I can explain why bones and steel beams use tube and plate shapes instead of solid rods.

NATURE NOTEBOOK

1. Draw a *Diplodocus* from the side as an engineer’s diagram. Label the columns (legs), the cantilevers (neck and tail), the cable (ligament along the backbone) and the balance point.
2. Sketch a cross-section of a solid rod, a hollow tube and an I-beam. Under each, write one place you have seen that shape in a building, bridge or bicycle.
3. Draw Dippy as mounted in 1905 (tail dragging) and as remounted in 1993 (tail raised). Under the drawings, write the evidence that changed the pose.

> **From history.** Andrew Carnegie sent casts of his *Diplodocus* to museums in Berlin, Paris, Vienna and other cities after London, so for many people in Europe and the Americas it was the first dinosaur they ever saw. London’s Dippy stood in the museum’s great entrance hall for decades. In 2017 the museum took it down to send it on a tour of Britain and hung in its place the real skeleton of a blue whale, about 25 m long, which it named “Hope.” So the two kinds of giants in this unit, the whale and the sauropod, have taken turns welcoming visitors in the same hall.

WORKED EXAMPLES

Example 1. In a simplified model, a sauropod's tail has a mass of 2,000 kg acting 6 m behind the balance point over its legs. Its neck and head act 4 m in front of the balance point. What mass of neck and head would balance the tail?

(Use the map or drawing "2,000 × 6 = 3,000 × 4." shown earlier in this lesson.)

1. Lever rule: mass × distance on one side = mass × distance on the other.
2. Tail side: 2,000 kg × 6 m = 12,000 kg·m.
3. Neck side: mass × 4 m must also equal 12,000 kg·m, so mass = 12,000 ÷ 4 = 3,000 kg.

Answer: 3,000 kg. A lighter tail can balance a heavier neck because the tail acts farther from the balance point.

Example 2. A 40,000 kg sauropod stands on four feet, each with a pad area of about 2,500 cm². A 5,000 kg elephant stands on four feet of about 1,250 cm² each. Assuming each animal's weight is shared equally among its feet, how many kilograms press on each square centimeter of foot?

1. Sauropod mass per foot: 40,000 ÷ 4 = 10,000 kg. Per square centimeter: 10,000 ÷ 2,500 = 4 kg/cm².
2. Elephant mass per foot: 5,000 ÷ 4 = 1,250 kg. Per square centimeter: 1,250 ÷ 1,250 = 1 kg/cm².
3. Compare: 4 ÷ 1 = 4.

Answer: About 4 kg/cm² for the sauropod and 1 kg/cm² for the elephant. The sauropod pressed about four times as hard on the ground, which is why its trackways sank deep and why it needed thick foot pads and pillar legs.

Example 3. Sample data from the Paper Pillars test (books held before buckling): wide tubes 12 and 14; narrow tubes 6 and 7; solid rods 2 and 2. Find each average. How many times more did the wide tubes hold than the solid rods?

1. Wide tubes: (12 + 14) ÷ 2 = 13 books.
2. Narrow tubes: (6 + 7) ÷ 2 = 6.5 books.
3. Solid rods: (2 + 2) ÷ 2 = 2 books.
4. Compare: 13 ÷ 2 = 6.5.

Answer: Averages: 13, 6.5 and 2 books. The wide tubes held 6.5 times as much as the solid rods, though every column used exactly one sheet of paper. Spreading material out away from the center makes a column much stiffer.

PRACTICE

1. EASY Why is it better for a heavy animal to stand with its legs straight under its body instead of sprawled out to the sides?
2. EASY What did sauropod trackways show about how they carried their tails?
3. EASY Name two ways a sauropod's backbone was like a steel I-beam or tube.
4. MEDIUM Using the lever rule, a neck of 4,000 kg acts 3 m in front of the balance point. What tail mass acting 6 m behind would balance it?
5. MEDIUM A 20,000 kg sauropod stands on four feet of 2,000 cm^2 each, with its weight shared equally. How many kilograms press on each square centimeter?
6. MEDIUM Data reading. Use the sample Paper Pillars averages: wide tube 13 books, narrow tube 6.5 books, solid rod 2 books. Which conclusion is best supported? (A) More paper always makes a stronger column. (B) With the same amount of paper, wider hollow tubes hold more. (C) Solid columns are strongest. (D) Shape does not matter.
7. MEDIUM Data reading. An engineering class tested three beams of equal mass and length, supported at both ends, and added weight to the middle until each bent 1 cm. Sample results: solid square bar, 20 kg; hollow square tube, 55 kg; I-beam, 70 kg. (a) Which shape was stiffest? (b) How many times stiffer was it than the solid bar? (c) What does this suggest about why sauropod vertebrae were built of thin plates?
8. HARD Dippy was mounted in 1905 with its tail on the floor and remounted in 1993 with its tail in the air. Explain why the change was good science, not just a change of opinion.
9. CHALLENGE Experiment design. Design an experiment to test whether a model animal holds more weight with its legs straight under its body or angled out to the sides. Use craft sticks or pencils for legs. Name the independent and dependent variables, three controls and how many trials you would do.
10. CHALLENGE You are an engineer asked to design a 50-tonne land animal. List four features you would give it, and for each explain the reason using ideas from this unit.

COMMON MISTAKES

- Picturing sauropods dragging their tails on the ground. Trackways show no tail drags; the tail was held out behind as a counterweight.
- Thinking the strongest bone is a solid one. For the same amount of material, a hollow tube or plate-built shape is stiffer and lighter.
- Drawing sauropods with legs sprawled out to the sides like lizards. Their legs stood straight under the body like an elephant's.

> **Make it a game · Balance the Giant.** Use the ruler-and-pencil seesaw from the warm-up. One player places a stack of coins (the tail) somewhere on one side. The other player must predict, using the lever rule, where to place a different stack (the neck) to balance it, then test. A balance on the first try scores 2 points; within one move, 1 point. Take turns, and try stacks of 1 to 4 coins.

> **Scripture.** “His bones are as strong pieces of brass; his bones are like bars of iron. He is the chief of the ways of God: he that made him can make his sword to approach unto him.” (Job 40:18–19, KJV)

God describes Behemoth with an engineer’s words: bones like brass and bars of iron. The greatest beasts are called “the chief of the ways of God,” yet they remain under the hand of the One who made them.

Practice answers

1. Straight legs act like columns: the weight presses straight down along the bones. Sprawled legs bend at the joints, so muscles must work hard all the time to keep the body from sagging, and the bones are bent instead of squeezed.
2. The trackways show footprints but almost never a groove from a dragging tail, so the tail was held up off the ground.
3. It was made of thin bony plates placed where the forces were greatest, and it had hollow air-filled spaces, so it was strong but light, just as I-beams and tubes put material where it is needed and leave the rest empty.
4. 4,000 × 3 = 12,000 kg·m. 12,000 ÷ 6 = 2,000 kg.
5. 20,000 ÷ 4 = 5,000 kg per foot. 5,000 ÷ 2,000 = 2.5 kg/cm^2.
6. (B). Every column used one sheet, so the amount of paper was the same; only the shape changed, and the wider hollow tubes held the most. (A) cannot be tested here because paper amount did not change.
7. (a) The I-beam. (b) 70 ÷ 20 = 3.5 times. (c) Shapes that place material in thin plates far from the center are stiffer for the same mass, so plate-like, hollow vertebrae gave sauropods strength without heavy weight.
8. The change was based on evidence: trackways showed no tail-drag marks, and study of how the tail bones fit together showed the tail was held out behind. Scientists changed the mount because new evidence showed the old pose was wrong. Good science follows the evidence and corrects mistakes.
9. Independent variable: leg position (straight down or angled out at, say, 45°). Dependent variable: the mass (or number of coins) the model holds before it collapses. Controls: same leg material and length, same body (a piece of cardboard), same way of joining legs, same place where weight is added, same surface. Do at least three trials of each and compare averages.
10. Sample answer: (1) Straight, thick, pillar-like legs under the body, because columns carry weight straight down and the square-cube law means big animals need thick bones. (2) Broad padded feet, to spread the weight and lower the pressure on each square centimeter. (3) Hollow, air-filled vertebrae built of thin plates, for strength without extra weight. (4) A long tail to counterbalance a long neck over the legs, held up by a strong ligament like a bridge cable. A small, light head and a powerful, thick-walled heart would also help.

Unit 7 review

Answer each question. Show your work for every calculation, include units, and use complete sentences for explanations. The test is worth 60 points.

1. (4 pts) Multiple choice. Which feature shows that a blue whale is a mammal? (A) It lives in the ocean. (B) It feeds its calf milk. (C) It has fins and a tail. (D) It eats krill.
2. (5 pts) A tag on a blue whale records 32 beats per minute at the surface and 2 beats per minute deep in a dive. How many times faster does the heart beat at the surface? Explain how slowing the heart helps the whale.
3. (5 pts) A blue whale eats about 3,600 kg of krill a day. How much does it eat in one week, in kilograms and in tonnes? Explain how baleen lets it eat such tiny animals.
4. (4 pts) Multiple choice. How many neck vertebrae does a giraffe have? (A) 3 (B) 7 (C) 15 (D) 19
5. (6 pts) Use the rule: pressure needed = 100 mmHg + 80 mmHg for each meter the head is above the heart. What pressure would a sauropod need with its head 6 m above its heart? About how many times a person’s 120 mmHg is that?
6. (5 pts) Explain two ways that air-filled (pneumatic) bones and air sacs helped a sauropod with a very long neck.
7. (6 pts) An animal of 5 tonnes is scaled up so that every length is 3 times larger. By what factor does its surface area grow? Its mass? What is its new mass? Why does this mean its bones must become relatively thicker?
8. (6 pts) A 1:20 scale model of an elephant displaces 750 mL of water. Estimate the real elephant’s volume in cubic meters and its mass, using 1,000 kg per cubic meter. Show your steps.
9. (6 pts) Diagram item. Draw a simple seesaw diagram of a sauropod: a beam on a pivot labeled “legs (balance point),” a tail on one side and a neck on the other. The tail has a mass of 1,500 kg and acts 8 m from the pivot. The neck acts 4 m from the pivot. Label both distances and both masses, and calculate the neck mass that balances the tail.
10. (6 pts) Name three engineering features of a sauropod body and explain how each helped it carry its great weight.
11. (7 pts) Short answer. The blue whale (about 150 tonnes) is heavier than any dinosaur whose bones have been found, while the largest titanosaurs are estimated at about 60 to 100 tonnes. (a) Explain, using the idea of buoyancy, why a whale can be heavier than any land animal. (b) Give two reasons why estimates for *Argentinosaurus* cover such a wide range.

Unit project: Giants to scale: a life-size chalk mural and engineer’s report

On a long driveway, empty parking lot or playground (with permission), measure and draw in chalk the life-size outlines of a blue whale (30 m) and a sauropod such as *Diplodocus* (26 m), side by side, with a sixth grader (1.5 m) and an elephant (about 7 m including the trunk) for

scale. Mark where each animal's heart would be. Photograph the mural from above or from a high window.

Then make an Engineer's Report on poster board or in your notebook: your photographs, your heart-rate graph and Water Tower, Weigh a Dinosaur and Paper Pillars data tables, one worked calculation each for blood pressure, the square-cube law and the lever rule, and a one-page essay answering the question "How big can an animal get, and why?" End with a ⏳ box of your own for one sauropod: what the sign says, what we observe and how Christians read it.

- **Accurate measurement**: The chalk outlines are measured to the correct lengths in meters, labeled, and include hearts and scale figures.
- **Data and calculations**: Data tables from the unit's experiments are complete with averages, and the three worked calculations are correct with units.
- **Scientific explanation**: The essay correctly uses buoyancy, blood pressure, the square-cube law and engineering ideas (columns, hollow bones, balance) to explain the limits of size.
- **Thinking about time and care**: The ⏳ box fairly separates the sign's claim, the observations and the Christian reading; the report is neat, organized and clearly labeled.

Answer key

1. (B). Mammals feed their young milk. Fish also live in the ocean and have fins and tails, so (A) and (C) do not show it is a mammal.
2. 32 ÷ 2 = 16 times faster. Slowing the heart (the dive response) saves oxygen and sends blood mainly to the brain and heart, so one breath lasts through a long dive.
3. 3,600 × 7 = 25,200 kg, or 25.2 tonnes. The whale gulps water full of krill, then pushes the water out through its baleen plates, whose frayed edges act like a fine strainer and keep the krill inside to be swallowed.
4. (B) 7, the same number as a person. Its neck bones are simply very long.
5. 6 × 80 = 480; 480 + 100 = 580 mmHg. 580 ÷ 120 ≈ 4.8, so almost 5 times a person's blood pressure.
6. (1) Air spaces made the neck bones much lighter, so the long neck was easier to hold up and move. (2) Bird-like air sacs kept fresh air flowing one way through the lungs, so the animal could breathe well even with a very long windpipe full of stale air.
7. Area grows 3 × 3 = 9 times; mass grows 3 × 3 × 3 = 27 times; new mass 5 × 27 = 135 tonnes. Bone strength depends on cross-section area, which only grows 9 times while the weight grows 27 times, so each square centimeter of bone would carry 3 times the load unless the bones become much thicker.
8. 20 × 20 × 20 = 8,000. 750 mL × 8,000 = 6,000,000 mL = 6 m^3. Mass about 6 × 1,000 = 6,000 kg, or 6 tonnes.
9. Diagram shows a beam on a pivot labeled as the legs, the tail box labeled 1,500 kg at 8 m on one side, and the neck box at 4 m on the other. Calculation: 1,500 × 8 = 12,000 kg·m; 12,000 ÷ 4 = 3,000 kg. Neck mass 3,000 kg. (Full credit requires a labeled pivot, both distances, both masses and the correct calculation.)

10. Any three, with reasons: column legs straight under the body carry weight straight down the bones; broad padded feet spread the weight over a large area; hollow vertebrae built of thin plates are strong but light, like I-beams and tubes; a long tail counterbalances the neck over the legs like a crane; a strong ligament along the backbone holds up the neck and tail like a bridge cable; a small, light head without grinding teeth is easy to hold at the end of the neck.
11. (a) Water holds up most of a whale’s weight (buoyancy), so its skeleton does not have to carry its full weight as legs on land would; its size is limited more by food and oxygen. (b) Any two: only a few bones have been found, so the rest of the body must be estimated from relatives; different methods (scale models, leg-bone thickness) give different answers; small changes in the guessed body shape change the volume a lot; scientists use different values for body density because of air sacs.

UNIT 8

Biomimicry

All through this year you have watched animals fly, migrate, echolocate, hide, build and work together. In this last unit you will ask an inventor's question: **what can people learn from the way living things are made?** Learning from the designs in creation to solve human problems is called **biomimicry**. The Wright brothers studied buzzards, and scientists found that bats had been using the idea behind sonar all along; now you will see the habit of learning from creation at work in four more stories.

You will start in 1941 with George de Mestral, who put a burdock burr under his microscope and, after ten years of failures, gave the world the hook-and-loop fastener. You will look at shark skin, covered with thousands of tiny "skin teeth" whose ridges help a shark slip through the water and stay clean, and see how engineers copied them for ships and planes. You will zoom in on a gecko's toe, from ridges to hairs to tips smaller than the wavelength of light, and learn how millions of faint molecular attractions let it run across a ceiling. Finally you will follow Eiji Nakatsu as a diving kingfisher showed him how to quiet Japan's bullet train, and you will use the same design cycle to invent something yourself.

In every lesson you will measure, calculate and test: hooks per square centimeter, percent drag reduction, forces in newtons, sizes in micrometers and nanometers, and averages from your own trials compared with a control. And you will see that the best inventors are humble students. As Job said, "ask now the beasts, and they shall teach thee" (Job 12:7). The designs were there all along, waiting to be searched out.

BEFORE YOU BEGIN

- Can multiply and divide decimals and find a percent of a number
- Can find the area of a rectangle in square centimeters
- Knows metric length units (km, m, cm, mm) and can convert between them
- Can name the independent variable, dependent variable and controlled variables in a simple experiment

MASTERY CHECKLIST

- I can define biomimicry and explain the difference between copying a living thing's shape and copying its principle.
- I can tell how George de Mestral invented the hook-and-loop fastener and explain how a burr helps a plant disperse its seeds.
- I can describe dermal denticles and explain how riblets reduce friction drag, and why claims like "shark-skin swimsuits" must be tested.
- I can describe a gecko's foot from toe pad to spatulae and explain how van der Waals forces let it cling and let go.
- I can use the six steps of the biomimicry design cycle to plan, build and test a prototype against a control.

- I can calculate areas, percents, averages, forces and scale lengths from design and test data.

OPTIONAL BOOKS AND RESOURCES

- **AskNature, from the Biomimicry Institute** (https://asknature.org/): Free. A searchable catalog of how living things solve problems such as gripping, staying clean or moving quietly, with short write-ups of the inventions they inspired. Good for choosing a living model in Lesson 8.4 and the portfolio. A parent may preview, since some entries use evolutionary language.
- ***Micrographia* by Robert Hooke (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/15491): Free. Hooke's 1665 book of what he saw through his microscope. Read his first observation, on the point of a sharp needle, which looked blunt and rough under the lens compared with the fine work he found in living things. A fine companion to de Mestral's burr.

8.1 Velcro from Burrs (de Mestral, 1941) ★

OBJECTIVES

- Tell how George de Mestral studied burdock burrs under a microscope and, after about ten years of tests, turned what he saw into the hook-and-loop fastener.
- Explain how a burr's hooks help the burdock plant spread its seeds, and why many weak hooks together make a strong fastener.
- Calculate holding strength per square centimeter and percentages from test data, and use them to compare fabrics.

Warm-up. Find something with a hook-and-loop strap, such as a shoe, a jacket cuff or a lunch bag. First pull the two sides so they slide along each other. Then peel the strap back slowly from one end. Which way is harder? Listen to the ripping sound as you peel. Now look at both sides with a magnifying glass (or your phone's camera zoomed in) and write one sentence describing each side.

Video. Coming soon. George de Mestral and the invention of Velcro, burdock burrs under a microscope, hook-and-loop fasteners up close, and seed dispersal by animals; search Smithsonian, Science Max, SciShow Kids, Homeschool Pop (Alternate) and microscope close-up footage of hook-and-loop tape.

KEY TERMS

biomimicry
Learning from the designs in living things to solve human problems. From the Greek *bios* (life) and *mimesis* (imitation).

burr
A dried seed head covered with hooks or spines that catch on fur and clothing. Burdock is the best-known burr plant.

seed dispersal
The ways seeds are carried away from the parent plant: by wind, water, animals or bursting pods.

hook-and-loop fastener
A fastener with tiny stiff hooks on one strip and soft loops on the other. Velcro is the brand name of the first one.

shear
A pull that makes two surfaces slide along each other. Hook-and-loop holds much more in shear than when it is peeled.

prototype
A first working model of an invention, built so it can be tested and improved.

CORE IDEAS

The story. In 1941 a Swiss electrical engineer named George de Mestral came home from a hunting walk in the countryside with his dog. Both of them were covered with burrs, the prickly seed heads of a tall weed called burdock. Pulling them off his trousers and out of his dog's fur took a long time, because each burr clung as if it did not want to let go. Most people would have thrown the burrs away and forgotten them. De Mestral was curious. He put a burr under his microscope to see *how* it held on so well.

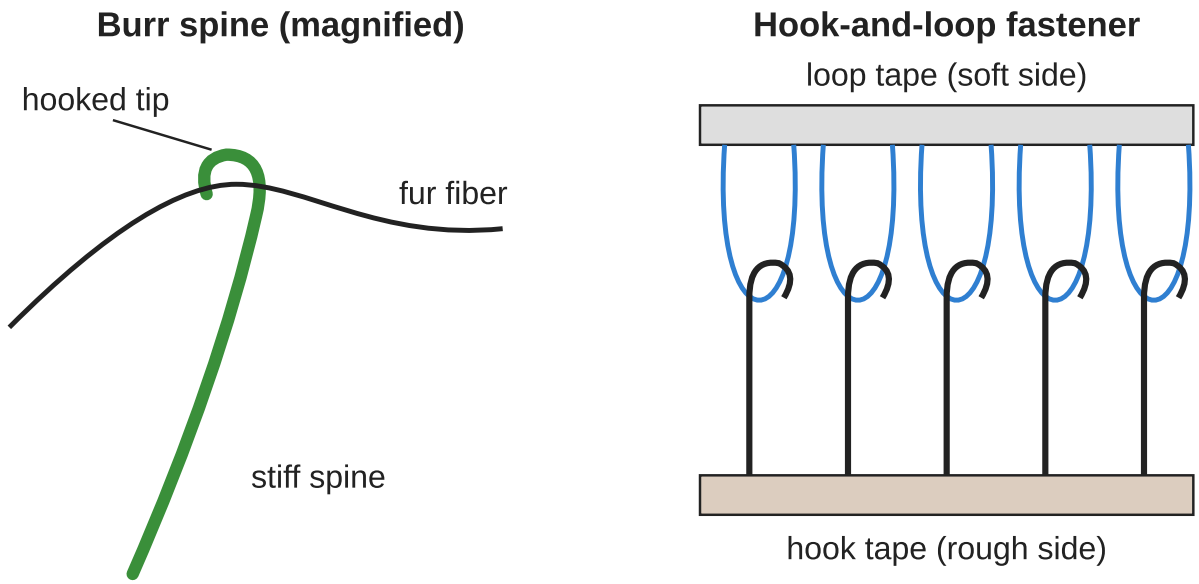
How they figured it out. Under the lens he saw that the burr was covered with stiff spines, and the tip of each spine was bent into a tiny hook. The hooks caught in anything that had loops: the threads of his cloth and the curly hairs of his dog. He wondered, if a burr can grab a loop, why not make a fastener with hooks on one strip and loops on the other? The idea was simple. Making it was not. Weavers in Lyon, France, a famous cloth-making city, helped him try cotton, but cotton hooks were too soft and wore out after a few uses. At last he turned to nylon, a strong new thread invented in the 1930s. He found that loops of nylon, hardened with heat and then snipped on one side, made strong, springy hooks. After about ten years of work and many failed **prototypes**, he applied for a Swiss patent in 1951, and it was granted in 1955. He named his invention Velcro, from two French words: *velours* (velvet) and *crochet* (hook).

The big idea. Learning from a design in a living thing to solve a human problem is called **biomimicry**. The burr was not made to annoy hunters. Its job is **seed dispersal**: carrying seeds away from the parent plant so the young plants do not crowd each other. A burdock burr is a dried flower head packed with seeds. When a deer, a fox or a dog brushes past, the hooks catch in its fur, and the animal carries the burr away, sometimes a long distance, until it is scratched or rubbed off. Other plants send their seeds by wind (dandelion parachutes), by water (coconuts) or inside tasty fruit that birds eat. Notice that de Mestral did not copy the *look* of a burr. He copied the *principle*: many small hooks catching many small loops.

Try it and see. Look at the rough side of a hook-and-loop strip with a magnifier, and you will see rows of tiny hooks, just like a burr's spines. The soft side is a tangle of loops. One hook holds almost nothing; you could straighten it with a fingernail. But a strip the size of a postage stamp has hundreds of hooks. Pull the two sides so they slide along each other, called **shear**, and all the hooks share the load at once, so the strip holds strongly. Peel it back from one end, and only one row of hooks lets go at a time, so it opens easily with a ripping sound. That is why your shoe strap stays shut while you run but opens when you peel it.

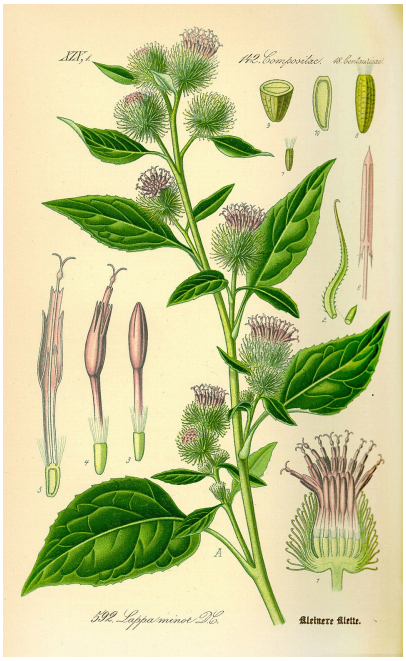
In the world today. Hook-and-loop fasteners close shoes, jackets, backpacks, blood pressure cuffs and tool pouches. During the Apollo missions to the moon, astronauts used hook-and-loop patches to keep pens, checklists and food packets from floating away inside their weightless spacecraft. Engineers today still follow de Mestral's path: notice something in creation, look closely, build a prototype, test it, fail, improve it and test again. In the next lessons you will see the same path lead from shark skin to faster boats and from gecko toes to grippers that hold heavy loads on glass.

God’s handiwork. The burdock’s hooks were doing their work in every pasture long before 1941. De Mestral did not invent the hook; he noticed it, studied it and put it to a new use. Solomon wrote, “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter” (Proverbs 25:2). Every time you peel open a hook-and-loop strap, you are using an idea first built into a weed by the Creator and found by a curious man with a microscope.



The burr’s hook and de Mestral’s copy. One hook is weak; hundreds of hooks catching hundreds of loops hold strongly.

PICTURE STUDY



Lesser Burdock (Arctium minus), from Flora von Deutschland, Österreich und der Schweiz, From the flora of Otto Wilhelm Thomé, 1885 · Chromolithograph (printed color botanical plate) · Printed in Gera, Germany; digital copies of the plates are shared on Wikimedia Commons

In the 1800s, before color photography, botanists published great picture books of plants so that anyone could name what grew in the fields. Otto Wilhelm Thomé, a German teacher and botanist, published a four-volume flora of the plants of Germany, Austria and Switzerland in 1885, with hundreds of carefully drawn color plates. His burdock plate shows exactly the kind of weed that clung to George de Mestral and his dog in the Swiss countryside.

Botanical artists drew the whole plant, then added small drawings of single parts, often magnified, so that a reader could see what the eye alone might miss. That is the same habit that led de Mestral to his microscope.

Look closely

- Find the round flower heads. What color are the flowers at the top of each head?
- Look closely at the outside of the flower heads. Can you see the spines that will later become the hooks of the burr?
- Find the small numbered drawings around the main plant. Which parts did the artist choose to show up close, and why?
- Compare the size of the leaves to the size of the flower heads. Why might a plant this tall be good at brushing against passing animals?

Talk about it

1. Why would a botanist draw a seed or a single flower much larger than life?

2. If you were de Mestral, which part of this plant would you put under the microscope first?
3. What other weeds or seeds in your area hitch a ride on clothes or pets?

> **Safety first.** If you gather burrs outdoors, wear long pants and closed shoes, stay out of poison ivy and stinging nettles, check for ticks afterward and wash your hands. Never eat wild seeds or plants. Burrs can tangle badly in pet fur, so keep them away from dogs and cats. Use scissors carefully when cutting tape, and do the water test over a sink or towel so no one slips.

EXPERIMENT: WHICH FABRIC GRABS BEST?

Question: Which fabric does a hook strip grab most strongly? You will press the same hook strip onto different fabrics and load it with water until it slides off. Because 1 mL of water has a mass of 1 g, you can measure the holding strength in grams.

Before you start, write your prediction: Which fabric will hold the most, and why? What we change: the fabric. What we keep the same: the hook strip, how hard and how long we press, and the direction of the pull. What we measure: the mass the strip holds before it slides off. Record everything in a table.

You will need

- One strip of the rough (hook) side of hook-and-loop tape, about 2 cm × 5 cm
- A piece of stiff cardboard about 5 cm × 8 cm, a hole punch and glue or a stapler
- Four or five fabric samples about 10 cm × 15 cm: for example fleece, felt, a wool sock, a cotton T-shirt, denim and a smooth nylon jacket lining
- Masking tape, a light plastic cup with a string handle, a kitchen scale if you have one
- Water and a measuring cup marked in mL
- A heavy book, a ruler, a magnifier, a notebook and pencil
- Optional: real burrs collected with a parent

Steps

1. Glue or staple the hook strip, hooks facing out, near the top of the cardboard tab. Punch a hole near the bottom of the tab and tie on the cup’s string. Weigh the empty cup and tab and record the mass (or write 0 and add it later).
2. Tape the first fabric flat against a cabinet door or the side of a bookcase, with tape along the top and bottom edges.
3. Press the hook strip onto the fabric the same way every time: hold the heavy book against it for 10 seconds.
4. Let the cup hang gently. Pour in water 25 mL at a time, waiting 5 seconds after each pour, until the tab slides off. Record the total water in mL.
5. Do three trials for each fabric and find the average. Total holding mass = water (g) + cup and tab (g).

6. Look at each fabric with the magnifier and count the loops or fuzzy fibers you can see in a 1 cm square.
7. Make a bar graph of average mass held for each fabric. Write two sentences: Was your prediction right? How did the number of loops relate to the holding strength?

Tips

- Catch the falling cup with a towel or do the test over the sink.
- If a fabric holds more than your cup can carry, use a bigger cup or add coins and weigh them.
- If you have real burrs, toss 20 burrs at each fabric from 30 cm away and count how many stick. Compare those results with your hook-strip results.

Check your work

- I wrote a prediction before testing.
- I changed only the fabric and kept the strip, pressing and pull the same.
- I did three trials for each fabric, found averages and made a bar graph.
- I can explain my results using the words hooks, loops and shear.

NATURE NOTEBOOK

1. Draw a burr twice: once as it looks to your eye and once as it looks under a magnifier. Label the hooked tips and, if you can open one, the seeds inside.
2. Draw the hook side and the loop side of a hook-and-loop strip as seen through a magnifier. Count the hooks in a 1 cm square and write the number beside your drawing.
3. Collect or sketch three different seeds (for example a dandelion, a maple key and a burr). Label each one with how it travels: wind, water, animal fur or animal stomach.

> **From history.** George de Mestral was born in Switzerland in 1907 and died there in 1990. His fastener was slow to catch on at first, because people thought the bare strips looked homemade, but it became popular in the 1960s once it was used in sportswear and in spacecraft. Because Velcro is a brand name, the company that carries it still asks people to call the general product a “hook-and-loop fastener,” just as a facial tissue is not always a Kleenex.

WORKED EXAMPLES

Example 1. Lena looks at a strip of hook tape under a magnifier, with a ruler beside it. In one square that is 1 cm on each side, she counts 6 rows with 8 hooks in each row. (a) How many hooks are there per square centimeter? (b) How many hooks are on a strip 2 cm wide and 5 cm long? (c) When the strip is pressed onto a cotton shirt, only about 1 hook in 4 catches a loop. About how many hooks are holding?

(Use the map or drawing "Not every hook finds a loop. Soft, loopy fabrics give more hooks something to ca" shown earlier in this lesson.)

1. (a) Hooks in 1 cm^2 = 6 rows × 8 hooks = 48 hooks per cm^2.
2. (b) Area of the strip = 2 cm × 5 cm = 10 cm^2. Total hooks = 48 hooks/cm^2 × 10 cm^2 = 480 hooks.
3. (c) One hook in 4 means divide by 4: 480 ÷ 4 = 120 hooks holding.

Answer: (a) 48 hooks per cm^2. (b) 480 hooks. (c) About 120 hooks are caught in loops.

Example 2. Two hook strips are pressed onto the same piece of fleece and loaded in shear. Strip A is 2 cm × 5 cm and holds 1,500 g before sliding off. Strip B is 2 cm × 2.5 cm and holds 760 g. Find the holding strength of each strip in grams per square centimeter. What do the results suggest, and about how much should a 4 cm × 5 cm strip hold?

1. Area of A = 2 cm × 5 cm = 10 cm^2. Strength of A = 1,500 g ÷ 10 cm^2 = 150 g/cm^2.
2. Area of B = 2 cm × 2.5 cm = 5 cm^2. Strength of B = 760 g ÷ 5 cm^2 = 152 g/cm^2.
3. The two strengths are almost the same. So the holding mass grows in proportion to the area: twice the area holds about twice the mass, because there are twice as many hooks.
4. A 4 cm × 5 cm strip has an area of 20 cm^2. Predicted hold ≈ 150 g/cm^2 × 20 cm^2 = 3,000 g.

Answer: A: 150 g/cm^2; B: 152 g/cm^2. Holding strength depends on area, so a 20 cm^2 strip should hold about 3,000 g (3 kg).

Example 3. A class tossed 20 burdock burrs at each of four fabrics from the same distance and counted how many stuck.
Fleece: 18 stuck. Wool sock: 17 stuck. Cotton T-shirt: 9 stuck. Smooth nylon raincoat: 1 stuck.
Find the percent that stuck for each fabric. Which fabric is most like an animal's fur, from the burr's point of view?

1. Percent stuck = (number stuck ÷ 20) × 100.
2. Fleece: 18 ÷ 20 = 0.90 → 90%. Wool sock: 17 ÷ 20 = 0.85 → 85%.
3. Cotton T-shirt: 9 ÷ 20 = 0.45 → 45%. Nylon raincoat: 1 ÷ 20 = 0.05 → 5%.
4. Fleece and wool have many soft loops and fibers, like fur, so they catch the most hooks. The smooth raincoat gives the hooks almost nothing to grab.

Answer: Fleece 90%, wool 85%, cotton 45%, nylon raincoat 5%. Fleece (and wool) act most like fur because they are full of loops for the hooks to catch.

PRACTICE

1. EASY What is biomimicry? Where does the word come from?
2. EASY What did George de Mestral see when he put a burr under his microscope?
3. EASY The name Velcro comes from two French words. What are they, and what do they mean?
4. EASY Name three ways seeds are dispersed, with one plant example for each. Which way does burdock use?
5. MEDIUM De Mestral's walk was in 1941. He applied for a Swiss patent in 1951, and it was granted in 1955. How many years passed from the walk to the patent application? From the walk to the granted patent?
6. MEDIUM Through a magnifier that makes things look 20 times larger (20×), Sam draws the hooked tip of a burr spine. His drawing is 30 mm long. How long is the real hooked tip?
7. MEDIUM Data reading. A student pressed the same hook strip onto four fabrics and recorded:
   Felt: 20 loops per cm^2, held 400 g.
   Cotton T-shirt: 35 loops per cm^2, held 650 g.
   Wool sock: 60 loops per cm^2, held 1,100 g.
   Fleece: 90 loops per cm^2, held 1,700 g.
   (a) Describe the trend. (b) Predict about how much a fabric with 75 loops per cm^2 would hold. (c) Which is the independent variable?
8. MEDIUM Data reading. A hook-and-loop strip held 3,000 g when loaded in shear but only 400 g when the same load peeled it from one end. (a) How many times stronger was it in shear? (b) Explain the difference.
9. HARD Experiment design. A company wants to know whether longer hooks make a hook strip hold better. Describe a fair experiment. Name the independent variable, the

dependent variable, three things to keep the same and how many trials to run.

10. CHALLENGE A burdock burr sticks firmly to a sheep's woolly coat but falls off a horse's short, smooth summer coat. Use the idea of hooks and loops to explain why, and explain how the burr's design helps the burdock plant.

COMMON MISTAKES

- Thinking biomimicry means copying how a living thing *looks*. De Mestral did not make fasteners shaped like burrs; he copied the working principle of many hooks catching many loops.
- Thinking hook-and-loop works like glue or tape. Nothing is sticky; it holds by mechanical hooks caught around loops, which is why it can be opened and closed thousands of times.
- Thinking a great invention comes in one flash. De Mestral had the idea in 1941 but needed about ten years of failed prototypes, new materials and testing before it worked.

Make it a game · Seed Travel Sort. A parent gathers or draws 10 seeds and fruits (dandelion, maple key, burr, acorn, coconut picture, berry, milkweed, pea pod, sunflower seed, cocklebur). Take turns drawing one card. Say how the seed travels (wind, water, fur, eaten by an animal, or bursting pod) for 1 point, and name a human invention it could inspire for a bonus point (for example, maple key to a spinning toy helicopter). First to 12 points wins.

Scripture. "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter." (Proverbs 25:2, KJV)

God hid a clever fastener in a common weed. De Mestral honored that design by searching it out with a microscope and patient work. Scientists and inventors are searchers of what God has made.

Practice answers

1. Biomimicry is learning from the designs in living things to solve human problems. It comes from the Greek *bios* (life) and *mimesis* (imitation).
2. He saw that the burr's spines ended in tiny hooks, and that the hooks caught in loops, such as the threads of his clothes and the hairs of his dog.
3. *Velours*, meaning velvet, and *crochet*, meaning hook.
4. Sample answer: wind (dandelion), water (coconut), animals eating fruit (berries), animal fur (burdock). Burdock uses animal fur: its hooks catch on passing animals.
5. 1951 − 1941 = 10 years to the application. 1955 − 1941 = 14 years to the granted patent.
6. Real size = drawing size ÷ magnification = 30 mm ÷ 20 = 1.5 mm.
7. (a) The more loops per cm^2 a fabric has, the more mass the strip holds. (b) Between 1,100 g and 1,700 g, about 1,400 g. (c) The independent variable is the fabric (its number of loops per cm^2); the mass held is the dependent variable.

8. (a) 3,000 ÷ 400 = 7.5 times stronger. (b) In shear all the hooks share the load at once. In peeling, only the one row of hooks at the edge carries the load at a time, so they let go one row after another.
9. Sample answer: Make strips with short, medium and long hooks (independent variable). Press each onto the same fleece and load it with water until it slides off; measure the mass held (dependent variable). Keep the same: strip size, hook material and spacing, fabric, pressing force and time, direction of pull. Run at least three trials for each hook length and compare averages.
10. Wool is made of many crimped, curly fibers that form loops for the hooks to catch, so many hooks hold at once. A horse’s short, smooth hairs lie flat and give the hooks almost nothing to hook around, so the burr slides off. Catching on furry or woolly animals lets the burr ride far from the parent plant before it falls or is rubbed off, so the seeds inside sprout in new places without crowding the parent.

8.2 Shark Skin

OBJECTIVES

- Describe dermal denticles, the tooth-like scales of shark skin, and explain how their shape and ridges help a shark slip through water and stay clean.
- Tell how engineers copied shark skin in riblet films and the Sharklet surface, and explain why scientists test claims like “shark-skin swimsuits” before believing them.
- Calculate percent change in drag and read data tables on surface patterns and swimming speed.

Warm-up. Rub your fingers along a piece of corduroy or velvet, first in one direction and then in the other. Which way feels smooth and which way feels rough? Now rub the back of a dog or cat from head to tail, then gently from tail to head. Shark skin works the same way, but it is so rough the wrong way that sailors once used it as sandpaper. Write one sentence guessing why a shark’s skin might be smooth only from head to tail.

Video. Coming soon. Shark skin dermal denticles under a microscope, riblets and drag, and shark-inspired surfaces; search Smithsonian Ocean, NOAA Ocean Service, Harvard science news, NASA Langley history, Science Max and underwater shark footage from nature channels.

KEY TERMS

dermal denticle
A tiny tooth-like scale in a shark’s skin, built like a tooth with a hard outer layer, dentine and a pulp cavity. The name means “little skin tooth.”

drag
The force that pushes back on something moving through water or air. Friction drag comes from the surface; shape drag comes from the object’s form.

streamlined
Shaped to let water or air flow smoothly around it, like a torpedo or a shark, so that there is less drag.

riblets
Tiny parallel ridges running in the direction of flow. Shark denticles have them, and engineers copy them to reduce friction drag.

biofouling
The slime, algae and barnacles that grow on things left in water, such as ship hulls and docks.

micrometer (µm)
One thousandth of a millimeter. A human hair is about 50 to 100 µm thick.

CORE IDEAS

The story. In 2002 Anthony Brennan, a materials engineer and professor at the University of Florida, was working on a problem for the U.S. Navy. Ships' hulls become covered with slime, algae and barnacles, a crusty growth called **biofouling**. It makes a ship rougher and heavier, so the ship burns more fuel, and scraping it off is slow, dirty work. As the story is told, on a visit to the navy base at Pearl Harbor, Hawaii, Brennan began to wonder about sharks. Whales collect barnacles, and so do ships. Why does a shark, which often cruises slowly, stay clean?

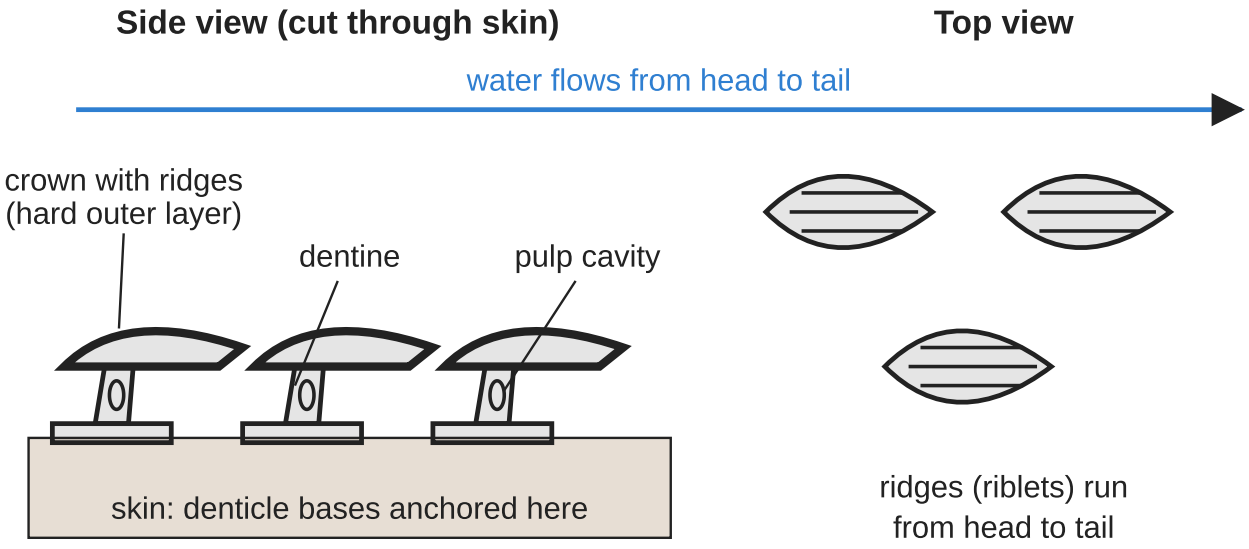
How they figured it out. Under a microscope, shark skin turns out to be covered with thousands of tiny scales called **dermal denticles**, which means "little skin teeth." Brennan's team measured the pattern of the denticles and copied it in plastic, making a surface of tiny diamond-shaped groups of ridges, each ridge only a few **micrometers** wide. Then they tested it. Far fewer spores of green algae settled on the shark-like pattern than on smooth plastic of the same kind. The surface, later named Sharklet, has since been tested on things where germs like to settle, such as surfaces in hospitals. Notice how the work went: an observation, a question, careful measuring, a copy and a fair test against a smooth control.

The big idea. A shark's denticles really are built like teeth. Each has a hard, enamel-like outer layer, dentine beneath it and a small pulp cavity in the middle, with a base anchored in the skin. The crowns all point back toward the tail, so the skin feels smooth when you stroke it from head to tail and rough like sandpaper the other way. On fast sharks such as the mako, each crown carries tiny ridges, or **riblets**, that run from head to tail. Anything moving through water feels **drag**. A shark's **streamlined** body cuts down shape drag. The riblets help with friction drag: they guide the thin layer of water right next to the skin and keep small swirls from tumbling sideways across it, so the water slides past with less resistance. The denticles can also flex a little as the shark swims, and their tiny, moving, ridged surface gives algae and barnacles a poor place to settle.

In the world today. In the 1980s, engineers at NASA's Langley Research Center in Virginia tested surfaces with tiny grooves and found that riblets could lower friction drag by a few percent. A thin riblet film was put on the hull of the American yacht *Stars & Stripes*, which won the America's Cup race in 1987. Since 2022 the German airline Lufthansa has put shark-skin-style riblet film on some of its cargo planes and reports about 1 percent less fuel burned. One percent sounds small, but over thousands of long flights it adds up to a great deal of fuel.

Test the claim. Around 2000, swimsuit makers began selling suits with fabric said to be inspired by shark skin, and swimmers in them set many records. Were the suits fast because of the shark-skin idea? In 2012, scientists at Harvard University tested the swimsuit fabric on a flexing model and found that its surface did little by itself, while real shark skin on the same kind of model helped it swim faster. Other parts of the suits, such as tight, smooth panels that squeezed the swimmer's body into a more streamlined shape, mattered more. A good scientist does not believe a label just because it names an animal. Test it, with a control.

God’s handiwork. Sharks keep making new teeth in their jaws all their lives, and they replace their skin denticles too as old ones wear. The Psalmist looked at the sea and wrote, “O LORD, how manifold are thy works! in wisdom hast thou made them all” (Psalm 104:24). Engineers with powerful microscopes and test tanks are still learning from a skin that the Creator designed for the sea.



Dermal denticles: little skin teeth. The crowns point toward the tail, and their ridges (riblets) run in the direction the water flows.

PICTURE STUDY



The Gulf Stream, Winslow Homer, 1899 · Oil on canvas · The Metropolitan Museum of Art, New York

Winslow Homer, one of America's greatest painters, made several winter trips to Florida and the Bahamas. There he sketched the bright water of the Gulf Stream, the powerful ocean current that flows out of the Gulf of Mexico and up past the American coast. In this painting a lone sailor rides a small boat whose mast has snapped, while sharks circle in the waves. The sharks' sleek, streamlined bodies cut through the water around the helpless boat.

When people first saw the painting, some wrote to Homer asking what happened to the sailor. Homer liked to leave a story open, so the viewer has to look closely and think.

Look closely

- Find the sharks. Look at their shape. Where is their body thickest, and how does it narrow toward the tail?
- Look at the boat. What is broken? How would that change the way it moves through the water?
- Look far into the distance. What do you see on the horizon and in the sky?
- Compare the sharks' bodies with the boat's hull. Which one looks made for speed in water?

Talk about it

1. Why do you think Homer placed the sharks so close to the boat? What feeling does it give you?
2. A shark is built for moving through water with little drag. Name two things about its body you can see in the painting that help it do that.
3. If you could add one more detail to the painting to tell what happens next, what would it be?

> **Safety first.** This project uses a bathtub or large tub of water. Work with an adult present, keep the water shallow, wipe up spills right away so no one slips, and empty the tub when you finish. Use scissors carefully.

EXPERIMENT: THE RIBLET RACE

Question: Do grooves running along the bottom of a small boat change how fast a falling weight can pull it through water? You will build three identical boats, pull each one with the same weight and time it over the same distance.

Before you start, write your prediction. What we change: the bottom surface (smooth, ridges running front to back, ridges running side to side). What we keep the same: the boat size and mass, the pulling weight, the distance, the water depth. What we measure: the time to travel 60 cm. Be honest about what you find. Real shark riblets are far smaller than any you can make at home, so you may find only a small difference, or none. Recording that truthfully is real science.

You will need

- Three identical flat plastic lids (such as the lids of food-storage tubs), about 12 to 15 cm long
- Clear packing tape and thin yarn or string
- Strong thread about 1.5 m long for each boat, a pencil and masking tape
- A small paper cup and 10 identical coins (the pulling weight)
- A bathtub or long plastic tub with about 8 cm of water, a ruler or measuring tape, a stopwatch
- Notebook and pencil

Steps

1. Boat A (smooth): cover the bottom of a lid with packing tape so it is smooth.
2. Boat B (riblets along the flow): lay pieces of yarn about 5 mm apart running from front to back across the bottom, then cover them with packing tape so they make raised ridges.
3. Boat C (ridges across the flow): do the same, but run the yarn from side to side.
4. Weigh or compare the boats; add a bit of tape to the lighter ones so all three have the same mass.
5. Tape a pencil across the far edge of the tub as a smooth pulley. Tie the thread to the front of a boat, run it over the pencil and tie the cup to the other end. Mark a start line and a finish line 60 cm apart on the tub side with masking tape.
6. Hold the boat at the start with the cup loaded with 10 coins. Let go and time how long the boat takes to reach the finish line.
7. Run five trials for each boat. Make a table, find each boat’s average time, and draw a bar graph.
8. Write three sentences: Which boat was fastest? Was the difference bigger than the spread between trials of the same boat? What would you change to make the test fairer?

Tips

- Let the water become completely still between trials.
- If the boats crash into the side, add a little tape weight to the back to steady them, the same on all three.
- Compare the difference between boats with the difference between trials. If two trials of the same boat differ by more than the boats differ from each other, you cannot say one boat is faster.

Check your work

- I wrote a prediction and named what I changed, kept the same and measured.
- I ran five trials per boat and calculated averages.
- I made a bar graph and reported my results honestly, even if they were surprising.
- I can explain why real riblets must be tiny and run in the direction of flow.

NATURE NOTEBOOK

1. Draw a side view of three shark denticles as in the figure. Label the crown, ridges, dentine, pulp cavity and base, and draw an arrow showing which way the water flows.
2. Draw the outline of a shark from the side and from above. Shade the thickest part of the body and write two sentences on why this shape is streamlined.
3. Look at a piece of sandpaper, a nail file and a smooth plastic lid with a magnifier. Sketch what you see and write which one is most like shark skin and why.

From history. Long before microscopes, people knew shark skin was rough. Dried skin of sharks and rays, often called shagreen, was used for centuries by woodworkers as a kind of sandpaper to smooth wood. Japanese sword makers wrapped sword handles in ray skin, whose hard, bumpy surface kept the grip from slipping in a sweaty hand. The same denticles that once smoothed furniture now guide engineers designing ships and planes.

WORKED EXAMPLES

Example 1. In a water tunnel, a smooth test plate feels a drag force of 50.0 N. The same plate covered with riblet film feels 47.0 N at the same speed. By what percent did the riblets reduce the drag?

1. Find the change: 50.0 N − 47.0 N = 3.0 N less drag.
2. Percent change = change ÷ original × 100 = 3.0 ÷ 50.0 × 100.
3. 3.0 ÷ 50.0 = 0.06, and 0.06 × 100 = 6%.

Answer: The riblets reduced the drag by 6%.

Example 2. A shark denticle crown is about 0.2 mm wide. (a) How many denticles fit side by side across 1 cm of skin? (b) About how many fit in 1 cm² of skin if they were packed in a square grid? (c) A patch of skin is 4 cm by 5 cm. About how many denticles does it have?

(Use the map or drawing “Each denticle is about the size of a fine grain of sand, so even a small patch o” shown earlier in this lesson.)

1. (a) 1 cm = 10 mm. Number across = 10 mm ÷ 0.2 mm = 50 denticles.
2. (b) In a square 1 cm on each side: 50 × 50 = 2,500 denticles per cm².
3. (c) Area = 4 cm × 5 cm = 20 cm². Number ≈ 2,500 × 20 = 50,000 denticles.

Answer: (a) 50. (b) About 2,500 per cm². (c) About 50,000 denticles on a 20 cm² patch.

Example 3. A long cargo flight burns about 80,000 kg of fuel. With riblet film the airline saves about 1% of its fuel. (a) How much fuel is saved on one flight? (b) The plane makes 300 such flights a year. How much fuel is saved in a year?

1. (a) 1% = 1/100 = 0.01. Fuel saved = 0.01 × 80,000 kg = 800 kg per flight.
2. (b) Yearly savings = 800 kg × 300 flights = 240,000 kg.
3. That is 240 metric tons (1 metric ton = 1,000 kg).

Answer: (a) 800 kg per flight. (b) 240,000 kg (240 metric tons) a year. A small percent becomes a large amount when repeated many times.

PRACTICE

1. EASY What are dermal denticles, and what part of the body are they built like?
2. EASY Why does shark skin feel smooth when stroked from head to tail but rough from tail to head?
3. EASY What is drag? Name the two kinds described in the lesson and the part of the shark that reduces each.
4. EASY What problem was Anthony Brennan trying to solve for the Navy, and what did he copy from sharks?
5. MEDIUM A smooth model boat hull feels 80 N of drag. With riblet film it feels 76 N at the same speed. What is the percent reduction in drag?
6. MEDIUM Data reading (sample data). Scientists counted algae spores settled on four plastic surfaces after the same time in the same tank:
   Smooth: 1,000 spores per mm².
   Random bumps: 700 per mm².
   Parallel ridges: 400 per mm².
   Shark-like diamond pattern: 150 per mm².
   (a) Which surface is the control? (b) Which surface worked best? (c) By what percent did it reduce settling compared with smooth plastic?
7. MEDIUM Data reading (sample data). A flexible test model covered with real shark skin swam at 20.0 cm/s. Then the denticles were sanded off the same skin, and the model swam at 18.0 cm/s with everything else the same. (a) What one variable was changed? (b) By what percent was the model faster with denticles than without? (c) Why was using the same skin a good idea?
8. HARD A denticle crown is 0.3 mm wide. In a textbook drawing it is 6 cm wide. What is the magnification of the drawing?
9. HARD Experiment design. You want to know whether grooves on the bottom of a toy boat make it faster. Describe a fair test: what you change, what you keep the same, what you measure, the control and how many trials.
10. CHALLENGE An advertisement says, “Our shark-skin swimsuit makes you faster!” Using what scientists found in 2012, explain why you should not simply believe the label, and describe what evidence would convince you.

COMMON MISTAKES

- Thinking shark scales are like the thin, flat scales of a goldfish. Shark denticles are tiny tooth-like structures with enamel-like outer layers, dentine and pulp.
- Thinking a rougher surface always means more drag. Tiny ridges lined up with the flow can lower friction drag, but ridges that are too big or that run across the flow add drag.
- Believing that anything labeled "inspired by nature" must work. Every copy must be tested against a control, as the shark-skin swimsuit study showed.

Make it a game · Drag Detectives. A parent names something that moves through water or air: a canoe, a bicycle racer, a swimmer, a jet, a rowboat, a penguin, a falling leaf. You have ten seconds to name one way it reduces drag (streamlined shape, smooth surface, tight clothing, folding wings, tiny ridges) for 1 point. Name a way it could be changed to have *more* drag on purpose, like a parachute or a boat anchor, for a bonus point. Play to 10 points.

Scripture. "O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches. So is this great and wide sea, wherein are things creeping innumerable, both small and great beasts." (Psalm 104:24–25, KJV)

"Manifold" means many and varied. Even the skin of a shark, covered with thousands of little teeth too small to see, shows the wisdom with which the sea's creatures were made.

Practice answers

1. Dermal denticles are the tiny tooth-like scales that cover a shark's skin. They are built like teeth, with a hard enamel-like outer layer, dentine and a pulp cavity.
2. All the denticle crowns point back toward the tail. Stroking head to tail slides over them; stroking tail to head rubs against their edges.
3. Drag is the force that pushes back on something moving through water or air. Shape drag is reduced by the shark's streamlined body; friction drag is reduced by the riblets on its denticles.
4. He was trying to keep algae, barnacles and slime (biofouling) off ship hulls. He copied the pattern of ridges on shark denticles to make a plastic surface (Sharklet) where fewer algae spores settle.
5. Change = 80 − 76 = 4 N. Percent = 4 ÷ 80 × 100 = 5%.
6. (a) The smooth surface is the control. (b) The shark-like diamond pattern. (c) Reduction = 1,000 − 150 = 850; 850 ÷ 1,000 × 100 = 85%.
7. (a) Whether the skin had its denticles. (b) 20.0 − 18.0 = 2.0 cm/s; 2.0 ÷ 18.0 × 100 ≈ 11%. (c) Using the same skin, model and conditions means the only difference was the denticles, so the change in speed can be blamed on them.
8. 6 cm = 60 mm. Magnification = drawing size ÷ real size = 60 mm ÷ 0.3 mm = 200 times (200×).
9. Sample answer: Change only the bottom surface (grooves running front to back vs smooth). Keep the same boat size, mass, pulling force, water depth and distance. Measure the time to travel a fixed distance. The smooth boat is the control. Run at least five trials each and compare averages, and check whether the difference is bigger than the spread between trials.

10. Naming an animal does not prove the design works. In 2012, Harvard scientists found that a swimsuit fabric sold as shark-inspired did little by itself, while real shark skin did help; other features, such as tight panels that streamlined the body, mattered more. I would want a fair test: the same swimmers or models in the suit and in a control suit identical except for the surface, with many trials, showing a difference larger than normal variation.

8.3 Gecko Feet

OBJECTIVES

- Describe the gecko foot from toe pad to lamellae to setae to spatulae, and explain how van der Waals forces let a gecko cling to smooth glass and let go in an instant.
- Tell how Kellar Autumn, Robert Full and their team measured the force of a single gecko hair in 2000, and how engineers have built gecko-inspired grippers.
- Use metric conversions (mm, µm, nm), multiplication and ratios to compute how many hairs a gecko has and how much force they could hold.

Warm-up. Take two paperback books or notebooks of about the same size. Lay them face to face and shuffle the pages together so that every page of one lies between two pages of the other, overlapping by about 3 cm. Now try to pull the books apart by their spines. Each page touches its neighbors only lightly, but hundreds of light touches add up. Write one sentence on what this tells you about many tiny forces working together.

Video. Coming soon. How gecko feet stick: setae and spatulae under the electron microscope, van der Waals forces, Stickybot and gecko-inspired grippers; search Smithsonian, NASA JPL, Stanford engineering, UC Berkeley, Science Max, SciShow Kids and slow-motion nature footage of geckos climbing glass.

KEY TERMS

adhesion
The attraction that makes two different surfaces cling together.

lamellae
The rows of soft, flat ridges across the underside of a gecko’s toes. Each one is covered with setae.

setae
The microscopic hairs on a gecko’s lamellae, each about 0.1 mm long. One hair is a seta.

spatulae
The hundreds of tiny flat tips at the end of each seta, about 0.2 µm (200 nm) wide. They are the parts that touch the wall.

van der Waals force
A very weak attraction between molecules that are extremely close together, only a few nanometers apart. Millions of them added together let a gecko cling.

nanometer (nm)
One millionth of a millimeter. 1 mm = 1,000 µm = 1,000,000 nm.

CORE IDEAS

The story. More than two thousand years ago the Greek naturalist Aristotle noticed that a gecko could run up and down a tree any way it liked, even head downward. For centuries no one could explain how. Then, in 2000, a team led by biologists Kellar Autumn of Lewis & Clark College in Oregon and Robert Full of the University of California, Berkeley, did something no one had done before. They removed a single microscopic hair from the toe of a tokay gecko and measured how hard it could cling. The hair was only about a tenth of a millimeter long. Yet it held with a force of about 200 micronewtons, close to the weight of one grain of rice. That was far stronger than anyone expected for one hair, and it pointed to the secret of the gecko's grip.

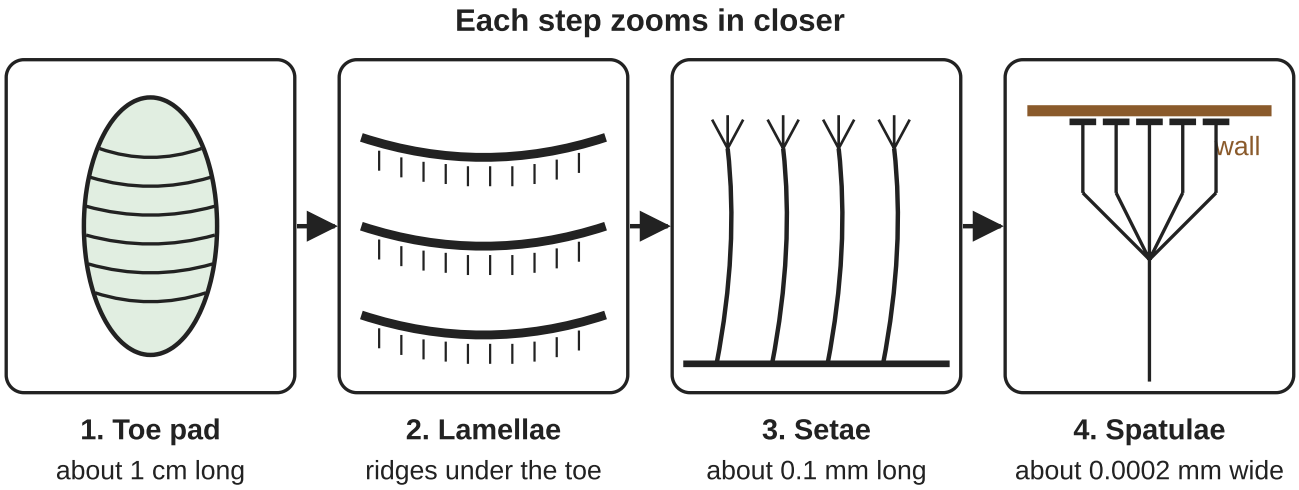
How they figured it out. Scientists first ruled things out. It is not suction: earlier experimenters found that geckos still cling when the air is pumped away. It is not glue: gecko toes have no glands and leave no wet footprints. It is not hooks: geckos run on polished glass, which has nothing to hook into. In 2002 Autumn's team tested setae on two kinds of surface, one that water spreads over and one that water beads up on. The hairs stuck about equally well to both. That pointed to **van der Waals forces**, the faint attraction between any molecules that come extremely close together, only a few **nanometers** apart. One such attraction is far too weak to feel. The gecko's secret is getting enormous numbers of them at once.

The big idea. Zoom in on a gecko's toe and the design unfolds in steps. Under each toe are soft ridges called **lamellae**. Each lamella is covered with **setae**, about 14,400 of them in every square millimeter on a tokay gecko. Each seta, about 0.1 mm long, splits at its tip into hundreds of flat tips called **spatulae**, each about 0.2 µm (200 nm) wide. Because the tips are so tiny and so flexible, they can press into every little bump of a wall and get close enough for van der Waals forces to act. Autumn's team calculated that if all of a tokay's roughly 6.5 million setae gripped at once, they could hold about 130 kg, far more than a gecko needs. It uses only a small part of its grip at any moment, which leaves a large margin of safety.

Letting go. A good climbing foot must also come off quickly. Setae grip strongly when the toe is pressed down and pulled slightly toward the body. When the angle between a seta and the wall grows to about 30 degrees, it pops free. So a gecko peels its toes up from the tips, like peeling a strip of tape, and each step lets go with almost no effort. The feet stay dry, work upside down and even clean themselves, because dirt sticks to the wall better than to the tiny tips. The design does have limits. Geckos struggle on slick nonstick (Teflon) pans, whose molecules attract other molecules very weakly, and on wet glass.

In the world today. In 2006 engineers at Stanford University built Stickybot, a four-legged robot with gecko-style rubber toes that could climb glass. In 2012 scientists at the University of Massachusetts Amherst announced Geckskin, a pad the size of an index card that could hold about 300 kg on smooth glass and then peel off cleanly. NASA engineers have tested gecko-style grippers for grabbing objects in space, where suction cups cannot work because there is no air to push on them. In every case the engineers copied the principle, many tiny flexible contacts, not the gecko itself.

God’s handiwork. Proverbs 30:28 says, “The spider taketh hold with her hands, and is in kings’ palaces.” Many Bible scholars think the Hebrew word translated “spider” here means a lizard, probably a gecko, the little creature that clings to the walls and ceilings of houses in the Middle East to this day. The first readers of Proverbs saw it take hold with its “hands.” Today we can see why it holds: a foot designed down to a size smaller than the wavelength of light.



Zooming in on a gecko toe: toe pad (about 1 cm), lamellae, setae (about 0.1 mm long) and spatulae (about 0.0002 mm wide), which touch the wall.

PICTURE STUDY



Geckos (Plate 108), from Locupletissimi rerum naturalium thesauri (Seba’s Thesaurus), volume 1, Albertus Seba (collector); engraved by Dutch artists of his workshop, 1734 · Engraving, hand-colored in some copies · Published in Amsterdam; copies are kept in natural-history libraries, and scans of the plates are shared on Wikimedia Commons

Albertus Seba was a Dutch druggist in Amsterdam who traded with sailors returning from Asia, Africa and the Americas. He bought shells, snakes, lizards, insects and other specimens until he had one of the largest natural-history collections in Europe. Then he hired artists to engrave them in a great four-volume book, the *Thesaurus* (Treasury). Volume 1, published in 1734, is full of plates of lizards, snakes and other creatures, including geckos from distant lands.

Linnaeus himself studied Seba's collection and plates, and some animals were first given scientific names from them. The engravers worked from preserved specimens, so some poses look stiff, but the scales and toes were drawn with great care.

Look closely

- Look at the toes of each lizard. Which ones have thin, clawed toes, and do any have wide, flat toe tips?
- Look at the scales. How did the engraver show tiny scales using only lines?
- Look at how the animals are arranged on the page. Why might Seba have placed different kinds side by side?
- Find the smallest animal on the plate. What details could the artist not show at that size?

Talk about it

1. Seba's artists had no microscopes powerful enough to see setae. What could they learn by looking, and what could they not?
2. Why are drawings from preserved specimens sometimes less lifelike than drawings of living animals?
3. If you were drawing a gecko for a book today, which part would you draw magnified in a corner of the page?

> **Safety first.** Do the water test over a towel or sink and wipe up spills so no one slips. If you test on a window, use only light loads and do not press hard on the glass. If you watch a pet or wild gecko, do not grab it by the tail; many geckos can drop their tails when frightened.

EXPERIMENT: HOW MUCH CAN A PATCH HOLD?

Question: Does a sticky patch with twice the contact area hold twice as much? A gecko's grip depends on how much of its foot truly touches the wall. You will test squares of painter's tape of different sizes on a smooth tile and load them with water until they slide.

Before you start, write your prediction. What we change: the contact area of the tape. What we keep the same: the tape, the surface, how hard and long we press, how long we wait, the direction of pull. What we measure: the mass the patch holds before it slides. Because 1 mL of water has a mass of 1 g, you can measure the load in grams.

You will need

- A roll of painter’s tape about 2 cm wide (or masking tape)
- A smooth surface: a glazed tile, a smooth cabinet door or a mirror
- A small paper cup, a paper clip and a hole punch or sharp pencil
- Water and a measuring cup marked in mL, a ruler, scissors, a kitchen scale if you have one
- A towel, a notebook and pencil

Steps

1. Cut a strip of tape about 15 cm long. Fold the bottom part back on itself so it is not sticky, leaving exactly 1 cm of sticky tape at the top (a 2 cm × 1 cm patch = 2 cm^2).
2. Press the sticky patch onto the vertical tile and rub it firmly with your thumb for 5 seconds. Wait 1 minute.
3. Poke the paper clip through the folded tail and hang the cup from it. Pour in water 10 mL at a time, waiting 10 seconds after each pour, until the patch slides or peels off. Record the total water plus the mass of the cup and clip.
4. Repeat with patches of 2 cm × 2 cm (4 cm^2) and 2 cm × 4 cm (8 cm^2). Do three trials for each size with fresh tape each time.
5. Find the average mass held for each size, then divide by the area to find grams per cm^2.
6. Plot a line graph with area (cm^2) on the x-axis and average mass held (g) on the y-axis.
7. Bonus test: use a 4 cm^2 patch, but pull the cup straight outward from the wall (a peel) instead of down along it (shear). Compare the results and connect them to how a gecko lifts its toes.

Tips

- Wipe the tile clean and dry before every trial, since dust and water weaken the grip, just as they do for a gecko.
- Use fresh tape every time; used tape has lost some of its sticky contact.
- If the patch holds more than your cup can carry, use a larger cup or add weighed coins.

Check your work

- I wrote a prediction and named what I changed, kept the same and measured.
- I did three trials for each size and calculated averages and grams per cm^2.
- I made a graph and described the pattern in a sentence.
- I can explain why a gecko splits its foot into millions of tiny tips.

NATURE NOTEBOOK

1. Copy the four-step zoom diagram of a gecko foot into your notebook. Beside each step write its name and its size in mm, µm or nm.
2. If you can watch a gecko or other lizard (at a pet store, zoo or on a video), sketch its foot from below and write how it lifts its toes when it steps.

3. Make a three-column table titled “How Things Stick”: hooks (burr), suction (suction cup) and molecular attraction (gecko). Draw a small picture and one everyday example in each column.

From history. In his *History of Animals*, written in the 300s B.C., Aristotle recorded that the gecko can run up and down a tree any way it likes, even with its head downward. More than 2,300 years later, in June 2000, Kellar Autumn, Robert Full and their colleagues published their measurement of a single gecko seta in the science journal *Nature*. To make it, they needed tiny force sensors built with the same methods used to make computer chips. Good questions can wait a long time for the right tools.

WORKED EXAMPLES

Example 1. A tokay gecko has about 14,400 setae in every square millimeter of its toe pads. One toe pad has about 10 mm² of setae. (a) How many setae are on that toe pad? (b) A tokay has 20 toes. If each had the same area, about how many setae would the gecko have? Compare with the scientists’ estimate of about 6.5 million.

(Use the map or drawing “Every toe pad is carpeted with setae, each ending in hundreds of spatulae.” shown earlier in this lesson.)

1. (a) Setae on one toe = 14,400 per mm² × 10 mm² = 144,000 setae.
2. (b) Setae on 20 toes = 144,000 × 20 = 2,880,000 setae, about 2.9 million.
3. This is the same size of number as the estimate of 6.5 million, but smaller. That tells us the real toe pads have more than 10 mm² of setae each, about twice as much on average.

Answer: (a) 144,000 setae. (b) About 2.9 million, less than half of the 6.5 million estimate, so the real pads must be larger than 10 mm² on average.

Example 2. One seta can hold about 200 micronewtons, which is 0.0002 N. (a) If all 6.5 million setae of a tokay gecko gripped at once, what total force could they hold? (b) An object with a mass of 1 kg weighs about 10 N on Earth. About what mass could that force hold up? (c) The gecko’s own mass is about 0.1 kg, so it weighs about 1 N. How many times its own weight could it hold in theory?

1. (a) Total force = 6,500,000 × 0.0002 N = 1,300 N.
2. (b) Mass held = 1,300 N ÷ 10 N per kg = 130 kg.
3. (c) Ratio = 1,300 N ÷ 1 N = 1,300 times its own weight.

Answer: (a) 1,300 N. (b) About 130 kg, the weight of two adults. (c) About 1,300 times its own weight. A real gecko never uses all its setae at once, but the huge margin keeps it safe.

Example 3. Compare sizes using 1 mm = 1,000 µm = 1,000,000 nm. A seta is 0.1 mm long. A spatula is 200 nm wide. (a) Write the seta length in µm and in nm. (b) How many times longer is the seta than the spatula is wide? (c) A gecko toe is about 1 cm (10 mm) long. How many times longer is the toe than one seta?

1. (a) 0.1 mm × 1,000 = 100 µm. 0.1 mm × 1,000,000 = 100,000 nm.
2. (b) 100,000 nm ÷ 200 nm = 500 times.
3. (c) 10 mm ÷ 0.1 mm = 100 times.

Answer: (a) 100 µm, or 100,000 nm. (b) The seta is 500 times longer than a spatula is wide. (c) The toe is 100 times longer than a seta.

PRACTICE

1. EASY Put these parts of a gecko foot in order from largest to smallest: seta, toe pad, spatula, lamella.
2. EASY What force lets a gecko cling to glass? Describe it in one sentence.
3. EASY How does a gecko let go of the wall so quickly?
4. MEDIUM Convert 0.2 µm to nanometers. Then convert 100 µm to millimeters.
5. MEDIUM At 14,400 setae per mm², how many setae are on a patch of toe 5 mm²?
6. MEDIUM Data reading (sample data). Engineers tested one gecko-style pad on four surfaces and recorded the force it held before sliding:
   Dry glass: 20 N.
   Painted wall: 15 N.
   Wet glass: 8 N.
   Nonstick (Teflon) pan: 2 N.
   (a) On which surface did the pad hold best, and on which worst? (b) Wet glass held what percent of the dry-glass force? (c) Give one reason the nonstick surface held so little.
7. HARD Data reading (sample data based on real experiments). Scientists measured how much a single seta held at different angles between the seta and the wall (as a percent of its best grip):
   10°: 100%. 20°: 95%. 25°: 80%. 30°: 30%. 35°: 5%.
   (a) Between which two angles does the grip drop the most? (b) Explain how a gecko uses this to walk quickly.
8. HARD Experiment design. A student thinks a gecko-style pad holds better when it is pressed on for a longer time. Design a fair test. Name the independent variable, dependent variable, at least three controlled variables and the number of trials.
9. HARD Explain how scientists ruled out suction, glue and hooks as the secret of the gecko’s grip.
10. CHALLENGE A gecko with a mass of 0.08 kg hangs from a ceiling. Its weight is about 0.8 N, and each seta holds about 0.0002 N. (a) What is the smallest number of setae that must grip to hold it? (b) What percent of its 6.5 million setae is that?

COMMON MISTAKES

- Thinking geckos stick with suction cups. Their grip works even with the air pumped away; it comes from van der Waals forces between molecules.
- Thinking gecko feet are sticky or wet like glue. They are dry, leave no residue and even clean themselves as the gecko walks.
- Thinking one big smooth pad would grip as well as millions of tiny tips. Real walls are bumpy at small sizes; only tiny, flexible tips can get close enough to most of the surface for the weak molecular forces to add up.

> **Make it a game · How Does It Stick?.** A parent names something that holds on: a burr, a gecko, a suction cup, a sticky note, a tree frog, a magnet, a barnacle, a hook-and-loop strap, a spider's thread, a squid's sucker. You answer "hooks," "suction," "glue," "molecular attraction" or "magnetism" for 1 point. Explain how it lets go for a bonus point. Switch roles after 10 items.

> **Scripture.** "The spider taketh hold with her hands, and is in kings' palaces." (Proverbs 30:28, KJV)

Agur, whose sayings fill Proverbs 30, listed small creatures that are "exceeding wise." Many scholars believe the Hebrew word here means a lizard such as the house gecko, which still climbs palace walls in that land. The little creature that "taketh hold with her hands" is now teaching engineers.

Practice answers

1. Toe pad, lamella, seta, spatula.
2. Van der Waals force: a very weak attraction between molecules that are extremely close together, added up over millions of tiny spatulae.
3. It peels its toes up from the tips. When the angle between the setae and the wall grows to about 30 degrees, the setae pop free, one row after another, like peeling tape.
4. 0.2 µm × 1,000 = 200 nm. 100 µm ÷ 1,000 = 0.1 mm.
5. 14,400 × 5 = 72,000 setae.
6. (a) Best on dry glass; worst on the nonstick pan. (b) 8 ÷ 20 × 100 = 40%. (c) The molecules of a nonstick surface attract other molecules very weakly, so van der Waals forces are small there.
7. (a) Between 25° and 30°, a drop of 50 percentage points (80% to 30%). (b) While the toe is flat and the angle is small, the setae hold strongly. To step, the gecko curls its toe up, raising the angle past about 30°, and the setae let go almost at once.
8. Sample answer: Independent variable: pressing time (for example 1, 5, 10 and 20 seconds). Dependent variable: the mass the pad holds before sliding. Controlled: the same pad (or identical pads), same surface cleaned the same way, same pressing force, same direction of pull, same rate of adding load. Do at least three trials at each time and compare averages.
9. Suction: geckos still cling when the air is pumped away, and suction needs air pressure. Glue: gecko toes have no glands and leave no wet footprints. Hooks: geckos run on polished glass, which has no bumps big enough to hook into.

10. (a) 0.8 N ÷ 0.0002 N = 4,000 setae. (b) 4,000 ÷ 6,500,000 × 100 ≈ 0.06%. Only a tiny part of its grip is needed.

8.4 Invent from Nature

OBJECTIVES

- Tell how Eiji Nakatsu used the kingfisher’s beak to redesign the nose of Japan’s 500 Series bullet train, and name other inventions drawn from living things.
- Use the six steps of the biomimicry design cycle to turn a problem into a tested prototype, copying a principle rather than a shape.
- Calculate speeds, percent savings, averages and scale lengths from design and test data.

Warm-up. Fill a sink or bowl with water. Hold a spoon flat and slap it onto the water from 10 cm above. Now dip it in edge first, then tip first, from the same height. Which way makes the biggest splash? Which slips in most quietly? Write one sentence on what shape enters water best, and name one bird that dives into water.

Video. Coming soon. Shinkansen 500 Series kingfisher nose and Eiji Nakatsu, kingfisher diving in slow motion, lotus leaf self-cleaning, owl feather silent flight and biomimicry design examples; search Smithsonian, JR West or Japanese rail history, Science Max, Homeschool Pop (Alternate) and slow-motion nature footage.

KEY TERMS

design cycle
The repeating steps engineers use to invent: define the problem, find ideas, build a prototype, test it and improve it.

principle
The rule that makes a design work, such as “many hooks catch many loops.” Biomimicry copies principles, not just shapes.

pressure wave
A pulse of squeezed air (or water) pushed ahead of a fast-moving object, which travels outward like a ripple.

control
The standard version in an experiment that the new design is compared with, such as a smooth surface or a blunt nose.

scale model
A smaller (or larger) copy of an object with every length multiplied by the same number, such as 1 : 250.

CORE IDEAS

The story. In the early 1990s, Japan’s railways wanted bullet trains, called Shinkansen, that could run faster. But speed caused a problem. When a train rushed into a tunnel at high

speed, it shoved the air ahead of it like a plunger in a pipe. A **pressure wave** raced through the tunnel, and at the far end it burst out with a loud boom that startled people living nearby. Eiji Nakatsu, an engineer at the West Japan Railway Company who loved watching birds, was helping design the new 500 Series train. He asked himself, Is there a creature that moves quickly from thin air into something thicker without making a splash? He thought of the **kingfisher**, a small bird that dives from the air into a stream to catch fish and barely leaves a ripple.

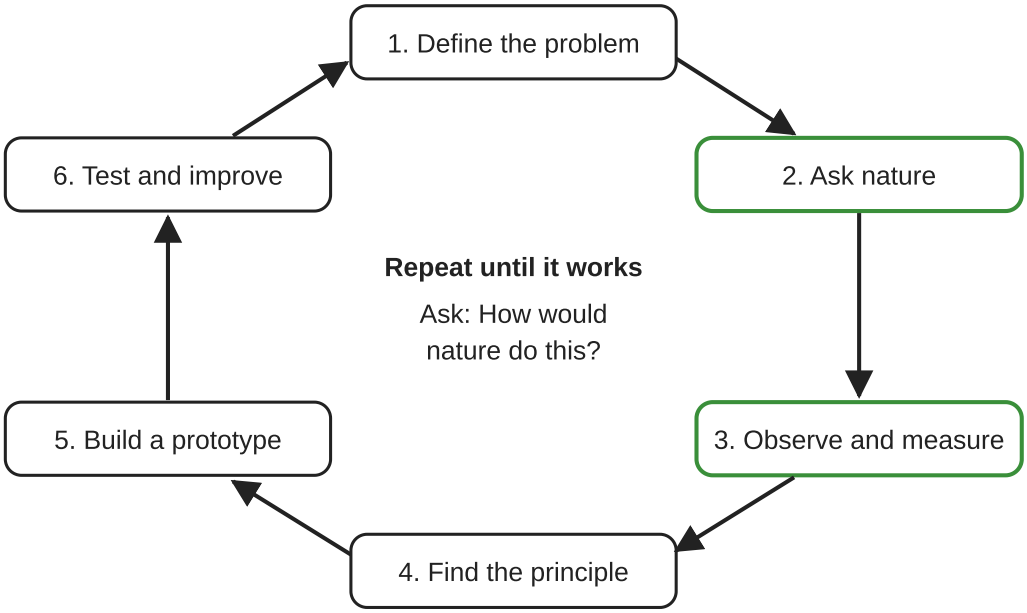
How they figured it out. The kingfisher's beak is long and narrow and widens smoothly from the tip back to the head, with no sudden bumps. Air ahead of it is not slammed all at once; it is eased aside little by little. Nakatsu's team tested many nose shapes on models, measuring the pressure waves each one made in a long test pipe built to act like a tunnel. The best performers were long, pointed and wedge-like, very close to a kingfisher's beak. The finished 500 Series, which began carrying passengers in 1997 at up to 300 km/h, had a nose about 15 m long. Engineers reported that it was quieter at tunnel exits, used about 15 percent less electricity and was faster than the trains before it. Nakatsu also borrowed from the owl: the notched edges of an owl's flight feathers break up the air and make its flight nearly silent, and his team gave the train's pantograph, the arm that touches the power wire, a similar notched edge to cut its noise.

The big idea. Every invention in this unit followed the same path, the **biomimicry design cycle**. (1) Define the problem: a tunnel boom, a fastener, a dirty hull, a gripper. (2) Ask nature: what living thing already solves this? (3) Observe and measure it closely. (4) Find the **principle**: eased entry, hooks and loops, ridges along the flow, millions of tiny contacts. (5) Build a prototype. (6) Test it against a **control** and improve it, again and again. The train does not look like a bird, and Velcro does not look like a burr. Copying the principle, not the shape, is the heart of biomimicry.

In the world today. Engineers keep a growing catalog of nature's solutions. In the 1970s the German botanist Wilhelm Barthlott studied why lotus leaves stay clean in muddy ponds; tiny waxy bumps make water bead up and roll off, carrying dirt with it, and that "lotus effect" led to self-cleaning paints and coatings. The bumps on the front edges of a humpback whale's flippers have inspired fan and turbine blades. Owl feathers have shaped quieter fans. A good inventor learns to look at a pond, a field or a sea and ask, How does this creature handle the same problem I have?

Try it and see. You will do Nakatsu's experiment in a tub. Shape clay noses that are blunt, cone-pointed and long like a kingfisher's beak, give them all the same mass, drop them into water from the same height and measure the splash. Then you will choose a problem of your own and walk it through the whole design cycle.

God's handiwork. When God set Adam in the garden "to dress it and to keep it" (Genesis 2:15), He gave people work that requires watching and learning from the living things around them. Job told his friends, "But ask now the beasts, and they shall teach thee" (Job 12:7). A kingfisher, a burr, a shark and a gecko were all teaching long before anyone listened. Biomimicry is the humble habit of a student in the Creator's workshop.



The biomimicry design cycle. Nakatsu's path: tunnel boom, kingfisher, beak measurements, eased entry, model noses, pressure-wave tests.

PICTURE STUDY



Belted Kingfisher (Plate 77, The Birds of America), John James Audubon (engraved by Robert Havell Jr.), about 1829 · Hand-colored engraving with aquatint · Published in London; complete sets are held by libraries and museums, and scans are shared on Wikimedia Commons

John James Audubon set out to paint every bird of North America life-size, and his great book *The Birds of America* was printed in London from 1827 to 1838 as 435 large hand-colored

plates. The belted kingfisher lives along streams and lakes across North America. It perches above the water, then dives headfirst to snatch a fish.

The kingfisher Eiji Nakatsu watched in Japan is a smaller cousin, the common kingfisher, but both have the same long, straight, wedge-shaped beak. As you look at Audubon's plate, imagine the bird folding its wings and dropping beak-first into the water.

Look closely

- Find the beak. Is it curved like a hawk's or straight like a dagger? Where is it thickest?
- Follow the outline from the tip of the beak back over the head. Are there any sudden bumps, or does it widen smoothly?
- If you see a rusty band across a bird's belly, that bird is a female. In belted kingfishers, the female is the more colorful one.
- Look at the head crest and the size of the head compared with the body. How would the bird look as it dives?

Talk about it

1. Why would a beak that widens smoothly enter water with less splash than a blunt one?
2. Audubon painted birds life-size. How would that help an engineer who wanted to measure a beak?
3. What other bird or animal shape would you like to study for an invention?

> **Safety first.** This project uses a tub of water. Work with an adult nearby, keep the floor dry and wipe up spills right away. Drop the clay from a measured height while standing on the floor, never from a chair or stool. Wash your hands after handling clay.

EXPERIMENT: KINGFISHER SPLASH TEST AND MY OWN INVENTION

Part 1 question: Which nose shape enters water with the smallest splash? You will make three clay noses with the same mass and drop them into water from the same height. What we change: the shape (blunt, cone, long kingfisher wedge). What we keep the same: mass, drop height, water depth, the way we release. What we measure: splash height on a ruler. Write your prediction first.

Part 2: Choose a problem in your home or yard and walk it through all six steps of the biomimicry design cycle, ending with a prototype you build and test.

You will need

- Modeling clay (about 60 g) and a kitchen scale
- A clear plastic tub or deep baking dish, about 10 cm of water
- A ruler taped upright to the back inside wall of the tub, and a meter stick or measuring tape for the drop height
- A phone camera with slow motion (optional but very helpful), a towel

- For Part 2: cardboard, tape, string, straws, foil, fabric scraps and other household odds and ends
- Notebook and pencil

Steps

1. Make three noses of 20 g each: (A) a blunt ball flattened on the bottom, (B) a short cone about 3 cm long, (C) a long, thin wedge about 7 cm long that widens smoothly like a kingfisher’s beak.
2. Hold each nose point-down with its tip 50 cm above the water and let it drop straight in. Do not throw it.
3. Read the highest point the splash reaches on the ruler (slow-motion video makes this much easier). Record the height in cm.
4. Do three drops for each shape, drying the ruler between drops. Find the average splash height for each shape, and make a bar graph.
5. Calculate the percent less splash for the wedge compared with the blunt nose (the control).
6. Part 2: Pick a problem (for example, a cup that tips over, a door that slams, a backpack strap that slips, a plant pot that dries out). Write each design-cycle step in your notebook: the problem, a living thing that solves it, what you observe, the principle, a sketch of your prototype, and a fair test with a control.
7. Build the prototype, test it at least three times against the control and write what you would improve next.

Tips

- Keep all three noses the same mass by weighing them; otherwise the heavier one may splash more just because it is heavier.
- Let the water settle completely between drops.
- For Part 2, look up the living thing in a field guide or watch it in your yard before you design. Measure something about it.

Check your work

- I kept the mass and drop height the same and changed only the shape.
- I did three drops for each shape, found averages and made a bar graph.
- I wrote all six design-cycle steps for my own invention.
- I built and tested a prototype against a control and wrote one improvement.

NATURE NOTEBOOK

1. Draw a kingfisher’s head and beak from the side, and below it the nose of a bullet train. Draw arrows showing how air (or water) is eased aside by each one.
2. Make a two-column chart: “Living thing” and “Invention.” Fill in at least six rows from this unit and your own reading (burr, shark, gecko, kingfisher, owl, lotus, humpback whale).

3. Go outside for 15 minutes and find one living thing that solves a problem well (a leaf shedding rain, a spider’s anchor line, a seed that spins). Sketch it and write a sentence: “This could help people to ____.”

From history. In 1849 the English gardener Joseph Paxton grew the giant Amazon water lily, *Victoria*, at Chatsworth House and got it to flower, the first time in England. Its leaves grew so big that he set his young daughter Annie on one, and it held her up. Paxton studied how the ribs on the underside of the leaf spread out and stiffen it, and he used the same idea of light ribs supporting a thin surface in his glass-and-iron lily house. In 1851 he designed the Crystal Palace in London for the Great Exhibition, a vast building of iron and glass that owed something to a lily leaf.

WORKED EXAMPLES

Example 1. The 500 Series bullet train ran at up to 300 km/h. (a) What is that speed in meters per second? (b) At that speed, how long does it take to pass through a tunnel 1,000 m long (count only the front of the train)?

1. (a) 300 km = 300,000 m and 1 h = 3,600 s. Speed = 300,000 m ÷ 3,600 s ≈ 83.3 m/s.
2. (b) Time = distance ÷ speed = 1,000 m ÷ 83.3 m/s ≈ 12 s.
3. Check: 83.3 m/s × 12 s ≈ 1,000 m.

Answer: (a) About 83.3 m/s. (b) About 12 seconds.

Example 2. Engineers reported that the kingfisher-nosed train used about 15% less electricity. Suppose an older train used 4,000 kWh (kilowatt-hours) of electricity on one trip. (a) How much would the new train use on the same trip? (b) How much would it save over 20 trips?

1. (a) 15% of 4,000 kWh = 0.15 × 4,000 = 600 kWh saved per trip.
2. New train use = 4,000 − 600 = 3,400 kWh per trip.
3. (b) Savings over 20 trips = 600 kWh × 20 = 12,000 kWh.

Answer: (a) 3,400 kWh per trip. (b) 12,000 kWh saved over 20 trips.

Example 3. A student ran the splash test and recorded splash heights in cm:
Blunt: 24, 25, 23.
Cone: 14, 15, 13.
Kingfisher wedge: 8, 9, 7.
(a) Find the average for each shape. (b) By what percent was the wedge's splash smaller than the blunt nose's (the control)?

(Use the map or drawing "The splash test is step 6, test and improve, with the blunt nose as the control." shown earlier in this lesson.)

1. (a) Blunt: (24 + 25 + 23) ÷ 3 = 72 ÷ 3 = 24 cm. Cone: (14 + 15 + 13) ÷ 3 = 42 ÷ 3 = 14 cm. Wedge: (8 + 9 + 7) ÷ 3 = 24 ÷ 3 = 8 cm.
2. (b) Difference = 24 − 8 = 16 cm. Percent = 16 ÷ 24 × 100 ≈ 67%.
3. The spread within each shape (about 2 cm) is much smaller than the differences between shapes, so the result is trustworthy.

Answer: (a) Blunt 24 cm, cone 14 cm, wedge 8 cm. (b) The wedge splashed about 67% less than the blunt nose.

PRACTICE

1. EASY List the six steps of the biomimicry design cycle in order.
2. EASY Match each invention with the living thing that inspired it: hook-and-loop fastener, riblet film, Geckskin, 500 Series train nose, self-cleaning paint. Choices: lotus, burdock, kingfisher, shark, gecko.
3. EASY What problem did Eiji Nakatsu need to solve, and why did the kingfisher come to mind?
4. MEDIUM Convert 270 km/h to meters per second.
5. MEDIUM Data reading. A student dropped clay noses into water three times each and measured splash height:
   Ball: 20, 22, 21 cm.
   Short cone: 12, 13, 11 cm.
   Long wedge: 6, 7, 8 cm.
   (a) Which shape is the control? (b) Find the average of the long wedge. (c) Write one conclusion supported by the data.
6. MEDIUM Data reading (sample data). Engineers tested model train noses of different lengths and measured the strength of the pressure wave at the tunnel exit (relative units):
   5 m nose: 100.
   10 m nose: 70.
   15 m nose: 50.
   (a) Describe the trend. (b) A student says a 30 m nose would give a wave of 0. Is that a safe conclusion? Explain.

7. MEDIUM A model of the 500 Series nose is built at a scale of 1 : 250. The model nose is 6 cm long. How long is the real nose in meters?
8. HARD Explain what it means to copy the principle and not the shape. Use the kingfisher train or Velcro as your example.
9. HARD Experiment design. You want to test whether a waxy, bumpy surface, like a lotus leaf, keeps itself cleaner than a smooth one. Design a fair test: what you compare, the control, what you keep the same and what you measure.
10. CHALLENGE Choose a problem (keeping a house cool, a quieter fan, a backpack that does not slip, or one of your own). Name a living thing that solves a similar problem, state the principle you would copy and describe how you would test your prototype against a control.

COMMON MISTAKES

- Thinking biomimicry means making a machine look like an animal. The best designs copy the working principle, which often looks nothing like the creature.
- Thinking a design from nature will work for people without testing. A trick that works for a 40 g bird may behave differently on a train weighing hundreds of tons, so every copy must be built, measured and tested against a control.
- Thinking one living thing gives the whole answer. The 500 Series borrowed from both the kingfisher and the owl, and many inventions combine several ideas.

Make it a game · Nature's Patent Office. One player is the Patent Clerk. The other players draw a slip naming a problem (stay cool, stay dry, grip glass, move quietly, see in the dark, carry a heavy load, keep clean). Each has 30 seconds to name a living thing that solves it and the principle to copy. The Clerk awards 1 point for a correct creature and 1 for a clear principle, and stamps the best idea of the round "Patent Granted." First to 8 points wins.

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's next words are "Who knoweth not in all these that the hand of the LORD hath wrought this?" (Job 12:9). The beasts, birds and fish teach engineers, and they also point beyond themselves to the One who made them.

Practice answers

1. 1. Define the problem. 2. Ask nature. 3. Observe and measure. 4. Find the principle. 5. Build a prototype. 6. Test and improve (then repeat).
2. Hook-and-loop fastener: burdock. Riblet film: shark. Geckskin: gecko. Train nose: kingfisher. Self-cleaning paint: lotus.
3. Fast trains entering tunnels pushed a pressure wave ahead of them that boomed out of the far end. The kingfisher dives from air into water, which resists much more, with hardly a splash, so its beak shape eases a sudden change in resistance.

4. 270,000 m ÷ 3,600 s = 75 m/s.
5. (a) The ball (blunt shape). (b) (6 + 7 + 8) ÷ 3 = 7 cm. (c) The longer and more pointed the nose, the smaller the splash; the long wedge splashed about one third as high as the ball (7 cm vs 21 cm).
6. (a) Longer noses make weaker pressure waves, but each extra 5 m helps less (a drop of 30, then 20). (b) No. The data only go to 15 m, and the improvements are getting smaller, so the wave probably will not reach 0. Predicting far beyond the data is risky, and a very long nose would also take away passenger space.
7. Real length = 6 cm × 250 = 1,500 cm = 15 m.
8. Sample answer: The train does not have feathers, eyes or a bird’s head. Engineers copied the rule that made the beak work: a long point that widens smoothly so the air ahead is pushed aside gradually instead of all at once. Likewise, Velcro is not shaped like a burr; it copies the rule of many hooks catching many loops.
9. Sample answer: Compare a card rubbed with candle wax (the lotus-like surface) with an identical plain card (the control). Sprinkle the same amount of fine dirt or cocoa powder on each, tilt both at the same angle, and drip the same number of water drops from the same height. Measure how much powder is washed away (for example, by counting clean spots or photographing and comparing). Repeat three times.
10. Sample answer: Problem: a backpack strap slips off my shoulder. Living thing: the gecko. Principle: many tiny, soft contacts grip a surface better than one smooth one. Prototype: a strap pad covered with many small rubber bumps. Test: walk the same route with a plain strap (control) and the bumpy strap, three times each, and count how often each slips.

Unit 8 review

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

1. (4 pts) Multiple choice. When George de Mestral looked at a burdock burr under his microscope in 1941, what did he see?
   (a) A sticky glue on the spines
   (b) Tiny hooks at the tips of the spines
   (c) Tiny suction cups
   (d) Fine hairs that cling by molecular attraction
2. (5 pts) What is seed dispersal? Explain how the burdock burr's design helps the plant disperse its seeds.
3. (6 pts) A hook strip 3 cm × 4 cm is loaded in shear on fleece and holds 1,800 g before sliding off. (a) What is its holding strength in g/cm²? (b) Predict how much a strip 3 cm × 8 cm would hold, and explain why.
4. (4 pts) Multiple choice. A shark's dermal denticles are built most like:
   (a) feathers
   (b) teeth
   (c) fingernails
   (d) the thin, flat scales of a goldfish
5. (6 pts) A smooth test panel feels 120 N of drag in a water tunnel. With riblet film it feels 114 N at the same speed. (a) What is the percent reduction in drag? (b) Which way must the riblets run compared with the flow of water?
6. (5 pts) Data reading. Algae spores settled per mm² after one week: smooth plastic 900; shark-like ridged pattern 180. (a) Which surface is the control? (b) By what percent did the shark-like pattern reduce settling? (c) Why would this matter to the Navy?
7. (6 pts) Diagram. Draw a gecko's foot at four levels of zoom, from largest to smallest, in four boxes joined by arrows. Label each level with its name and approximate size. Mark which part actually touches the wall, and name the force that holds it there.
8. (6 pts) One gecko seta holds about 0.0002 N. (a) How much force could 2,000,000 setae hold? (b) If 1 kg weighs about 10 N, what mass is that? (c) A gecko weighs about 1 N. How many setae are needed, at minimum, to hold it?
9. (4 pts) Multiple choice. A gecko clings to a glass window mainly by:
   (a) suction
   (b) a sticky liquid from its toes
   (c) van der Waals forces between molecules
   (d) tiny hooks catching in the glass
10. (6 pts) Use the six steps of the biomimicry design cycle to tell the story of the 500 Series bullet train. Write one sentence for each step.
11. (8 pts) Experiment design. You want to know whether a kingfisher-shaped clay nose makes a smaller splash than a blunt one. Describe a fair experiment: your question, the

independent variable, the dependent variable, the control, at least three things you keep the same, the number of trials and how you will decide which shape is better.

UNIT PROJECT: MY INVENTION FROM NATURE

Invent something useful by learning from a living thing. Choose a real problem at home, on the farm or in your yard, find a plant or animal that solves a similar problem, and work through all six steps of the biomimicry design cycle. Build a working prototype from household materials and test it at least three times against a control, recording your measurements in a table and a graph.

Present your invention on a poster or in a notebook spread: a labeled sketch of the living thing (with at least one measurement or magnified drawing), a labeled sketch of your prototype, the principle you copied in one sentence, your data table and graph, and a paragraph explaining what worked, what did not and what you would improve next. Add a short note on what your living model shows about the wisdom of its Maker.

- **Observation of nature**: The living model is drawn carefully, labeled and measured, and the principle it uses is clearly identified.
- **Design**: All six design-cycle steps are shown; the prototype copies the principle rather than just the shape, and it is neatly built and labeled.
- **Fair test and data**: The prototype is tested at least three times against a control with only one variable changed; data are recorded with units, averaged and graphed correctly.
- **Explanation**: The paragraph honestly reports what the data show, explains why the design did or did not work and proposes a specific improvement.

Answer key

1. (b) Tiny hooks at the tips of the spines, which caught in loops of cloth and fur.
2. Seed dispersal is the carrying of seeds away from the parent plant (by wind, water or animals) so the young plants do not crowd each other. A burdock burr is a seed head covered with hooked spines; the hooks catch in the fur of passing animals, which carry the burr away until it is scratched or rubbed off in a new place.
3. (a) Area = 12 cm^2. Strength = 1,800 g ÷ 12 cm^2 = 150 g/cm^2. (b) Area = 24 cm^2, so about 150 × 24 = 3,600 g. Twice the area has twice as many hooks catching loops, so it holds about twice as much.
4. (b) Teeth. Each denticle has a hard enamel-like outer layer, dentine and a pulp cavity.
5. (a) 120 − 114 = 6 N; 6 ÷ 120 × 100 = 5%. (b) The riblets must run in the same direction as the flow, from front to back (on a shark, head to tail).
6. (a) Smooth plastic. (b) 900 − 180 = 720; 720 ÷ 900 × 100 = 80%. (c) Less biofouling on hulls means smoother, lighter ships that burn less fuel and need less scraping.
7. Boxes in order: (1) toe pad, about 1 cm; (2) lamellae, the ridges under the toe; (3) setae, hairs about 0.1 mm long; (4) spatulae, tips about 0.2 µm (200 nm, or 0.0002 mm) wide. The spatulae touch the wall. The force is the van der Waals force, a weak attraction between molecules very close together. (Full marks: 4 levels in correct order with names, at least 3 sizes, spatulae marked, force named.)

8. (a) 2,000,000 × 0.0002 N = 400 N. (b) 400 N ÷ 10 N/kg = 40 kg. (c) 1 N ÷ 0.0002 N = 5,000 setae.
9. (c) Van der Waals forces. Geckos still cling with the air pumped away (not suction), leave no wet footprints (not glue) and glass has nothing to hook (not hooks).
10. 1. Define the problem: fast trains entering tunnels made a pressure wave that boomed out of the far end. 2. Ask nature: Eiji Nakatsu thought of the kingfisher, which dives from air into water with almost no splash. 3. Observe and measure: the beak is long and widens smoothly from the tip. 4. Find the principle: a long, gradually widening point eases the air aside instead of slamming it. 5. Build a prototype: engineers built model noses of many shapes. 6. Test and improve: they measured pressure waves in a test tunnel and chose a long, beak-like nose about 15 m long, which was quieter and used less electricity.
11. Sample answer: Question: Does a long, wedge-shaped nose make a smaller splash than a blunt one? Independent variable: nose shape. Dependent variable: splash height in cm on a ruler. Control: the blunt nose. Keep the same: mass of clay (weighed), drop height, water depth, release method, ruler position. Do at least three drops per shape and compare the averages; the shape with the clearly lower average (by more than the spread between its own trials) is better.

Bonus: Nature Lab

All year you have studied how animals fly, travel, echo, hide, build, live together and grow to giant size. This bonus unit sends you outdoors to do what the naturalists in those stories did: look, measure, count and record for yourself. “The works of the LORD are great, sought out of all them that have pleasure therein” (Psalm 111:2). These four lessons are lighter and more playful, and they can be done in any season and in any order.

You will keep a nature journal like Gilbert White of Selborne, survey your backyard birds and plants like the counters of the first Christmas Bird Count in 1900, study animal behavior at a zoo, farm or museum the way Charles Willson Peale’s visitors studied his mastodon, and build a small labeled collection the way Lewis and Clark filled a boat with specimens for President Jefferson. Along the way you will practice real science skills: telling observations from inferences, sampling with quadrats, recording an ethogram and building a dichotomous key.

Everything you make goes into one field notebook. By the end of the unit it will hold dated journal pages, survey tallies and graphs, a time budget for an animal you watched, and a catalog of your own specimens: the start of a naturalist’s lifelong record.

BEFORE YOU BEGIN

- Can measure length in centimeters and meters and find an average
- Can turn a fraction into a percentage
- Can read and draw a simple bar graph
- Knows the difference between a variable that is changed and one that is measured in an experiment

MASTERY CHECKLIST

- I can keep a nature journal page with a full header, a labeled sketch with a scale and separate observations and questions.
- I can measure distance by pacing and estimate a population using quadrats.
- I can record an animal’s behavior with an ethogram and calculate its time budget in percentages.
- I can read a museum sign and sort what was observed from what is interpreted.
- I can collect, preserve and label specimens lawfully and build a dichotomous key that another person can use.

OPTIONAL BOOKS AND RESOURCES

- **Merlin Bird ID, from the Cornell Lab of Ornithology** (https://merlin.allaboutbirds.org/): Free app. Helps identify birds by photo, sound or a

few simple questions. Use it with a parent during the backyard survey (Lesson 9.2), then check the answer in a printed field guide.

- **Great Backyard Bird Count** (https://www.birdcount.org/): Free. Each February families everywhere count birds for at least 15 minutes and send in their tallies. A real way to add your Lesson 9.2 survey to science.
- **eBird, from the Cornell Lab of Ornithology** (https://ebird.org/): Free. A parent can set up an account to record checklists from your journal walks and see what birds others have reported nearby.

9.1 Nature Journal Walk

OBJECTIVES

- Keep a nature journal page the way field scientists do, with date, time, place, weather, a labeled sketch and notes.
- Tell an observation (what I see, hear or measure) from an inference (what I think it means).
- Measure distance outdoors by pacing and convert paces to meters.

Warm-up. Sit by a window for 5 minutes with a pencil and a scrap of paper. Make a tally mark every time you see or hear a living thing move: a bird, an insect, a squirrel, a leaf blown by an animal. At the end, count your marks. Was it more or fewer than you guessed before you started?

Video. Coming soon. How to keep a nature journal and sketch animals outdoors for kids; search John Muir Laws nature journaling, Cornell Lab of Ornithology, Smithsonian, and Gilbert White Selborne documentaries.

KEY TERMS

nature journal
A field notebook where a naturalist records dated observations, sketches, measurements and questions about living things.

observation
Something you notice directly with your senses or a tool, such as a color, a sound, a count or a length.

inference
An idea about what an observation means, reasoned from evidence but not seen directly.

pace
The distance covered by one natural walking step; once you measure it, you can use it to measure distances outdoors.

phenology
The study of when things happen in nature each year, such as the first robin, the first bloom or the first frost.

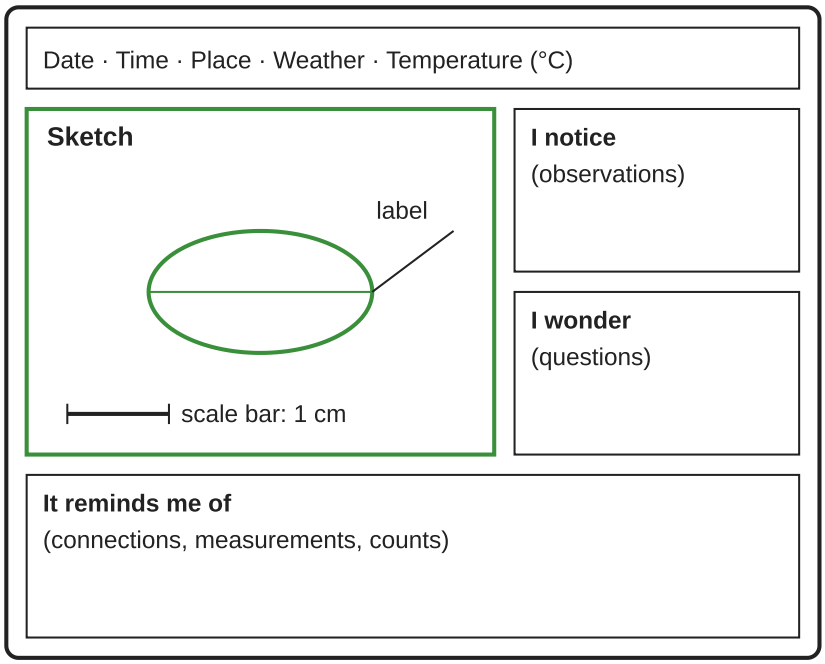
CORE IDEAS

The story. In the little village of Selborne, in Hampshire, England, a quiet pastor named Gilbert White began keeping a printed “Naturalist’s Journal” in 1768. Every day, for the rest of his life, he wrote in its columns: the weather, the wind, the temperature, which birds were singing and which flowers were open. He noted the day the swifts screamed back over the village in spring and the day they vanished in late summer. By listening carefully, he showed

that three little greenish birds that most people lumped together were really three different kinds, because each had its own song. In 1789 he gathered his letters and notes into a book, *The Natural History of Selborne*, and readers have loved it ever since. White never traveled far. He simply looked at one parish, year after year, and wrote it down.

The big idea. A nature journal turns a walk into science. Each page starts with the same **header**: date, time, place, weather and temperature. Then comes a sketch with labels and measurements, and notes. Good naturalists keep two kinds of notes apart. An **observation** is what you actually see, hear or measure: “the leaf has six round holes, each about 4 mm wide.” An **inference** is what you think it means: “something chewed this leaf, maybe a caterpillar.” Both are useful, but mixing them up is how mistakes creep into science. A simple layout helps: *I notice* (observations), *I wonder* (questions) and *It reminds me of* (connections). To measure outdoors without a tape, use your **pace**. Count how many steps it takes to walk a measured 20 m, divide, and you have a ruler you always carry with you. Pages written on the same path in different seasons build a record of **phenology**, the timing of nature’s year.

God’s handiwork. White wrote that the more he watched, the more wonders he found in the commonest creatures, even earthworms, which he argued were far more important to the soil than people supposed. The Bible invites this kind of slow, patient looking: “stand still, and consider the wondrous works of God” (Job 37:14). You do not need a jungle or a far-off island. A hedge, a ditch, a city park or a single tree, watched faithfully and written down honestly, is enough to make you a real naturalist.



A nature journal page: header first, then a labeled sketch with a scale, then notes that keep observations and questions apart.

PICTURE STUDY



Young Hare, Albrecht Dürer, 1502 · Watercolor and bodycolor (opaque watercolor) on paper · Albertina, Vienna

Albrecht Dürer was a German artist from Nuremberg who lived more than five hundred years ago. He was famous for his engravings, but he also made careful nature studies in watercolor, as if he were keeping a nature journal of his own. In *Young Hare* he painted a hare hair by hair, with the fur lying in different directions on the back, the ears and the legs. Below the hare he signed his initials and the year, 1502, just as a naturalist dates every page.

Look closely at the eye. Dürer painted a tiny window reflected in it, which tells us he probably studied a real hare indoors, near a window. That is what this lesson asks of you: look long enough to see what most people miss.

Look closely

- Follow the direction of the fur. Where does it lie flat, and where does it stand up or change direction?
- Find the reflected window in the hare’s eye. What does it tell you about where the hare was sitting?
- Compare the long hind feet with the front feet. Which are bigger, and why might a hare need them?
- Find Dürer’s initials and date. Where would you put the date on your own sketch?

Talk about it

1. Which parts of this painting are observations Dürer could see, and is anything in it an inference?

2. How long do you think it took to paint every hair? What does that tell you about the value of patient looking?
3. If Dürer had added a journal header to this painting, what would he need to write?

> **Safety first.** Walk with an adult, stay on paths, and dress for ticks (long pants tucked into socks) and check for ticks afterward. Learn to recognize poison ivy ("leaves of three, let it be") and stinging nettles before you go. Watch wild animals from a distance and never touch or feed them. Do not taste any berry, mushroom or plant.

EXPERIMENT: MY PACE RULER AND JOURNAL LOOP

You will calibrate your own pace, then use it to map a short walking loop and fill two journal pages on it. The question: How long is my loop, and what lives along it?

You will need

- Nature journal or a sketchbook with unlined pages
- Pencil, colored pencils and an eraser
- Measuring tape (at least 5 m) or a 1 m string marked with tape
- Outdoor thermometer (optional)
- Clipboard or a stiff piece of cardboard
- Hand lens (optional)

Steps

1. Measure a straight 20 m course on a sidewalk or lawn with the tape. Mark the start and finish.
2. Prediction: write how many of your normal steps you think the 20 m will take.
3. Walk the 20 m at your normal speed, counting steps. Do it three times and record each count. Keep the same: your speed, your shoes, the course. Find the average count.
4. Divide 20 m by your average number of steps. That is your pace length in meters. Write it inside the cover of your journal.
5. Now walk a loop of your choice (around the yard, the block or a park path). Count paces all the way around and multiply by your pace length to find the length of the loop in meters.
6. Stop at two places on the loop. At each, fill a journal page: header (date, time, place, weather, temperature), one labeled sketch with a measurement or scale bar, and notes under I notice, I wonder and It reminds me of.
7. At home, draw a simple map of your loop with an arrow for north, your two stops marked, and the loop length written on it.

Tips

- Walk naturally; long "giant steps" make your pace ruler wrong.
- Sketch first, then color later at home if time is short. Shapes and labels matter more than beauty.

- Write questions even if you cannot answer them. Questions are where experiments begin.

Check your work

- I know my pace length and used it to measure my loop.
- Each journal page has a full header, a labeled sketch with a measurement and separate notes.
- I can point to one observation and one inference on my pages.

NATURE NOTEBOOK

1. Sketch one leaf at life size. Measure its length in millimeters and add a 1 cm scale bar beside the drawing.
2. Make a two-column chart titled “Observation or Inference?” and sort ten of your walk notes into the columns.
3. Start a phenology list on the last page of your journal: “First seen this year,” with columns for date, living thing and place.

> **From history.** Gilbert White kept a pet tortoise named Timothy that he inherited from an aunt in 1780. For years he recorded in his journal when Timothy buried himself in the ground for the winter and when he came out in spring, and how he hurried to shelter before rain. Timothy’s shell is kept today at the Natural History Museum in London, a small reminder that careful notes about one ordinary animal can last for centuries.

WORKED EXAMPLES

Example 1. Grace walks a measured 20 m course three times and counts 31, 32 and 33 steps. Then she walks around a park loop and counts 480 steps. How long is her pace, and how long is the loop?

1. Average steps for 20 m: (31 + 32 + 33) ÷ 3 = 96 ÷ 3 = 32 steps.
2. Pace length: 20 m ÷ 32 steps = 0.625 m per step.
3. Loop length: 480 steps × 0.625 m = 300 m.

Answer: Her pace is 0.625 m (about 63 cm), and the loop is about 300 m long.

PRACTICE

1. EASY List the five things that belong in the header at the top of every nature journal page.
2. EASY Label each note as an observation (O) or an inference (I): (a) The bird has a red crest. (b) The bird is a male because it is bright red. (c) The puddle is 30 cm across. (d) A deer walked here last night.

3. MEDIUM Sam takes 20 steps to walk a measured 15 m. Later he walks 600 steps along a creek. How far did he walk?
4. HARD A student watched the same patch of flowers for 5 minutes on four spring mornings and recorded the air temperature and the number of insect visits.
   Morning 1: 8 °C, 2 visits
   Morning 2: 12 °C, 5 visits
   Morning 3: 16 °C, 9 visits
   Morning 4: 20 °C, 14 visits
   (a) Describe the trend. (b) Predict the visits at 14 °C. (c) Does this data prove that warmth causes insects to visit? Explain.
5. CHALLENGE Design a journal study to answer: “Do more birds visit our feeder in the morning or in the afternoon?” Name what you change, what you keep the same, what you measure and how many days you would collect data.

COMMON MISTAKES

- Writing inferences as if they were observations, such as “a fox lives here” when you only saw a hole in the ground.
- Leaving off the date and place. A beautiful sketch with no date or place is a picture, not a scientific record.
- Thinking you must travel somewhere wild to do real nature study. Gilbert White made his discoveries in one small village.

> **Make it a game · Observation Detective.** One player describes something in the yard using only observations (shape, color, size in centimeters, sound, location) and no names. The others try to find it. If the describer slips and uses an inference such as “the bird’s nest” instead of “a cup of twigs 12 cm wide,” the turn passes. Score a point for each object found in under one minute.

> **Scripture.** “Hearken unto this, O Job: stand still, and consider the wondrous works of God.” (Job 37:14, KJV)

A nature journal is a way to “stand still and consider.” Slowing down to look closely is both good science and a way to honor the Maker of what we see.

Practice answers

1. Date, time, place, weather and temperature.
2. (a) O, (b) I, (c) O, (d) I. The deer note is an inference from tracks or droppings unless you actually saw the deer.
3. Pace = 15 m ÷ 20 = 0.75 m. Distance = 600 × 0.75 m = 450 m.
4. (a) As temperature rises, insect visits increase. (b) Between 5 and 9, about 7 visits. (c) No. It shows a pattern (a correlation), but other things also changed from morning to morning, such as how many flowers were open or the time of day. A test that changes only one thing would be needed to show cause.

5. Change: the time of day (for example, 8:00 and 16:00). Keep the same: the feeder, the amount and kind of seed, the length of each watch (say 15 minutes), the place you sit and the way you count. Measure: the number of bird visits in each 15-minute watch. Repeat for at least 7 to 10 days and compare averages, writing the weather in the header each time because rain or wind could affect results.

9.2 Backyard Survey

OBJECTIVES

- Carry out a timed bird count and a quadrat survey of a small plot, recording results in a tally table.
- Use sample counts to estimate the population of a living thing over a larger area.
- Read a bar graph of survey data and explain why scientists repeat counts and use many counters.

Warm-up. Scatter a handful of dried beans over a large towel or bedsheet. Lay a square of paper 10 cm × 10 cm on three different spots and count the beans under each. Using your counts, guess how many beans are on the whole towel. Then count them all. How close was your estimate?

Video. Coming soon. How to do a backyard bird count and a quadrat survey for students; search Cornell Lab of Ornithology (Great Backyard Bird Count, eBird), National Audubon Society Christmas Bird Count, and biology field-sampling demonstrations.

KEY TERMS

survey
A careful, organized count of the living things in a place, done the same way each time so results can be compared.

population
All the members of one kind of living thing in one area, such as all the dandelions in a lawn.

quadrat
A square frame of known size (often 1 m × 1 m) laid on the ground to mark an area for counting plants or slow animals.

sample
A small part of an area or group that is counted carefully and used to estimate the whole.

species
A group of living things that look alike and can reproduce together, like the American robin; scientists count how many different species live in a place.

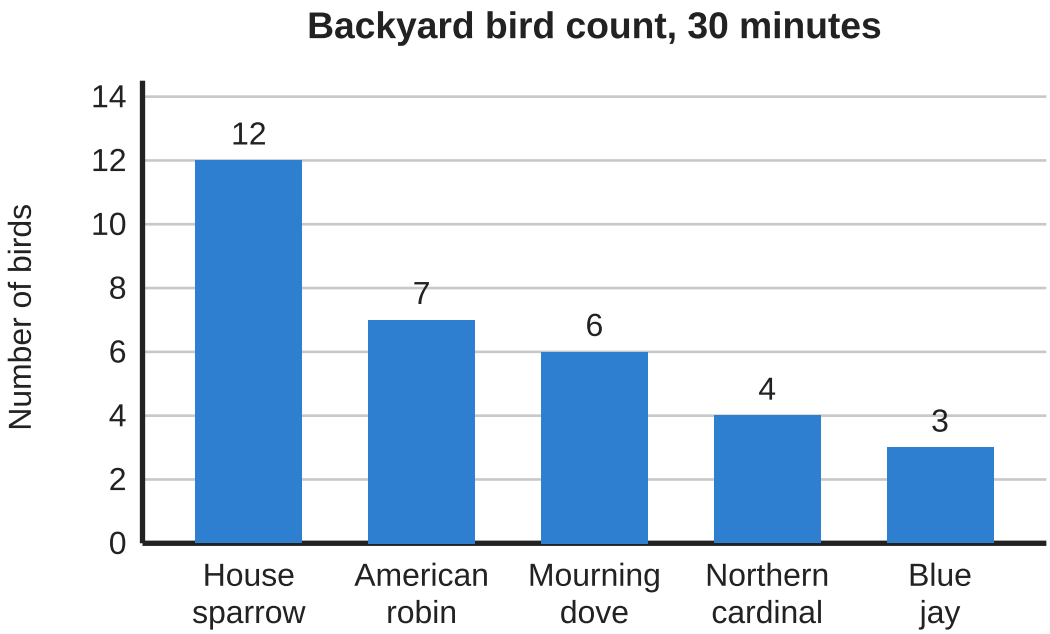
CORE IDEAS

The story. In the 1800s many Americans kept a strange Christmas custom called the “side hunt.” Teams went out on Christmas Day and shot as many birds and small animals as they could, and the side with the biggest pile won. Frank M. Chapman, a bird scientist at the American Museum of Natural History in New York, proposed something better. On Christmas Day, 1900, he invited people to go out and *count* birds instead of shooting them. That first

Christmas Bird Count had 27 counters in 25 places, from Toronto in Canada to Pacific Grove in California, and they listed about 90 kinds of birds. Volunteers have kept the count going every winter since, and it is now one of the longest-running wildlife surveys in the world.

How they figured it out. No one can count every bird in North America or every dandelion in a big field. Scientists count a **sample** and use it to estimate the whole. For birds, a counter watches one spot for a set time, such as 15 or 30 minutes, and tallies each **species**, writing down the highest number of each kind seen at one moment so the same bird is not counted twice. For plants or slow animals like snails, a scientist lays a **quadrat**, a square of known size, in several places chosen at random, counts what is inside, and finds the average per square meter. Multiply by the area and you have an estimate of the **population**. Random places matter: if you lay every square on the thickest patch, your estimate will be far too high.

Try it and see. A backyard survey is real science when it is done the same way each time. Write the date, time, weather and length of your count. Use the same quadrat, the same number of squares and the same counting rules. Then your survey in spring can be compared with your survey in fall, and your family's count can be added to thousands of others. Many counters and many repeats make results more reliable, because one odd day or one tired counter matters less in a big pile of careful data. Jesus pointed his listeners to the very birds you are counting: "Behold the fowls of the air" (Matthew 6:26). To behold is to look carefully, and a survey is beholding with a pencil in hand.



One family's 30-minute backyard bird count, drawn as a bar graph.

PICTURE STUDY



Seal Rocks, Farallons, Albert Bierstadt, 1872 · Oil on canvas mounted on cardboard · Museum of Fine Arts, Boston

Albert Bierstadt was a German-born American painter famous for huge pictures of the Rocky Mountains and Yosemite. In the early 1870s he worked in California, and one of his subjects there was the Farallon Islands, a cluster of rocky islands in the Pacific Ocean about 43 km west of the Golden Gate at San Francisco. The rocks are crowded with sea lions and seals and nest sites for many thousands of seabirds.

Bierstadt painted the animals packed together on the wave-battered rocks. Although the title says “seals,” the animals crowding the Farallon rocks were most likely sea lions, which have small outer ear flaps and can turn their back flippers forward to walk on land. Scientists still survey the Farallon animals today, counting them from photographs and lookout points.

Look closely

- Try to count the animals on the rocks. Where is it easy to count, and where do they blur together?
- Find the largest animals. Are they on the high rocks or near the water?
- Look at the waves. How might rough water make a survey of these animals hard?
- Look for any birds in the sky or on the rocks.

Talk about it

1. If you had to estimate how many sea lions were on these rocks, how could you use a sample instead of counting every one?
2. Why might a count made from a boat give a different number than one made from a photograph taken from above?

3. What would you write in the journal header if you were counting on this day?

> **Safety first.** Survey with an adult. Wear gloves when parting grass or turning over boards and stones, and turn them back gently the same way. Watch for stinging insects, ticks and poison ivy, and do not reach where you cannot see. Wash your hands afterward.

EXPERIMENT: LAWN CENSUS: A QUADRAT EXPERIMENT

Question: Is there a difference in the number of dandelions (or clover heads, or another common plant) between a sunny lawn and a shady lawn? You will use quadrats to find out.

You will need

- Four sticks or tent stakes and 4 m of string, or four 1 m lengths of wood or PVC pipe, to make a 1 m × 1 m quadrat
- Measuring tape
- Two dice or a list of random numbers
- Tally sheet and pencil
- Garden gloves
- Clipboard

Steps

1. Choose a sunny area and a shady area of lawn. Measure the length and width of each in meters and find its area.
2. Prediction: write which area you think will have more dandelions per square meter, and why.
3. Pick random spots: stand at a corner, roll two dice, walk that many paces along one edge, roll again, and walk that many paces in. Lay the quadrat there.
4. Count every dandelion plant whose base is inside the quadrat. Count a plant on the edge only if more than half of it is inside.
5. Repeat for 5 quadrats in the sunny area and 5 in the shady area. Keep the same: quadrat size, counting rule and the day you count.
6. For each area, find the average per square meter and multiply by the area to estimate the population.
7. Also do a 15-minute bird count from one spot: tally each species and record the most of each kind you see at one time. Make a bar graph of your bird count.
8. Write a conclusion: Was your prediction supported? What else besides sunlight might explain the difference?

Tips

- Do not choose “interesting” spots for the quadrat. Let the dice choose.
- If you cannot name a plant or bird, sketch it and give it a nickname (“yellow-throat bird”). You can look it up later.

- Add your bird count to a real survey such as the Great Backyard Bird Count each February.

Check your work

- I placed my quadrats at random and counted with a clear rule.
- I calculated an average per square meter and an estimated population.
- I made a bar graph of my bird count and wrote a conclusion.

NATURE NOTEBOOK

1. Draw a map of your survey area from above, with its measurements in meters and an X for each quadrat.
2. Sketch the three most common plants inside your quadrats, each with a leaf shape and a label.
3. Draw your bird count as a bar graph with a title, labeled axes and the date.

> **From history.** In 1966 the bird scientist Chandler Robbins started the North American Breeding Bird Survey. Volunteers drive the same roadside route each June, stopping 50 times, 0.8 km apart, and counting every bird seen or heard in exactly 3 minutes at each stop. Because the method never changes, counts from different years and places can be compared, and the survey is still running today.

WORKED EXAMPLES

Example 1. Five random 1 m × 1 m quadrats in a lawn hold 4, 7, 3, 6 and 5 dandelions. The lawn is 12 m long and 8 m wide. Estimate the dandelion population.

1. Total in the samples: 4 + 7 + 3 + 6 + 5 = 25 dandelions in 5 m².
2. Average density: 25 ÷ 5 = 5 dandelions per m².
3. Lawn area: 12 m × 8 m = 96 m².
4. Estimate: 5 per m² × 96 m² = 480 dandelions.

Answer: About 480 dandelions.

PRACTICE

1. EASY What is a quadrat, and why should quadrats be placed at random spots?
2. MEDIUM Use the bar graph of the backyard bird count. (a) Which species was most common? (b) How many birds were counted in all? (c) What fraction of the birds were American robins?
   (Use the map or drawing "Backyard bird count, 30 minutes." shown earlier in this lesson.)
3. MEDIUM A student uses a small quadrat 0.5 m × 0.5 m (area 0.25 m²) in four places and counts 2, 3, 1 and 2 snails. Estimate the number of snails in a garden bed of 20 m².

4. HARD Two families count birds at the same feeder. Family A counts for 10 minutes once and sees 3 species. Family B counts for 10 minutes every morning for a week and sees 9 species in all. Which survey better describes the birds that use the feeder? Explain using the idea of sample size.
5. CHALLENGE Design an experiment to test whether mowing affects the number of clover flowers. Name the independent variable, the dependent variable, two things to keep the same, and how you would collect the data.

COMMON MISTAKES

- Counting the same bird again each time it returns to the feeder. Record the most of each species seen at one moment instead.
- Putting quadrats only where the plants look interesting, which makes the estimate too high.
- Thinking an estimate is a guess. An estimate from a fair sample is a calculated number that scientists trust, especially when the sample is large.

Make it a game · Bean Field Estimate. Scatter 100 to 300 dried beans across a tablecloth while one player looks away. That player gets three throws of a 10 cm paper square, counts the beans under each, and estimates the total. Then everyone counts. The closest estimate scores a point; switch roles and play five rounds.

Scripture. “Behold the fowls of the air: for they sow not, neither do they reap, nor gather into barns; yet your heavenly Father feedeth them. Are ye not much better than they?” (Matthew 6:26, KJV)

Every bird on your tally sheet is fed by God. Counting them carefully is a way of beholding His care, and the verse reminds you that you are worth even more to Him.

Practice answers

1. A quadrat is a square frame of known size used to mark an area for counting. Random placement keeps the sample fair; choosing only thick or thin patches would make the estimate too high or too low.
2. (a) House sparrow (12). (b) 12 + 7 + 6 + 4 + 3 = 32 birds. (c) 7/32, about 22%.
3. Area sampled: 4 × 0.25 m^2 = 1 m^2. Snails found: 2 + 3 + 1 + 2 = 8, so 8 snails per m^2. Estimate: 8 × 20 = 160 snails.
4. Family B. A larger sample (seven counts instead of one) catches species that visit only some days and lowers the effect of one odd day, such as bad weather or a hawk nearby. One short count can easily miss many visitors.
5. Independent variable: mowing (one plot mowed weekly, one plot left unmowed). Dependent variable: number of clover flower heads per m^2. Keep the same: plot size, sunlight and soil (side by side in the same lawn), watering, and the date you count. Data: after three or four weeks, count flower heads in 5 random 1 m^2 quadrats in each plot, average them, and compare. Repeating with a second pair of plots makes the result stronger.

9.3 Zoo, Farm or Museum Visit

OBJECTIVES

- Plan a visit to a zoo, farm, aquarium or natural history museum with a clear question to investigate.
- Record an animal's behavior with an ethogram and turn the data into percentages and a bar graph.
- Read a museum sign carefully, telling what is observed from what is interpreted.

Warm-up. Watch a family pet, a bird outside or even a person reading for 3 minutes. Every 30 seconds, write one word for what it is doing at that moment (eating, resting, walking, grooming, looking). Count your words. What did it do most?

Video. Coming soon. How scientists study animal behavior at zoos (ethograms, focal animal sampling) and a virtual tour of a natural history museum; search Smithsonian National Zoo, Smithsonian National Museum of Natural History virtual tour, farm animal behavior for students, and Charles Willson Peale museum history.

KEY TERMS

behavior
What an animal does, such as eating, resting, moving, grooming or calling.

ethogram
A list of an animal's behaviors, each with a short definition, used to record what the animal does during a watch.

time budget
The share of an animal's time spent on each behavior, often shown as percentages.

specimen
A real plant, animal, bone, shell or fossil kept for study, usually with a label telling where and when it was found.

domestic animal
An animal kind that people have raised and bred for generations, such as goats, sheep, horses and chickens.

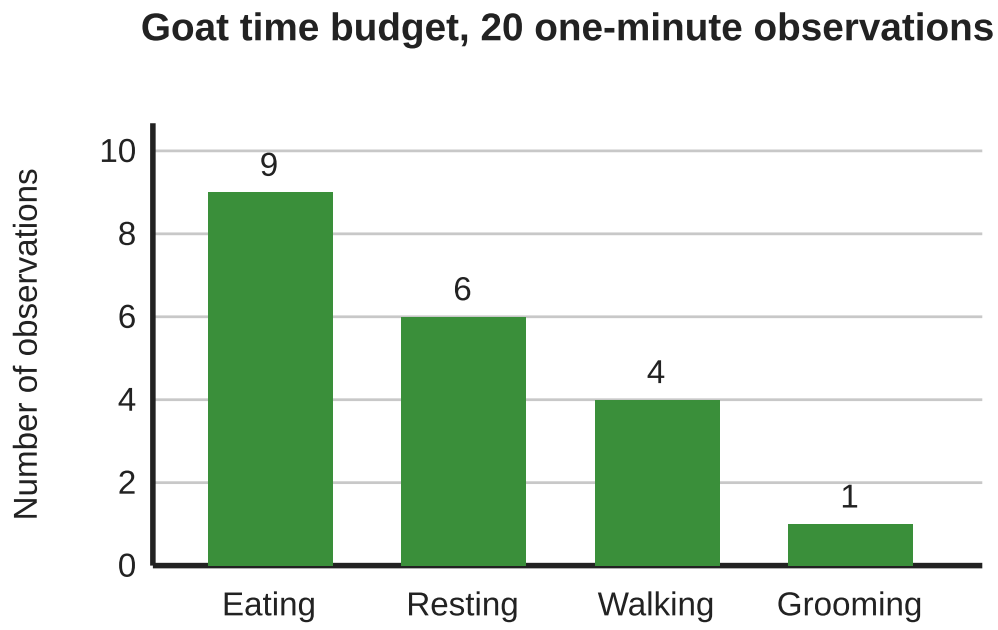
CORE IDEAS

The story. In 1786 the painter Charles Willson Peale opened a museum in his own house in Philadelphia. He wanted ordinary families, not only scholars, to see God's creatures up close and learn their names. He mounted birds and mammals in glass cases and painted backgrounds behind them showing the places where they lived, and he arranged them in the order of Linnaeus's classification. In 1801 he went to a farm near Newburgh, New York, where workers had found huge bones in a marshy pit. Peale built a great wooden wheel,

turned by men walking inside it, to drive pumps that kept the pit dry while the bones were dug out. Back in Philadelphia his team assembled the skeleton of a **mastodon**, a relative of the elephant, and visitors lined up to see it. Peale's museum showed that a visit can teach what no book can: real size, real shape, real animals.

How they figured it out. Scientists who study animals at zoos and farms do more than stroll and look. They pick one animal and one question, then watch with an **ethogram**, a short list of behaviors with clear definitions: eating means food is in the mouth or being chewed, resting means lying or standing still with no chewing, and so on. Every minute, at the beep of a timer, they mark what the animal is doing at that exact moment. After 20 minutes they can calculate a **time budget**, the percentage of time spent on each behavior. On a farm you can compare a goat with a sheep, or morning with afternoon. At a museum, the same careful eyes work on **specimens**: measure a skull against your hand, count the teeth, and read the sign slowly, sorting what was measured from what is interpreted.

Try it and see. Before the visit, write your question and your ethogram. During the visit, collect at least one 20-minute watch and fill a journal page on one specimen or animal. After, make a bar graph and write a paragraph. Wherever you go, treat the animals with kindness and respect the rules of the people who care for them. The Bible says, "Be thou diligent to know the state of thy flocks, and look well to thy herds" (Proverbs 27:23). A good farmer and a good zookeeper are careful observers, and you can learn a great deal by asking them what they watch for each day.



A time budget for one goat, from an ethogram taken once a minute for 20 minutes.

⏳ **Thinking About Time**

What the sign says. What the sign says: Museum signs usually call mastodons Ice Age animals of the Pleistocene and say they died out in North America about 11,000 years ago, after living there for millions of years.

What we observe. What we observe: Mastodon bones, tusks and teeth are found near the surface in bogs, marshes, gravel and cave deposits across North America, sometimes with plant material still in their gut area. Their cone-shaped, knobby cheek teeth are built for browsing twigs and leaves, and their skeletons closely match those of living elephants.

How Christians read it. How Christians read it: Many Christians read the Ice Age as a period of heavy snow and ice after the Flood (Genesis 7–8), when ocean water was warm and volcanic dust cooled the land. On that reading mastodons belong to the elephant kind that came off the Ark and spread across the earth, then died out within the last few thousand years. The bones are real either way; the dates on the sign are an interpretation.

Try it. At the museum, copy one sign word for word into your journal, then underline what was measured and circle what is interpreted.

Genesis 8:19

PICTURE STUDY



The Artist in His Museum, Charles Willson Peale, 1822 · Oil on canvas · Pennsylvania Academy of the Fine Arts, Philadelphia

When Peale was 81 years old, the trustees of his museum asked him to paint his own portrait. He painted himself lifting a curtain, as if inviting you in. Behind him stretches the Long Room of his museum, where it stood in what is now Independence Hall, with row upon

row of bird cases. In the corner are the giant bones of the mastodon he dug up in 1801, and on the left is a wild turkey waiting to be mounted, with his tools beside it.

Peale believed a museum should be a school for everyone. His picture asks a question of you: when you go through the curtain, what will you look at, and how carefully?

Look closely

- Find the mastodon bones. How big is the jawbone compared with Peale's legs?
- Find the turkey and the tools on the table. What job was Peale in the middle of?
- Look down the Long Room at the bird cases. How are the birds arranged?
- Find the visitors in the gallery. What is each one doing?

Talk about it

1. Why do you think Peale chose to show himself lifting a curtain?
2. What can you learn from seeing a real skeleton that you cannot learn from a picture in a book?
3. If you painted yourself at your favorite zoo, farm or museum, what would you put in the background?

> **Safety first.** Stay with your adult. Follow every posted rule and the instructions of keepers and farmers. Never feed, reach into or climb on enclosures. Approach large farm animals only with the owner, and never stand directly behind a horse, cow or goat. Wash your hands with soap and water after touching any animal or fence, and before eating, because farm animals can carry germs such as E. coli and Salmonella.

EXPERIMENT: TWENTY-MINUTE ETHOGRAM

Question: How does one animal spend its time, and does it change between morning and afternoon (or between two animals)? You will collect two 20-minute watches and compare their time budgets.

You will need

- Journal and pencil
- Watch, phone timer or kitchen timer that can beep each minute
- Clipboard
- Ethogram data sheet you make at home (see steps)
- Ruler or measuring tape for museum sketches

Steps

1. At home, choose your place and write your question, for example: Does a goat spend more time eating in the morning or the afternoon?
2. Prediction: write what you expect, with a reason.

3. Make your ethogram: four or five behaviors with one-line definitions (eating, resting, walking, grooming, other). Draw a data table with 20 rows, one for each minute.
4. At the visit, pick one animal you can tell apart from the others by a mark or color. Sketch it so you will know it again.
5. Start the timer. Each time it beeps, look at the animal and write the one behavior it is doing at that instant. Do not count what it did between beeps.
6. Repeat the watch at a second time of day, or on a second animal. Keep the same: the ethogram, the 1-minute interval and the 20-minute length.
7. At home, count each behavior, divide by 20 and multiply by 100 to get percentages. Make a bar graph for each watch.
8. Write a conclusion paragraph and one new question you would test on another visit.
9. If you visit a museum instead, fill one journal page on a skeleton or specimen: measure one bone or tooth, copy the sign, and sort the sign into observations and interpretations.

Tips

- Ask a keeper or farmer when the animals are fed, and write it down. Feeding time can change behavior a lot.
- If the animal goes out of sight at a beep, write “out of view.” Do not guess.
- Many farms and zoos are glad to answer questions from young scientists. Bring two questions written in your journal.

Check your work

- I wrote a question, a prediction and an ethogram before the visit.
- I recorded two 20-minute watches at 1-minute intervals and calculated time budgets.
- I made bar graphs and wrote a conclusion supported by my data.

NATURE NOTEBOOK

1. Draw your animal from the side with labels for at least five body parts and one measurement or size comparison.
2. Sketch one museum specimen (a skull, tooth, shell or bone) at life size or with a scale bar, and copy its label.
3. Draw your time budget as a bar graph with a title, labeled axes and the date and place.

> **From history.** America’s first public zoo, the Philadelphia Zoo, received its charter in 1859, but the Civil War delayed construction, and it finally opened its gates on July 1, 1874. Visitors arrived by horse-drawn streetcar and steamboat to see animals many had known only from books and engravings.

WORKED EXAMPLES

Example 1. Ella watched a goat for 20 minutes, marking its behavior at each 1-minute beep: eating 9 times, resting 6, walking 4 and grooming 1. Find the goat's time budget in percentages.

(Use the map or drawing "Ella's goat data as a bar graph." shown earlier in this lesson.)

1. Check the total: 9 + 6 + 4 + 1 = 20 observations.
2. Eating: 9 ÷ 20 = 0.45 = 45%.
3. Resting: 6 ÷ 20 = 0.30 = 30%.
4. Walking: 4 ÷ 20 = 0.20 = 20%.
5. Grooming: 1 ÷ 20 = 0.05 = 5%. Check: 45 + 30 + 20 + 5 = 100%.

Answer: Eating 45%, resting 30%, walking 20%, grooming 5%.

PRACTICE

1. EASY What is an ethogram, and why must each behavior on it have a clear definition?
2. MEDIUM Use Ella's goat bar graph. (a) What percentage of the time was the goat resting or grooming? (b) How many times more often was it eating than walking?
   (Use the map or drawing "Goat time budget." shown earlier in this lesson.)
3. MEDIUM A zoo sign says an adult male giraffe can stand about 5.5 m tall. A student is 1.5 m tall. About how many times taller is the giraffe? If the student draws herself 3 cm tall in her journal, how tall should the giraffe be drawn at the same scale?
4. HARD A student watched the same sheep for 20 minutes in the morning and 20 minutes in the afternoon (1-minute intervals).
   Morning: eating 12, resting 4, walking 4
   Afternoon: eating 3, resting 14, walking 3
   (a) Which behavior changed the most? (b) Give one possible explanation. (c) What more data would make the conclusion stronger?
5. CHALLENGE A museum sign reads: "This mastodon tooth, 18 cm long, was found in a bog in New York. Mastodons browsed on twigs and died out at the end of the Ice Age, about 11,000 years ago." Sort the sign into what was observed or measured and what is interpreted.

COMMON MISTAKES

- Writing down everything the animal does between beeps. In this method you record only what it is doing at the beep, or the totals will not add up.
- Watching for a few minutes and deciding "the lion is lazy." Many animals rest most of the day; a fair conclusion needs a full watch and, better, several watches.
- Reading every sentence on a museum sign as a measured fact. Signs mix observations (size, place found) with interpretations (dates, how the animal lived).

Make it a game · Freeze-Frame Ethogram. One player acts as an animal and keeps changing behaviors (eating, resting, walking, grooming). Every 15 seconds the timekeeper calls “Freeze!” and the others write what the animal is doing at that instant. After 10 calls, compare sheets. Score a point for every call where your record matches the actor’s own list.

Scripture. “Be thou diligent to know the state of thy flocks, and look well to thy herds.” (Proverbs 27:23, KJV)

Knowing animals well takes diligent watching. An ethogram is a scientist’s way of looking well to the herd.

Practice answers

1. An ethogram is a list of an animal’s behaviors used to record what it does during a watch. Clear definitions make sure every observer (and you on different days) records the same action the same way, so the data can be compared.
2. (a) 6 + 1 = 7 of 20 observations = 35%. (b) 9 ÷ 4 = 2.25 times as often.
3. 5.5 ÷ 1.5 ≈ 3.7 times taller. Drawing: 3 cm × 3.7 ≈ 11 cm tall.
4. (a) Resting rose by 10 (from 20% to 70%), and eating fell by 9; resting changed the most. (b) The sheep may have been fed in the morning and rested to chew its cud in the warm afternoon. (c) Watch on several more days and other sheep, and record feeding times and temperature, so one odd day or one sheep does not decide the answer.
5. Observed or measured: the tooth is 18 cm long; it was found in a bog in New York; its shape (cone-shaped cusps) can be seen. Interpreted: that mastodons browsed on twigs (a good inference from tooth shape and plant remains), and the date of about 11,000 years and the label “Ice Age,” which depend on dating methods and assumptions rather than direct observation.

9.4 Specimen Collection

OBJECTIVES

- Collect, preserve and label natural specimens responsibly and lawfully, with full data on every label.
- Sort a collection into groups and build a simple dichotomous key to identify its specimens.
- Explain why museum collections with careful labels are valuable to scientists for centuries.

Warm-up. Empty a junk drawer or a jar of buttons onto the table. Sort the items into two groups using one yes-or-no question (for example, “Is it metal?”). Then split each group again with a new question. How many questions did it take until every item stood alone?

Video. Coming soon. How natural history museums collect, preserve and label specimens, and how to use a dichotomous key; search Smithsonian National Museum of Natural History behind the scenes, Field Museum collections, Lewis and Clark natural history discoveries, and dichotomous key lessons for students.

KEY TERMS

specimen
A real natural object (leaf, shell, seed, bone, cast skin) kept for study, with a label recording where, when and by whom it was collected.

specimen label
A small card kept with a specimen that gives its name (if known), date, exact place, habitat and collector.

dichotomous key
An identification tool made of paired choices; each choice leads to another pair or to a name.

habitat
The natural home of a living thing, such as a pond edge, an oak woods or a sandy beach.

preserve
To keep a specimen from rotting or breaking, for example by pressing and drying a leaf or cleaning and drying a shell.

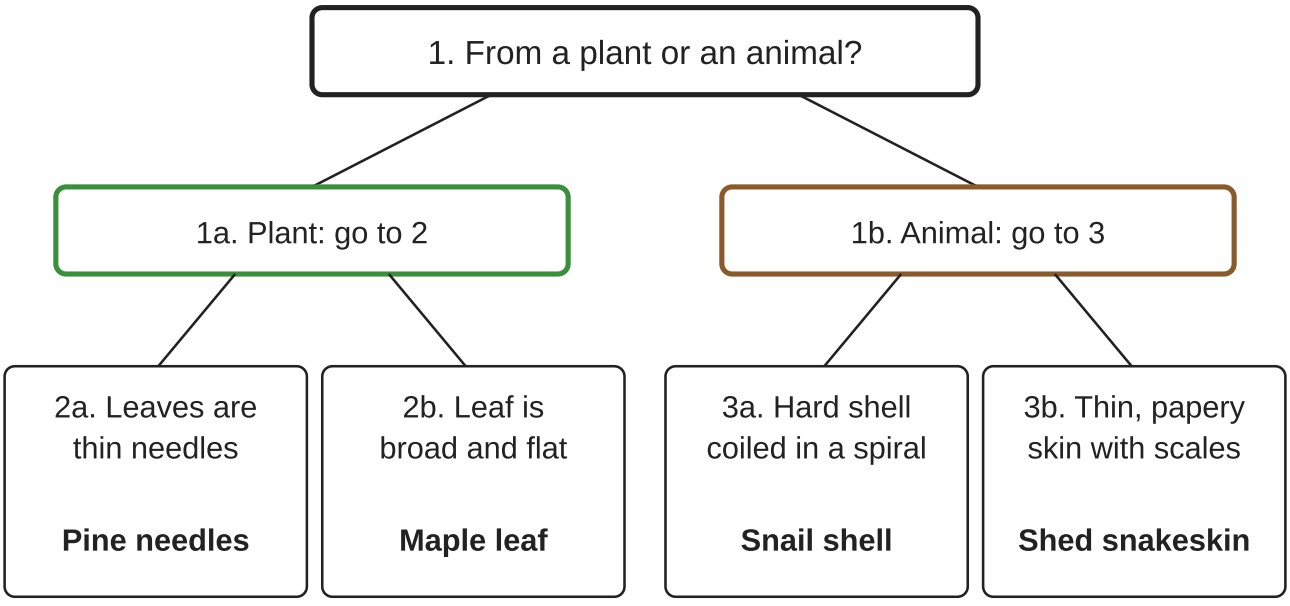
CORE IDEAS

The story. In the spring of 1804 Meriwether Lewis and William Clark set out up the Missouri River, sent by President Thomas Jefferson to explore the West. Jefferson asked them to observe the plants and animals of the country and bring back what they could. That September, on the Great Plains beside the Missouri, the men found a “village” of little

burrowing animals that barked like dogs. They poured barrels of water down a burrow until one came out, and Lewis described it carefully. In April 1805, from Fort Mandan in present-day North Dakota, they sent a boat back down the river loaded with skins, skeletons, horns, pressed plants, insects, minerals and labeled notes, plus a few live animals, including that prairie dog and four magpies. Months later the prairie dog and one magpie reached Jefferson alive. Historians count about 178 plants and 122 animals that the expedition described for science for the first time.

The big idea. A specimen is only as useful as its label. Every label needs the name (if known), the **date**, the **exact place**, the **habitat** and the **collector**. With that, a leaf pressed today could answer a scientist's question a hundred years from now. Collect lawfully and gently: take things that are already shed or plentiful (fallen leaves, seeds and cones, empty shells, cast insect skins, shed snakeskins), take only a little, and leave nests, eggs, live animals and rare plants alone. In the United States it is against the law to keep feathers, nests or eggs of most wild native birds, so collect feathers only from chickens, ducks, turkeys or other farm birds. Then **preserve**: press leaves flat between newspaper under heavy books for about two weeks, rinse and dry shells, and store small items in labeled boxes or bags. Finally, sort your collection with a **dichotomous key**, a chain of paired yes-or-no choices that leads to a name, just as museum scientists do.

God's handiwork. King Solomon was a collector of knowledge as well as a king. The Bible says "he spake of trees, from the cedar tree that is in Lebanon even unto the hyssop that springeth out of the wall: he spake also of beasts, and of fowl, and of creeping things, and of fishes" (1 Kings 4:33). Naming and sorting creatures goes back to Adam (Genesis 2:19–20). A small, well-labeled collection of your own place is a record of what God has made there, and a gift to anyone who studies it after you.



A simple dichotomous key for four specimens from a backyard collection.

PICTURE STUDY



The Herring Net, Winslow Homer, 1885 · Oil on canvas · Art Institute of Chicago

Winslow Homer was an American painter who, in 1883, moved to Prouts Neck on the rocky coast of Maine. There he watched fishermen at work in all weather. In *The Herring Net* two men in a small rowboat called a dory haul in a net full of herring, silvery fish that swim in huge schools in the North Atlantic. One man pulls the net while the other lifts fish into the boat, which is already heavy with the catch.

Fishermen and naturalists both gather from God’s creation. A fisherman gathers for food; a naturalist gathers a few samples for study. Both must know their creatures, their seasons and their waters well.

Look closely

- Find the herring in the net. How did Homer make them look wet and shiny?
- Look at how low the boat sits in the water. What does that tell you about the size of the catch?
- Find the ships in the fog. Why might the fishermen want to stay close to them?
- Look at the men’s clothing. What kind of weather were they dressed for?

Talk about it

1. How is hauling a net like taking a sample in a science survey? How is it different?
2. Why do wise fishermen and wise collectors both avoid taking more than they need?
3. If a scientist kept one herring from this catch as a specimen, what should its label say?

> **Safety first.** Collect with an adult and only where it is allowed. Many parks and nature preserves forbid collecting anything, so ask first. Wear gloves, and do not pick up dead

> animals, bones with flesh on them, wild mushrooms or unknown berries. Never put specimens near your mouth, and wash your hands after handling them. Do not collect feathers, nests or eggs of wild birds. Use scissors or clippers only with an adult's permission.

EXPERIMENT: MY BACKYARD MUSEUM DRAWER

You will build a small, lawful collection of at least 12 specimens from one area, preserve and label each one, and write a dichotomous key that identifies at least six of them. The question: How many different kinds of living things have left something behind in my area, and how can someone else tell them apart?

You will need

- Garden gloves and small paper bags or envelopes
- Pencil and journal for field notes
- Newspaper and heavy books (or a homemade plant press)
- An egg carton, shoebox or tackle box with compartments
- Index cards cut into small labels
- Hand lens and a ruler
- Field guides from the library, or an identification app used with a parent

Steps

1. Choose your area and get permission. Write in your journal: date, place, weather and the habitat (lawn, hedge, creek bank, woods edge).
2. Collect only shed or plentiful things: fallen leaves, seeds, cones, empty snail shells, acorn caps, cast insect skins, galls on fallen twigs. Take one or two of each kind, no more.
3. Put each specimen in its own bag and write a field number on the bag that matches a line in your journal (1, 2, 3...).
4. At home, preserve: press leaves between newspaper under books for about two weeks; rinse and air-dry shells; let seeds and cones dry in an open box.
5. Measure each specimen and write a label: number, name (or "unknown"), date, exact place, habitat, collector.
6. Sort the specimens into groups using what you can see. Count each group and make a bar graph.
7. Write a dichotomous key for at least six specimens. Start with a big split (plant or animal), then use clear features (needle or broad leaf, coiled or not).
8. Test your key: give a family member three specimens and see if your key leads them to the right names.

Tips

- Write labels in pencil. Pencil does not run if it gets damp.

- In a key, use features anyone can see, like “leaf edge has teeth,” not “looks pretty.”
- An empty shell, a fallen leaf and a shed skin harm nothing. Leave living animals where they are and sketch them instead.

Check your work

- Every specimen has a complete label with date, place, habitat and collector.
- I collected only lawful, plentiful or shed items and took only a few of each.
- My dichotomous key leads another person to the right name for at least six specimens.

NATURE NOTEBOOK

1. Draw your three favorite specimens at life size, each with its label copied neatly beside it.
2. Copy your dichotomous key as a flowchart with boxes and arrows.
3. Draw a page from Lewis and Clark’s point of view: a prairie dog sketch with its length, the place, the date and two observations.

> **From history.** Sir Hans Sloane, a London physician, spent his life gathering specimens of plants, animals, shells, fossils and books, more than 70,000 objects in all. When he died in 1753, his will offered the collection to the nation for £20,000, far less than it was worth, and Parliament founded the British Museum to keep it. His natural history specimens later went to the Natural History Museum in London, where many still carry the labels written in his day.

WORKED EXAMPLES

Example 1. Use the key in the figure to identify a specimen: it came from an animal, and it is a thin, see-through, papery tube with a pattern of scales on it.

(Use the map or drawing “Follow the paired choices from the top.” shown earlier in this lesson.)

1. Step 1 asks whether it came from a plant or an animal. It came from an animal, so go to step 3.
2. Step 3 asks whether it is a hard shell coiled in a spiral (3a) or a thin, papery skin with a scale pattern (3b).
3. The specimen is thin and papery with scales, so choose 3b.

Answer: A shed snakeskin.

PRACTICE

1. EASY Name five things a complete specimen label should include.
2. MEDIUM A student’s collection has these groups: leaves 15, seeds and cones 9, shells 4, cast insect skins 2. (a) How many specimens are there? (b) What percent are leaves?

(c) What percent are shells, to the nearest whole percent?

3. MEDIUM A student finds an oak leaf and uses the key in the figure. Which name does the key give, and what is wrong? How should the key be fixed?
   (Use the map or drawing "The four-specimen key." shown earlier in this lesson.)
4. HARD Why is it against the law in the United States to keep the feathers of most wild native birds, even ones you find on the ground? What feathers may a student collect?
5. CHALLENGE Lewis and Clark sent Jefferson both a live prairie dog and dried skins and skeletons of other animals. Explain what scientists could learn from each kind of specimen, and why the written notes and labels mattered as much as the objects.

COMMON MISTAKES

- Thinking a specimen without a label is still useful to science. Without date and place, it can only be a decoration.
- Collecting as much as possible. Good collectors take only a little of what is plentiful and leave living things in place.
- Writing a key with vague choices like "big or small." Good keys use clear, visible features that two people would judge the same way.

Make it a game · Twenty Questions Key. Lay out eight specimens or household objects. One player secretly picks one. The others may ask only yes-or-no questions about visible features, and each answer removes some items. Write the questions down as you go: you have just built a dichotomous key. Score a point for guessing in three questions or fewer (with eight objects, three good questions are enough).

Scripture. "And he spake of trees, from the cedar tree that is in Lebanon even unto the hyssop that springeth out of the wall: he spake also of beasts, and of fowl, and of creeping things, and of fishes." (1 Kings 4:33, KJV)

Solomon's wisdom included knowing God's creatures from the greatest tree to the smallest wall plant. A labeled collection is a small step in the same kind of learning.

Practice answers

1. Name (or "unknown"), date, exact place, habitat and collector. A specimen number and a measurement are also helpful.
2. (a) 15 + 9 + 4 + 2 = 30. (b) 15 ÷ 30 = 50%. (c) 4 ÷ 30 ≈ 0.133, about 13%.
3. The key leads to "maple leaf" (2b, broad flat leaf), which is wrong. The key needs a new pair of choices after 2b, such as "main veins spread out from one point at the base, like fingers from a palm = maple leaf" versus "main veins branch off one long central vein, like a feather = oak leaf." A key only works for the specimens it was built for until it is extended.
4. The Migratory Bird Treaty Act of 1918 protects native wild birds, including their feathers, nests and eggs. Because no one can tell a found feather from one taken from a killed bird, keeping them is forbidden, which removes any reason to harm birds for feathers. Feathers from domestic birds such as chickens, ducks and turkeys may be collected.

5. A live animal shows behavior, sounds, diet and how it moves, which a skin cannot. Skins and skeletons last for many years and can be measured, compared with other animals and studied again by later scientists. Without notes telling where and when each was found and what the habitat was, the objects could not be placed on a map, compared across seasons, or used to describe the animal’s range.

Unit 9 review

This is a short review of the Nature Lab. Answer each question. Show your work for calculations and use complete sentences for explanations. The review is worth 60 points.

1. (10 pts) Multiple choice. Which journal note is an *observation*?
   (a) A woodpecker made these holes.
   (b) The bark has a row of 8 holes, each about 1 cm wide.
   (c) The tree is probably sick.
   (d) Insects must live under the bark.
   Then explain why the other three are inferences.
2. (10 pts) Noah walks a measured 20 m in 25 steps. He then walks the edge of a field in 350 steps. Find his pace length and the length of the field's edge.
3. (10 pts) Six random 1 m² quadrats in a meadow hold 3, 5, 2, 6, 4 and 4 clover plants. The meadow is 25 m × 10 m. (a) Find the average number per m². (b) Estimate the clover population. (c) Give one reason the quadrats must be placed at random.
4. (10 pts) A student records a horse's behavior every minute for 20 minutes: grazing 11, standing still 6, walking 2, grooming 1. (a) Give the time budget in percentages. (b) Write one question the student could test on a second visit, and name what she would change and what she would keep the same.
5. (10 pts) Diagram item. Draw a dichotomous key, as a flowchart of boxes and arrows, that separates these four specimens: an acorn, a pine cone, an empty snail shell and a chicken feather. Use only features that anyone can see.
6. (10 pts) Short answer. (a) List the information that belongs on a specimen label. (b) Name two things a young collector should leave behind, and explain why. (c) Why did Lewis and Clark's notes matter as much as the specimens they sent to Jefferson?

Unit project: my naturalist's field notebook

Put together a field notebook of your Nature Lab work: at least four dated journal pages from your walking loop (with your pace length and loop map), your quadrat survey and bird count with bar graphs, your two ethogram watches with time budgets and a conclusion, and a catalog of your specimen collection with your dichotomous key. Finish with a one-page "State of My Place" report that tells what lives in your area, what surprised you, and one question you want to keep studying next season.

- **Records**: Every page and specimen has a complete header or label: date, time, place, weather or habitat, and collector.
- **Data and calculations**: Pace, population estimates and time budgets are calculated correctly and shown on clear, labeled bar graphs.
- **Scientific thinking**: Observations and inferences are kept apart, questions are testable, and conclusions are supported by the data.
- **Care and stewardship**: Sketches are neat and labeled with scales, specimens were collected lawfully and gently, and the notebook is organized so another person could

use it.

Answer key

1. (b). It reports what was seen and measured. (a), (c) and (d) are explanations of what the holes might mean; they may be good guesses, but they were not observed directly.
2. Pace = 20 m ÷ 25 = 0.8 m. Edge = 350 × 0.8 m = 280 m.
3. (a) 3 + 5 + 2 + 6 + 4 + 4 = 24; 24 ÷ 6 = 4 per m^2. (b) Area = 250 m^2; 4 × 250 = 1,000 clover plants. (c) Choosing spots by eye tends to pick thick or interesting patches, which would make the estimate too high (or too low); random spots give a fair sample.
4. (a) Grazing 55%, standing 30%, walking 10%, grooming 5%. (b) Example: Does the horse graze more in the morning than in the afternoon? Change the time of day; keep the same horse, ethogram, 1-minute interval and 20-minute watch.
5. Sample key: 1a From a plant: go to 2. 1b From an animal: go to 3. 2a Smooth nut with a scaly cap = acorn. 2b Woody cone made of many overlapping scales = pine cone. 3a Hard shell coiled in a spiral = snail shell. 3b Soft, flat, with a central shaft and vanes = chicken feather. Any key that uses clear visible paired choices and leads to all four correct names earns full credit.
6. (a) Name (or “unknown”), date, exact place, habitat and collector. (b) Any two: feathers, nests or eggs of wild birds (protected by law); live animals (they belong in their habitat); rare plants (taking them could harm the population); anything in a park where collecting is forbidden. (c) The notes recorded where, when and in what habitat each plant and animal was found, so scientists could map its range and compare it with others; without that record the objects lose most of their scientific value.