SCHOOL LAUNCH · LIFE SCIENCE K–8

Grade 8 Life Science: Heredity, Design and Origins

A year of true stories about how living things are made and passed on, from a friar counting peas in a monastery garden at Brno and the X-ray image called Photo 51 to the finches of the Galápagos, William Paley's watch on the heath, the Cambrian rocks, soft tissue in a dinosaur bone and the bison brought back from the edge, each one examined, measured and weighed so that a student can tell what we observe from what we conclude and stand ready for high-school biology.

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 follows the living world through eight units in one school year: Gregor Mendel and the laws of heredity, DNA and the code of life, variation within kinds, design in nature, fossils and the history of life, origins fairly told, ecology and stewardship, and careers in life science. Each unit is built around real people and real moments: Mendel's seven years of pea crosses in the garden of St. Thomas's Abbey (1856–1863), Rosalind Franklin's Photo 51 and the double helix of Watson and Crick (1953), Peter and Rosemary Grant measuring finch beaks on Daphne Major, William Paley's *Natural Theology* (1802), Mary Schweitzer's soft tissue from a *Tyrannosaurus* bone (2005), and the men and women who saved the American bison and the whooping crane.

Every lesson follows the same path. First comes **the story**. Then **how they figured it out**: what question they asked, what they counted, what they controlled and what surprised them. Then **the big idea**, explained at the depth of a strong eighth grader: dominant and recessive traits, probability in a Punnett square, the base-pairing rules, how a gene becomes a protein, variation and selection, information and design, how fossils form, and how a population is counted. Last, the student **observes and measures**: crossing paper "peas," pulling DNA from a strawberry, measuring seeds and leaves, graphing beak sizes, modeling a population with beans, and keeping a nature notebook all year.

The thread of the year is a single question: **what stays the same, and what can change?** Mendel shows that traits are passed on in faithful units. DNA shows that those units are written information. Finches, dogs and bacteria show how much variety is folded into a living kind, and how quickly it can appear. The fossil and origins units then lay out the major views of life's history plainly and fairly, so the student can state each one in words its own holders would accept, separate evidence from interpretation, and write a respectful comparison. The year closes with stewardship of the creatures we have been given and a look at the callings of veterinarians, nurses, doctors, wildlife biologists and farmers.

The course is taught from a Christian view of creation. "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 order that Mendel found in his peas, the information written in every cell, and the variety a single kind can carry are read as the handiwork of a faithful Creator. Students also learn the reasoning of those who disagree, because honest study of God's world never needs to fear a fair hearing.

WHO IT IS FOR

Written for students in grade 8 (about ages 13–14) who read on their own, can work with fractions, ratios and percentages, and can draw and read a simple bar or line graph. The course builds toward high-school biology. A parent or teacher reads along when helpful, supervises the experiments, and leads the discussions in the fossil and origins units. Nothing needs to be bought beyond ordinary household items: a notebook, a metric ruler, a kitchen scale, dried beans, strawberries, dish soap, salt and rubbing alcohol.

HOW TO USE THIS COURSE

The weekly rhythm. The year has 32 lessons, one a week, in two sessions of about 45 minutes. Session 1 is the warm-up, the video, the core ideas, the worked examples and the picture study. Session 2 is the experiment, the nature notebook and the practice set. In the last week of each unit, add a third session for the unit test and the unit project. An optional ninth unit, the **Nature Lab**, offers four outdoor lessons (a journal walk, a backyard survey, a zoo, farm or museum visit, and a specimen collection) to use in good weather, over the summer, or alongside the year.

The ★ quarter path. Ten lessons are marked ★: Mendel's peas, Photo 51, Darwin's finches, dog breeds, Paley's watch, the Cambrian explosion, dinosaur soft tissue, creation in Genesis, dominion and care, and careers in medicine. Together they make a one-quarter course for families who want a shorter study, keeping heredity, DNA, design, origins and stewardship.

The nature notebook. Use one graph-paper composition book for the whole year. Every experiment ends with something measured and recorded in metric units: a cross and its offspring counts, a data table, a labeled sketch, a graph or a population tally. Date every page, write the question at the top, and finish with one sentence on what the data show and one on what you would change. Honest records matter more than the hoped-for result.

Experiments and safety. A parent supervises every experiment. Wear safety glasses when using rubbing alcohol, keep it away from flame and never taste any lab material, even food used in an experiment. No bacteria are grown at home; antibiotic resistance is modeled with beans and cards. In the field, ask permission before entering private land, wash hands after handling soil, animals or specimens, leave nests and protected plants and animals alone, and follow your state's rules for collecting.

Worked examples and practice. Each lesson has three worked examples, step by step, with the numbers shown: Punnett squares, ratios and percentages, rates of change, reading a graph, half-life steps and scale. Then come ten practice problems, including two data-reading items in the style of the SAT and ACT science sections and one in which the student designs an experiment. Answers are given so the student can check each problem and find the mistake before moving on.

Unit tests and unit projects. Each unit ends with a 60-point test of 10 to 12 problems (multiple choice, short answer and one diagram item) and a unit project that pulls the unit together, such as a three-generation pedigree, a DNA model, a design argument written out and answered, a fossil timeline, or a field study report. Keep the projects in one folder for the year.

A word about time. The course is written from a Christian view of creation (Genesis 1:1) and 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, a ⏳ *Thinking About Time* box sets out what the sign says, what we observe, and how Christians read it.

SCOPE AND SEQUENCE

Unit 1: Mendel and the Laws of Heredity (1–4)

Gregor Mendel's pea experiments at Brno; dominant and recessive traits; Punnett squares and the 3:1 ratio; and reading family pedigrees.

Unit 2: DNA: The Code of Life (5–8)

Rosalind Franklin's Photo 51 and the double helix of Watson and Crick; pulling DNA from a strawberry; the genetic code as written information; and how genes become proteins.

Unit 3: Variation Within Kinds 🐾 (9–12)

The Galápagos finches and the beak measurements of Peter and Rosemary Grant; the many breeds of the one dog; antibiotic resistance; and what a created "kind" may be.

Unit 4: Design in Nature (13–16)

William Paley's watch argument (1802); the eye; the bacterial flagellum and irreducible complexity; and the fine-tuning of the physical constants, each with its strongest objections.

Unit 5: Fossils and Life's History 🦕⏳ (17–20)

How fossils form; the sudden appearance of animal body plans in the Cambrian rocks; Mary Schweitzer's dinosaur soft tissue; Archaeopteryx and Tiktaalik; and how each view reads the same fossils.

Unit 6: Origins Fairly Told ⏳ (21–24)

The creation account of Genesis 1–2; Darwin's theory stated accurately in his own terms; the case for intelligent design; and a respectful written comparison of the three.

Unit 7: Ecology and Stewardship (25–28)

Dominion and care from Genesis 1:28 and 2:15; how biologists count populations; the comeback of the American bison and the whooping crane; and hunting and game management.

Unit 8: Careers in Life Science (29–32)

The work of veterinarians, nurses and doctors; wildlife biologists and game wardens; agricultural scientists; and a capstone field study report.

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

Four outdoor lessons for good weather or summer: a nature journal walk, a backyard species survey, 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: data tables, Punnett squares, graphs, labeled sketches, pedigrees and field notes.
- **A metric ruler, a measuring tape and a kitchen scale that reads grams**: For measuring seeds, leaves, beaks drawn to scale and specimens. All measurements in the course are metric.
- **A calculator**: A basic one is fine for ratios, percentages and rates. A free spreadsheet (Google Sheets or LibreOffice Calc) helps with graphs but is never required.
- **Two colors of dried beans (or buttons) and a few paper cups or bags**: For modeling genetic crosses, variation, selection and population counts.
- **Strawberries, dish soap, table salt, a zip-top bag, a coffee filter and chilled rubbing alcohol**: For the DNA extraction in Unit 2. Use with safety glasses and a parent nearby.
- **Safety glasses**: Worn for every experiment that uses rubbing alcohol or any liquid that could splash.
- **A hand lens (magnifying glass) and colored pencils**: For close observation and nature notebook sketches.
- **Card stock, pipe cleaners, string and tape**: For DNA models, pedigree charts and the fossil timeline.
- **A phone or camera, zip-top bags and a shoebox**: For field photos and the small specimen collection in the Nature Lab.
- **Optional: a regional field guide to birds, trees or insects**: Never required. Any guide for your area, or a free identification website, is fine.

GRADING

Grades come from unit tests and quizzes, the nature notebook and the experiments and unit projects. An experiment whose results did not match the prediction but are honestly recorded and explained earns full credit.

- Unit tests and quizzes (60-point unit tests and lesson practice): 35%
- Nature notebook (dated pages, metric data tables, labeled graphs and sketches): 20%
- Experiments (prediction, careful measurement, honest records and the improve-it step): 25%
- Unit projects: 20%

A 90–100, B 80–89, C 70–79, D 60–69. Below 60: review the unit with help and retake the test.

- Grade the process, not just the result. Did the student ask a clear question, predict, control variables, measure carefully, record honestly and explain the data?
- A notebook page earns full marks when it has a date, a question, a labeled data table with metric units, a graph or sketch where called for, and one sentence on what the data mean.

- On the origins unit project, grade fairness and clear reasoning: each view is stated accurately in words its own holders would accept, evidence is kept separate from interpretation, and the student's own conclusion is given with reasons.
- Unit tests may be done orally for a student who writes slowly; the parent writes down the answers.
- Keep each unit's project in one folder. Together they make a strong record of the year for a high-school transcript.

A NOTE TO PARENTS

You do not need to be a biologist to teach this course. Read the story together, work through the examples, and then be the lab partner in the experiment. Ask "What did you predict?", "What did you actually measure?" and "What else could explain that?" Those three questions are most of what a good science teacher does.

The fossil and origins units teach several views of life's history, and they teach each one fairly. Your student will learn Darwin's theory well enough to explain it accurately, will learn the case for design and its critics, and will learn why Christians read Genesis as true history. The aim is not to win arguments but to help a young person think clearly, separate what we observe from what we conclude, and speak with gentleness and respect to people who see things differently (1 Peter 3:15).

Above all, the course hopes your student will come away amazed at the living world and grateful to the One who made it, ready for high-school biology and perhaps for a calling in medicine, animal care, farming or wildlife work. "O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches." (Psalm 104:24)

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Unit 7: Ecology and Stewardship

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Unit 8: Careers in Life Science

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Unit 9: Bonus: Nature Lab (optional)

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

★ quarter path · ⏳ Thinking About Time box

UNIT 1

Mendel

Why do children look like their parents, and why do they sometimes show a trait neither parent shows? For thousands of years farmers and shepherds knew that “like begets like,” but no one could say how. The answer came from a quiet garden in Brno, where between 1856 and 1863 an Augustinian friar named Gregor Mendel crossed pea plants by hand and counted the results. His counts revealed that heredity comes in separate units passed whole from parent to child, and that a hidden trait can return, unchanged, a generation later.

In this unit you will follow Mendel through his garden and learn to think the way he did: choose a clear question, control the crosses, count large numbers and look for the ratio. You will learn the language of modern genetics (gene, allele, dominant, recessive, genotype, phenotype), draw Punnett squares the way Reginald Punnett taught them at Cambridge, and read family pedigrees, including the famous one that carried hemophilia from Queen Victoria into the royal houses of Europe.

All through the unit you will see that living things reproduce “after their kind” (Genesis 1:11–12): peas give peas, and yet each kind carries a rich store of variety that can show up in children and grandchildren. Heredity is faithful and full of surprises at once, and Mendel’s patient counting shows how orderly God’s handiwork is.

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and decimals, and turn a fraction into a percent
- Knows the basic parts of a flower (petals, stamens, pistil) and what pollination is
- Can read a simple data table and draw a bar graph
- Understands that a coin toss has a 1 in 2 chance of heads

MASTERY CHECKLIST

- I can tell the story of Gregor Mendel’s pea experiments and explain why he chose peas and counted so many plants.
- I can use the words gene, allele, dominant, recessive, genotype, phenotype, homozygous and heterozygous correctly.
- I can draw a Punnett square for one-trait crosses and predict expected ratios and numbers of offspring.
- I can explain that a Punnett square gives probabilities, and compare real data with the prediction.
- I can read a pedigree, decide whether a trait is dominant or recessive, and find the carriers.
- I can explain why sex-linked traits like hemophilia appear mostly in males.

OPTIONAL BOOKS AND RESOURCES

- **Learn.Genetics, from the University of Utah** (https://learn.genetics.utah.edu/): Free. Clear interactive lessons on heredity, alleles, Punnett squares and pedigrees, written for students. A parent can preview pages and choose the ones that fit this unit.
- **DNA from the Beginning, from the DNA Learning Center at Cold Spring Harbor Laboratory** (https://dnaftb.org/): Free. The first concepts walk through Mendel's experiments, with animations of his crosses, short biographies and problems to try.
- **Mendel Museum of Masaryk University, Brno** (https://mendelmuseum.muni.cz/): The museum stands in the old Augustinian abbey where Mendel worked. Its website shows the abbey, the garden site and Mendel's story, a good companion to Lesson 1.1.

1.1 The Friar and His Peas (1856–1863) ★

OBJECTIVES

- Tell the story of Gregor Mendel's pea experiments at St. Thomas's Abbey in Brno (1856–1863) and explain why he chose the garden pea.
- Describe Mendel's crosses through the P, F1 and F2 generations and calculate the ratios he found.
- Explain why Mendel's results did not fit the old idea of blending inheritance and why counting large numbers of plants mattered.

Warm-up. Put one drop of blue food coloring and one drop of yellow food coloring into a clear glass of water and stir. Now try to get the blue back out. You can't. Next, put ten blue beads (or black beans) and ten yellow beads (or white beans) in a cup and shake them together. Can you get the blue ones back out? In the 1850s most people thought heredity worked like the food coloring: a child was a blend of the parents. Write one sentence predicting which model Mendel's peas will follow.

Video. Coming soon. Gregor Mendel's pea experiments, hand-pollinating pea flowers and the 3 to 1 ratio; search Learn.Genetics (University of Utah), the DNA Learning Center (Cold Spring Harbor), the Mendel Museum in Brno, Amoeba Sisters, and garden footage of pea flowers and pods.

KEY TERMS

heredity
The passing of traits from parents to their offspring.

trait
A feature that can be passed on, such as seed shape, seed color or stem length.

true-breeding
A plant line that always produces offspring with the same form of a trait when it pollinates itself, such as tall plants that give only tall plants.

cross-pollination
Moving pollen from the flower of one plant to the pistil of a different plant. Mendel did this by hand with a small brush.

P, F1 and F2 generations
The parent generation (P), their offspring (F1, the first filial generation) and the offspring of the F1 plants (F2, the second filial generation).

ratio
A comparison of two numbers by division. Mendel's 5,474 round seeds to 1,850 wrinkled seeds is a ratio of about 2.96 to 1.

CORE IDEAS

The story. In 1856, in the garden of St. Thomas's Abbey in Brno, Moravia (today in the Czech Republic), a friar bent over rows of pea plants with a pair of fine tweezers and a small brush. His name was Gregor Mendel. He had been born Johann Mendel in 1822 to a farming family in Silesia, where as a boy he helped his father tend fruit trees. He joined the Augustinian friars in 1843, took the name Gregor, and was later ordained a priest. His abbot, Cyril Napp, valued science and sent him to the University of Vienna from 1851 to 1853, where he studied physics under Christian Doppler and plants under the botanist Franz Unger. Back in Brno he taught science at a local school, and in the abbey garden he began an experiment that would run through eight summers, from 1856 to 1863.

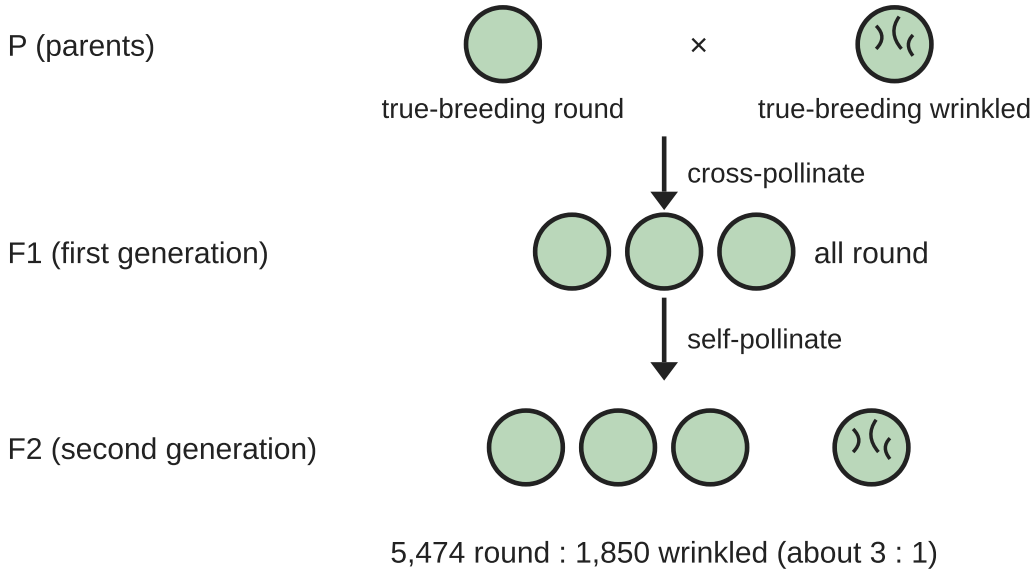
How he figured it out. Mendel chose the garden pea, *Pisum sativum*, for good reasons. Peas grow quickly, make many seeds, and come in varieties that differ in clear, either-or ways. A pea flower also normally pollinates itself, because its petals stay closed around the male parts (stamens) and the female part (pistil). So Mendel could keep his lines pure, and when he wanted to cross two plants he opened a young bud, pulled out its stamens before they shed pollen, and dusted the pistil with pollen from another plant. First he grew 34 varieties for two years to be sure they were **true-breeding**. Then he followed seven traits: seed shape (round or wrinkled), seed color (yellow or green), seed coat color (gray or white, which goes with purple or white flowers), pod shape (inflated or constricted), pod color (green or yellow), flower position (along the stem or at the tip) and stem length (tall or short). Unlike most naturalists of his day, he did not only describe. He counted, year after year, many thousands of plants and seeds.

The big idea. When Mendel crossed a true-breeding round-seeded plant with a true-breeding wrinkled-seeded plant, every seed in the first generation (F1) was round. The wrinkled trait seemed to have vanished. But when he let the F1 plants pollinate themselves, wrinkled seeds came back in the second generation (F2): 5,474 round and 1,850 wrinkled, almost exactly 3 to 1. All seven traits behaved the same way, with F2 ratios between 2.82 and 3.15. Mendel reasoned that each plant carries two hereditary "factors" for each trait, one from each parent; that the factors do not blend like paint but stay whole; and that each parent passes on only one of its two, by chance. A trait can hide for a generation and come back unchanged. We now call his factors *genes*, and you will learn their modern names in the next lesson.

In the world today. Mendel read his results to the Natural History Society of Brünn (the German name for Brno) at two meetings in February and March 1865, and published them in 1866 as *Experiments on Plant Hybrids*. Few readers grasped what he had done. In 1868 he was elected abbot, and running the abbey left little time for the garden. He died in 1884. Then in 1900 three botanists, Hugo de Vries in the Netherlands, Carl Correns in Germany and Erich von Tschermak in Austria, each came upon his paper and saw that he had found the rules first. Today Mendel is called the father of genetics, and plant breeders, ranchers and biology students all use the patterns he counted out in a monastery garden.

Try it and see. Why did Mendel need so many plants? Because each seed is a matter of chance, like a coin toss. Ten seeds might come out 6 round to 4 wrinkled, or even 9 to 1. Only when you count hundreds or thousands does the true pattern show through. In this lesson's project you will draw "factors" out of bags the way pollen and egg cells carry them, and watch the 3 to 1 ratio appear as your numbers grow.

God's handiwork. Mendel was a priest and a careful scientist at the same time. The order he found is part of the order God built into living things when He made plants "yielding seed after his kind" (Genesis 1:12). Peas give peas, yet within the pea kind there is room for tall and short, yellow and green, round and wrinkled. Heredity is faithful and full of variety at once.



Mendel's seed-shape cross. The wrinkled trait hid in the F1 and returned in about one F2 seed out of four.

PICTURE STUDY



Portrait of Gregor Mendel, Unknown photographer, about 1862 · Photograph · Widely reproduced; public domain. The abbey in Brno where Mendel worked now houses the Mendel Museum of Masaryk University.

This photograph was taken around 1862, in the middle of Mendel's pea years, when he was about forty. Photography was still young. A sitter had to hold perfectly still while the picture was taken, which is one reason faces in old photographs look so serious.

This is the man who knelt in the abbey garden with tweezers and a brush, and who filled notebooks with counts of round and wrinkled, yellow and green. In a group photograph of the friars of St. Thomas's from about the same years, Mendel is the one holding a flower.

Look closely

- Look at his clothing. What tells you he belonged to a religious community?
- Look at his face. What words would you use to describe his expression?
- Early photographs needed long, still poses. Where can you see that in this picture?
- Imagine the same man in his garden. What tools and notebooks might be beside him?

Talk about it

1. Mendel was a friar, a priest, a teacher and a scientist. How might each of those roles have helped him do patient, careful work?
2. His work was ignored for 34 years. How do you think a person keeps working faithfully when no one notices?

EXPERIMENT: DRAWING FACTORS LIKE MENDEL

Each F1 pea plant carries one round factor and one wrinkled factor. When it makes pollen and egg cells, each one gets just one factor, by chance. You will model this with beans in

bags and test a question Mendel faced: how many offspring do you need to count before the 3 to 1 pattern shows clearly?

Question: Will 20 offspring or 200 offspring come closer to a 3 to 1 ratio? **Prediction:** write yours before you start. **What we change:** the number of draws. **What we keep the same:** the bags, the beans, putting beans back after each draw. **What we measure:** the number of round and wrinkled offspring and the ratio.

You will need

- 2 paper bags (or opaque cups), labeled Parent 1 and Parent 2
- 20 light beans (white navy beans or chickpeas) to stand for the round factor
- 20 dark beans (black or pinto beans) to stand for the wrinkled factor
- Lab notebook, pencil and calculator

Steps

1. Put 10 light beans and 10 dark beans in each bag. Each bag is an F1 plant carrying one round and one wrinkled factor in equal amounts.
2. In your notebook, make a table with columns: Draw number, Parent 1 bean, Parent 2 bean, Offspring seed (round or wrinkled).
3. Without looking, draw one bean from each bag. The pair is one offspring seed. If at least one bean is light, the seed is round. Only two dark beans make a wrinkled seed.
4. Record the result, put both beans back in their own bags, and shake each bag.
5. Repeat until you have 20 offspring. Count round and wrinkled seeds and divide round by wrinkled to get the ratio.
6. Keep going until you have 200 offspring in all (180 more draws). A family member can draw while you record to go faster.
7. Find the ratio for all 200. Compare your two ratios with Mendel’s 2.96 to 1 for seed shape.
8. Write a conclusion of three sentences: Was your prediction right? Which sample came closer to 3 to 1? Why did Mendel count thousands of seeds?

Tips

- If you get zero wrinkled seeds in a small sample, the ratio cannot be calculated. That itself shows why small samples are risky.
- Combine your 200 draws with a sibling’s or a friend’s to make 400 or more and see whether the ratio gets even closer.

Check your work

- I recorded every draw in a table.
- I calculated the ratio for 20 offspring and for 200 offspring.
- I can explain why larger samples usually come closer to the expected ratio.

NATURE NOTEBOOK

1. Draw a pea flower from the side and label the petals, the stamens and the pistil. Mark with an arrow where Mendel removed the stamens and where he brushed on new pollen.
2. Make a chart of Mendel's seven traits with a small sketch of both forms of each: round and wrinkled seed, yellow and green seed, gray and white seed coat, inflated and constricted pod, green and yellow pod, flowers along the stem and at the tip, tall and short stem.
3. Draw a bar graph of Mendel's seed-shape F2 counts (5,474 round, 1,850 wrinkled). Use a scale of 1 cm for every 500 seeds.

From history. Peas were not Mendel's only science. For years he took careful daily weather readings in Brno and sent them to the Central Institute for Meteorology in Vienna, and he kept hives of bees in the abbey grounds and tried to breed better strains of them. The same habits ran through all of it: measure carefully, write it down, and look for the pattern.

WORKED EXAMPLES

Example 1. In the F2 generation for seed shape, Mendel counted 5,474 round seeds and 1,850 wrinkled seeds. What is the ratio of round to wrinkled, written as a number to 1?

(Use the map or drawing "The F2 counts behind this ratio." shown earlier in this lesson.)

1. A ratio "to 1" means divide the first number by the second.
2. 5,474 ÷ 1,850 = 2.959...
3. Round to two decimal places: 2.96.

Answer: About 2.96 to 1, very close to 3 to 1.

Example 2. For seed color, Mendel counted 6,022 yellow and 2,001 green seeds in the F2. What percent of the seeds were yellow? Compare it with the 3 out of 4 a 3 to 1 ratio predicts.

1. Total seeds: 6,022 + 2,001 = 8,023.
2. Fraction yellow: 6,022 ÷ 8,023 = 0.7506.
3. Percent: 0.7506 × 100 = 75.1%.
4. A 3 to 1 ratio means 3 out of every 4, which is 75%.

Answer: 75.1% yellow, only 0.1 percentage point from the expected 75%.

Example 3. For stem length, Mendel counted 787 tall and 277 short plants in the F2. If the true ratio is 3 to 1, how many tall and short plants would he expect out of that total? How far off was he?

1. Total plants: 787 + 277 = 1,064.
2. Expected tall: 3/4 × 1,064 = 798. Expected short: 1/4 × 1,064 = 266.
3. Difference: 798 − 787 = 11 fewer tall; 277 − 266 = 11 more short.
4. As a share of all plants: 11 ÷ 1,064 = 0.010, about 1%.

Answer: Expected 798 tall and 266 short. He was off by 11 plants each way, about 1% of the total, which is the kind of small wobble chance produces.

PRACTICE

1. EASY Where and in what years did Gregor Mendel carry out his pea experiments?
2. EASY What does it mean for a pea variety to be true-breeding? Why did Mendel test his varieties for two years before starting?
3. EASY Why did Mendel pull out the stamens of a young flower before cross-pollinating it?
4. MEDIUM In the F2 for seed coat color, Mendel counted 705 gray and 224 white. Find the ratio of gray to white as a number to 1.
5. MEDIUM Data reading. Mendel's F2 counts for four traits:
   Seed shape: 5,474 round, 1,850 wrinkled (total 7,324; ratio 2.96)
   Seed color: 6,022 yellow, 2,001 green (total 8,023; ratio 3.01)
   Pod color: 428 green, 152 yellow (total 580; ratio 2.82)
   Stem length: 787 tall, 277 short (total 1,064; ratio 2.84)
   (a) Which trait's ratio is closest to 3.00? (b) Which is farthest? (c) What pattern links the total counted and closeness to 3.00? (d) Does this table prove that larger samples always come closer?
6. MEDIUM Data reading. A student ran the bean-bag model three times:
   20 draws: 13 round, 7 wrinkled
   100 draws: 72 round, 28 wrinkled
   400 draws: 302 round, 98 wrinkled
   Which statement is best supported? (A) The ratio was 3 to 1 every time. (B) As the number of draws increased, the ratio moved closer to 3 to 1. (C) Small samples are more accurate than large ones. (D) Round beans are drawn more often when the bag is shaken.
7. MEDIUM Mendel crossed true-breeding tall plants with true-breeding short plants. All the F1 plants were tall. If the F1 plants pollinate themselves and produce 1,200 F2 plants, about how many will be short?
8. HARD Many people in Mendel's day believed in blending inheritance, the idea that offspring are a mixture of their parents, like mixed paint. In three or four sentences, explain how Mendel's seed-shape results contradict that idea.

9. CHALLENGE Experiment design. Does it matter which parent gives the pollen? Design an experiment, using true-breeding round and wrinkled pea plants, to find out. Name what you change, what you keep the same, what you measure, and what result would mean "it does not matter."
10. HARD What percent of Mendel's 7,324 F2 seeds for seed shape were wrinkled? Compare it with the percent a 3 to 1 ratio predicts.

COMMON MISTAKES

- Thinking offspring are always a blend of their parents. Mendel's F1 seeds were fully round, not halfway wrinkled, and the wrinkled form came back whole.
- Thinking a trait that disappears in one generation is lost for good. The wrinkled factor was carried, hidden, in every F1 plant.
- Expecting real counts to come out exactly 3 to 1. Each seed is a chance event, so real data come close to the ratio, and come closer as the sample grows, but are rarely exact.

Make it a game · Seven Traits Match. Make 14 cards, one for each form of Mendel's seven traits (round, wrinkled, yellow, green, and so on), with a small sketch on each. Shuffle and lay them face down. Take turns flipping two cards. If they are the two forms of the same trait, keep the pair, but only after you name which form showed up in all the F1 plants (round, yellow seed, gray coat, inflated pod, green pod, flowers along the stem, tall). Most pairs wins.

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

This verse, in Latin, was carved over the door of the Cavendish Laboratory in Cambridge, where great physicists worked. It fits a friar counting peas just as well: studying what God made is a joy, and the works are great enough to reward a lifetime of looking.

Practice answers

1. In the garden of St. Thomas's Abbey in Brno, Moravia (now the Czech Republic), from 1856 to 1863.
2. A true-breeding variety always gives offspring with the same form of the trait when it pollinates itself. Mendel tested them so he would know for certain what each parent would pass on; otherwise a hidden trait in a parent could spoil his results.
3. The stamens make pollen. Removing them before they shed pollen kept the flower from pollinating itself, so the only pollen to reach the pistil was the pollen Mendel chose to brush on.
4. 705 ÷ 224 = 3.15, so about 3.15 to 1.
5. (a) Seed color, 3.01 (off by 0.01). (b) Pod color, 2.82 (off by 0.18). (c) The two traits with the largest totals (8,023 and 7,324) are closest to 3.00, and the trait with the smallest total (580) is farthest. (d) No. It supports the idea that chance evens out in larger samples, but four traits are a small set, and any single large sample can still wander a little from 3 to 1.

6. (B). The ratios are 13 ÷ 7 = 1.86, 72 ÷ 28 = 2.57 and 302 ÷ 98 = 3.08, moving toward 3 as the sample grows. The data say nothing about shaking (D), and (A) and (C) are contradicted.
7. About one in four: 1,200 ÷ 4 = 300 short plants (and about 900 tall).
8. If traits blended, crossing round and wrinkled peas should give in-between, slightly wrinkled seeds, but every F1 seed was fully round. Blending also could not be undone, yet fully wrinkled seeds, just like the original wrinkled parent, reappeared in the F2. So the wrinkled factor must have been carried whole and hidden inside the F1 plants. Heredity works by separate units that are passed on intact, not by mixing.
9. Make two kinds of crosses (reciprocal crosses): pollen from round onto wrinkled flowers, and pollen from wrinkled onto round flowers. What changes: which parent supplies the pollen. Keep the same: the varieties, soil, water, sunlight, planting date and the number of flowers crossed (for example 20 each way), and remove stamens the same way every time. Measure: the shape of the F1 seeds from each set of crosses, and then the F2 ratio after the F1 plants self-pollinate. If both directions give all-round F1 seeds and about 3 to 1 in the F2, the direction does not matter. (This is what Mendel found.)
10. 1,850 ÷ 7,324 = 0.2526, or 25.3%. A 3 to 1 ratio predicts 1 out of 4, or 25%, so his result was only 0.3 percentage point away.

1.2 Dominant and Recessive

OBJECTIVES

- Define gene, allele, dominant, recessive, genotype and phenotype, and use letter symbols (R and r) correctly.
- Explain how Mendel showed that round F2 peas were of two hidden kinds, and calculate the 1 : 2 : 1 pattern from his data.
- Use a test cross to tell a homozygous dominant organism from a heterozygous one, and calculate how confident a test cross can make you.

Warm-up. Take two index cards. On one, write ROUND in big, thick marker. On the other, write “wrinkled” small, in pencil. Lay the ROUND card on top of the wrinkled card and ask someone what the stack says. Is the wrinkled card gone? Now lift the top card. Write one sentence: how is this like Mendel’s F1 peas, which looked round but still carried wrinkled?

Video. Coming soon. Dominant and recessive alleles, genotype and phenotype, and the test cross; search Learn.Genetics (University of Utah), the DNA Learning Center (Cold Spring Harbor), Amoeba Sisters, Bozeman Science, and plant-breeding footage from university extension programs.

KEY TERMS

gene
A unit of heredity, a section of DNA, that is passed from parent to offspring and affects a trait. Mendel called it a “factor.”

allele
One of the different forms of a gene. The seed-shape gene in peas has a round allele (R) and a wrinkled allele (r).

dominant
Describes an allele whose trait shows even when only one copy is present. Written with a capital letter.

recessive
Describes an allele whose trait shows only when two copies are present, with no dominant allele. Written with a lowercase letter.

genotype
The pair of alleles an organism carries for a trait, such as RR, Rr or rr.

phenotype
The trait you can actually observe, such as a round seed or a wrinkled seed.

CORE IDEAS

The story. Seed shape was the quickest trait for Mendel to read. A pea seed holds the young plant of the next generation, so when he dusted the flowers of a round-seeded plant with pollen from a wrinkled-seeded plant, the answer lay in the pods that formed that same summer. He split them open and found every seed round. It did not matter which parent gave the pollen: the hybrid seeds were round either way. When he wrote his paper in 1866, Mendel needed names for the two forms. He called the form that showed in the hybrids **dominant**, and the form that dropped out of sight **recessive**, from a Latin word meaning to go back or withdraw. The recessive trait had not been destroyed. It had only stepped back, and in the next generation it walked out again in about one seed in four.

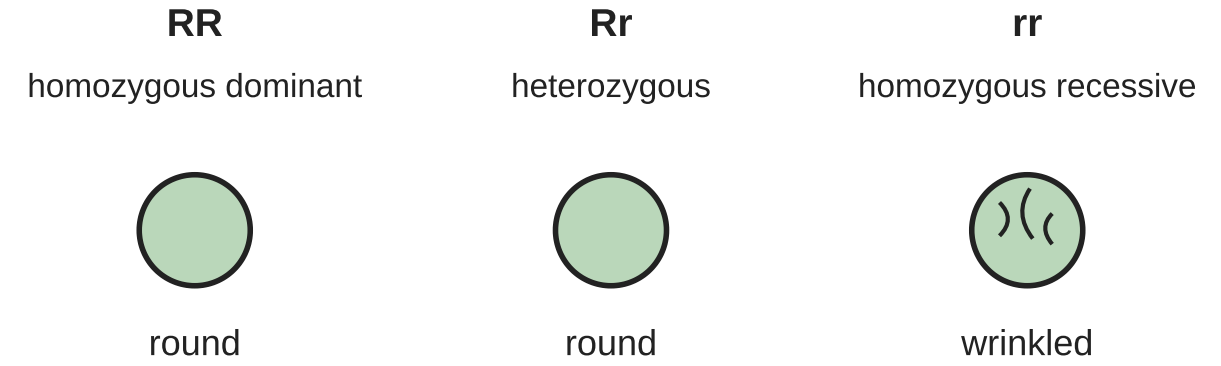
How he figured it out. Mendel then asked a sharper question. Three of every four F2 seeds were round, but were all those round seeds the same inside? He planted 565 round F2 seeds and let each plant pollinate itself. 193 plants gave only round seeds: they were true-breeding. The other 372 gave both round and wrinkled seeds, again about 3 to 1. That is 372 to 193, close to 2 to 1. So the round F2 plants were really of two kinds that looked exactly alike: one-third pure round and two-thirds hybrid round. Adding the wrinkled plants, the F2 was 1 pure round : 2 hybrid round : 1 wrinkled. Mendel found the same 1 : 2 : 1 hidden under each trait he tested this way.

The big idea. Today we say each of these traits is controlled by a **gene**, and a gene can come in different forms called **alleles**. A pea carries two alleles for seed shape, one from the pollen and one from the egg cell. Geneticists write the dominant allele as a capital letter (R for round) and the recessive allele as the same letter in lowercase (r for wrinkled). The pair of letters is the **genotype**; the trait you can see is the **phenotype**. An organism with two matching alleles (RR or rr) is *homozygous*; one with two different alleles (Rr) is *heterozygous*. Because one R is enough to make a round seed, RR and Rr both look round. Only rr looks wrinkled.

In the world today. In 1990, scientists at the John Innes Centre in Norwich, England, found Mendel’s seed-shape gene. The R allele carries the instructions for an enzyme that builds branched starch inside the seed. In the r allele, an extra piece of DNA has been inserted into the gene, and the enzyme no longer works. A growing rr seed therefore stores less starch and more sugar. The sugar draws in extra water, so the seed swells; when it dries at the end of the season, it shrinks and wrinkles. That extra sugar is why many sweet garden peas are wrinkled-seeded kinds. A recessive allele is often one that does not make a working product, and a single good copy is enough.

Try it and see. If RR and Rr look the same, how can a breeder tell them apart? Mendel’s answer was the **test cross**: cross the mystery plant with a wrinkled (rr) plant, which can pass on only r. If any offspring are wrinkled, the mystery plant must carry an r. In the project you will run test crosses on mystery bags of beans. Remember, too, that Mendel chose his traits well. Many traits, such as height in people, are shaped by several genes and by food and health, and some genes show *incomplete dominance*: a red snapdragon crossed with a white one gives pink flowers.

God’s handiwork. A recessive allele can ride hidden for generations and come back whole. Nothing is lost; the information is kept. God made plants with their “seed is in itself” (Genesis 1:11), each kind carrying a rich store of variety that can show up in children and grandchildren. A wrinkled pea that appears from two round parents is a faithful copy kept safe, not a mistake.



Top: genotype (the two alleles). Bottom: phenotype (what you see).

One R is enough to make a round seed.

Three genotypes, two phenotypes. One R is enough to make a round seed.

PICTURE STUDY



Garden Pea (Pisum sativum), From the flora of Otto Wilhelm Thomé, 1885 · Chromolithograph (color-printed botanical plate) · Published in Gera, Germany, in *Flora von Deutschland, Österreich und der Schweiz*; scanned copies are in the Biodiversity Heritage Library and on Wikimedia Commons

Otto Wilhelm Thomé was a German botanist and teacher. His great flora of Germany, Austria and Switzerland, first published in 1885, filled several volumes with hundreds of color plates, each showing a whole plant and its parts drawn separately, the way a scientist would take it apart.

This plate shows the same species Mendel grew in Brno only about twenty-five years earlier. Botanical artists of the time aimed for accuracy, not decoration: a student should be able to identify the plant and see how its flower is built.

Look closely

- Find the tendrils, the thin curling threads at the ends of the leaves. What job do they do for a climbing pea vine?
- Find a flower. A pea flower has a large upper petal (the banner), two side petals (the wings) and a boat-shaped keel that wraps around the stamens and pistil. Can you see these parts?
- Find the small separate drawings. Which parts of the plant has the artist taken apart and enlarged?
- Find a pod and its seeds. What color are they drawn? Are the seeds shown round or wrinkled?

Talk about it

1. Why does the closed keel of the pea flower make the plant pollinate itself? Why was that so useful to Mendel?
2. Which of Mendel’s seven traits can you check on this plate, and which can you not?

EXPERIMENT: THE MYSTERY BAG TEST CROSS

Two pea plants both have round seeds. One is RR and the other is Rr, but you cannot tell by looking. You will find out the way breeders do: by test crossing each with a wrinkled (rr) plant and watching the offspring.

Question: How many test-cross offspring do you need before you can be confident a round plant is RR? **Prediction:** write a number before you start. **What we change:** which mystery bag is crossed. **What we keep the same:** the tester bag, the number of beans, putting beans back after each draw. **What we measure:** the draw number of the first wrinkled offspring, and the number of wrinkled offspring in 20 draws.

You will need

- 3 paper bags or opaque cups
- 30 light beans (round allele, R) and 30 dark beans (wrinkled allele, r)
- A parent or partner to fill the mystery bags in secret
- Lab notebook and pencil

Steps

1. Ask your helper to fill two mystery bags in secret: one with 20 light beans (an RR plant) and one with 10 light and 10 dark beans (an Rr plant). The helper labels them A and B and writes down which is which, out of your sight.
2. Fill a third bag, the tester, with 20 dark beans. This is the rr wrinkled plant.
3. Make a table: Draw number, Bean from mystery bag, Bean from tester, Offspring (round or wrinkled). Make one table for Bag A and one for Bag B.
4. Draw one bean from Bag A and one from the tester. Record the offspring. Put the beans back in their own bags and shake.
5. Do 20 crosses with Bag A, then 20 with Bag B. Circle the draw number where the first wrinkled offspring appeared in each.
6. Decide which bag is RR and which is Rr. Check with your helper.
7. Ask the helper to secretly swap or keep the labels and run the test twice more. Each time, note how many draws it took before the first wrinkled offspring showed up from the Rr bag.
8. Write your conclusion: How many draws did it take, on average, to unmask the Rr bag? If a bag gave 20 round offspring in a row, how sure can you be that it was RR? (Use the worked example to calculate it.)

Tips

- Never look into the bags while drawing. Peeking ruins the chance, just as a breeder cannot choose which pollen grain wins.
- One wrinkled offspring is enough to prove the mystery plant carries r. No number of round offspring can prove it absolutely, but many in a row make it very likely.

Check your work

- I can explain why a test cross uses a homozygous recessive partner.
- I correctly identified the RR and Rr bags and recorded every draw.
- I can explain why one wrinkled offspring proves more than many round ones.

NATURE NOTEBOOK

1. Draw the genotype chart for pea seed color, where yellow (Y) is dominant to green (y): show YY, Yy and yy, label each homozygous or heterozygous, and color the seed each would make.
2. Sketch two round pea seeds side by side, one RR and one Rr. Under them write: “Same phenotype, different genotype.” Then draw a cutaway showing the two alleles inside each, using two colors.
3. Make a two-column page titled “Dominant does not mean…” and list at least two false ideas (more common, stronger, better) with a true sentence beside each.

> **From history.** Mendel never used the words gene, allele, genotype or phenotype. William Bateson, Mendel’s great defender in England, introduced the word *allelomorph* in 1902, which was later shortened to allele. In 1909 the Danish botanist Wilhelm Johannsen

coined the word *gene*, and he also introduced the terms genotype and phenotype. The ideas were Mendel's; the vocabulary came a generation later.

WORKED EXAMPLES

Example 1. Mendel crossed a true-breeding round plant (RR) with a true-breeding wrinkled plant (rr). What genotype and phenotype will every F1 seed have?

(Use the map or drawing "Rr is heterozygous and looks round." shown earlier in this lesson.)

1. The RR parent can pass on only R. The rr parent can pass on only r.
2. So every F1 seed gets one R and one r: genotype Rr.
3. One R is enough for a round seed, so the phenotype is round.

Answer: 100% of the F1 seeds are Rr (heterozygous) and round.

Example 2. Mendel let 565 round F2 plants pollinate themselves. 193 gave only round seeds; 372 gave both round and wrinkled. Find the ratio of hybrid to pure plants and the percent that were pure (RR).

1. Ratio of hybrid (Rr) to pure (RR): 372 ÷ 193 = 1.93, about 2 to 1.
2. Percent pure: 193 ÷ 565 = 0.342, or 34.2%.
3. One-third is 33.3%, so the data fit the prediction that 1 of every 3 round F2 plants is RR and 2 are Rr.

Answer: About 1.93 to 1 (close to 2 to 1); 34.2% were RR, close to one-third.

Example 3. A breeder test crosses a tall pea plant (T_) with a short plant (tt). The first 5 offspring are all tall. If the tall plant were really Tt, what is the chance it would give 5 tall offspring in a row? What about 10 in a row?

1. In Tt × tt, each offspring has a 1 in 2 chance of being tall (Tt) and 1 in 2 of being short (tt).
2. Chances of independent events multiply. For 5 tall in a row: (1/2) × (1/2) × (1/2) × (1/2) × (1/2) = 1/32.
3. 1 ÷ 32 = 0.031, about 3.1%.
4. For 10 in a row: $(1/2)^{10}$ = 1/1,024, about 0.1%.

Answer: About a 3.1% chance after 5 tall offspring, and about 0.1% after 10. The more tall offspring in a row, the more confident the breeder can be that the plant is TT.

PRACTICE

1. EASY What is the difference between a gene and an allele?
2. EASY In peas, yellow seed (Y) is dominant to green seed (y). Give the phenotype of a plant with genotype Yy, and say whether it is homozygous or heterozygous.
3. EASY In peas, green pods (G) are dominant to yellow pods (g). Which of these genotypes has yellow pods: GG, Gg, gg?
4. MEDIUM Label each genotype homozygous dominant, heterozygous or homozygous recessive: TT, Tt, tt, Pp, aa.
5. MEDIUM Data reading. Mendel repeated his self-pollination test with seed color. Of 519 yellow F2 plants, 166 gave only yellow seeds and 353 gave both yellow and green.
   (a) What is the ratio of mixed to pure plants? (b) What percent were pure yellow (YY)? (c) Do these results support the 1 : 2 : 1 pattern? Explain.
6. MEDIUM Data reading. A class crossed red snapdragons with white snapdragons. All the F1 plants had pink flowers. The F1 plants were crossed with each other, and the F2 gave 52 red, 101 pink and 47 white.
   Which explanation best fits the data? (A) Red is dominant to white. (B) White is dominant to red. (C) Neither allele is fully dominant; heterozygous plants are pink, and the F2 is about 1 : 2 : 1. (D) The colors blended and cannot separate again.
7. MEDIUM Two round-seeded pea plants produce some wrinkled seeds. Explain how this can happen and give the genotypes of both parents.
8. HARD In people, having an extra finger or toe (polydactyly) can be caused by a dominant allele, yet it is rare. Explain why “dominant” does not mean “common.”
9. CHALLENGE Experiment design. You have a purple-flowered pea plant. Purple (P) is dominant to white (p). Design a test to find whether the plant is PP or Pp. Say what you would cross it with, what you would keep the same, what you would measure, and what each possible result would mean.
10. HARD A test cross of an unknown round plant with an rr plant gives 8 round offspring and no wrinkled ones. If the unknown plant were Rr, what is the chance of this result? Give a fraction and a percent.

COMMON MISTAKES

- Thinking dominant means more common or stronger. Dominance only describes whether one copy of an allele shows; a dominant allele can be rare and a recessive one common.
- Thinking a recessive allele disappears when it is hidden. It is carried unchanged in heterozygotes and can show up again in their offspring.
- Thinking every trait is controlled by one gene with a dominant and a recessive allele. Mendel’s seven pea traits are simple, but many traits, such as human height, depend on several genes and on the environment, and some alleles show incomplete dominance.

Make it a game · Dominant Detective. Write genotypes on cards (RR, Rr, rr, YY, Yy, yy, TT, Tt, tt) and shuffle. One player draws a card in secret and says only the phenotype (for example, “tall”). The other players may ask for one test cross: the card holder flips a coin to give the result of each offspring from a cross with the recessive plant (heads and tails stand for the two alleles of a heterozygote; a homozygous dominant always gives the dominant offspring). After up to five offspring, players guess the genotype. Correct guesses score a point; the holder then explains why.

Scripture. “And God said, Let the earth bring forth grass, the herb yielding seed, and the fruit tree yielding fruit after his kind, whose seed is in itself, upon the earth: and it was so.” (Genesis 1:11, KJV)

“Whose seed is in itself”: every seed carries within it what the next generation needs, including alleles that may stay hidden for a generation and then appear again. The variety within each kind was built in from the beginning.

Practice answers

1. A gene is the unit of heredity for a trait (for example, the seed-shape gene). Alleles are the different forms of that gene (the round allele R and the wrinkled allele r).
2. Yellow seeds; heterozygous.
3. Only gg. Both GG and Gg have at least one dominant G, so their pods are green.
4. TT homozygous dominant; Tt heterozygous; tt homozygous recessive; Pp heterozygous; aa homozygous recessive.
5. (a) 353 ÷ 166 = 2.13, about 2 to 1. (b) 166 ÷ 519 = 0.320, or 32.0%. (c) Yes. If yellow F2 plants are 1 YY to 2 Yy, about one-third (33.3%) should be pure and two-thirds mixed; 32.0% and a ratio of 2.13 are close to that.
6. (C). If red were dominant, the F1 would be red and the F2 about 3 red to 1 white. Instead the heterozygotes are pink and the F2 is close to 50 : 100 : 50 (1 : 2 : 1) out of 200. (D) is wrong because pure red and pure white came back in the F2.
7. A wrinkled seed is rr, so it must get an r from each parent. Both parents look round, so each must have one R and one r. Both parents are Rr (heterozygous).
8. Dominant describes how an allele acts when it is present: one copy is enough to show the trait. How common an allele is depends on how many people in a population carry it, which is a separate question. A dominant allele carried by very few people stays rare, and a recessive allele carried by many people can be common.
9. Test cross it with a white-flowered (pp) plant, removing the stamens from one parent and hand-pollinating. Keep the same: growing conditions for all offspring and careful prevention of stray pollen. Grow a good number of offspring, for example 20 or more, and count purple and white flowers. If any offspring are white, the purple parent must be Pp (expect about half white). If all of a large number are purple, the parent is almost certainly PP (the chance a Pp plant gives 20 purple offspring in a row is about 1 in a million).
10. $(1/2)^8 = 1/256$, about 0.39%, or roughly 0.4%. The plant is very likely RR.

1.3 Punnett Squares

OBJECTIVES

- Build and read a Punnett square for a one-trait cross and state the expected genotype and phenotype ratios.
- Use Punnett squares to predict expected numbers of offspring and compare them with real data, including Mendel's two-trait cross.
- Explain that a Punnett square gives probabilities, not guarantees, and that each offspring is an independent chance event.

Warm-up. Draw a 2 by 2 grid like a small multiplication table. Write 1 and 2 across the top and 3 and 4 down the left side. Fill each box with the product of its row and column. Now erase the numbers and write the letters R and r across the top and R and r down the side. Fill each box with its row letter and column letter. You have just drawn your first Punnett square.

Video. Coming soon. How to draw and read a Punnett square, monohybrid and dihybrid crosses, and probability in genetics; search Learn.Genetics (University of Utah), the DNA Learning Center (Cold Spring Harbor), Amoeba Sisters, Bozeman Science, and university extension videos on cattle and poultry breeding.

KEY TERMS

Punnett square
A grid that shows every way the alleles from two parents can combine, used to predict the chances of each genotype in the offspring.

gamete
A reproductive cell (pollen or egg cell in plants; sperm or egg cell in animals) that carries only one allele of each gene.

law of segregation
Mendel's rule that the two alleles of a gene separate when gametes form, so each gamete carries just one of them.

probability
The chance that an event will happen, written as a fraction, decimal or percent. Each box of a 2 by 2 Punnett square has a probability of 1/4, or 25%.

law of independent assortment
Mendel's rule that alleles for different traits are passed on independently of each other, which holds for genes on different chromosomes or far apart on the same one.

expected ratio
The ratio of offspring types a Punnett square predicts on average, such as 3 : 1 or 9 : 3 : 3 : 1.

CORE IDEAS

The story. In the first years of the 1900s, at Cambridge University in England, a young zoologist named Reginald Punnett went to work with William Bateson, the scientist who had become Mendel's loudest champion in Britain. Bateson even gave the new science its name: in 1905 he proposed calling it *genetics*. Together Bateson and Punnett crossed sweet peas and bred chickens, testing whether Mendel's rules held for animals as well as plants. They did. To show students and readers how two parents' alleles combine, Punnett used a simple grid of boxes. It caught on so well that it still bears his name: the **Punnett square**.

How they figured it out. A Punnett square rests on Mendel's **law of segregation**: the two alleles a parent carries separate when it makes **gametes**, so each pollen grain or egg cell carries just one. To build a square: (1) write each parent's genotype; (2) split each parent's two alleles, writing one parent's along the top and the other's down the side; (3) fill each box with the letter from its column and the letter from its row, capital letter first; (4) count the boxes. For two hybrid round peas, Rr × Rr, the four boxes read RR, Rr, Rr and rr.

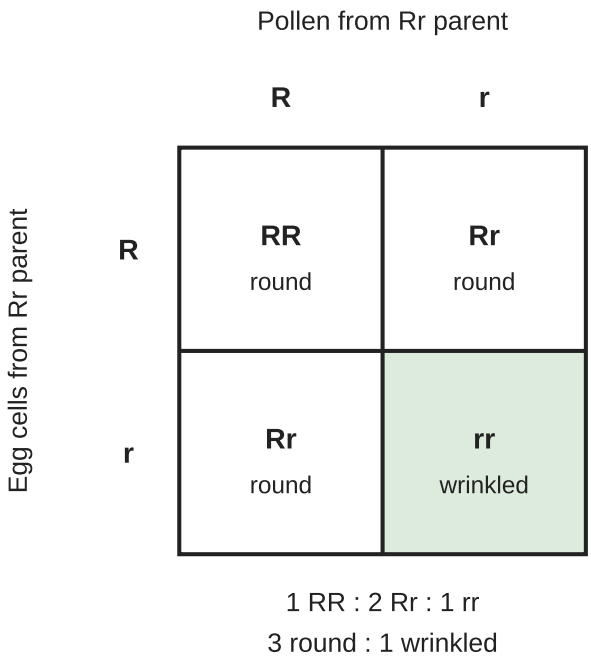
The big idea. Each box is one equally likely outcome, so each stands for a **probability** of 1 in 4, or 25%. For Rr × Rr the square predicts 1 RR : 2 Rr : 1 rr, and because RR and Rr both look round, 3 round : 1 wrinkled, exactly Mendel's F2 pattern. But a Punnett square does not promise that a pod of four seeds will hold three round and one wrinkled. It tells what to expect on average, over many offspring. Each seed is a fresh draw, just as a coin has no memory of its last toss. Three wrinkled seeds in a row do not make the next one more likely to be round.

Try it and see. Squares work for any cross. A test cross, Rr × rr, gives two Rr boxes and two rr boxes: 1 round : 1 wrinkled. Mendel also followed two traits at once. When he crossed plants that were hybrid for both seed shape and seed color (RrYy × RrYy), a 4 by 4 square of 16 boxes predicts 9 round yellow : 3 round green : 3 wrinkled yellow : 1 wrinkled green. Mendel counted 315, 108, 101 and 32 seeds, very close to 9 : 3 : 3 : 1. This showed his second rule, the **law of independent assortment**: the allele a pea passes on for shape does not decide which allele it passes on for color. Later scientists learned that this holds for genes on different chromosomes or far apart on the same one.

In the world today. Breeders use Punnett squares every season. In cattle, the allele for being polled (born without horns) is dominant to the allele for horns. A rancher with a polled bull who wants a hornless herd needs to know whether the bull is PP or Pp, because a Pp bull bred to horned cows will give horned calves about half the time. Punnett himself put the method to work: around 1930 he and Michael Pease bred the Cambar, a chicken whose chicks can be sorted into males and females by the color of their down on the day they hatch. Genetic counselors use the same squares to help families understand the chance of passing on a condition.

God's handiwork. The fall of a coin and the meeting of pollen and egg look like pure chance, yet out of many such chances comes a steady, predictable ratio. Scripture says the same thing in its own way: the lot is cast, but its outcome is the Lord's (Proverbs 16:33).

Chance in nature is not chaos. It works inside an order God set, and that order is what lets a friar with a notebook predict a pea patch.



Rr × Rr gives 1 RR : 2 Rr : 1 rr, or 3 round : 1 wrinkled.

PICTURE STUDY



Jacob Laying the Peeled Rods before the Flocks of Laban, Bartolomé Esteban Murillo, about 1665 · Oil on canvas · Meadows Museum, Southern Methodist University, Dallas, Texas

Murillo, a painter of Seville in Spain, made a series of paintings on the life of Jacob. This one shows the story of Genesis 30, when Jacob agreed to work for his uncle Laban and take as

his wages every speckled, spotted and dark animal born in the flock. Jacob set peeled branches by the watering troughs, and the flock bore many speckled young.

Genesis 31 adds that God showed Jacob in a dream that the increase was His doing, not the work of the branches. Shepherds today know something Jacob's neighbors did not: solid-colored animals can carry hidden recessive alleles for spotting, so two solid parents can have a spotted lamb or kid, just as two round peas can have a wrinkled seed.

Look closely

- Find Jacob. What is he doing with his hands?
- Look at the animals. How many different coat patterns can you find?
- Notice how much of the canvas is landscape and sky. How does Murillo make the scene feel calm and wide?
- Find the water. Why would a shepherd gather the flock there?

Talk about it

1. If two solid white sheep have a spotted lamb, what does a Punnett square tell you about the parents' genotypes, if spotting is recessive?
2. Why do you think Genesis is careful to say that the increase came from God and not from the peeled rods?

EXPERIMENT: COIN CROSSES

A heterozygous parent (Rr) gives R or r to each offspring with equal chance, like a coin landing heads or tails. You will use two coins as two Rr parents, run 100 crosses, and test the Punnett square's prediction.

Question: How closely do 100 coin crosses match the predicted 1 RR : 2 Rr : 1 rr? **Prediction:** write the counts you expect. **What we change:** the number of tosses (first 20, then 100). **What we keep the same:** the two coins, the way you toss, the surface they land on. **What we measure:** the count of RR, Rr and rr offspring.

You will need

- Two coins (for example a penny and a nickel)
- Masking tape and a pen
- A tray or box lid to toss into
- Lab notebook, pencil and calculator

Steps

1. Put a small piece of tape on each side of both coins. Write R on the heads side and r on the tails side. The penny is the pollen parent; the nickel is the egg parent.
2. Draw a Punnett square for Rr × Rr and write your predicted counts for 100 offspring.
3. Make a tally table with three rows: RR, Rr, rr.

4. Toss both coins into the tray together. Read the two letters and make a tally. (R on one coin and r on the other is Rr, whichever coin shows which.)
5. After 20 tosses, stop and write the counts and percents.
6. Continue to 100 tosses. Find the percent of each genotype and the ratio of round (RR plus Rr) to wrinkled (rr).
7. Make a bar graph with two bars for each genotype: predicted and observed.
8. Write a conclusion: Did 20 or 100 tosses come closer to 25% : 50% : 25%? Why do real results wobble around the prediction?
9. Extension: tape four coins, two for seed shape (R/r) and two for seed color (Y/y). Toss 160 times and compare with the expected 90 round yellow : 30 round green : 30 wrinkled yellow : 10 wrinkled green.

Tips

- Toss the coins high enough to spin. Sliding them out of your hand is not a fair toss.
- Pool your results with family members to get 300 or 400 tosses; the percents usually settle closer to the prediction.

Check your work

- I drew a correct Punnett square before tossing.
- I recorded 100 crosses and calculated percents for RR, Rr and rr.
- I can explain why the observed numbers are close to, but usually not exactly, the predicted ones.

NATURE NOTEBOOK

1. Draw a Punnett square for a test cross, Rr × rr, with tiny pea sketches in each box showing round or wrinkled.
2. Draw the 4 by 4 square for RrYy × RrYy. Shade the wrinkled green box (rryy) and color the boxes by phenotype. Count each color to check 9 : 3 : 3 : 1.
3. Sketch a polled calf and a horned calf. Under them, draw the Punnett square for a Pp bull and a pp cow and write the chance of each.

> **From history.** Critics of Mendel’s ideas had raised a hard question: if brachydactyly (short fingers) is dominant, why doesn’t it spread until nearly everyone has it? In 1908 Punnett took the puzzle to his Cambridge friend and fellow cricketer, the mathematician G. H. Hardy, who quickly showed that, without other forces acting, allele frequencies in a large population stay the same from generation to generation. The German physician Wilhelm Weinberg found the same rule independently that year, and it is now called the Hardy-Weinberg principle, the starting point of population genetics.

WORKED EXAMPLES

Example 1. Two hybrid round peas are crossed: Rr × Rr. Draw the Punnett square. Out of 400 seeds, how many of each genotype and phenotype do you expect?

(Use the map or drawing "Each box is one-fourth of the offspring." shown earlier in this lesson.)

1. Write R and r across the top (pollen) and R and r down the side (egg).
2. Fill the boxes: RR, Rr, Rr, rr. Each box is 1/4 of the offspring.
3. Expected genotypes: RR = 1/4 × 400 = 100; Rr = 2/4 × 400 = 200; rr = 1/4 × 400 = 100.
4. Phenotypes: round = RR + Rr = 300; wrinkled = rr = 100.

Answer: 100 RR, 200 Rr, 100 rr; 300 round and 100 wrinkled (3 : 1).

Example 2. A rancher breeds a polled bull that is Pp to horned cows (pp). In cattle, polled (P) is dominant to horned (p). What fraction of calves should be horned? Out of 40 calves, how many polled and horned are expected?

1. Bull's alleles across the top: P and p. Cow's alleles down the side: p and p.
2. Boxes: Pp, pp, Pp, pp. Two of four are Pp (polled) and two are pp (horned).
3. Fraction horned = 2/4 = 1/2.
4. Out of 40: 1/2 × 40 = 20 polled and 20 horned.

Answer: Half the calves should be horned: about 20 polled and 20 horned out of 40.

Example 3. Mendel crossed plants that were RrYy (round, yellow) with each other and got 556 seeds: 315 round yellow, 108 round green, 101 wrinkled yellow, 32 wrinkled green. Find the expected number of each using 9 : 3 : 3 : 1.

1. The parts of the ratio add to 9 + 3 + 3 + 1 = 16, matching the 16 boxes of the square.
2. Round yellow: 9/16 × 556 = 312.75, about 313.
3. Round green: 3/16 × 556 = 104.25, about 104. Wrinkled yellow: also about 104.
4. Wrinkled green: 1/16 × 556 = 34.75, about 35.
5. Compare: observed 315, 108, 101, 32; expected 313, 104, 104, 35. Every class is within 4 seeds.

Answer: Expected about 313 : 104 : 104 : 35. Mendel's 315 : 108 : 101 : 32 is very close, supporting independent assortment.

PRACTICE

1. EASY In a 2 by 2 Punnett square, what does each box stand for, and what is the probability of each box?
2. EASY Draw (or describe) the Punnett square for RR × rr. What fraction of offspring are Rr?
3. MEDIUM In peas, tall (T) is dominant to short (t). Cross Tt × tt. Give the genotype ratio and the phenotype ratio.
4. MEDIUM Two Yy plants (yellow seeds) are crossed. Out of 600 seeds, how many green seeds do you expect?
5. MEDIUM Data reading. A rancher bred two polled bulls to horned (pp) cows and recorded the calves:
   Bull A: 22 polled, 0 horned
   Bull B: 13 polled, 11 horned
   (a) What is Bull B's most likely genotype? (b) What is Bull A's most likely genotype? (c) If Bull A were Pp, what would be the chance of 22 polled calves in a row?
6. MEDIUM Data reading. Look again at Mendel's two-trait cross: 315 round yellow, 108 round green, 101 wrinkled yellow, 32 wrinkled green (556 in all).
   (a) How many seeds were round, whatever their color? How many wrinkled? (b) What is the round to wrinkled ratio? (c) Do the same for yellow to green. (d) What do (b) and (c) suggest about each trait on its own?
7. HARD From an Rr × Rr cross, the first three seeds you open are all wrinkled. What is the probability that the fourth seed is wrinkled? Explain.
8. HARD Cross Rr × RR. What are the expected genotype and phenotype ratios? Can any offspring be wrinkled?
9. CHALLENGE Experiment design. Design a pea experiment to test whether seed shape and seed color are inherited independently. Name the parents you start with, the generations you grow, what you measure, and what result would support independence.
10. CHALLENGE In the cross RrYy × RrYy, what fraction of offspring are wrinkled and green? Out of 800 offspring, how many are expected to be wrinkled green, and how many round yellow?

COMMON MISTAKES

- Thinking a Punnett square predicts exact counts. It gives probabilities; a family of four children or a pod of four seeds can easily differ from 3 : 1.
- Thinking past results change the next one ("three wrinkled in a row, so the next must be round"). Each offspring is an independent chance event.
- Writing both of a parent's alleles in one row or column (putting "Rr" at the top of a single column). Each gamete carries only one allele, so a parent's two alleles go on two separate rows or columns.

Make it a game · Square Off. A caller reads out a cross (for example Tt × tt, Yy × Yy, or Pp × PP). Two players race to draw the Punnett square and call out the phenotype ratio. The first correct answer wins the round; a wrong ratio gives the point to the other player. After ten rounds, the winner chooses a two-trait cross for a bonus round worth three points.

Scripture. “The lot is cast into the lap; but the whole disposing thereof is of the LORD.” (Proverbs 16:33, KJV)

A lot was something like a die or a marked stone. To us each toss looks random, yet Scripture says the outcome is never outside God’s rule. The chances in a Punnett square work the same way: unpredictable one at a time, orderly in the whole.

Practice answers

1. Each box is one possible combination of one allele from each parent, a possible offspring genotype. Each box has a probability of 1/4, or 25%.
2. Top: R, R. Side: r, r. All four boxes are Rr. 4/4, or 100%, are Rr, and all are round.
3. Boxes: Tt, Tt, tt, tt. Genotypes 1 Tt : 1 tt. Phenotypes 1 tall : 1 short (50% each).
4. Green seeds are yy, which is 1 box in 4. 1/4 × 600 = 150 green seeds (and about 450 yellow).
5. (a) Pp. A PP bull can give only P, so any horned calf proves he carries p; 13 to 11 is close to the 1 : 1 expected from Pp × pp. (b) PP, since all 22 calves were polled. (c) $(1/2)^{22}$ = 1 in 4,194,304, about 1 in 4 million, so Bull A is almost certainly PP.
6. (a) Round: 315 + 108 = 423. Wrinkled: 101 + 32 = 133. (b) 423 ÷ 133 = 3.18, about 3 to 1. (c) Yellow: 315 + 101 = 416; green: 108 + 32 = 140; 416 ÷ 140 = 2.97, about 3 to 1. (d) Each trait still gives its own 3 to 1 ratio even when followed together, showing that shape and color are inherited independently.
7. 1/4, or 25%. Each seed is an independent event; the earlier seeds do not change the chances for the next one. Thinking a round seed is now “due” is a common error called the gambler’s fallacy.
8. Boxes: RR, RR, Rr, Rr. Genotypes 1 RR : 1 Rr. Phenotype: all round. No offspring can be wrinkled, because every offspring gets an R from the RR parent.
9. Cross true-breeding round yellow (RRYY) plants with true-breeding wrinkled green (rryy) plants. The F1 will all be RrYy (round yellow). Let the F1 plants self-pollinate and count a large number of F2 seeds (several hundred) in four classes: round yellow, round green, wrinkled yellow, wrinkled green. Keep growing conditions the same for all plants. If the counts are close to 9 : 3 : 3 : 1, and the new combinations (round green and wrinkled yellow) appear about 3/16 of the time each, the traits are inherited independently. If the F2 were mostly the parent combinations, with few new ones, the genes would be linked.
10. Wrinkled (1/4) × green (1/4) = 1/16. 1/16 × 800 = 50 wrinkled green. Round yellow is 9/16 × 800 = 450.

1.4 Pedigrees

OBJECTIVES

- Read and draw a pedigree using standard symbols, and decide from the clues whether a trait is dominant or recessive.
- Use Punnett squares with pedigrees to find carriers and to calculate the chances for future children.
- Explain sex-linked inheritance through the story of hemophilia in Queen Victoria's family.

Warm-up. On a sheet of paper, draw your family as far back as your grandparents, but use only shapes: a square for each male and a circle for each female. Join each married couple with a horizontal line, and drop a vertical line from it to their children. Don't write any names yet. Could someone who doesn't know your family read who is related to whom just from the shapes and lines?

Video. Coming soon. Reading pedigree charts for dominant, recessive and X-linked traits, and the history of hemophilia in Queen Victoria's descendants; search Learn.Genetics (University of Utah), the DNA Learning Center (Cold Spring Harbor), Amoeba Sisters, Bozeman Science, and history documentaries on Queen Victoria and the Romanovs.

KEY TERMS

pedigree
A chart of a family's relationships, drawn in standard symbols, that shows which members have a trait across several generations.

affected
Showing the trait being studied. Affected people are drawn as shaded symbols in a pedigree.

carrier
A person who has one copy of a recessive allele and does not show the trait but can pass the allele to children.

autosomal trait
A trait whose gene lies on one of the chromosomes that are the same in males and females (the autosomes), so it is inherited the same way by sons and daughters.

sex-linked trait
A trait whose gene lies on the X chromosome. Recessive sex-linked traits show up far more often in males, who have only one X.

hemophilia
An inherited condition in which the blood lacks a working clotting protein, so bleeding takes a long time to stop. Its genes are on the X chromosome.

CORE IDEAS

The story. On April 7, 1853, Queen Victoria of Great Britain gave birth to her eighth child, Prince Leopold. As he grew, his parents noticed something frightening: a small bump left a deep bruise, and a minor cut could bleed for a long time. Leopold had **hemophilia**, a condition in which the blood lacks one of the proteins it needs to clot. No one in Victoria's or Prince Albert's families was known to have had it before. Leopold grew into a thoughtful, studious man, married and became a father, but he died in 1884, at thirty, after a fall. By then the condition was already moving quietly through his sisters' families. Two of Victoria's daughters, Alice and Beatrice, were carriers, and through their children hemophilia appeared in the royal houses of Germany, Russia and Spain. The best-known case was Alexei, son of the last Russian tsar, born in 1904, a great-grandson of Victoria.

How they figured it out. No one can run crosses on people the way Mendel did on peas, so scientists study families that already exist. They draw a **pedigree**, a family tree in standard symbols. Squares are males and circles are females. A horizontal line joins two parents, and a vertical line drops to their children, drawn left to right from oldest to youngest. A shaded symbol marks a person who shows the trait (**affected**). Generations get Roman numerals and the people in each get ordinary numbers, so II-2 means the second person in the second generation. In 1902 the English physician Archibald Garrod, with Bateson's help, used family records to show that alkaptonuria, a rare condition that makes urine turn dark in air, follows Mendel's rules for a recessive trait. It was one of the first human traits shown to do so.

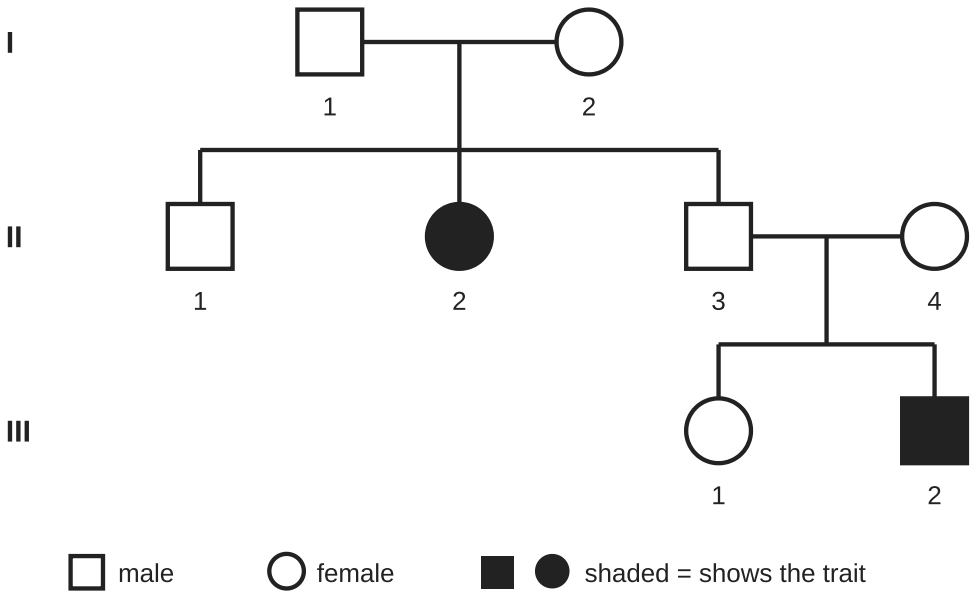
The big idea. A pedigree is a puzzle with clues. If two unaffected parents have an affected child, the trait must be recessive, and both parents must be **carriers** (Aa): healthy themselves, but each holding one hidden allele. That is why recessive traits often seem to skip generations. A dominant trait leaves the opposite clue: every affected person has at least one affected parent. Once you know the pattern, Punnett squares give the odds. Two carriers have a 1 in 4 chance, with each child, of having an affected (aa) child, and an unaffected brother or sister of that child has a 2 in 3 chance of being a carrier.

In the world today. Hemophilia follows a different pattern from Mendel's peas because its gene lies on the X chromosome. A female has two X chromosomes; a male has one X and one Y. A woman with one hemophilia allele is a carrier, because her other X still makes the clotting protein. A man has no second X to make up for it, so one allele is enough to cause the condition. That is why a recessive **sex-linked trait** shows up mostly in sons. Victoria was a carrier, probably because of a new change in the gene that began with her or one of her parents, and each of her children had a 1 in 2 chance of receiving that X. In 2009 scientists tested DNA from the remains of the Russian royal family and confirmed that Alexei had hemophilia B, the form caused by the gene for clotting factor IX.

Try it and see. Pedigrees are used every day. Genetic counselors draw them to help families understand recessive conditions such as cystic fibrosis. Dog, horse and cattle breeders keep pedigrees going back many generations to avoid pairing two carriers of a hidden problem. In the project you will build a pedigree from bean draws and challenge a partner to read the

hidden genotypes. Be careful with traits you see in some books: earlobe shape and tongue rolling are often taught as one-gene traits, but family studies show they are not that simple.

God's handiwork. The Bible is full of pedigrees, from the generations of Adam in Genesis 5 to the family line of Jesus in Matthew 1. A pedigree may show who carries a hidden allele, but it never shows who is worth more. Leopold, Alexei and every child with hemophilia were made in the image of God (Genesis 1:27), and the psalmist's words belong to each of us: "I am fearfully and wonderfully made."



A pedigree for a recessive trait such as albinism. Shaded symbols show the trait; open symbols do not.

PICTURE STUDY



The Family of Queen Victoria, Franz Xaver Winterhalter, 1846 · Oil on canvas · Royal Collection, United Kingdom (painted for Osborne House on the Isle of Wight)

Winterhalter, a German painter, was a favorite portrait artist of Queen Victoria and of many royal families in Europe. In 1846 he painted Victoria and Albert with the five children they had then: Victoria, Albert Edward (later King Edward VII), Alice, Alfred and baby Helena. Four more children were still to come, among them Leopold in 1853 and Beatrice in 1857.

Look at this painting as a geneticist would. Somewhere among these children is Alice, who was a carrier of hemophilia. No one in the room could have known it. Her allele, hidden in a healthy-looking girl, would one day pass to the heir of the Russian throne.

Look closely

- Count the people. Which two are the parents, and how does Winterhalter show it?
- Find the baby. Born in May 1846, she is Helena. How can you tell she is the youngest?
- Look at the clothing and the room. What does the painter want you to feel about this family?
- Imagine drawing this scene as a pedigree. How many squares and how many circles would you need?

Talk about it

1. Could anyone have told, by looking, which of these children carried a hidden allele? Why not?
2. Royal families often married their cousins in other royal houses. How might that have helped hemophilia spread across Europe?
3. What does this painting show about the family that a pedigree chart cannot?

EXPERIMENT: PEDIGREE DETECTIVE

You will grow a pretend family for three generations using bean draws for a recessive trait, draw it as a pedigree, and hand it to a partner. Can they work out the hidden genotypes from the pedigree alone?

Question: How many hidden genotypes can be determined for certain from a pedigree? **Prediction:** guess what fraction your partner will get right for certain. **What changes:** the random draws, so each family is different. **What stays the same:** the starting bags and the rules. **What we measure:** the number of genotypes your partner names with certainty, and how many of those are correct.

You will need

- 4 paper bags or cups
- Light beans (dominant allele A) and dark beans (recessive allele a), about 40 of each
- A coin (heads = son, tails = daughter)
- Ruler, pencil, lab notebook and a separate “secret” sheet

Steps

1. Fill two bags for the grandparents, I-1 (male) and I-2 (female), each with 10 light and 10 dark beans. Both are carriers (Aa).
2. Make generation II: for each of four children, draw one bean from each grandparent bag, flip the coin for son or daughter, and record the genotype on your secret sheet. Return the beans and shake.
3. Choose one child of generation II to marry. Fill a spouse bag with 10 light and 10 dark beans (a carrier spouse from outside the family).
4. For the chosen child, fill a bag to match his or her genotype: 20 light beans for AA, 10 and 10 for Aa, 20 dark for aa.
5. Make generation III: draw three grandchildren from the chosen child’s bag and the spouse’s bag, flipping the coin for each.
6. Draw the pedigree with correct symbols: squares, circles, marriage and sibling lines, Roman numerals for generations and numbers for people. Shade only the aa people.
7. Give your partner the pedigree (not the secret sheet). They write AA, Aa or aa for each person they can be sure of, and A_ for anyone who could be either AA or Aa.
8. Compare with the secret sheet. Count how many people your partner named for certain and how many were right. Repeat with a new family, swapping roles.

Tips

- Every shaded person is certainly aa. Every unshaded parent of a shaded child is certainly Aa. Those are the strongest clues.
- Optional: draw your own real family in pedigree symbols with names and birth years. If your family history is private or unknown, draw Queen Victoria’s family instead.

Check your work

- My pedigree uses standard symbols, generation numbers and correct lines.
- I can explain which genotypes a pedigree proves and which it leaves uncertain.
- I compared my partner's answers with the secret sheet and recorded the results.

NATURE NOTEBOOK

1. Copy the pedigree in this lesson's figure. Beside each person, write the genotype if you are sure of it, or A_ if not.
2. Draw a short pedigree of Queen Victoria's hemophilia: Victoria (carrier) and Albert; their children Alice (carrier), Leopold (affected) and Beatrice (carrier); then Alice's daughter Alix (carrier), who married Tsar Nicholas II, and their son Alexei (affected). Use a dot inside a circle to mark a carrier female.
3. Write a short paragraph: Why is a pedigree like Mendel's garden turned upside down? (Hint: Mendel chose his crosses; a geneticist studying people must read the crosses that already happened.)

> **From history.** Breeders kept pedigrees long before anyone knew about genes. In 1791 James Weatherby of England published *An Introduction to a General Stud Book*, recording the ancestry of racehorses, and the General Stud Book is still kept today. Every Thoroughbred racehorse traces its male line back to three stallions brought to England between the 1680s and about 1730: the Byerley Turk, the Darley Arabian and the Godolphin Arabian.

WORKED EXAMPLES

Example 1. In the pedigree figure, II-2 is affected, but her parents I-1 and I-2 are not. Is the trait dominant or recessive? What are the parents' genotypes, and what is the chance that their next child is affected?

(Use the map or drawing "Use the pedigree to find the hidden genotypes." shown earlier in this lesson.)

1. Two unaffected parents had an affected child, so the trait must be recessive. (A dominant trait would need at least one affected parent.)
2. II-2 is aa, so she received an a from each parent. Both parents are unaffected, so each must also have an A: both are Aa.
3. Punnett square for Aa × Aa: AA, Aa, Aa, aa. One box in four is aa.
4. Each new child is an independent event.

Answer: Recessive. I-1 and I-2 are both Aa (carriers). The chance of an affected next child is 1/4, or 25%.

Example 2. In the same pedigree, II-1 is the unaffected brother of II-2. What is the probability that he is a carrier?

1. His parents are Aa × Aa, giving AA, Aa, Aa and aa.
2. We know he is unaffected, so he cannot be aa. Cross out that box.
3. Three boxes remain: AA, Aa, Aa. Two of the three are Aa.
4. Probability = 2/3, about 67%.

Answer: 2/3 (about 67%). Knowing he is unaffected removes the aa box, so the chance is 2 out of the 3 remaining, not 2 out of 4.

Example 3. Victoria's daughter Alice was a hemophilia carrier (X^HX^h), and her husband was unaffected (X^HY). What were the chances for each son and each daughter?

1. Mother's gametes: X^H or X^h. Father's gametes: X^H or Y.
2. Boxes: X^HX^H (unaffected daughter), X^HX^h (carrier daughter), X^HY (unaffected son), X^hY (son with hemophilia).
3. Among daughters (the two X X boxes): 1 of 2 is a carrier, and none has hemophilia, because every daughter gets her father's X^H.
4. Among sons (the two X Y boxes): 1 of 2 has hemophilia.

Answer: Each son had a 1 in 2 (50%) chance of hemophilia; each daughter had a 1 in 2 chance of being a carrier and essentially no chance of having hemophilia. Overall, 1 child in 4 is expected to be an affected son.

PRACTICE

1. EASY In a pedigree, what does each of these mean: a square, a circle, a shaded symbol, a horizontal line between two people, and a vertical line below it?
2. EASY What is a carrier? Can a carrier have the trait?
3. MEDIUM In the pedigree figure, III-2 is affected but his parents, II-3 and II-4, are not. What are the genotypes of II-3 and II-4?
   (Use the map or drawing "Look at II-3, II-4 and their children." shown earlier in this lesson.)
4. MEDIUM In the pedigree figure, what is the probability that III-1 (the unaffected daughter of II-3 and II-4) is a carrier?
5. MEDIUM Data reading. A genetic counselor recorded four families for the same trait:
   Family 1: mother unaffected, father unaffected; 4 children, 1 affected
   Family 2: mother affected, father unaffected; 3 children, 0 affected
   Family 3: mother unaffected, father affected; 2 children, 1 affected
   Family 4: mother affected, father affected; 3 children, 3 affected
   (a) Which family proves the trait cannot be dominant? (b) Is Family 4 consistent with a

recessive trait? (c) If the trait is recessive, what genotype must every child in Family 2 have?

6. MEDIUM Data reading. In Queen Victoria's family: Prince Leopold had hemophilia. His daughter, Princess Alice, had no symptoms, but her son Rupert had hemophilia. Leopold's son, Charles Edward, did not have hemophilia.
   (a) Why must every daughter of a man with hemophilia be a carrier? (b) Why could Charles Edward not have inherited hemophilia from his father? (c) What chance did each of Princess Alice's sons have of hemophilia?
7. MEDIUM If a trait is caused by a dominant allele, can two unaffected parents have an affected child? Explain.
8. HARD Explain in three or four sentences why recessive X-linked traits such as hemophilia appear much more often in males than in females.
9. CHALLENGE Experiment design. A rabbit breeder notices that a few kits in the rabbitry have an unusual coat color, though their parents look normal. Design a breeding plan to test whether the color is caused by a recessive allele. Say which rabbits you would mate, what you would record, and what results would support the recessive explanation.
10. CHALLENGE Two carriers (Aa × Aa) plan to have three children. What is the probability that none of the three will be affected? What is the probability that at least one will be?

COMMON MISTAKES

- Thinking a carrier is sick or shows a mild form of the recessive trait. A carrier (Aa) usually looks and lives just like an AA person; the hidden allele shows only in the next generation.
- Thinking only males can have a sex-linked recessive trait. A female can, if she receives the allele on both X chromosomes, but it is much rarer.
- Using traits like earlobe shape, tongue rolling or eye color as simple one-gene examples. Family studies show these depend on more than one gene or do not follow a clean Mendelian pattern, so they make unreliable pedigree puzzles.

> **Make it a game · Pedigree Clue Cards.** Make cards with short clues, such as "two unaffected parents, one affected son," "affected father, all daughters carriers," or "every affected person has an affected parent." Draw a card and say whether it points to recessive, dominant or sex-linked inheritance, and why. A correct answer with a correct reason scores two points; a correct answer alone scores one. Bonus: sketch the smallest pedigree that fits the clue.

> **Scripture.** "I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well." (Psalm 139:14, KJV)

David wrote this about his own body, knit together by God. Every person in every pedigree, carrier or affected or neither, is included in it. Genetics can tell us the odds of a trait; it cannot tell us the worth of a person.

Practice answers

1. Square: male. Circle: female. Shaded: affected (shows the trait). Horizontal line: the two people are parents together (a couple). Vertical line: leads down to their children.
2. A carrier has one copy of a recessive allele (Aa) and passes it on half the time, but does not show the recessive trait, because the dominant allele covers it.
3. Both are Aa. III-2 is aa, so he received an a from each parent, and since both parents are unaffected each must also carry an A.
4. Her parents are Aa × Aa. She is unaffected, so the aa box is removed; 2 of the 3 remaining boxes are Aa. The probability is 2/3.
5. (a) Family 1. Two unaffected parents had an affected child, which a dominant trait cannot do (except by a rare new mutation). (b) Yes. Two affected (aa) parents can pass on only a, so all their children are aa and affected. (c) Every child in Family 2 got an a from the affected (aa) mother and is unaffected, so each is Aa, a carrier.
6. (a) A father gives his only X chromosome to every daughter, and Leopold's X carried the hemophilia allele, so each daughter received it. With a normal X from her mother, she is a carrier. (b) A father gives a son his Y chromosome, not his X, so Leopold could not pass his X-linked allele to a son. (c) As a carrier, Princess Alice gave each son either her normal X or her hemophilia X, a 1 in 2 (50%) chance of hemophilia for each son.
7. Not normally. Unaffected parents of a dominant trait are both aa, so they can pass on only a, and all their children are unaffected. (The rare exception is a brand-new mutation.)
8. A male has one X and one Y, so a single recessive allele on his X has no second X to cover it, and he shows the trait. A female has two X chromosomes, so she shows the trait only if both carry the recessive allele. That requires an affected father and a carrier (or affected) mother, which is much rarer. So most females with one copy are carriers, while every male with one copy is affected.
9. (1) Mate two affected rabbits with each other: if the color is recessive (aa × aa), all their kits should have the unusual color. (2) Mate an affected rabbit with an unrelated normal rabbit from a line that has never shown it (likely AA): all kits should look normal (Aa). (3) Mate those Aa kits with each other: about 1 in 4 of their kits should have the unusual color, and test crosses of normal-looking parents of affected kits with affected rabbits should give about 1 : 1. Record every litter in a pedigree, with the color and sex of each kit, and keep housing and feed the same so the environment is not the cause. Litters matching these ratios, with no difference between males and females, support a simple autosomal recessive allele.
10. Each child has a 3/4 chance of being unaffected. For all three: (3/4) × (3/4) × (3/4) = 27/64, about 42%. The chance that at least one is affected is 1 − 27/64 = 37/64, about 58%.

Unit 1 review

Answer each question. Show your work for every calculation and Punnett square, and use complete sentences for explanations. The test is worth 60 points.

1. (4 pts) Multiple choice. Which reason helped make the garden pea a good choice for Mendel's experiments?
   (A) Pea plants take many years to make seeds.
   (B) Pea flowers normally pollinate themselves, but Mendel could also cross them by hand.
   (C) Every pea plant looks exactly the same.
   (D) Peas cannot be cross-pollinated.
2. (4 pts) Multiple choice. In peas, round (R) is dominant to wrinkled (r). Which genotype gives wrinkled seeds?
   (A) RR (B) Rr (C) rr (D) both Rr and rr
3. (4 pts) Multiple choice. In peas, tall (T) is dominant to short (t). What fraction of the offspring of Tt × tt is expected to be short?
   (A) 0 (B) 1/4 (C) 1/2 (D) 3/4
4. (5 pts) Mendel crossed true-breeding round-seeded peas with true-breeding wrinkled-seeded peas. Describe what he saw in the F1 and in the F2 generations, including his F2 numbers or ratio. What did this show about blending inheritance?
5. (5 pts) For pod shape, Mendel counted 882 inflated pods and 299 constricted pods in the F2. Find the ratio of inflated to constricted as a number to 1, and the percent that were constricted.
6. (6 pts) Define genotype and phenotype. Then explain the difference between homozygous and heterozygous, giving one example genotype of each.
7. (6 pts) A purple-flowered pea plant (purple P is dominant to white p) is crossed with a white-flowered plant. The offspring are 24 purple and 22 white. What is the genotype of the purple parent? Explain how you know, and name this kind of cross.
8. (8 pts) Diagram item. In peas, yellow seed (Y) is dominant to green seed (y). Draw and fill in a Punnett square for Yy × Yy. Label the alleles of each parent. Then give (a) the genotype ratio, (b) the phenotype ratio, and (c) the expected number of green seeds out of 400.
9. (6 pts) In Mendel's two-trait cross (RrYy × RrYy) he got 556 seeds, 32 of which were wrinkled and green. What number of wrinkled green seeds does the 9 : 3 : 3 : 1 ratio predict? Is Mendel's count a good match? Explain why real counts rarely match a Punnett square exactly.
10. (6 pts) In a pedigree, two unaffected parents have three children; one daughter is affected and two sons are not. (a) Is the trait dominant or recessive? (b) What are the parents' genotypes? (c) What is the chance their next child is affected? (d) What is the chance that one of the unaffected sons is a carrier?
11. (6 pts) Hemophilia is a recessive sex-linked trait. A carrier woman ($X^{H}X^{h}$) and an unaffected man ($X^{H}Y$) have children. (a) What is the chance that a son has hemophilia?

(b) What is the chance that a daughter has hemophilia? (c) Using Queen Victoria's family, explain why the condition appeared in her sons and grandsons but not her daughters.

UNIT PROJECT: MY MENDEL LAB REPORT

Choose one of Mendel's seven pea traits and make an illustrated lab report about it, as if you were writing up Mendel's experiment for a science journal. Include: a labeled drawing of a pea flower showing how a cross is made; a P, F1 and F2 diagram for your trait with Mendel's real F2 counts and your calculated ratio; a labeled Punnett square explaining the F2; your own bean-bag or coin data from this unit with a bar graph comparing observed and expected; and a three-generation pedigree (from the Pedigree Detective project or Queen Victoria's family) with genotypes marked.

End with a one-page letter to Gregor Mendel, written in 1900 as if you were Hugo de Vries, Carl Correns or Erich von Tschermak, telling him what his work explains and why it matters.

- **Scientific accuracy**: Terms (allele, genotype, phenotype, dominant, recessive) are used correctly, Mendel's numbers are copied correctly, and ratios and Punnett squares are calculated without errors.
- **Data and graphs**: The student's own data are recorded in tables, graphed with labeled axes and units, and honestly compared with the expected ratio.
- **Explanation**: The report and letter explain why the recessive trait hides and returns, why large samples matter, and how a pedigree reveals carriers.
- **Care and presentation**: Drawings are neat and labeled, the report is organized like a real lab write-up (question, method, results, conclusion), and the work is complete.

Answer key

1. (B). Self-pollination let him keep true-breeding lines, and removing the stamens let him make controlled crosses. Peas also grow quickly and have clear either-or traits.
2. (C) rr. A wrinkled seed needs two recessive alleles; any R makes the seed round.
3. (C) 1/2. The square gives Tt, Tt, tt, tt.
4. All F1 seeds were round; the wrinkled trait seemed to disappear. When the F1 plants self-pollinated, the F2 had 5,474 round and 1,850 wrinkled seeds, about 3 to 1. Fully wrinkled seeds returned unchanged, so traits do not blend; they are carried by separate units (factors, now called genes) that stay whole.
5. 882 ÷ 299 = 2.95, about 2.95 to 1. Total 1,181; 299 ÷ 1,181 = 0.253, or 25.3% constricted, close to the expected 25%.
6. Genotype: the pair of alleles an organism carries for a trait (for example Rr). Phenotype: the trait you can observe (for example a round seed). Homozygous: two identical alleles, such as RR or rr. Heterozygous: two different alleles, such as Rr.
7. Pp. The white parent (pp) can give only p, so white offspring (pp) must have received a p from the purple parent too. A roughly 1 : 1 ratio (24 : 22) is what Pp × pp predicts. This is a test cross.
8. Square: Y and y across the top, Y and y down the side; boxes YY, Yy, Yy, yy (2 points for a correctly labeled and filled square). (a) 1 YY : 2 Yy : 1 yy (2 points). (b) 3 yellow : 1 green (2

points). (c) 1/4 × 400 = 100 green seeds (2 points).

9. 1/16 × 556 = 34.75, about 35. Mendel's 32 is close (within 3 seeds). Each seed is an independent chance event, so real results scatter around the expected value; a Punnett square gives probabilities, not exact counts. Larger samples usually come closer.
10. (a) Recessive, because unaffected parents had an affected child. (b) Both Aa. (c) 1/4 (25%). (d) 2/3, because an unaffected child must be AA or Aa, and 2 of those 3 equally likely boxes are Aa.
11. (a) 1/2. (b) Essentially 0, because every daughter receives her father's X^H; half the daughters are carriers. (c) Victoria was a carrier. Her son Leopold received her X^h and, with only one X, had hemophilia. Daughters such as Alice and Beatrice received X^h from her but a normal X from Albert, so they were healthy carriers who passed it to some of their sons and grandsons, such as Alice's son Friedrich and her grandson Alexei of Russia.

UNIT 2

DNA

In Unit 1 you watched Gregor Mendel count his peas and discover that traits are passed on by invisible “factors.” In this unit you will find out what those factors are made of. In 1953, Rosalind Franklin’s X-ray Photo 51, Erwin Chargaff’s base rule and the model building of James Watson and Francis Crick revealed the **double helix**: a twisted ladder whose rungs pair A with T and G with C. You will give each of them fair credit and use their measurements to work out the size and length of DNA.

Then you will become a scientist yourself. You will pull real DNA out of strawberries, just as Friedrich Miescher first pulled it from cells in 1869. You will learn how Marshall Nirenberg cracked the first word of the **genetic code** in 1961, read genes three letters at a time, and test what happens when a letter is changed. Finally, with Frederick Sanger and his insulin puzzle, you will see how the code becomes **proteins**, the folded chains that build feathers, carry oxygen and speed the chemistry of life, and you will measure an enzyme at work.

All through the unit you will practice the habits of science reasoning that high-school Biology and college entrance tests expect: reading data tables and graphs, planning fair tests with one changed variable and a control, and calculating with metric units. And you will see, at every step, how “fearfully and wonderfully made” (Psalm 139:14) every living thing is.

BEFORE YOU BEGIN

- Can explain dominant and recessive traits and complete a simple Punnett square (Unit 1)
- Knows that living things are made of cells and that plant and animal cells have a nucleus and a cell membrane
- Can work with percentages, averages and metric units (mm, cm, m, nm)
- Can identify the independent and dependent variables in a simple experiment

MASTERY CHECKLIST

- I can tell how Franklin, Chargaff, Watson and Crick each contributed to discovering the structure of DNA in 1953.
- I can describe the double helix and use the base-pairing rule (A–T, G–C) and Chargaff’s rule to solve problems.
- I can extract DNA from strawberries and explain what each step of the extraction does.
- I can transcribe DNA into mRNA and translate mRNA codons into amino acids with a codon table.
- I can explain how a protein’s amino acid sequence determines its shape and job, and how heat or a mutation can change it.
- I can read data tables and graphs about DNA and enzymes and design a fair experiment with a control.

OPTIONAL BOOKS AND RESOURCES

- **Learn.Genetics, from the University of Utah Genetic Science Learning Center** (https://learn.genetics.utah.edu/): Free. Clear interactive pages on DNA, genes and proteins, including a “transcribe and translate a gene” activity, a printable codon table and directions for extracting DNA from many foods. Good for Lessons 2.2 to 2.4.
- **Talking Glossary of Genomic and Genetic Terms, from the National Human Genome Research Institute** (https://www.genome.gov/genetics-glossary): Free. Short definitions, diagrams and audio explanations from scientists for terms such as double helix, codon, mutation and protein.
- **PDB-101, from the RCSB Protein Data Bank** (https://pdb101.rcsb.org/): Free. The “Molecule of the Month” pages show beautiful pictures of real proteins such as hemoglobin, insulin, catalase and collagen, with short explanations. Best with a parent for Lesson 2.4.

2.1 Watson, Crick and Rosalind Franklin's Photo 51 (1953) ★

OBJECTIVES

- Tell the story of how Rosalind Franklin's X-ray Photo 51, Erwin Chargaff's base rule and the model building of James Watson and Francis Crick together revealed the double helix in 1953, giving each person fair credit.
- Describe the structure of DNA: two sugar-phosphate backbones, four bases (A, T, G, C) and complementary base pairs, A with T and G with C.
- Use Chargaff's rule and the measured sizes of the helix (2 nm wide, 0.34 nm per base pair, 3.4 nm per turn) to solve percentage, scale and length problems.

Warm-up. Take a strip of paper about 30 cm long and 3 cm wide. Draw ten rungs across it like a ladder. Hold one end still and twist the other end two full turns. Look down the strip from the side and from the end. Sketch what you see. Now imagine you could only see the shadow of the twisted strip on a wall, never the strip itself. What clues in the shadow would tell you it was twisted? That is the puzzle Rosalind Franklin faced.

Video. Coming soon. Search for the discovery of the DNA double helix, Rosalind Franklin and Photo 51, and how X-ray diffraction works, on channels such as the Cold Spring Harbor Laboratory DNA Learning Center (DNALC), HHMI BioInteractive, the Royal Institution, Amoeba Sisters and Crash Course Biology; preview first for tone.

KEY TERMS

DNA (deoxyribonucleic acid)
The long molecule in every living cell that carries the hereditary instructions passed from parents to offspring.

nucleotide
One building block of DNA: a sugar (deoxyribose), a phosphate group and one of four bases: adenine (A), thymine (T), guanine (G) or cytosine (C).

base pair
Two bases joined across the middle of the DNA ladder by hydrogen bonds. A always pairs with T, and G always pairs with C; the two strands are called complementary.

double helix
The shape of DNA: two strands wound around each other like a twisted ladder, about 2 nm wide, making one full turn every 3.4 nm (10 base pairs).

X-ray diffraction
A way of studying the arrangement of atoms by shining X-rays through a crystal or fiber and recording the pattern of spots the scattered rays make on film.

Chargaff's rule

In double-stranded DNA the amount of A equals the amount of T, and the amount of G equals the amount of C. Erwin Chargaff reported it in 1950.

CORE IDEAS

The story. In May 1952, in a basement laboratory at King's College London, a young chemist named Rosalind Franklin and her student Raymond Gosling aimed a fine beam of X-rays at a single fiber of DNA, thinner than a hair. They kept the fiber damp, held it perfectly still and let the film soak up the scattered rays for many hours. When the film was developed, it showed a pattern of dark smudges in the shape of an X, with a gap at the top and bottom. They numbered it Photo 51. Franklin was 31 and had learned X-ray methods in Paris; she was one of the most careful X-ray workers in Britain. She knew that Photo 51 was a clue, but she was not a person to announce an answer before she could prove it.

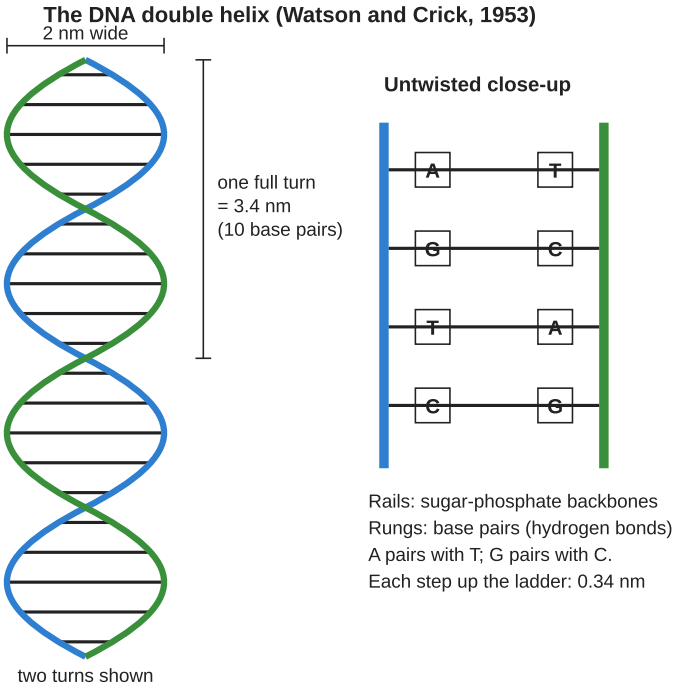
How they figured it out. About 80 km away, at the Cavendish Laboratory in Cambridge, James Watson, a 24-year-old American, and Francis Crick, a 36-year-old Englishman, were trying to solve the same puzzle by building models out of wire and metal plates. Their first model, in 1951, was wrong, and Franklin pointed out why. Then, in January 1953, Maurice Wilkins, who worked in Franklin's lab, showed Photo 51 to Watson without asking her. Watson knew at once that an X pattern meant a helix. Crick also saw a research report containing Franklin's measurements. They put this together with **Chargaff's rule**: in every sample Erwin Chargaff had tested, A equaled T and G equaled C. Watson cut out cardboard shapes of the bases and found that an A–T pair and a G–C pair were exactly the same width. By early March they had a model that fit every fact. On April 25, 1953, the journal *Nature* printed their one-page paper, side by side with papers by Wilkins and by Franklin and Gosling. Watson and Crick ended with a famous understatement: "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material."

The big idea. DNA is a **double helix**, a twisted ladder (see the diagram). The two rails are chains of sugar and phosphate. The rungs are pairs of bases, held together by weak hydrogen bonds: **A always with T, G always with C**. Each building block of sugar, phosphate and base is a **nucleotide**. The helix is about 2 nanometers (nm) wide, each rung is 0.34 nm above the last, and the ladder makes one full turn every 3.4 nm, or 10 base pairs. Because the pairing rule is strict, each strand holds all the information needed to rebuild the other. When a cell divides, the ladder unzips down the middle, and new partners line up on each old strand, giving two identical copies. That is the copying mechanism Watson and Crick hinted at. Gregor Mendel's invisible "factors" from Unit 1 turned out to be stretches of this molecule, which we call genes.

In the world today. Watson, Crick and Wilkins received the Nobel Prize in 1962. Rosalind Franklin could not share it; she had died of cancer in April 1958, at only 37, and the prize is not given after death. By then she had moved to Birkbeck College and done important work on the structure of viruses. Historians still debate how much credit each person deserves, and the fair answer is that the discovery needed all of them: Franklin's exact photographs and measurements, Chargaff's chemistry, Wilkins's early X-ray work, and Watson and Crick's

bold model building. The X-ray method Franklin used is still how scientists find the shapes of proteins, medicines and viruses.

God's handiwork. The same four letters, A, T, G and C, are used by bacteria, oak trees, eagles and people. The DNA in one of your cells, stretched out, would be about 2 meters long, yet it is folded into a nucleus far too small to see. David did not know about nucleotides, but he knew what to say when he considered how he was made: "I am fearfully and wonderfully made: marvellous are thy works" (Psalm 139:14).



The double helix. The rails are sugar-phosphate backbones; the rungs are base pairs, A with T and G with C.

PICTURE STUDY



Hand with Rings (the first X-ray photograph of a human hand), Wilhelm Conrad Röntgen, December 22, 1895 · Photographic print from an X-ray exposure on a glass plate · Widely reproduced; prints are held in many museum and university collections

In November 1895, the German physicist Wilhelm Röntgen was experimenting with an electric tube in his laboratory at Würzburg when he noticed a screen across the room glowing. Some unknown ray was passing through cardboard and paper. He called it the X-ray, X for unknown. A few weeks later he asked his wife, Anna Bertha, to hold her hand over a photographic plate while the tube shone on it. The picture showed her bones and her wedding ring.

This picture is the grandfather of Photo 51. Rosalind Franklin also used X-rays, but instead of letting them cast a shadow, she let them scatter off the regularly spaced atoms of DNA, and she read the pattern of spots like a code. Röntgen received the first Nobel Prize in Physics in 1901.

Look closely

- Find the ring. Why does metal show up so dark while the flesh is only a faint shadow?
- Count the bones you can see in one finger. Do the joints show as gaps?
- Find the small bones of the wrist. How many can you make out?
- Compare this picture in your mind with Photo 51. Which one is a shadow, and which one is a pattern that must be decoded?

Talk about it

1. Why do you think this one picture made X-rays famous around the world within weeks?

2. Röntgen saw something no one expected and then tested it carefully. How was Franklin's way of working like his?
3. What can X-rays show that our eyes cannot?

> **Safety first.** The project uses a laser pointer. Never look into the beam or point it at anyone's face, a pet or a shiny surface that could reflect it into an eye. Use an ordinary low-power pointer of the kind sold for presentations, keep it aimed at the wall, and have an adult present.

EXPERIMENT: MAKE YOUR OWN PHOTO 51

Franklin never saw DNA itself. She saw how X-rays scattered off it. You can do the same thing on a larger scale: light scattering off a coiled spring makes an X pattern very much like Photo 51. Your question: **Does stretching the coil change the pattern?**

Prediction: write what you think will happen to the spacing of the spots when the spring is stretched. What you change: how far the spring is stretched. What you keep the same: the laser, the spring, the distance from spring to wall and the darkness of the room. What you measure: the distance in millimeters between neighboring spots along one arm of the X.

You will need

- A small coiled spring from a click ballpoint pen
- A low-power laser pointer (red is fine)
- Modeling clay or tape to hold the spring and the pointer steady
- A sheet of white paper taped to a wall 2 to 3 meters away
- Metric ruler or tape measure, pencil and lab notebook
- A dark room

Steps

1. Tape the white paper to the wall. Mark a spot on the floor 2.5 m from the wall and set a table edge there.
2. Press the laser pointer into a lump of clay so it points level at the paper without being held.
3. Hold the spring in a second lump of clay so the beam passes through the side of the spring, across the coils, about 5 cm in front of the laser. Keep the spring's length running up and down.
4. Darken the room and turn on the laser. Adjust the spring until you see an X of spots on the paper instead of a single dot.
5. Trace the spots on the paper with a pencil. Label this tracing "relaxed spring."
6. Measure the distance between the center spot and the next spot along one arm of the X, in millimeters. Measure three times and average.
7. Gently stretch the spring to about one and a half times its length, mount it again in the same place and repeat the tracing and measurements. Label it "stretched spring."

8. Record both results in a table: spring condition, trial 1, trial 2, trial 3, average spacing (mm).
9. Write a conclusion: Did stretching the coil change the spacing? Was your prediction right? What does this tell you about how a pattern can reveal the shape of something too small to see?

Tips

- If you see only a smear, rotate the spring slightly so the beam crosses the coils squarely.
- The spring is like the helix and the pattern is like Photo 51. Scientists worked backward from the pattern to the shape, and so are you.
- Keep the spring and wall distance exactly the same for both trials, or your comparison will not be fair.

Check your work

- I made an X pattern from a coiled spring and traced it.
- I measured spot spacing in millimeters, three times each, and found averages.
- I can explain why an X pattern was evidence that DNA is a helix.

NATURE NOTEBOOK

1. Draw an untwisted section of DNA with six base pairs. Label the sugar-phosphate backbone, a base pair, a hydrogen bond and one nucleotide. Use A–T and G–C correctly.
2. Make a timeline card for 1950 to 1962 with these events: Chargaff's rule (1950), Photo 51 (May 1952), the model and the *Nature* papers (1953), Franklin's death (1958), the Nobel Prize (1962).
3. Paste or trace your spring X pattern and write beside it, in your own words, how a scientist can learn the shape of something by the pattern it scatters.

> **From history.** X-ray diffraction itself was a father-and-son discovery. In 1912 Max von Laue showed that crystals scatter X-rays into patterns of spots, and in 1913 William Henry Bragg and his son William Lawrence Bragg worked out how to use those patterns to find where the atoms sit. They shared the Nobel Prize in Physics in 1915, when Lawrence was only 25, still the youngest person ever to win the physics prize. Forty years later, Sir Lawrence Bragg was the head of the Cavendish Laboratory in Cambridge, where Watson and Crick built their model, and he wrote the foreword to Watson's book about the discovery.

WORKED EXAMPLES

Example 1. A sample of double-stranded DNA is 22% guanine (G). What percentages are cytosine (C), adenine (A) and thymine (T)?

1. By Chargaff's rule, G = C, so C = 22%.
2. G and C together: 22% + 22% = 44%.
3. The rest is A and T: 100% − 44% = 56%.
4. A = T, so each is half: 56% ÷ 2 = 28%.

Answer: C = 22%, A = 28%, T = 28%.

Example 2. One full turn of the DNA helix is 3.4 nm tall, and each base pair adds 0.34 nm. How many base pairs are in one turn? If you build a model with rungs 1 cm apart, how wide should you make it to keep the true proportions (real width 2 nm)?

(Use the map or drawing "Use the measurements on the diagram." shown earlier in this lesson.)

1. Base pairs per turn: 3.4 nm ÷ 0.34 nm = 10 base pairs.
2. In the model, 0.34 nm becomes 1 cm. The width is 2 nm ÷ 0.34 nm = 5.9 rung-spacings wide.
3. So the model width is 5.9 × 1 cm ≈ 5.9 cm, about 6 cm.
4. Check the scale: 1 cm = 10,000,000 nm, and 10,000,000 nm ÷ 0.34 nm ≈ 29,000,000. The model is about 29 million times life size.

Answer: 10 base pairs per turn; make the model about 6 cm wide, with one full twist every 10 rungs (10 cm).

Example 3. A human body cell holds about 6.4 billion base pairs of DNA. Each base pair adds 0.34 nm of length. About how long would all the DNA in one cell be if it were stretched out end to end?

1. Length = number of base pairs × length of each: 6,400,000,000 × 0.34 nm.
2. 6.4 × 0.34 = 2.176, so the length is 2.176 billion nm.
3. There are 1,000,000,000 nm in 1 meter, so 2.176 billion nm = 2.176 m.
4. Round sensibly: about 2.2 m.

Answer: About 2 meters of DNA in a single cell, taller than most adults, folded into a nucleus only a few thousandths of a millimeter across.

PRACTICE

1. EASY Name the four bases of DNA and state which base pairs with which.

2. EASY Who made Photo 51, where, and in what year? What did its X shape tell scientists?
3. EASY What are the rails of the DNA ladder made of, and what are the rungs made of?
4. MEDIUM A DNA sample is 31% thymine (T). Find the percentages of A, G and C.
5. MEDIUM Write the complementary strand for this DNA strand: A T G C C T A G
6. MEDIUM A short stretch of DNA is 17 nm long. How many base pairs does it contain, and how many full turns of the helix does it make? (0.34 nm per base pair; 10 base pairs per turn)
7. MEDIUM Data reading. The table gives approximate base percentages (rounded) of the kind Chargaff reported.
   Human: A 31, T 29, G 20, C 20
   Wheat: A 27, T 27, G 23, C 23
   Yeast: A 31, T 33, G 19, C 17
   E. coli bacterium: A 25, T 24, G 26, C 26
   (a) Which pairs of bases have nearly equal percentages in every organism? (b) Which organism has the highest combined G + C? (c) Do all four organisms have the same base percentages?
8. HARD Data reading. A lab measures two unknown samples.
   Sample X: A 20%, T 20%, G 30%, C 30%
   Sample Y: A 25%, T 40%, G 15%, C 20%
   One sample comes from a virus whose DNA has only a single strand. Which one, and how do you know?
9. HARD Experiment design. Using a laser pointer and pen springs, design an experiment to test whether a spring with wider coils (a larger diameter) gives a different X pattern than a narrow spring. Name the independent variable, the dependent variable, three things you keep the same, and how you will make your result reliable.
10. CHALLENGE In a short paragraph, explain how Franklin's Photo 51 and Chargaff's rule each gave Watson and Crick a different piece of the answer, and why the A–T, G–C pairing "suggests a possible copying mechanism."

COMMON MISTAKES

- Thinking Watson and Crick discovered DNA. DNA was first isolated by Friedrich Miescher in 1869. In 1953 Watson and Crick, using Franklin's data, discovered its *structure*.
- Thinking any base can pair with any other. A pairs only with T, and G pairs only with C. An A–G pair would be too wide, and a C–T pair too narrow, to fit the even ladder.
- Thinking Photo 51 is an ordinary photograph of a DNA molecule. It is a diffraction pattern, made by X-rays scattering off the regularly spaced atoms in a fiber. The shape had to be worked out from the pattern.

> **Make it a game · Base Pair Snap.** Make a deck of 40 cards: 10 each of A, T, G and C. Deal them out between two players. Players take turns flipping a card onto a pile. When the top two cards form a correct base pair (A–T, T–A, G–C or C–G), the first player to slap the pile and call "base pair!" wins the pile. A wrong slap gives the pile to the other player.

Bonus round: the winner of each pile must state one fact about Franklin, Watson, Crick or Chargaff to keep it.

Scripture. “I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well.” (Psalm 139:14, KJV)

Every discovery about how we are made gives us one more reason to agree with David. The more closely scientists looked at DNA, the more marvellous it turned out to be.

Practice answers

1. Adenine (A), thymine (T), guanine (G) and cytosine (C). A pairs with T; G pairs with C.
2. Rosalind Franklin with her student Raymond Gosling, at King’s College London, in 1952. The X pattern showed that DNA has the shape of a helix.
3. The rails are chains of sugar (deoxyribose) and phosphate. The rungs are pairs of bases (A–T or G–C) joined by hydrogen bonds.
4. A = 31% (A = T). A + T = 62%, leaving 38% for G and C, so G = 19% and C = 19%.
5. T A C G G A T C
6. 17 ÷ 0.34 = 50 base pairs. 50 ÷ 10 = 5 full turns.
7. (a) A and T are nearly equal, and G and C are nearly equal, in every organism. (b) E. coli: 26 + 26 = 52%. (c) No. The A–T and G–C equalities hold, but the overall mix differs from one kind of organism to another.
8. Sample Y. In double-stranded DNA every A is paired with a T and every G with a C, so A = T and G = C. Sample X follows that rule; sample Y does not (A 25% vs T 40%, G 15% vs C 20%), which means its bases are not all paired, as in single-stranded DNA.
9. Independent variable: the diameter of the spring (wide vs narrow). Dependent variable: the pattern on the wall, measured as the spot spacing in mm (and the angle of the X). Keep the same: the laser, the distance from spring to wall, the spacing between coils (or stretch), the room darkness and the position of the spring in the beam. Reliability: measure each spring three times and average, and repeat with a second pair of springs if possible.
10. Photo 51 showed that DNA is a helix and, with Franklin’s measurements, gave its width and the distance of each turn. Chargaff’s rule (A = T, G = C) suggested that A always sits opposite T and G opposite C. Watson and Crick combined them into two strands wound around each other with paired bases inside. Because each base has only one partner, each strand fixes the order of the other. If the strands separate, each one can serve as a pattern for building a new partner, giving two identical copies.

2.2 Extract Strawberry DNA

OBJECTIVES

- Tell how Friedrich Miescher first isolated DNA in 1869 and how later experiments showed that DNA carries hereditary information.
- Extract DNA from strawberries and explain what the mashing, the soap, the salt and the cold alcohol each do.
- Plan a fair experiment with one changed variable, record measurements in millimeters, and calculate averages from repeated trials.

Warm-up. Put a drop of cooking oil in a small glass of water and stir. Now add one drop of dish soap and stir again. What happens to the oil? Write one sentence. The outer skin of every cell, the cell membrane, is made of fatty, oily molecules. Predict what soap will do to a strawberry cell.

Video. Coming soon. Search for strawberry DNA extraction demonstrations and the story of Friedrich Miescher's discovery of nuclein on channels such as the Cold Spring Harbor Laboratory DNA Learning Center (DNALC), the University of Utah Genetic Science Learning Center, HHMI BioInteractive, Science Buddies and Smithsonian; preview first.

KEY TERMS

cell membrane
The thin, oily outer layer that surrounds every cell and controls what goes in and out. Plant cells also have a stiff cell wall outside it.

nucleus
The control center of a plant or animal cell, wrapped in its own membrane, where most of the DNA is kept.

chromosome
A long DNA molecule wound around proteins. Each kind of living thing has a set number; people have 46 in most body cells.

polyploid
Having more than two full sets of chromosomes. Garden strawberries have eight sets.

precipitate
To come out of a liquid as a solid that can be seen. DNA precipitates in cold alcohol because it does not dissolve there.

extraction
Separating one substance, such as DNA, from everything else in a mixture.

CORE IDEAS

The story. In 1869 a young Swiss doctor named Friedrich Miescher was working in a laboratory set up in the old kitchen of the castle at Tübingen, in Germany. He wanted to learn what the nucleus of a cell is made of, so he needed a good supply of cells. He found it in an unpleasant place: the pus on used bandages from a nearby hospital, which is full of white blood cells. Miescher washed the cells off the bandages, broke them open and treated them with salt solutions and a digestive enzyme from a pig's stomach. He was left with a substance from the nuclei that was not protein and was unusually rich in phosphorus. He called it *nuclein*. Today we call it DNA. Later, in Basel, he extracted it from salmon sperm, which is almost all nucleus.

How they figured it out. For seventy years most scientists thought nuclein was too simple to carry hereditary information. Proteins, with their twenty building blocks, seemed a better candidate. Then in 1944 Oswald Avery, Colin MacLeod and Maclyn McCarty at the Rockefeller Institute in New York showed that a harmless strain of bacteria could be changed into a disease-causing strain by DNA alone, taken from dead bacteria of the dangerous strain. When they destroyed the DNA with an enzyme, the change did not happen; when they destroyed the protein, it still did. In 1952 Alfred Hershey and Martha Chase confirmed that when a virus infects a bacterium, it is the virus's DNA, not its protein coat, that goes inside and directs the making of new viruses. Miescher's nuclein was the material of heredity after all.

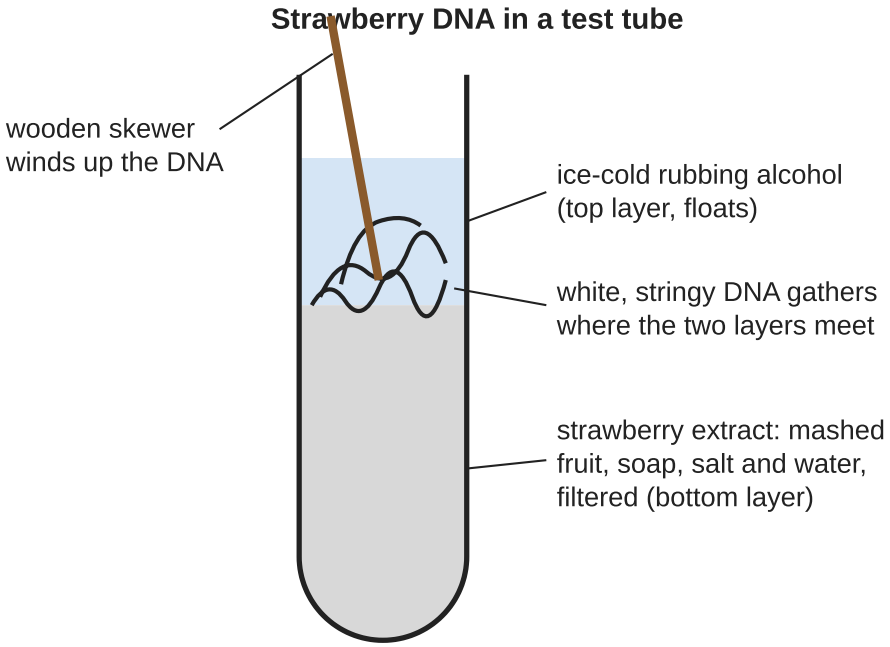
The big idea. Getting DNA out of a cell takes four steps, and each one has a reason. First, **mashing** breaks the tough plant cell walls and spreads the cells out. Second, **dish soap** breaks open the cell membrane and the nuclear membrane, which are made of fatty molecules, the same way soap breaks up grease on a plate. Third, **salt** helps the long DNA strands clump together. Each DNA strand carries negative charges along its backbone that make the strands push each other apart, and the salt's positive ions shield those charges. Fourth, **ice-cold alcohol** is gently poured on top. DNA dissolves in water but not in alcohol, so where the two layers meet, the DNA **precipitates** as white, cloudy strings you can wind onto a wooden stick (see the diagram). A single DNA molecule is only 2 nm wide, far too thin to see, but millions of strands tangled together make a thread you can hold.

Try it and see. Strawberries are a favorite fruit for this experiment for three reasons. Ripe strawberries are soft and easy to mash. They contain enzymes that help break down their cell walls. And garden strawberries are **polyploid**: each cell has eight sets of chromosomes, 56 in all, while their small wild cousins have only two sets, 14 in all. More copies of each chromosome means more DNA from every cell. A banana has three sets, 33 chromosomes, and gives less. People have two sets, 46 chromosomes.

In the world today. Every DNA test begins with an extraction like yours, only more careful. Doctors extract DNA to test for inherited diseases. Farmers and plant breeders extract it to check which seedlings carry a useful trait, such as disease resistance, without waiting for them to grow. Police laboratories extract it from a drop of blood or a single hair. The steps

are the same ones Miescher began: break the cells, remove the membranes and proteins, and collect the DNA.

God's handiwork. On the third day of creation God made the fruit tree "yielding fruit after his kind, whose seed is in itself" (Genesis 1:11). A strawberry wears its seeds on the outside, about two hundred of them, and in every cell of the fruit is the DNA that makes the next strawberry a strawberry, after its kind.



DNA precipitates where the cold alcohol meets the strawberry extract.

PICTURE STUDY



The Basket of Wild Strawberries, Jean-Siméon Chardin, about 1761 · Oil on canvas · Musée du Louvre, Paris

Jean-Siméon Chardin was a French painter who spent his life painting quiet kitchen things: copper pots, loaves, fruit, cups of water. He painted them so patiently that ordinary objects seem to glow. In this picture he heaped hundreds of tiny wild strawberries into a tall cone in a basket. He showed it at the Paris Salon of 1761, and it has been loved ever since.

Chardin painted wild strawberries, which have two sets of chromosomes. In his own century, in France, a new and much larger strawberry appeared when two American kinds of strawberry were grown side by side and crossed. In 1766 a young French botanist named Antoine Nicolas Duchesne explained where it had come from. That cross is the ancestor of the big garden strawberry with eight sets of chromosomes that you will use in your experiment.

Look closely

- Look at the shape of the pile of strawberries. How did Chardin make it look heavy and solid?
- Find the glass of water. How did he show that it is clear?
- Look closely at the strawberries. Can you see their seeds? How many different reds can you find?
- Find the white flowers. Why might he have placed something white beside so much red?

Talk about it

1. How is a painter who studies one basket of fruit for weeks like a scientist who studies one fruit fiber with X-rays?

2. Wild strawberries and garden strawberries are clearly the same kind of plant, yet very different in size. What does that tell you about variation within a kind?
3. Why do you think people still enjoy pictures of simple things like a basket of fruit?

> **Safety first.** Rubbing alcohol (isopropyl alcohol) is poisonous to drink and catches fire easily. Keep it away from flames, stoves and sparks, use it in a room with fresh air, wear safety glasses, and have an adult pour it. Do not eat the strawberries or anything in the experiment. Wash hands when finished.

EXPERIMENT: DOES SALT HELP? A STRAWBERRY DNA EXPERIMENT

You will pull real DNA out of strawberries, and you will run a fair test while you do it. Your question: **Does adding salt to the extraction mix give more DNA?**

Prediction: write whether you think the salt bag or the no-salt bag will give a thicker layer of DNA, and why. What you change: salt or no salt. What you keep the same: the number and size of strawberries, the amount of soap and water, mashing time, filtering, the amount of alcohol and the waiting time. What you measure: the thickness of the white DNA layer in millimeters after 5 minutes, and a stringiness score from 0 (none) to 3 (long strings that wind onto the stick).

You will need

- 4 ripe strawberries of similar size (fresh or thawed frozen), green tops removed
- 2 zip-top sandwich bags, labeled “salt” and “no salt”
- Dish soap, water, table salt and a measuring cup and spoons
- Rubbing alcohol (70% or stronger), chilled in the freezer for at least an hour
- 2 coffee filters or squares of cheesecloth, and 2 clear cups
- 2 tall, narrow clear glasses or test tubes, labeled
- 2 wooden skewers or coffee stirrers
- Metric ruler, timer, safety glasses, lab notebook

Steps

1. Make two extraction mixes in separate cups. Mix A: 90 mL water, 10 mL dish soap and 3 g salt (about half a teaspoon). Mix B: 90 mL water and 10 mL dish soap, no salt. Stir gently so it does not foam.
2. Put 2 strawberries in each bag. Add 20 mL of Mix A to the “salt” bag and 20 mL of Mix B to the “no salt” bag. Squeeze out the air and seal.
3. Mash each bag with your fingers for exactly 2 minutes. Use a timer. Mash both bags the same way.
4. Set a coffee filter in each clear cup and pour in the matching mash. Let it drip for about 5 minutes. Gently squeeze the filter if needed.
5. Pour the filtered liquid from each cup into its labeled glass or test tube until it is about 3 cm deep. Measure carefully so both are the same.

6. An adult tilts each glass and slowly pours ice-cold alcohol down the inside wall until there is an equal layer, about 3 cm, floating on top. Do not stir.
7. Wait 5 minutes without moving the glasses. Watch the boundary between the layers.
8. Measure the thickness of the white, cloudy layer in millimeters with your ruler held against the glass. Give each glass a stringiness score from 0 to 3.
9. Dip a skewer into the white layer and slowly twirl it. Lift out the DNA and look at it closely.
10. If you have time and strawberries, repeat the whole test twice more and average your results. Write a conclusion that answers your question and says whether your prediction was right.

Tips

- The alcohol must be very cold and poured very slowly. If it mixes into the extract, the DNA will not gather in a clear layer.
- The white strings are millions of DNA molecules tangled together, along with some protein and other cell material. Real labs add more steps to make it pure.
- You can save your DNA in a small capped vial of rubbing alcohol for your portfolio.

Check your work

- I extracted visible DNA from strawberries.
- I can explain what the mashing, soap, salt and cold alcohol each did.
- I changed only one variable, measured in millimeters and wrote a conclusion from my data.

NATURE NOTEBOOK

1. Draw and label your test tube as it looked after 5 minutes: alcohol layer, DNA layer, strawberry extract. Add the measured thickness in mm.
2. Make a four-box comic strip of the extraction steps from a strawberry cell’s point of view: mashed, membranes broken by soap, DNA clumped by salt, DNA rising out in cold alcohol.
3. Draw a strawberry from life with a hand lens. Count the seeds on one side, then estimate the total.

> **From history.** On September 10, 1984, at the University of Leicester in England, the scientist Alec Jeffreys looked at an X-ray film of DNA from members of his technician’s family and saw that each person’s pattern of bands was different, yet related to the parents’ patterns. He had discovered DNA fingerprinting. Within a few years it was used to settle family immigration cases and, in a famous English criminal case, to prove that a young man who had confessed to a crime was innocent before it helped find the real offender. Every one of those tests began by extracting DNA.

WORKED EXAMPLES

Example 1. A single DNA molecule is about 2 nm wide. The white thread of DNA on your skewer is about 1 mm thick. If the strands lay side by side, about how many would fit across the thread?

1. Convert to the same unit: 1 mm = 1,000 µm = 1,000,000 nm.
2. Divide by the width of one strand: 1,000,000 nm ÷ 2 nm = 500,000.
3. So at least half a million strands lie side by side across the thread, and there are many more along its length and depth.

Answer: About 500,000 strands across. That is why you can see a clump of DNA but never a single molecule.

Example 2. The basic strawberry chromosome set has 7 chromosomes, and the basic banana set has 11. A wild strawberry has 2 sets, a garden strawberry has 8 sets and a common grocery banana has 3 sets. Find the chromosome number in a body cell of each, and the ratio of garden strawberry sets to wild strawberry sets.

1. Wild strawberry: 2 × 7 = 14 chromosomes.
2. Garden strawberry: 8 × 7 = 56 chromosomes.
3. Banana: 3 × 11 = 33 chromosomes.
4. Ratio of sets, garden to wild: 8 : 2 = 4 : 1.

Answer: Wild strawberry 14, garden strawberry 56, banana 33. The garden strawberry has 4 times as many copies of each chromosome as its wild cousin, which is one reason it gives so much DNA.

Example 3. A class tested how much salt to put in 100 mL of extraction mix. Each group ran three trials and measured the DNA layer in mm (sample class data).
0 g: 1, 2, 1
1 g: 3, 4, 3
2 g: 5, 6, 5
3 g: 5, 5, 6
Find the average for each amount and describe the pattern.

1. 0 g: (1 + 2 + 1) ÷ 3 = 4 ÷ 3 ≈ 1.3 mm.
2. 1 g: (3 + 4 + 3) ÷ 3 = 10 ÷ 3 ≈ 3.3 mm.
3. 2 g: (5 + 6 + 5) ÷ 3 = 16 ÷ 3 ≈ 5.3 mm.
4. 3 g: (5 + 5 + 6) ÷ 3 = 16 ÷ 3 ≈ 5.3 mm.
5. Pattern: the layer grows from 0 g to 2 g, then stays the same from 2 g to 3 g.

Answer: Averages 1.3, 3.3, 5.3 and 5.3 mm. Salt helps up to about 2 g; adding more after that gives no extra DNA in these trials.

PRACTICE

1. EASY Who first isolated DNA, in what year, and what did he call it?
2. EASY What does the dish soap do in a DNA extraction?
3. EASY Why does DNA appear only where the alcohol meets the strawberry extract?
4. MEDIUM Avery's team found that destroying the DNA in their extract stopped the change in the bacteria, but destroying the protein did not. What did this show?
5. MEDIUM Bread wheat has 6 sets of 7 chromosomes. How many chromosomes are in a wheat body cell? Is wheat polyploid?
6. MEDIUM A student's DNA layer measured 4 mm, 6 mm, 5 mm and 5 mm in four trials. Find the average and the range.
7. MEDIUM Data reading. A class extracted DNA from the same mass (20 g) of four foods, using the same method, and measured the DNA layer (sample class data).
   Garden strawberry (8 sets): 6 mm
   Banana (3 sets): 3 mm
   Kiwifruit: 5 mm
   Onion (2 sets): 2 mm
   (a) Which food gave the most DNA? (b) Among the three foods whose number of sets is given, what pattern do you see? (c) Can this data alone prove that more chromosome sets cause more DNA? Explain.
8. HARD Data reading. A student tested alcohol temperature, with three trials each (DNA layer in mm):
   Ice-cold (about 0 °C): 6, 5, 6
   Refrigerator (about 4 °C): 5, 5, 4
   Room temperature (about 22 °C): 2, 3, 2

(a) Find each average. (b) Which temperature worked best? (c) By how many millimeters did the best average beat the worst?

9. HARD Experiment design. Design a fair test to answer: “Does mashing time change how much DNA we get?” Give your independent variable (with at least three values), dependent variable, four things you keep the same, and how many trials you will run.
10. CHALLENGE Your friend says, “The white stuff on the stick is one giant DNA molecule from the strawberry.” Write a short paragraph explaining what it really is, using the width of DNA and what you know about the extraction.

COMMON MISTAKES

- Thinking the white strings are a single DNA molecule. They are millions of tangled strands from thousands of cells.
- Thinking only animals, or only the seeds of a plant, contain DNA. Every living cell of the strawberry fruit, leaf and root contains DNA, and so do the cells of bacteria, mushrooms and people.
- Thinking that eating DNA from food changes your own DNA. Your digestive system breaks food DNA into small pieces like any other food; it does not become part of your genes.

Make it a game · Extraction Relay. Write each extraction step on a card: mash the fruit, add soap, add salt, filter, add cold alcohol, spool the DNA. Write each reason on a separate card: breaks the cell walls, breaks the fatty membranes, clumps the DNA strands, removes the pulp, makes the DNA precipitate, collects the DNA. Shuffle all twelve cards. Players race to lay the steps in order and match each to its reason. Time each player; the fastest correct match wins. Lose 5 seconds for each mistake.

Scripture. “And God said, Let the earth bring forth grass, the herb yielding seed, and the fruit tree yielding fruit after his kind, whose seed is in itself, upon the earth: and it was so.” (Genesis 1:11, KJV)

“Whose seed is in itself”: every fruit carries within it the means of making more of its own kind. Today we know that each seed, and each cell, carries the DNA instructions that keep strawberries reproducing after their kind.

Practice answers

1. Friedrich Miescher, in 1869. He called it nuclein.
2. It breaks apart the fatty cell membrane and nuclear membrane so the DNA can come out of the cells.
3. DNA dissolves in the watery extract but not in alcohol. Where the two meet, the DNA comes out of solution (precipitates) and clumps as white strings.
4. That DNA, not protein, carried the hereditary information that changed the bacteria.
5. $6 \times 7 = 42$ chromosomes. Yes, it has more than two sets, so it is polyploid.
6. Average: $(4 + 6 + 5 + 5) \div 4 = 20 \div 4 = 5$ mm. Range: $6 - 4 = 2$ mm.

7. (a) Garden strawberry, 6 mm. (b) More chromosome sets went with a thicker DNA layer: 8 sets 6 mm, 3 sets 3 mm, 2 sets 2 mm. (c) No. The foods also differ in water content, softness, cell size and enzymes, so other variables could explain the difference. It shows a pattern, not proof of cause.
8. (a) Ice-cold: $17 \div 3 \approx 5.7$ mm. Refrigerator: $14 \div 3 \approx 4.7$ mm. Room temperature: $7 \div 3 \approx 2.3$ mm. (b) Ice-cold alcohol. (c) $17 \div 3 - 7 \div 3 = 10 \div 3 \approx 3.3$ mm.
9. Independent variable: mashing time, such as 30 seconds, 1 minute, 2 minutes and 4 minutes. Dependent variable: thickness of the DNA layer in mm after 5 minutes. Keep the same: number and size of strawberries, amount of extraction mix (soap, salt, water), filtering method, volume and temperature of the alcohol, waiting time. Run at least three trials of each time and average them.
10. A single DNA molecule is only about 2 nm wide, far too thin to see even with a classroom microscope. The white stuff is a tangle of millions of DNA strands from many thousands of broken strawberry cells, clumped together by the salt and pulled out of solution by the cold alcohol. It also contains some proteins and other cell material, so it is a crude sample. We see it only because so many strands are bundled together.

2.3 The Code as Information

OBJECTIVES

- Tell how Marshall Nirenberg and Heinrich Matthaei cracked the first word of the genetic code in 1961, and explain how a fair experiment with controls revealed it.
- Explain how DNA's four-letter alphabet is read three letters at a time, and use a codon table to transcribe DNA into mRNA and translate mRNA into a chain of amino acids.
- Compare the genetic code with written language and Morse code, calculate how much information a genome holds, and predict the effect of substitution and frameshift mutations.

Warm-up. Write the sentence THE FAT CAT ATE THE RED RAT on a strip of paper, in capital letters with no spaces. Now read it aloud in groups of three letters from the start. Then cross out the first letter and read it again in groups of three. What happened to the meaning? Keep the strip: you have just made a model of a genetic mutation.

Video. Coming soon. Search for how the genetic code was cracked (Nirenberg and Matthaei, 1961), transcription and translation animations, and codons and mutations, on channels such as HHMI BioInteractive, the Cold Spring Harbor Laboratory DNA Learning Center (DNALC), the National Human Genome Research Institute, Amoeba Sisters and Crash Course Biology; preview first.

KEY TERMS

gene
A stretch of DNA that carries the instructions for making one protein (or a working RNA). Mendel's hereditary "factors" are genes.

genetic code
The set of rules by which the order of bases in DNA and RNA is translated into the order of amino acids in a protein.

codon
A group of three bases in mRNA that stands for one amino acid or for "stop." There are 64 codons.

mRNA (messenger RNA)
A single-stranded working copy of a gene that carries the message from the DNA in the nucleus to a ribosome. RNA uses uracil (U) in place of thymine (T).

transcription
Copying a gene's DNA into mRNA by base pairing. It happens in the nucleus.

translation
Reading the mRNA codons at a ribosome and joining the matching amino acids into a protein chain.

CORE IDEAS

The story. In May 1961, at the National Institutes of Health in Bethesda, Maryland, a young American biochemist named Marshall Nirenberg and a German visitor named Heinrich Matthaei set up a row of test tubes. Each held the juices of broken bacteria, which still contained the machinery for building proteins, plus all twenty amino acids. In each tube a different one of the twenty was made slightly radioactive so it could be traced. Into every tube they added an artificial RNA that had only one letter repeated over and over: U, U, U, U. Only one tube made a radioactive protein chain: the tube with radioactive **phenylalanine**. The message UUU meant phenylalanine. The first word of the genetic code had been read.

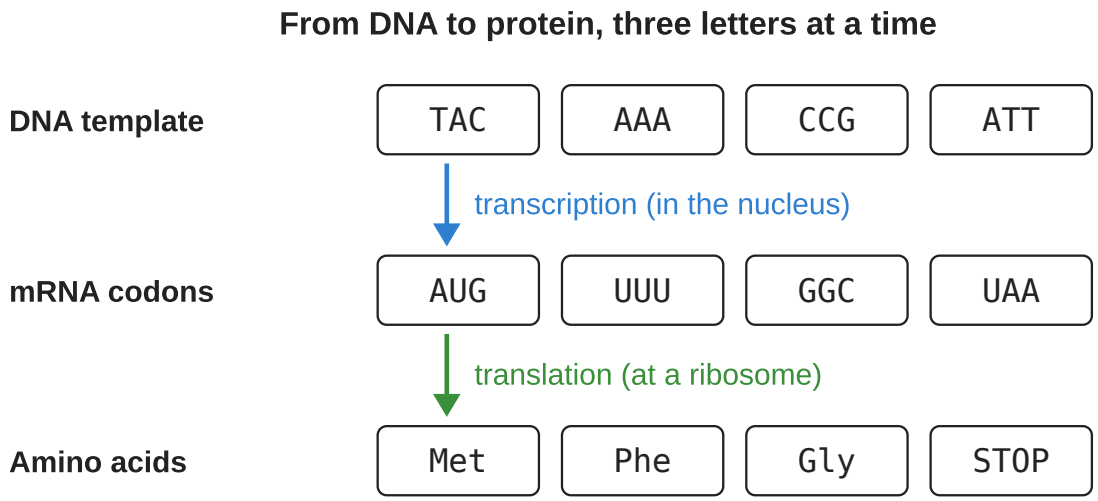
How they figured it out. The experiment worked because it was a fair test. Every tube was the same except for which amino acid carried the radioactive tag, and control tubes with no added RNA made almost no protein. That same year Francis Crick and Sydney Brenner showed, by adding and removing letters in the genes of a virus, that the code is read three letters at a time from a fixed starting point. Over the next five years, Nirenberg, Har Gobind Khorana and others made RNAs with different patterns and tested each one. By 1966 every one of the 64 three-letter words was known. Nirenberg, Khorana and Robert Holley shared the Nobel Prize in 1968.

The big idea. A **gene** is written in DNA's four-letter alphabet. To use it, the cell first makes a working copy called **mRNA**, pairing letters just as in DNA except that RNA uses U where DNA uses T. This is **transcription**. The mRNA travels out of the nucleus to a ribosome, which reads it three letters at a time. Each group of three is a **codon**. Four letters in groups of three give $4 \times 4 \times 4 = 64$ codons: 61 stand for amino acids and 3 mean "stop." AUG means "start here" and also stands for methionine. Several codons can mean the same amino acid; GGU, GGC, GGA and GGG all mean glycine. Turning codons into a chain of amino acids is **translation** (see the diagram). The same code is used, with only a few small exceptions, by bacteria, plants, animals and people.

The code as information. DNA is a chemical, but its message is not in its chemistry. The sugar-phosphate backbone will hold the four bases in any order, just as paper will hold ink letters in any order. What matters is the *sequence*, the way the meaning of a sentence is in the order of its letters, not in the ink. That is why one wrong letter can matter. A **substitution** changes one codon and may change one amino acid, or none, if the new codon means the same thing. An **insertion** or **deletion** of one letter shifts the reading frame, and every codon after it is garbled, like your warm-up sentence.

In the world today. The Human Genome Project, finished in 2003, read about 3.1 billion letters of human DNA, and in 2022 scientists filled in nearly all of the remaining gaps. Only about 1 to 2 percent of those letters spell out the roughly 20,000 genes for proteins; much of the rest helps control when and where genes are used. A machine can now read a whole human genome in a day, and doctors use those readings to find the single misspelled letter behind some inherited diseases.

God's handiwork. Long before anyone had heard of codons, David wrote to God, "in thy book all my members were written" (Psalm 139:16). In everyday experience, codes and written messages come from minds. In Unit 4 you will weigh what that observation does and does not prove. For now, notice how fitting the comparison is: every cell carries a written library of instructions, read and copied with astonishing accuracy.



Pairing: DNA A to RNA U, T to A, C to G, G to C. RNA uses U (uracil) in place of T.
AUG = methionine (start). UUU = phenylalanine. GGC = glycine. UAA = stop.
The finished chain here is Met-Phe-Gly: three amino acids.

Transcription copies DNA into mRNA; translation reads the mRNA three letters at a time.

PICTURE STUDY



Gallery of the Louvre, Samuel F. B. Morse, 1831–1833 · Oil on canvas · Terra Foundation for American Art, Chicago

Before he invented a code, Samuel Morse was a painter. In Paris in 1831 and 1832 he worked day after day in the Louvre on this huge canvas, painting small copies of about forty famous European pictures as if they all hung together in one room. He hoped to carry the treasures of Europe home to Americans who could never see them. Morse painted himself in the middle of the room, bending to help a student who is drawing.

On the ship home in the autumn of 1832, Morse fell into conversation about electricity and began sketching an idea for sending messages along a wire. The rest of his life went to the telegraph and to the code of dots and dashes that bears his name. Morse code, like the genetic code, turns a message into a short alphabet of signals that must be read in the right order.

Look closely

- Count how many framed pictures you can see. How did Morse fit them all in?
- Find Morse himself near the center. What is he doing?
- Look for people copying paintings. What tools are they using?
- Find a painting within the painting that you recognize, or one that catches your eye. Why?

Talk about it

1. Morse copied about forty paintings into one. How is a copy of a painting like an mRNA copy of a gene? How is it different?
2. Why might a painter’s patience and eye for detail help an inventor?
3. Morse code uses two signals, a dot and a dash; DNA uses four letters. Which do you think can say more in fewer signals, and why?

EXPERIMENT: MUTATION LAB: WHICH MISTAKE MATTERS MORE?

You will play the part of a ribosome and translate a real-style gene, then make mistakes on purpose and measure their effects. Your question: **Which changes a protein more: a one-letter substitution or a one-letter insertion?**

Prediction: write which mutation you expect to change more amino acids, and why. What you change: the type of mutation and where in the gene it happens. What you keep the same: the original gene, the codon table and the reading rule (start at AUG, read in threes, stop at a stop codon). What you measure: the number of amino acids that differ from the original protein.

You will need

- Lab notebook, pencil and colored pencils
- A printed standard codon table (found in any biology textbook and on the Learn.Genetics website listed in the unit resources)
- Index cards or paper strips cut into 36 small squares, for letter tiles (optional)

Steps

1. Copy this mRNA gene into your notebook, leaving space between codons: AUG GCU UUU GGC AAA GAA CAU UGG CCU ACU GUG UAA
2. Translate it with the codon table. You should get: Met Ala Phe Gly Lys Glu His Trp Pro Thr Val, then stop. Count the amino acids: 11. This is your original protein.
3. Substitution test 1: change the third letter of codon 4 (GGC to GGA). Translate the new gene. Count how many amino acids differ from the original.
4. Substitution test 2: change the first letter of codon 5 (AAA to GAA). Translate and count the differences.
5. Insertion test 1: insert an extra A just after the start codon (AUG A GCU...). Rewrite the letters in groups of three from AUG and translate until you reach a stop codon or the end. Count the differences.
6. Insertion test 2: insert an extra A just before the stop codon (after GUG). Translate and count the differences.
7. Make a data table: mutation, position, number of amino acids changed, did the protein end early or late?
8. Draw a bar graph of the number of amino acids changed for each of your four tests.
9. Write a conclusion: Which type of mutation changed more? Did the position matter? Was your prediction right?

Tips

- After an insertion, keep reading in threes even if the words look strange. That is exactly what a ribosome does.
- Some substitutions change nothing because more than one codon can mean the same amino acid. That is a real result, not a mistake.
- Color the original amino acids green and the changed ones another color to make counting easy.

Check your work

- I translated an mRNA gene into amino acids with a codon table.
- I measured the effect of four mutations and graphed my results.
- I can explain why an insertion near the start of a gene usually does more harm than a substitution.

NATURE NOTEBOOK

1. Draw a cell with a nucleus and a ribosome. Show with arrows how a gene’s message travels: DNA, transcription, mRNA leaving the nucleus, translation at the ribosome, protein.
2. Write your first name in Morse code and in amino acid one-letter abbreviations if you can (for example, A = alanine, G = glycine). Which letters of the alphabet have no amino acid?

3. Copy the warm-up sentence and its shifted version. Underline where the meaning breaks. Label it “frameshift.”

> **From history.** On May 24, 1844, Samuel Morse sat in the Supreme Court chamber of the U.S. Capitol in Washington and tapped out the first message on his new telegraph line to Baltimore, about 60 km away. The words had been chosen by young Annie Ellsworth, daughter of the Commissioner of Patents, from the Bible: “What hath God wrought” (Numbers 23:23). Morse’s partner Alfred Vail received it in Baltimore and sent it back. The paper tape with its dots and dashes is kept at the Library of Congress.

WORKED EXAMPLES

Example 1. DNA has 4 different bases. How many different “words” can be made if words are 1 letter long? 2 letters long? 3 letters long? Which is the shortest word length that can name all 20 amino acids?

1. 1-letter words: 4 choices = 4 words.
2. 2-letter words: 4 choices for the first letter × 4 for the second = 16 words.
3. 3-letter words: 4 × 4 × 4 = 64 words.
4. There are 20 amino acids. 4 and 16 are too few; 64 is enough, with extra words left over for “stop” and for more than one word meaning the same amino acid.

Answer: 4, 16 and 64. Three letters is the shortest word length that works, and the code is in fact read in triplets.

Example 2. A DNA template strand reads TAC AAA CCG ATT. Write the mRNA, then translate it. (AUG = methionine, start; UUU = phenylalanine; GGC = glycine; UAA = stop.)

(Use the map or drawing “Each DNA letter pairs with its RNA partner; each codon names one amino acid.” shown earlier in this lesson.)

1. Pair each DNA letter with its RNA partner: A to U, T to A, C to G, G to C.
2. TAC becomes AUG; AAA becomes UUU; CCG becomes GGC; ATT becomes UAA.
3. mRNA: AUG UUU GGC UAA.
4. Translate: AUG = Met (start), UUU = Phe, GGC = Gly, UAA = stop. The stop codon adds no amino acid.

Answer: mRNA AUG UUU GGC UAA; protein chain Met-Phe-Gly (3 amino acids).

Example 3. The human genome has about 3.1 billion letters. Each letter is one of 4 choices, which takes 2 bits (two yes-or-no answers) to store in a computer. 8 bits make 1 byte. (a) How many bytes does one copy of the genome need? (b) If a printed book holds about 600,000 letters, how many such books would it fill?

1. Bits: 3,100,000,000 letters × 2 bits = 6,200,000,000 bits.
2. Bytes: 6,200,000,000 ÷ 8 = 775,000,000 bytes, which is 775 megabytes.
3. Books: 3,100,000,000 ÷ 600,000 ≈ 5,167 books.

Answer: (a) About 775 megabytes. (b) More than 5,000 thick books, and a copy of that library (two copies, in fact, one from each parent) is in nearly every cell of your body.

PRACTICE

1. EASY What is a codon, and how many different codons are there?
2. EASY Name the two steps of making a protein from a gene and say where each happens.
3. EASY What base does RNA use in place of thymine (T)? Write the mRNA made from the DNA template GCA TTA.
4. MEDIUM A DNA template reads TAC CTT GGA ATT. Write the mRNA and translate it. (GAA = glutamic acid; CCU = proline; AUG = methionine; UAA = stop.)
5. MEDIUM A protein has 300 amino acids. What is the smallest number of mRNA bases needed to code for it, including the stop codon?
6. MEDIUM A gene’s mRNA is AUG GGU AAA UAA (Met-Gly-Lys-stop). The third codon changes from GGU to GGC by a substitution. Does the protein change? Explain. (GGU and GGC both code for glycine.)
7. MEDIUM Data reading. Results like those of Nirenberg’s experiments:
   Tube 1: poly-U RNA (UUUUUU…) made a chain of phenylalanine.
   Tube 2: poly-A RNA (AAAAAA…) made a chain of lysine.
   Tube 3: no RNA added made almost no protein chain.
   (a) Which codon stands for lysine? (b) Why was Tube 3 important? (c) If the code were read in pairs instead of triplets, would these results alone tell you? Explain.
8. HARD Data reading. Approximate genome sizes and protein-coding gene counts:
   E. coli bacterium: 4.6 million base pairs, about 4,300 genes
   Baker’s yeast: 12 million base pairs, about 6,000 genes
   Fruit fly: 140 million base pairs, about 14,000 genes
   Human: 3,100 million base pairs, about 20,000 genes
   (a) How many times larger is the human genome than the fruit fly genome? (b) How many times more genes do humans have than fruit flies? (c) What does this suggest about how much of the human genome codes for proteins?
9. HARD Experiment design. Using Nirenberg’s method, design an experiment to find which amino acid is coded by an artificial RNA made only of C’s (poly-C). Describe the tubes, what is the same in every tube, what changes, your control and what you will measure.

10. CHALLENGE Write a short paragraph explaining why an insertion of one base near the start of a gene usually harms the protein far more than a substitution of one base, and why the code's "extra" codons can protect against some mistakes.

COMMON MISTAKES

- Thinking one base codes for one amino acid. The code is read in codons of three bases; one base alone has only 4 possibilities, too few for 20 amino acids.
- Thinking the DNA itself leaves the nucleus to make proteins. The DNA stays safely in the nucleus; an mRNA copy carries the message out to the ribosomes.
- Thinking every kind of living thing uses a different code. The same codon table works, with only a few small exceptions, for bacteria, plants, animals and people. That is why a human gene placed in a bacterium can make a human protein.

> **Make it a game · Secret Message Codons.** Each amino acid has a one-letter abbreviation (A alanine, C cysteine, D aspartic acid, E glutamic acid, F phenylalanine, G glycine, H histidine, I isoleucine, K lysine, L leucine, M methionine, N asparagine, P proline, Q glutamine, R arginine, S serine, T threonine, V valine, W tryptophan, Y tyrosine). Each player secretly picks a short word using only those letters, such as HELP, SMART or GRACE, and writes it as an mRNA starting with AUG and ending with a stop codon, using the codon table. Players swap messages and race to translate. The first correct decoder scores a point; a player who hides a correct frameshift trap that the other spots scores a bonus.

> **Scripture.** "Thine eyes did see my substance, yet being unperfect; and in thy book all my members were written, which in continuance were fashioned, when as yet there was none of them." (Psalm 139:16, KJV)

David pictured his body being planned in God's book before it was formed. Scientists now read the written instructions in every cell, and the comparison of the genome to a book has become one of the most common ways to describe it.

Practice answers

1. A codon is a group of three mRNA bases that stands for one amino acid or for stop. There are 64 codons (61 for amino acids and 3 stop codons).
2. Transcription, copying DNA into mRNA, happens in the nucleus. Translation, reading the mRNA to join amino acids, happens at a ribosome.
3. Uracil (U). GCA TTA becomes CGU AAU.
4. mRNA: AUG GAA CCU UAA. Protein: Met-Glu-Pro, then stop.
5. 300 × 3 = 900 bases for the amino acids, plus 3 for the stop codon = 903 bases.
6. No. Both codons mean glycine, so the protein is still Met-Gly-Lys. This is why some substitutions are "silent."
7. (a) AAA. (b) It is the control. It shows that the protein chains in Tubes 1 and 2 were made because of the added RNA, not by something already in the juice. (c) No. A message of all U's reads the same whether you group it in twos or threes (UU UU or UUU UUU), so these

results alone cannot show the word length. Other experiments, like Crick and Brenner’s, showed that it is three.

8. (a) 3,100 ÷ 140 ≈ 22 times larger. (b) 20,000 ÷ 14,000 ≈ 1.4 times as many genes. (c) The genome grows much faster than the number of genes, so only a small part of the human genome (about 1 to 2 percent) spells out proteins; most of it does other work, such as controlling when genes are used.
9. Set up 20 tubes of bacterial juice with all 20 amino acids. In each tube, a different single amino acid is radioactive; that is the only thing that changes. Add the same amount of poly-C to every tube and keep temperature and time the same. Controls: a matching set of tubes with no RNA added. After the reaction, collect the protein chains and measure their radioactivity. The tube whose chains are strongly radioactive, compared with its control, identifies the amino acid. (The real answer turned out to be proline: CCC = proline.)
10. The ribosome reads in groups of three from the start codon. A substitution changes only one codon, so at most one amino acid changes, and sometimes none, because several codons mean the same amino acid (for example, any codon beginning GG means glycine). An insertion shifts every following group of three, so every codon after it is read wrong; the amino acids after that point are changed, and a stop codon often appears early, cutting the protein short. Near the start, that ruins almost the whole protein.

2.4 Proteins

OBJECTIVES

- Tell how Frederick Sanger showed, by working out the order of the 51 amino acids in insulin, that every protein has an exact sequence.
- Explain that a protein is a chain of amino acids folded into a shape, that its shape fits its job, and that heat or a one-letter change in a gene can change that shape.
- Measure how temperature affects the enzyme catalase, graph the results, and calculate amino acid and base counts for real proteins.

Warm-up. Chew one plain, unsalted cracker slowly for a full minute without swallowing. Notice whether the taste changes. Many people find it becomes slightly sweet. Write down what you noticed. Your saliva contains a protein called amylase that cuts long starch molecules into sugars. You have just watched a protein at work.

Video. Coming soon. Search for protein folding and structure, how enzymes work, the catalase and hydrogen peroxide experiment, and Frederick Sanger's sequencing of insulin, on channels such as HHMI BioInteractive, the RCSB Protein Data Bank (PDB-101), Amoeba Sisters, Crash Course Biology and Science Buddies; preview first.

KEY TERMS

protein
A large molecule made of one or more chains of amino acids folded into a particular shape. Proteins do most of the work in cells.

amino acid
One of the 20 kinds of small building blocks that are linked in a chain to make a protein.

peptide bond
The chemical link that joins one amino acid to the next in a protein chain.

enzyme
A protein that speeds up a chemical reaction without being used up. Amylase and catalase are enzymes.

denature
To unfold a protein from its working shape, for example by heat or strong acid, so that it no longer does its job.

ribosome
The small structure in the cell that reads mRNA codons and links amino acids into a protein chain.

CORE IDEAS

The story. In the mid-1940s a quiet young English biochemist named Frederick Sanger began work at Cambridge on insulin, the protein that tells the body's cells to take sugar out of the blood. At that time no one knew whether a protein had a definite order of building blocks or was a loose jumble that varied from one molecule to the next. Sanger spent about ten years finding out. By 1955 he had worked out the complete order of all 51 amino acids in cow insulin: two chains, one of 21 amino acids and one of 30, held together by sulfur bridges. Every insulin molecule from that kind of animal had exactly the same sequence. He received the Nobel Prize in Chemistry in 1958, and later a second one, in 1980, for a method of reading DNA.

How they figured it out. A protein is far too small to see, so Sanger worked like a detective with a jigsaw puzzle. He found a chemical that sticks to the amino acid at the free end of a chain and colors it yellow, so he could tell which amino acid came first. Then he broke the chains into short pieces with acid and with digestive enzymes, separated the pieces on paper, and worked out the order of the few amino acids in each piece. Because different methods broke the chain in different places, the pieces overlapped. By lining up the overlaps, like matching the edges of puzzle pieces, he rebuilt the whole sequence. His result proved what the genetic code would later explain: each protein is spelled out exactly by its gene.

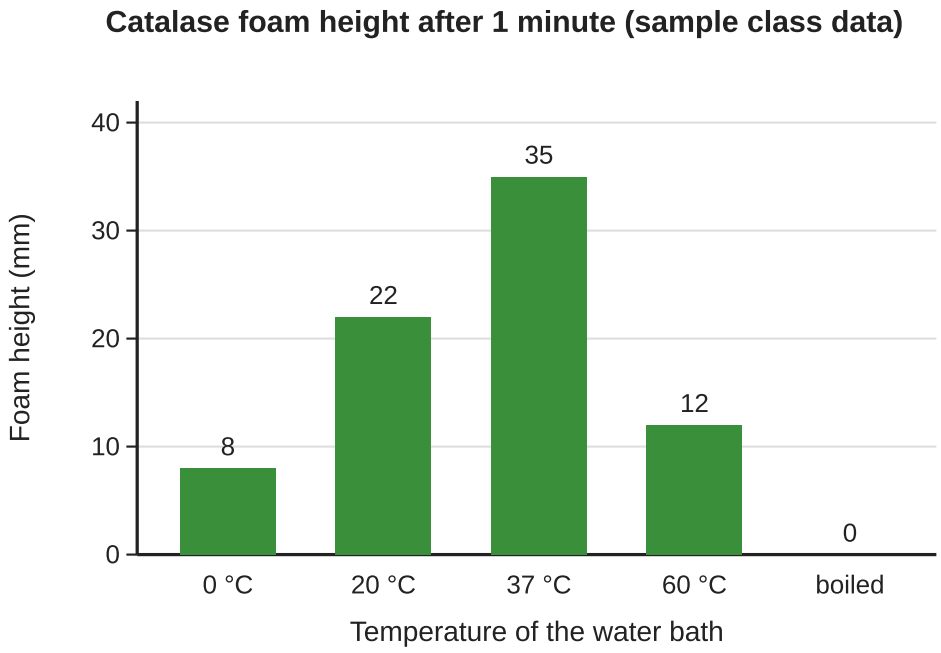
The big idea. A **protein** is a chain of **amino acids**, from a few dozen to thousands long, joined by **peptide bonds** at a **ribosome** in the order the mRNA codons dictate. There are 20 kinds of amino acids. Some attract water, some avoid it, some carry charges, and these differences make the chain fold itself into a particular shape, and the shape decides the job. **Enzymes** such as amylase and catalase speed up chemical reactions. Keratin builds hair, nails, feathers and claws. Collagen, the most plentiful protein in your body, gives strength to skin, tendons and bones. Actin and myosin slide past each other to move your muscles. Hemoglobin carries oxygen in red blood cells. Antibodies help defend the body from germs, and insulin carries a message.

Try it and see. Because a protein works by its shape, anything that changes the shape changes the work. When you fry an egg, heat **denatures** the clear egg-white proteins: their chains unfold and tangle, and the white turns solid and opaque. The chain of amino acids is still there, but the shape is lost and does not come back when the egg cools. Enzymes work best at a certain temperature; for most human enzymes it is close to body temperature, 37 °C. Warmer speeds them up to a point, and then too much heat ruins them. Your project measures this with catalase, an enzyme in potatoes and in your own liver that breaks down harmful hydrogen peroxide into water and oxygen. A change in the gene can change the shape too. In sickle-cell disease, one letter in the gene for part of hemoglobin is changed (GAG becomes GTG), so one amino acid out of 146 in that chain is different. That single change makes the hemoglobin clump when oxygen is low and bends red blood cells into stiff sickle shapes.

In the world today. For sixty years people with diabetes injected insulin taken from cows and pigs. Since 1982, human insulin has been made by bacteria (and later yeast) into which

the human insulin gene has been placed, and today most insulin is made this way. Because the genetic code is shared, the microbes read the human gene and build human insulin, exactly as Sanger's sequence describes it.

God's handiwork. Job said to God, "Thou hast clothed me with skin and flesh, and hast fenced me with bones and sinews" (Job 10:11). Skin, flesh, bones and sinews are all built and held together by proteins, folded into thousands of exact shapes, each fitted to its work.



Sample class data: catalase works best near body temperature and stops working after boiling.

PICTURE STUDY



Snowy Owl (Plate 121 of The Birds of America), John James Audubon; engraved by Robert Havell Jr., Published in *The Birds of America*, 1827–1838 · Hand-colored engraving and aquatint, made from Audubon's watercolor · Copies in many libraries and museums; Audubon's original watercolors for the book are at the New-York Historical Society

John James Audubon set out to paint every bird in America life size. He traveled the frontier with his gun, his paints and his notebooks, and in Britain he found engravers to turn his watercolors into enormous printed plates. *The Birds of America* has 435 of them. The two snowy owls on this plate are shown at night, perched as if they had just turned toward a sound.

Most of what you see of these owls is made of one kind of protein, keratin. Every feather, the hooked covering of the beak, the long curved talons and the thick feathers that cover the toes are keratin, built cell by cell from instructions in the owls' DNA. A gene's message, read three letters at a time, became the white feathers that keep a snowy owl warm in the Arctic winter.

Look closely

- Find the owls' feet. What covers them, and how might that help a bird that lives in snow?
- Look at the pattern of dark marks on the white feathers. Are the two owls marked the same way?
- Find the beak and the talons. What jobs do they do?
- How did Audubon make the white owls stand out?

Talk about it

1. Feathers, hair, fingernails and hooves are all keratin. Why might one protein be useful for so many different coverings?
2. Audubon studied real birds closely before painting them. Why does careful observation matter in both art and science?
3. Snowy owls vary in how many dark marks they have. What might cause that variation within one kind of bird?

> **Safety first.** Drugstore hydrogen peroxide (3%) can sting the eyes and skin and bleach clothing: wear safety glasses, do not taste or drink anything, and rinse any splash with plenty of water. An adult should cut the potato with a sharp knife and handle the hot and boiling water. Water at 60 °C can scald.

EXPERIMENT: CATALASE AND TEMPERATURE: A POTATO ENZYME EXPERIMENT

Potato cells contain catalase, an enzyme that splits hydrogen peroxide into water and oxygen gas. The oxygen makes foam, and the height of the foam tells you how hard the enzyme is working. Your question: **How does temperature affect how well catalase works?**

Prediction: write which temperature you expect to give the most foam, and what you think boiling will do. What you change: the temperature of the water bath. What you keep the same: the size of the potato pieces, the amount and strength of hydrogen peroxide, the size of the glasses, the time in the bath and the reaction time. What you measure: foam height in millimeters after 1 minute.

You will need

- 1 raw potato, cut by an adult into five 1 cm cubes (or five 5 g piles of grated potato)
- 3% hydrogen peroxide from a drugstore, about 60 mL
- 5 identical narrow clear glasses or test tubes, labeled
- 4 bowls for water baths: ice water (about 0 °C), room-temperature water (about 20 °C), warm water (about 37 °C) and hot tap water (about 60 °C)
- A small pot of boiling water (adult only)
- Kitchen thermometer, measuring syringe or spoon, metric ruler, timer, safety glasses, notebook

Steps

1. Make a data table: water bath, foam height after 1 minute (mm) for trial 1, trial 2 and trial 3, and average.
2. An adult boils one potato cube for 5 minutes, then lifts it out and lets it cool in the 37 °C bath. Label it “boiled.”
3. Pour 10 mL of hydrogen peroxide into each of four glasses. Stand one glass in each water bath. Put a raw potato cube in a small cup or bag floating in the same bath, so the potato and peroxide warm or cool together.
4. Pour 10 mL of hydrogen peroxide into the fifth glass and stand it in the 37 °C bath for the boiled cube.

5. Wait 5 minutes. Check each bath with the thermometer and record the real temperatures.
6. Starting with the ice bath, drop the potato cube into its glass of peroxide and start the timer. After exactly 1 minute, measure the height of the foam above the liquid in mm.
7. Repeat for each bath, one at a time, and then for the boiled cube.
8. If you have enough potato and peroxide, repeat the whole test two more times and average each temperature.
9. Draw a bar graph with temperature on the horizontal axis and foam height (mm) on the vertical axis. Write a conclusion: At what temperature did catalase work best? What did boiling do, and why?

Tips

- Measure from the surface of the liquid to the top of the foam, at eye level.
- Hot tap water cools quickly. Check the temperature just before you test.
- Compare your graph with the sample class graph in this lesson. Real data are rarely perfectly smooth, and that is fine.

Check your work

- I measured foam height in millimeters at five conditions and recorded it in a table.
- I graphed my results and found the temperature where catalase worked best.
- I can explain why boiling stops catalase from working, using the word denature.

NATURE NOTEBOOK

1. Draw a protein as a string of 12 colored beads (amino acids), then draw the same string folded into a compact shape. Label: amino acid, peptide bond, folded shape.
2. Make a two-column chart, Protein and Its Job, with at least six rows: amylase, catalase, keratin, collagen, hemoglobin, insulin.
3. Fry or boil an egg with a parent and sketch it before and after cooking. Label which part changed and write one sentence about denaturing.

> **From history.** In the summer of 1921, at the University of Toronto, the surgeon Frederick Banting and his student Charles Best extracted insulin from the pancreas of dogs, and the chemist James Collip helped purify it. In January 1922 a 14-year-old boy named Leonard Thompson, dying of diabetes in a Toronto hospital, became the first person treated with it, and he recovered his strength. Banting, Best and Collip sold the patent to the university for one dollar each, so that the medicine could be made widely and cheaply. Thirty-four years later Sanger showed exactly what insulin is made of.

WORKED EXAMPLES

Example 1. The two chains of finished insulin contain 21 + 30 = 51 amino acids. How many mRNA bases are needed to code for 51 amino acids? The cell actually builds a longer starting chain of 110 amino acids and then trims it. How many bases code for that longer chain, including one stop codon?

1. Each amino acid needs one codon of 3 bases: 51 × 3 = 153 bases.
2. Longer starting chain: 110 × 3 = 330 bases.
3. Add the stop codon: 330 + 3 = 333 bases.

Answer: 153 bases for the 51 amino acids of finished insulin; 333 bases for the 110-amino-acid starting chain plus its stop codon.

Example 2. One hemoglobin molecule is made of four chains: two alpha chains of 141 amino acids and two beta chains of 146. Each molecule carries up to 4 oxygen molecules. A red blood cell holds about 270 million hemoglobin molecules. (a) How many amino acids are in one hemoglobin molecule? (b) About how many oxygen molecules can one red blood cell carry?

1. Alpha chains: 2 × 141 = 282 amino acids.
2. Beta chains: 2 × 146 = 292 amino acids.
3. Total: 282 + 292 = 574 amino acids.
4. Oxygen: 270,000,000 × 4 = 1,080,000,000 molecules.

Answer: (a) 574 amino acids. (b) About 1.1 billion oxygen molecules in a single red blood cell.

Example 3. Use the bar graph of catalase foam heights. (a) At which temperature did catalase work best? (b) How many times more foam was made at 37 °C than at 0 °C? (c) The foam at 60 °C was lower than at 37 °C even though the reaction was warmer. Explain the 60 °C and boiled results.

(Use the map or drawing "Read each bar's height from the graph." shown earlier in this lesson.)

1. The tallest bar is 37 °C, at 35 mm.
2. Ratio: 35 mm ÷ 8 mm ≈ 4.4.
3. From 0 °C to 37 °C the foam rises because molecules move faster and meet the enzyme more often.
4. Above 37 °C the foam falls: heat begins to unfold (denature) the catalase, so fewer enzyme molecules keep their working shape.
5. The boiled potato made no foam because boiling denatured all of its catalase.

Answer: (a) 37 °C. (b) About 4.4 times as much. (c) At 60 °C much of the catalase was denatured, so it made less foam; boiling denatured all of it, so it made none.

PRACTICE

1. EASY What are proteins made of, and how many kinds of building blocks are used?
2. EASY Name four different jobs proteins do, with one example protein for each.
3. EASY What does it mean to denature a protein? Give one example from the kitchen.
4. MEDIUM The beta chain of hemoglobin has 146 amino acids. How many mRNA bases code for it, including the stop codon?
5. MEDIUM In sickle-cell disease, the sixth codon of the beta-globin mRNA changes from GAG (glutamic acid) to GUG (valine). What kind of mutation is this, how many amino acids change, and why can such a small change matter?
6. MEDIUM Suppose one catalase molecule breaks down 5 million hydrogen peroxide molecules every second. How many could it break down in 1 minute? What does this show about whether enzymes are used up?
7. MEDIUM Data reading. Use the catalase bar graph (0 °C 8 mm, 20 °C 22 mm, 37 °C 35 mm, 60 °C 12 mm, boiled 0 mm). (a) Between which two neighboring temperatures did the foam height change the most, and by how much? (b) A student says, "Higher temperature always makes enzymes work faster." Does the graph support this? Explain.
   (Use the map or drawing "Sample class data." shown earlier in this lesson.)
8. HARD Data reading. Students mixed starch with amylase at different temperatures and timed how long it took for the starch to disappear (the iodine test stopped turning blue-black). Sample class data:
   10 °C: 12 minutes
   25 °C: 6 minutes
   37 °C: 3 minutes

50 °C: 5 minutes
70 °C: starch still present after 20 minutes
(a) At which temperature was amylase fastest? (b) How many times faster was it at 37 °C than at 10 °C? (c) Explain the 70 °C result. (d) Why is a shorter time a sign of a faster enzyme?

9. HARD Experiment design. Fresh pineapple contains an enzyme, bromelain, that breaks down proteins. Gelatin dessert sets because of a protein made from collagen. Canned pineapple has been heated. Design an experiment to test whether fresh pineapple keeps gelatin from setting and whether canned pineapple does too. Give your groups, the control, what you keep the same, what you observe or measure, and your prediction.
10. CHALLENGE Write a paragraph tracing how a gene becomes a trait you can see, using one example (for instance, keratin in an owl's feathers or hemoglobin in red blood cells). Use the words DNA, mRNA, codon, ribosome, amino acid, protein and shape.

COMMON MISTAKES

- Thinking protein means only meat or muscle. Every living cell, plant and animal, is full of proteins, and most enzymes, hairs, feathers, hormones and antibodies are proteins too.
- Thinking enzymes are used up in the reaction. An enzyme comes out of each reaction unchanged and can be used over and over, millions of times.
- Thinking that heat always makes enzymes work faster, or that denaturing breaks a protein into separate amino acids. Above its best temperature an enzyme slows and then stops, because denaturing unfolds its shape; the chain of amino acids is still there, but the shape is lost.

Make it a game · Protein Folding Charades. Write the names of proteins on cards: amylase, catalase, keratin, collagen, hemoglobin, insulin, actin and myosin, antibody. One player draws a card and acts out the protein's job without words (for example, carrying an oxygen "ball" around the room for hemoglobin, or snipping with fingers for amylase). The others guess the protein and must name its job to score. Then the actor must say one place in the body or in nature where that protein is found to earn a bonus point.

Scripture. "Thou hast clothed me with skin and flesh, and hast fenced me with bones and sinews." (Job 10:11, KJV)

Job saw his own body as something God had clothed and fenced. The collagen in skin and sinews, the proteins of muscle and the keratin of hair are the threads of that clothing, each made exactly to its pattern.

Practice answers

1. Chains of amino acids joined by peptide bonds. There are 20 kinds of amino acids.

2. Any four, such as: speeding reactions (enzymes: amylase, catalase); structure (keratin in hair and feathers, collagen in skin and tendons); carrying oxygen (hemoglobin); movement (actin and myosin in muscle); defense (antibodies); messages (insulin).
3. To unfold it from its working shape so it can no longer do its job. Cooking an egg denatures the egg-white proteins, which turn from clear and runny to white and solid.
4. 146 × 3 = 438 bases, plus 3 for the stop codon = 441 bases.
5. A substitution of one base. Only one amino acid out of 146 changes. It matters because a protein works by its shape; the new amino acid makes hemoglobin molecules stick together when oxygen is low, which bends red blood cells into stiff sickle shapes that can block small blood vessels.
6. 5,000,000 × 60 = 300,000,000 (300 million) in one minute. The same enzyme molecule is used again and again; enzymes speed up reactions without being used up.
7. (a) Between 37 °C and 60 °C, a drop of 35 − 12 = 23 mm. (b) No. Foam rises from 0 °C to 37 °C, but falls at 60 °C and is zero after boiling. Warmth helps only up to an optimum; beyond it the enzyme is denatured.
8. (a) 37 °C (shortest time). (b) 12 ÷ 3 = 4 times faster. (c) At 70 °C the amylase was denatured by heat, so it could no longer break down starch. (d) The faster the enzyme works, the sooner all the starch is broken down, so less time passes before the iodine stops turning blue-black.
9. Make three identical cups of gelatin from the same mix, same volume and same temperature. Cup 1: add 20 g fresh pineapple. Cup 2: add 20 g canned pineapple (drained). Cup 3 (control): no pineapple, or 20 g of a fruit without the enzyme. Chill all for the same time in the same refrigerator. Observe whether each sets, and measure firmness, for example how far a coin sinks in mm, or tip each cup and record whether it flows. Repeat each cup at least twice. Prediction: the fresh pineapple gelatin stays runny because bromelain breaks the gelatin protein; the canned pineapple gelatin sets, because heating during canning denatured the bromelain.
10. Sample: An owl’s DNA contains genes for keratin. In a feather cell, a keratin gene is transcribed into mRNA, which carries the message to the ribosomes. The ribosome reads the mRNA one codon at a time and links the matching amino acids into a chain. The chain folds into the shape of a keratin protein, and many keratin molecules bundle together into the tough, light material of a feather. So the order of bases in DNA sets the order of amino acids, which sets the protein’s shape, which produces the trait we see. A change in the gene can change the protein and the trait.

Unit 2 review

Answer each question. For multiple-choice items, write the letter and give a one-sentence reason. Show your work for calculations and use complete sentences for explanations. A codon table may be used where codons are not given. The test is worth 60 points.

1. (5 pts) Multiple choice. Photo 51 (1952) was important because it: (A) showed the order of bases in a gene; (B) was an X-ray diffraction pattern whose X shape showed that DNA is a helix; (C) was the first photograph taken through a light microscope of a DNA molecule; (D) proved that DNA, not protein, carries hereditary information.
2. (5 pts) A sample of double-stranded DNA is 18% cytosine (C). Find the percentages of G, A and T. Show your work.
3. (5 pts) Write the complementary DNA strand for G G A T C C A T. Then explain in one or two sentences why base pairing lets DNA be copied.
4. (6 pts) Diagram. Draw an untwisted section of DNA with four base pairs, using the bases A, G, T and C on one side. Label (a) a sugar-phosphate backbone, (b) one base pair, (c) a hydrogen bond, and (d) one nucleotide. Below your drawing, state how far apart neighboring base pairs are and how many base pairs make one full turn of the real helix.
5. (5 pts) Multiple choice. In the strawberry DNA extraction, the dish soap: (A) makes the DNA visible by dyeing it white; (B) breaks open the fatty cell and nuclear membranes; (C) makes the alcohol float; (D) cuts the DNA into short pieces so it can pass through the filter.
6. (5 pts) Give two reasons garden strawberries are a good choice for DNA extraction, and explain why you can see the DNA on your skewer even though one DNA molecule is only about 2 nm wide.
7. (5 pts) Multiple choice. The genetic code uses codons of three bases because: (A) there are three kinds of RNA; (B) three-base codons give 64 combinations, enough for 20 amino acids plus stop signals, while two-base codons give only 16; (C) DNA has three strands; (D) every amino acid has exactly three codons.
8. (6 pts) A DNA template strand reads TAC GGC AAA ATC. (a) Write the mRNA. (b) Translate it. (AUG = methionine, start; CCG = proline; UUU = phenylalanine; UAG = stop.) (c) How many amino acids are in the finished chain?
9. (5 pts) Explain the difference between a substitution mutation and an insertion mutation, and say which one usually changes more of the protein and why.
10. (6 pts) Data reading. A class measured catalase foam after 1 minute: 0 °C 8 mm, 20 °C 22 mm, 37 °C 35 mm, 60 °C 12 mm, boiled potato 0 mm. (a) At which temperature did catalase work best? (b) How many millimeters more foam formed at 37 °C than at 20 °C? (c) Explain why the boiled potato made no foam, using the words shape and denature.
11. (7 pts) Experiment design. Design a fair experiment to answer: “Does the amount of potato change how much foam catalase makes?” Name the independent variable (with

at least three values), the dependent variable, four things you will keep the same, a control, and how you will make your results reliable. Then predict the result.

UNIT PROJECT: MY DNA LAB BOOK

Make a lab book that follows the path from DNA to protein. Include: (1) a hand-built scale model of the double helix, about 6 cm wide with ten rungs per full turn and correct A–T and G–C pairs, with its scale written on a card; (2) your strawberry DNA experiment, with the question, prediction, data table, averages and conclusion, and a small capped vial of your extracted DNA if you saved it; (3) your mutation lab, with the original and mutated translations and a bar graph; and (4) your catalase experiment, with a data table, a bar graph and an explanation using the word denature.

Finish with a one-page illustrated summary titled “From Gene to Trait” that traces one real protein (such as keratin, hemoglobin or insulin) from DNA to mRNA to protein to a trait you can see, and give fair credit to at least four scientists from the unit.

- **Scientific accuracy**: The model, labels, base pairs, codons and explanations are correct, and the scale of the model is calculated correctly.
- **Experiments and data**: Each experiment states a question, prediction and variables; data are recorded in metric units in tables, averaged and graphed with labeled axes.
- **Explanation**: The summary clearly connects gene, mRNA, codon, amino acid, protein shape and trait, and credits the scientists fairly.
- **Care and presentation**: The lab book is neat, dated and organized, with clear drawings and careful handwriting.

Answer key

1. (B). The X pattern of scattered X-rays, made by Rosalind Franklin and Raymond Gosling, showed a helix and gave its measurements. It was not an ordinary photograph, did not show base order, and (D) was shown by Avery and by Hershey and Chase.
2. G = C = 18%. G + C = 36%, so A + T = 100% − 36% = 64%. A = T = 32% each.
3. C C T A G G T A. Because each base has only one partner, each strand determines the other. When the strands separate, each serves as a pattern for building a new matching strand, making two identical copies.
4. A ladder with two rails and four rungs, for example A–T, G–C, T–A, C–G, with correct partners on the opposite rail. Labels: (a) either rail, (b) one rung, (c) the joint in the middle of a rung, (d) one sugar plus phosphate plus base. Base pairs are 0.34 nm apart; one full turn has 10 base pairs (3.4 nm). Scoring: 1 point for correct pairs, 1 point for each label, 1 point for the measurements.
5. (B). Membranes are made of fatty molecules, and soap breaks them apart the way it breaks up grease, releasing the DNA.
6. Reasons (any two): they are polyploid, with eight sets of chromosomes (56), so each cell has a lot of DNA; ripe strawberries are soft and easy to mash; they contain enzymes that help break down cell walls. We can see the DNA because millions of strands from thousands of cells clump together into a visible tangle.
7. (B). 4 × 4 × 4 = 64, while 4 × 4 = 16 is too few for 20 amino acids.

8. (a) AUG CCG UUU UAG. (b) Met-Pro-Phe, then stop. (c) 3 amino acids.
9. A substitution swaps one base for another and changes at most one codon, so at most one amino acid (sometimes none). An insertion adds a base, which shifts the reading frame so every codon after it is read wrong. The insertion usually changes far more of the protein, and often creates an early stop codon.
10. (a) 37 °C. (b) 35 − 22 = 13 mm. (c) Catalase is a protein that works because of its folded shape. Boiling denatured it, unfolding the shape, so it could no longer break down hydrogen peroxide and no oxygen foam formed.
11. Independent variable: mass of grated potato, such as 2 g, 4 g, 6 g and 8 g. Dependent variable: foam height in mm after 1 minute. Keep the same: volume (10 mL) and strength (3%) of hydrogen peroxide, temperature, size and shape of the glasses, reaction time, freshness of the potato. Control: a glass of hydrogen peroxide with no potato (should make almost no foam). Reliability: three trials of each amount, averaged. Prediction: more potato means more catalase and more foam, at least until the peroxide runs short. Scoring: 1 point each for the independent variable, dependent variable, controlled variables, control, reliability, prediction, and clear writing.

UNIT 3

Variation Within Kinds

"And God made the beast of the earth after his kind" (Genesis 1:25). Living things reproduce after their kind, yet within each kind there is astonishing variety. In this unit you will put the genetics of Units 1 and 2 to work on real populations and ask one question again and again: **what changed, and what didn't?**

You will sail with Charles Darwin to the Galápagos Islands in 1835 and measure finch beaks with Peter and Rosemary Grant through drought and flood. You will attend the first dog show in 1859 and use Punnett squares to predict Labrador puppies. You will stand at Alexander Fleming's bench in 1928 and watch bacteria become resistant to penicillin. Finally you will meet Frank Lewis Marsh, who coined the word **baramin** for a created kind, and use real hybrid records to test where the edges of a kind may lie.

Every scientist, whatever his view of origins, agrees on the observations in this unit: beaks shift, breeds multiply, bacteria become resistant. You will learn to state those facts accurately, calculate with them, and then explain fairly how mainstream biologists and creation biologists each interpret them.

BEFORE YOU BEGIN

- Can complete a one-trait Punnett square and use the words dominant, recessive, genotype and phenotype (Unit 1)
- Knows that genes are made of DNA and that a mutation is a change in the DNA sequence (Unit 2)
- Can calculate a percent and a ratio and read a bar graph
- Can name the variables in a simple experiment (independent, dependent, kept the same)

MASTERY CHECKLIST

- I can explain natural selection using the Grants' measurements of finch beaks, and say what changed and what didn't.
- I can explain how breeders made dog breeds by artificial selection and use Punnett squares to predict coat colors and inherited diseases.
- I can explain how a population of bacteria becomes resistant to an antibiotic and calculate growth by doubling.
- I can read graphs and data tables about variation and spot an axis that does not start at zero.
- I can define baramin, use hybrid and chromosome data to group species, and name a limit of the hybrid test.
- I can state fairly how mainstream and creation biologists each read the evidence for variation.

OPTIONAL BOOKS AND RESOURCES

- **Darwin Online (The Complete Work of Charles Darwin Online)** (http://darwin-online.org.uk/): Free. Scans of Darwin's books, notebooks and the 1845 *Journal of Researches*, including the page with the four finch heads (Lesson 3.1). A parent may choose passages, since the site holds all of Darwin's writing.
- ***The Voyage of the Beagle*** **by Charles Darwin (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/944): Free. Read aloud Darwin's chapter on the Galápagos Archipelago, where he describes the finches, tortoises and iguanas he found in 1835.

3.1 Darwin's Finches: What Changed and What Didn't

★

OBJECTIVES

- Describe what Charles Darwin collected in the Galápagos Islands in 1835, what John Gould found in 1837, and what Peter and Rosemary Grant measured on Daphne Major.
- Use population counts and beak measurements to calculate percent change and explain how natural selection shifts the average trait of a population.
- Separate what changed in the finches (average beak size and shape) from what stayed the same (they remained finches that can interbreed), and state fairly how creation and mainstream biologists each read the evidence.

Warm-up. Make a "beak kit": tweezers, a clothespin and a pair of pliers. Pour a small pile of mixed food on a plate: uncooked rice, sunflower seeds in the shell and dried beans. Give yourself 30 seconds per tool to move as many pieces of one food as you can into a cup. Which "beak" is best for tiny seeds? Which is best for big, hard ones? Is any tool best at everything?

Video. Coming soon. Galápagos finches, beak variation and Peter and Rosemary Grant's drought study on Daphne Major; search HHMI BioInteractive, Smithsonian, PBS nature programs and Galápagos wildlife footage of ground finches cracking seeds.

KEY TERMS

variation
Differences in a trait among members of the same population, such as some finches having deeper beaks than others.

population
All the members of one species living in one place at one time, such as the medium ground finches on Daphne Major.

natural selection
The process in which individuals whose inherited traits suit their surroundings survive and reproduce more, so those traits become more common in the next generation.

adaptation
An inherited trait that helps a living thing survive and reproduce where it lives, such as a deep, strong beak for cracking hard seeds.

microevolution
Small changes in the traits of a population over generations, such as a shift in average beak size. These changes are observed and accepted by scientists of every view.

hybrid
The offspring of parents from two different species or varieties.

CORE IDEAS

The story. In September 1835 the British survey ship HMS *Beagle* anchored among the Galápagos Islands, about 1,000 kilometers west of Ecuador in the Pacific Ocean. Its naturalist was 26-year-old Charles Darwin. For five weeks he collected rocks, plants, tortoises, iguanas and birds. Among the birds were many small, dull brown and black birds that he took to be a mix of wrens, blackbirds, grosbeaks and finches. He did not carefully label which island each one came from. Back in London in January 1837, the bird expert John Gould examined the skins and announced a surprise: nearly all of them were finches, a closely related group of new species that differed mainly in the size and shape of their beaks. In the 1845 edition of his travel book, Darwin wrote: “Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends.”

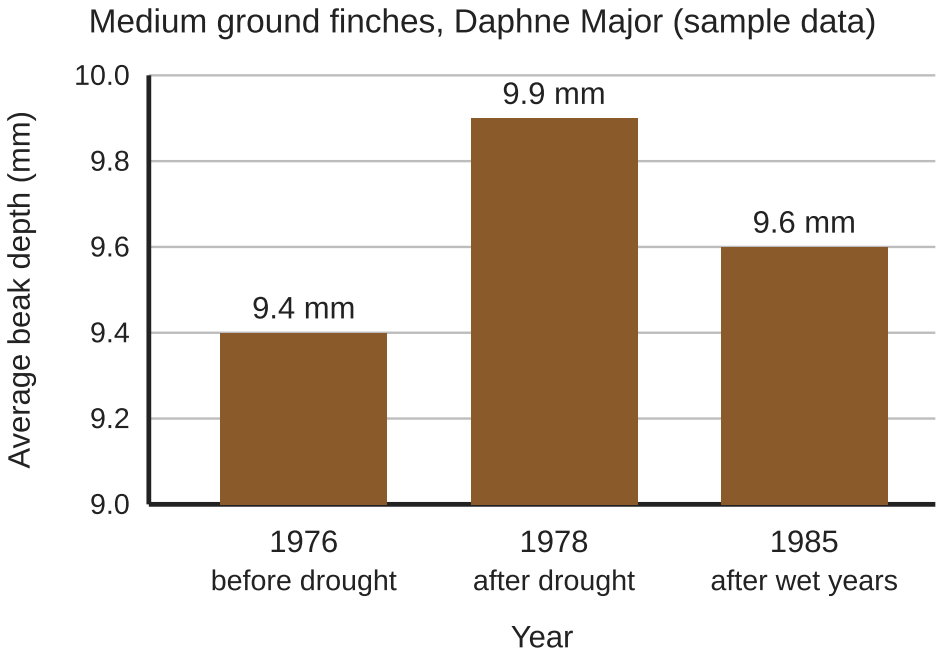
How they figured it out. More than a century later, two biologists, Peter and Rosemary Grant, began in 1973 to study the finches of Daphne Major, a small volcanic island in the Galápagos. Year after year they caught, banded, weighed and measured nearly every finch on the island and counted the seeds the birds ate. In 1977 almost no rain fell. Small, soft seeds ran out, and what remained were large, hard seeds such as those of the caltrop plant. Medium ground finches with deeper beaks could crack them; many with shallower beaks starved. The population fell from roughly 1,200 birds to about 180. When the survivors bred, their young had beaks that were, on average, about 4 to 5 percent deeper. Then came very wet years in 1982 and 1983. Small seeds became plentiful, and over the following years the average beak size drifted back toward smaller. The change swung back and forth with the weather.

The big idea. This is **natural selection**, and it needs three things: **variation** (finches differ), inheritance (beak size is passed from parents to young through genes) and different survival (the surroundings decide which birds live to breed). No single bird grew a bigger beak. Instead, the *average* of the population shifted because some birds survived and others did not. Scientists have since found genes that help set beak shape, including *BMP4*, which is more active in birds with deep, broad beaks, and *ALX1*, which affects beak shape. The Grants also saw medium ground finches mate with cactus finches and small ground finches, and some of the **hybrid** young survived and bred. Because the lines between species are blurry, experts count anywhere from about 13 to 18 species of Galápagos finches, depending on how they draw the lines.

What changed and what didn’t. What changed: average beak depth and width, average body size, and how common each type of bird was. What did not change: they stayed finches, with the same feathers, wings, skeleton plan and way of life, and many of the “species” can still interbreed. No new organ appeared. Scientists of every view agree on these measurements. They disagree about how far to extend them. Mainstream biologists see the finches as natural selection in action and argue that the same process, continued over many, many generations, can explain how all living things came from a common ancestor (you will study that claim fairly in Unit 6). Creation biologists see the finches as **variation within one**

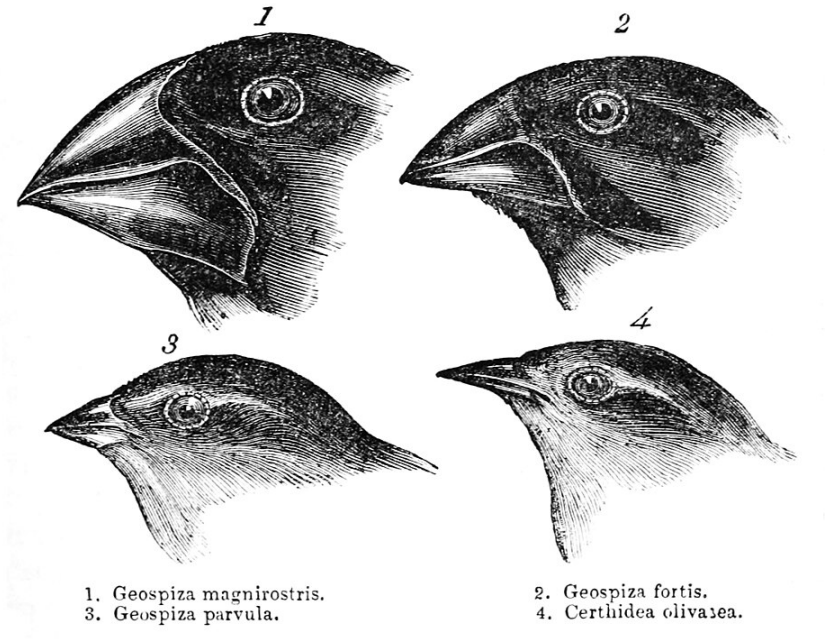
created kind: a finch kind made with rich genetic variety, able to spread to many islands and suit many foods, but still finches. Both read the same data. Notice that the change Darwin and the Grants saw happened inside a single “intimately related group,” in Darwin’s own words.

God’s handiwork. Jesus said, “Behold the fowls of the air,” and told His hearers that the heavenly Father feeds them (Matthew 6:26). On dry islands where food can vanish in a single season, a finch population carries enough built-in variety that some birds can still eat when the soft seeds are gone. That flexibility is a kind of wisdom written into living things. When you measure a beak, you are looking at the care of the One who feeds the birds.



Sample data shaped like the Grants’ results: average beak depth rose after the 1977 drought, then drifted back after the wet years.

PICTURE STUDY



Four Galápagos finch heads, from Darwin's Journal of Researches, After drawings by John Gould, published by Charles Darwin, 1845 · Printed book illustration · Charles Darwin, *Journal of Researches*, second edition (London: John Murray, 1845); copies in many libraries and online at Darwin Online

This small picture is one of the most famous illustrations in biology. Darwin added it to the 1845 edition of his travel book so readers could see what John Gould had noticed: the Galápagos finches look alike in body and feathers but differ in their beaks. The four heads are (1) the large ground finch, with a huge, deep beak for hard seeds; (2) the medium ground finch, the bird the Grants later measured on Daphne Major; (3) the small tree finch; and (4) the warbler finch, with a thin beak for picking insects.

Gould was one of the best bird artists and naturalists of his day, and he and his wife Elizabeth produced many beautiful plates of birds. Look at this picture the way a naturalist would: compare, measure with your eye, and ask what each beak is good for.

Look closely

- Compare beak 1 and beak 4. How many times deeper does the first one look?
- Look at the heads apart from the beaks: the eyes, the feathers, the shape of the skull. Are they more alike or more different?
- Which beak looks like a nutcracker? Which looks like tweezers?
- Find the medium ground finch (number 2). How is it "in between"?

Talk about it

1. What food would you guess each bird eats, based only on its beak?
2. What in this picture changed from bird to bird, and what stayed the same?
3. Why might Darwin have chosen to print a picture of heads rather than whole birds?

EXPERIMENT: THE BEAK AND SEED EXPERIMENT

You will test whether the shape of a “beak” decides which seeds a bird can gather, then stage a drought to see which beaks “survive.” This is a model, not real birds, but it lets you see how the surroundings sort variation.

You will need

- Four “beaks”: tweezers, a clothespin, a pair of pliers and a teaspoon
- Three “seeds”: a handful each of uncooked rice, sunflower seeds in the shell and dried beans (or unshelled peanuts if no one has a nut allergy)
- Paper plates, four small cups, a timer and a lab notebook

Steps

1. Write your question: Does beak shape affect how many seeds of each size a bird can gather in 30 seconds?
2. Write a prediction for each beak and each seed.
3. Variables: what you change is the beak and the seed type. What you keep the same is the time (30 seconds), the number of seeds on the plate (30 of each), the same person and the same cup distance. What you measure is the number of seeds moved into the cup.
4. Rule a table with beaks down the side and seeds across the top. Run each beak on each seed type three times and record every count. Find the average of the three trials.
5. Now stage a “drought”: remove all the rice (the small soft seeds). Any beak that cannot gather at least 10 seeds in 30 seconds “starves.” Which beaks survive?
6. Stage a “wet year”: put the rice back and take away the beans. Which beaks do best now?
7. Make a bar graph of your averages and write three sentences: What changed? What did the drought select for? Did any “beak” turn into a different kind of tool?

Tips

- Run three trials of each test, because one fast or slow try can fool you.
- No beak changes its shape during the game. Selection only decides which ones “survive,” just as no real finch grew a new beak during the drought.

Check your work

- I named what I changed, what I kept the same and what I measured.
- I recorded three trials and calculated averages.
- I can explain how the drought changed which beaks were common without changing any single beak.

NATURE NOTEBOOK

1. Draw the four finch heads from the picture study side by side, at the same head size. Measure each beak's depth on your drawing in millimeters and label it.
2. Make a T-chart titled "Darwin's Finches": What changed (left) and What didn't (right). Put at least four items in each column.
3. Draw a timeline from 1835 to 1983 with five dated events from this lesson: Darwin's visit, Gould's report, Darwin's 1845 edition, the start of the Grants' study and the 1977 drought.

From history. Darwin was so busy on the islands that he lumped most of his finches together without noting which island each came from. When he later realized the islands might matter, he had to borrow specimens collected by Captain Robert FitzRoy and Darwin's servant Syms Covington, who had labeled theirs more carefully. The name "Darwin's finches" was made popular more than a century later by the British bird scientist David Lack in his 1947 book *Darwin's Finches*.

WORKED EXAMPLES

Example 1. During the 1977 drought on Daphne Major, the medium ground finch population fell from about 1,200 birds to about 180. What percent of the birds survived? What percent died?

1. Percent surviving = survivors ÷ starting number × 100 = 180 ÷ 1,200 × 100.
2. 180 ÷ 1,200 = 0.15, so 0.15 × 100 = 15%.
3. Birds that died = 1,200 − 180 = 1,020. Percent died = 1,020 ÷ 1,200 × 100 = 85%.
4. Check: 15% + 85% = 100%.

Answer: About 15% survived and about 85% died.

Example 2. Use the bar graph of average beak depth (sample data). By how many millimeters and by what percent did the average beak depth change from 1976 to 1978? Then find the change from 1978 to 1985.

(Use the map or drawing "Read each bar against the axis, which begins at 9.0 mm." shown earlier in this lesson.)

1. Read the bars: 1976 = 9.4 mm, 1978 = 9.9 mm, 1985 = 9.6 mm.
2. 1976 to 1978: 9.9 − 9.4 = 0.5 mm increase. Percent = 0.5 ÷ 9.4 × 100 ≈ 5.3%.
3. 1978 to 1985: 9.6 − 9.9 = −0.3 mm, a decrease. Percent = 0.3 ÷ 9.9 × 100 ≈ 3.0% smaller.
4. Notice the axis starts at 9.0 mm, not 0, so the bars exaggerate the differences. The real change is about half a millimeter, about the thickness of a fingernail.

Answer: Up 0.5 mm (about 5.3%) from 1976 to 1978, then down 0.3 mm (about 3.0%) from 1978 to 1985.

Example 3. A student says: "Beak depth grew 0.5 mm in one generation. If it keeps growing 0.5 mm every generation, in 20 generations the average beak will be 0.5 × 20 = 10 mm deeper." Starting from 9.9 mm, what would the student predict? What did the real data do instead, and what does that teach about extending a trend?

1. Predicted increase = 0.5 mm × 20 = 10 mm.
2. Predicted depth = 9.9 mm + 10 mm = 19.9 mm, about twice the starting size.
3. The real data did not keep climbing. After the wet years of 1982 and 1983, selection favored smaller beaks and the average drifted back down (to about 9.6 mm in the sample data).
4. Lesson: a measured change is an observation; stretching it far beyond the data is a prediction or a claim, and it must be tested. Changes in finch beaks have swung back and forth within a range.

Answer: The student would predict about 19.9 mm, but the real average reversed direction. A short-term trend cannot simply be multiplied out without evidence that it continues.

PRACTICE

1. EASY Who first recognized that Darwin's small Galápagos birds were a closely related group of finches, and in what year?
2. EASY Name the three things natural selection needs in order to work.
3. EASY During the 1977 drought on Daphne Major, which kind of seed was left, and which finches survived best?

4. MEDIUM On another island, a finch population drops from 400 birds to 60 during a drought. What percent survived?
5. MEDIUM Data reading. The table shows sample data for one island.
   Year A: rainfall 130 mm; small seeds 10 g per square meter; average beak depth of the next generation 9.4 mm.
   Year B: rainfall 25 mm; small seeds 3 g per square meter; next generation 9.9 mm.
   Year C: rainfall 1,350 mm; small seeds 14 g per square meter; next generation 9.6 mm.
   Which statement is best supported? (a) More rain causes deeper beaks. (b) When small seeds were scarce, the next generation had deeper beaks on average. (c) Beak depth controls the rainfall. (d) The data show no pattern.
6. MEDIUM Data reading. On the bar graph of beak depth, the axis starts at 9.0 mm. The 1976 bar rises 0.4 mm above the bottom of the graph and the 1978 bar rises 0.9 mm. How many times taller does the 1978 bar look? How many times larger is the real 1978 value? What does this teach about reading graphs?
7. MEDIUM Explain in two or three sentences why it is wrong to say “each finch grew a deeper beak so it could eat hard seeds.”
8. HARD The Grants saw medium ground finches and cactus finches mate and raise hybrid young that later bred successfully. What does this suggest about how separate these “species” really are, and how would a creation biologist read it?
9. HARD Experiment design. You want to test whether the “beak” tool used affects how many sunflower seeds can be gathered in 30 seconds. Name the independent variable, the dependent variable, three things to keep the same and how many trials you would run.
10. CHALLENGE Darwin wrote that one might fancy that “one species had been taken and modified for different ends.” Explain what he meant, then explain how a creation biologist could agree with part of the sentence and disagree with the larger claim others built on it.

COMMON MISTAKES

- Thinking individual finches changed their beaks during the drought. The birds did not change; the population’s average changed because some birds survived and bred and others did not.
- Thinking natural selection creates new traits on demand. Selection can only choose among variation that already exists; it does not plan or aim.
- Thinking that the beak data by themselves prove or disprove that all life shares one ancestor. The measurements are agreed by everyone; how far to extend them is the debated part.

> **Make it a game · Beak Match.** A parent names a food (tiny grass seeds, a hard nut, a beetle under bark, cactus flowers, a worm in mud). You have five seconds to name or act out the best beak shape (nutcracker, tweezers, probe, scoop) and say why. Score a point for each good match. For a bonus point, name one thing every finch shares no matter what its beak looks like.

> **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)

Finches do not plant gardens, yet in drought and in rain they find food. Their varied beaks are part of how God feeds them, and Jesus uses them to remind us that we are worth even more to Him.

Practice answers

1. John Gould, the London bird expert, in January 1837.
2. Variation in a trait, inheritance of that trait from parents to offspring, and differences in survival or reproduction caused by the surroundings.
3. Large, hard seeds (such as caltrop seeds) were left, and medium ground finches with deeper, stronger beaks survived best.
4. 60 ÷ 400 × 100 = 15% survived (85% died).
5. (b). Year B had the fewest small seeds and the deepest average beaks. (a) is backwards, (c) reverses cause and effect, and (d) ignores the clear pattern.
6. The 1978 bar looks 0.9 ÷ 0.4 = 2.25 times taller, but the real value is only 9.9 ÷ 9.4 ≈ 1.05 times larger (about 5% more). A graph whose axis does not start at zero makes small differences look large, so always read the axis numbers.
7. An adult finch’s beak does not grow deeper because it needs to. During the drought, finches that already had deeper beaks survived and bred more often, and they passed on genes for deeper beaks. The average of the population changed, not the beak of any single bird.
8. It suggests the species are not sharply separate; they can still exchange genes, so the lines between them are blurry (which is why experts count anywhere from about 13 to 18 species). A creation biologist would read this as evidence that the Galápagos finches belong to one created kind that has varied into several forms.
9. Independent variable: the tool (tweezers, clothespin, pliers, spoon). Dependent variable: the number of sunflower seeds moved into the cup in 30 seconds. Keep the same: the time, the number and type of seeds on the plate, the person, the distance to the cup and the plate. Run at least three trials per tool and average them.
10. Darwin meant that the many Galápagos finches might all have come from one original kind of finch that reached the islands and then varied to suit different foods. A creation biologist can agree that the finch species share a common finch ancestor and varied after arriving, which is variation within a kind. The disagreement is over extending the same process to say that finches, all birds and all living things share one ancestor; that larger claim goes far beyond what was observed in the finches.

3.2 Dog Breeds ★

OBJECTIVES

- Explain how breeders produced hundreds of dog breeds by artificial selection of existing variation and occasional mutations, and name two genes linked to body size and short legs.
- Use Punnett squares to predict coat colors in Labrador retrievers and calculate size and mass ratios between breeds.
- Weigh what dog breeds show (enormous variety within one kind) and what they do not show, and describe the health costs of breeding from a narrow gene pool.

Warm-up. With a parent, find pictures of six very different dogs in books or magazines, such as a Chihuahua, a Great Dane, a dachshund, a bulldog, a greyhound and a husky. Sort them into groups any way you like: by size, leg length, ears or coat. Then list three things that every one of them has in common. Are they all dogs? How do you know?

Video. Coming soon. How dog breeds were developed by selective breeding, dog genetics of size and coat color, and working dog footage; search Smithsonian, PBS nature programs, university veterinary schools and kennel club breed history channels.

KEY TERMS

breed
A group of domestic animals within one species that people have bred to share a set look and abilities, such as the beagle or the border collie.

artificial selection
Selective breeding: people choose which animals or plants become parents in order to make certain traits more common.

allele
One of the different forms of a gene, such as the B (black) and b (brown) forms of a coat-color gene.

mutation
A change in the DNA sequence of a gene. Some mutations have no effect, some are harmful and a few give a trait breeders want, such as short legs.

gene pool
All the alleles of all the genes in a population. A breed’s gene pool is smaller than that of dogs as a whole.

inbreeding
Breeding closely related animals. It makes it more likely that a puppy inherits two copies of the same harmful recessive allele.

CORE IDEAS

The story. On June 28 and 29, 1859, in the town hall of Newcastle upon Tyne in England, about sixty pointers and setters were shown and judged. It was the first organized dog show. Five months later, in November 1859, Charles Darwin published *On the Origin of Species*, and its first chapter, "Variation under Domestication," talks about the pigeons, dogs and farm animals that breeders had shaped. Over the next decades dog lovers founded the Kennel Club in Britain (1873) and the American Kennel Club (1884). They wrote breed standards describing exactly how each breed should look and kept "closed" studbooks, which meant only registered dogs of the same breed could be parents. Most of the roughly 200 breeds the American Kennel Club recognizes today were shaped or standardized in the 1800s and 1900s.

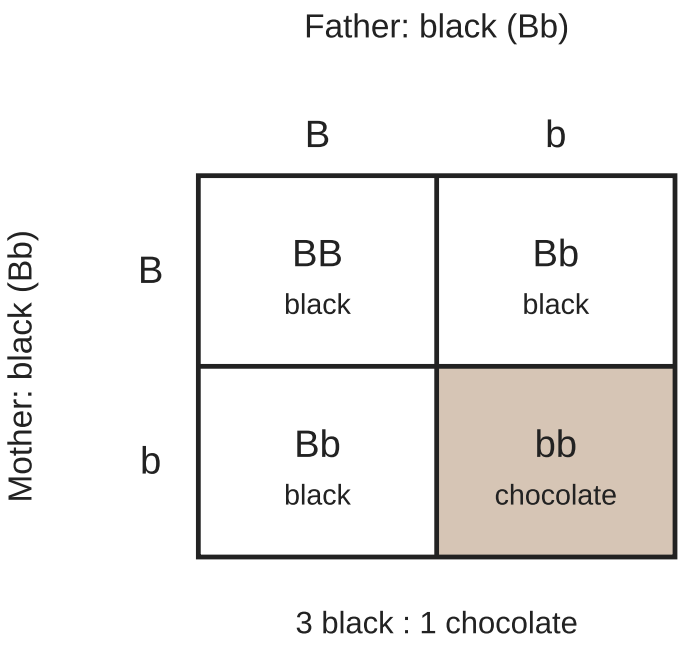
How they figured it out. Breeders used **artificial selection**: they chose the fastest, smallest, gentlest or best-herding dogs as parents, generation after generation. They did not need to understand DNA; they simply sorted variation that dogs already had. In this century geneticists found some of the genes behind the results. A 2007 study found that one form of the gene *IGF1*, which helps control growth, is common in small breeds and rare in giant breeds. A 2009 study found that the short legs of dachshunds, corgis and basset hounds come from an extra copy of a growth gene called *FGF4*, a **mutation** that changes how leg bones grow. These are changes in genes that adjust size and proportion. Breeders did not add a new organ; they turned the "dials" on parts every dog already has.

The big idea. A Chihuahua may weigh 2 kilograms and an English mastiff 80 kilograms or more, forty times as much, yet every breed belongs to one species, the domestic dog, *Canis familiaris*. Any two breeds can produce healthy puppies (size makes some pairings impractical, but not impossible with help). Dogs have 78 chromosomes, the same number as wolves, coyotes and golden jackals, and dogs can produce fertile puppies with all three. Scientists of every view agree that dogs came from wolf-like ancestors and that the breeds are all variations of one family. Creation biologists call this the **dog kind**: a created kind with enormous built-in variety, like the finches in Lesson 3.1 on a larger scale.

What breeding costs. Selection sorts genes, and sorting leaves some out. Each breed has a smaller **gene pool** than dogs as a whole, and when closely related dogs are bred together, puppies are more likely to receive two copies of the same harmful recessive allele, just as you learned with Punnett squares in Unit 1. That is why some breeds suffer from hip dysplasia, certain blindness disorders or, in very flat-faced breeds such as bulldogs and pugs, trouble breathing. Today responsible breeders use health tests and DNA screening to avoid pairing two carriers. Notice what breeding shows and what it does not: it shows that a kind holds astonishing variety, and that selection can change looks quickly; it does not show a dog becoming something other than a dog.

God's handiwork. God gave people dominion over the animals (Genesis 1:28) and brought the animals to Adam to name (Genesis 2:19). Breeding dogs to herd sheep, guard homes, guide the blind or find lost hikers is a fitting use of that dominion. But dominion is also care. "A righteous man regardeth the life of his beast" (Proverbs 12:10). A wise breeder aims not

only for a striking look but for a healthy dog that can breathe, run and live a long, useful life. The variety packed into the dog kind is a gift; using it well is our responsibility.



Two black Labradors that each carry the brown allele (Bb) can have chocolate puppies.

PICTURE STUDY



Dignity and Impudence, Sir Edwin Landseer, 1839 · Oil on canvas · Tate Britain, London

Edwin Landseer was the most famous animal painter of Victorian England; he later sculpted the bronze lions at the foot of Nelson’s Column in Trafalgar Square, London. In this painting a huge bloodhound (“Dignity”) and a small white terrier (“Impudence”) share the doorway of

one kennel. Landseer painted it in 1839, twenty years before the first dog show, when breeds were just beginning to be written down and standardized.

The two dogs could hardly look more different, yet they are the same species. Landseer studied animals closely and painted fur, eyes and muscle with great care, so his pictures are useful to a naturalist as well as pleasing to look at.

Look closely

- Compare the two heads. Estimate how many terrier heads would fit inside the bloodhound's head.
- Look at the bloodhound's long ears and loose skin. What job were bloodhounds bred for, and how might those features help?
- Find the terrier's eyes and ears. How does Landseer show its lively personality?
- Look at the kennel. What clues tell you these are cared-for dogs?

Talk about it

1. What traits differ between the two dogs? What traits do they share?
2. Why do you think Landseer titled the painting *Dignity and Impudence*?
3. If these two dogs had puppies, what might they look like? Why can they have puppies at all?

> **Safety first.** Measure only dogs whose owner is present and gives permission. Let the dog sniff your hand first, move slowly, and stop if the dog seems nervous, growls or stiffens. Never approach a stray or chained dog. Wash your hands afterward.

EXPERIMENT: DOG HEIGHT AND MASS SURVEY

Is a dog that is twice as tall also twice as heavy? You will collect real measurements and find out how mass changes with height across breeds.

You will need

- A metric measuring tape or meter stick
- A bathroom scale (kilograms)
- Five or more cooperative dogs of different sizes, with their owners (or published breed-standard heights and masses from a dog breed book if you cannot measure real dogs)
- Lab notebook and graph paper

Steps

1. Write your question and a prediction: If one dog is twice as tall as another, will it be twice as heavy, more than twice, or less?
2. Variables: what you change is the dog (breed and size). What you keep the same is the method: each dog stands on a level floor, and you measure height at the withers (the

top of the shoulders) to the nearest centimeter. What you measure is height in centimeters and mass in kilograms.
3. To weigh a dog, the owner steps on the scale alone, then again holding the dog. Dog's mass = (owner with dog) − (owner alone).
4. Record each dog's name, breed, height and mass in a table.
5. Make a graph with height on the x-axis and mass on the y-axis. Plot each dog as a point.
6. Pick your shortest and tallest dog. Calculate the height ratio (tall ÷ short) and the mass ratio (heavy ÷ light). Compare them with the cube of the height ratio.
7. Write a conclusion: Was your prediction right? Why does mass grow faster than height?

Tips

- Measure each dog twice and use the average.
- Mass depends on length, width and height together, so doubling every dimension multiplies mass by about $2 \times 2 \times 2 = 8$ if the shape stays the same.

Check your work

- I measured every dog the same way and recorded units.
- My graph has labeled axes with units.
- I compared the mass ratio with the height ratio and explained the difference.

NATURE NOTEBOOK

1. Sketch the skeleton outline of a dachshund and a greyhound side by side. Label the leg bones and note which parts are the same and which differ in proportion.
2. Make a "breed family tree" for a breed you like: write what job it was bred for, what traits breeders selected, and one health problem the breed is known for.
3. Draw a Punnett square for two black Labradors that carry chocolate (Bb × Bb) and color each box black or brown.

> **From history.** The Westminster Kennel Club Dog Show was first held in New York City in May 1877, seven years before the American Kennel Club was founded. It has been held every year since and is often called the second-oldest continuously held sporting event in the United States, after the Kentucky Derby.

WORKED EXAMPLES

Example 1. In Labrador retrievers (that do not carry the yellow gene), the allele B for black coat is dominant over b for chocolate. Two black Labs, each Bb, are bred. What fraction of their puppies are expected to be black and what fraction chocolate?

(Use the map or drawing "Bb × Bb gives a 3 : 1 ratio of black to chocolate puppies." shown earlier in this lesson.)

1. Each parent can pass on B or b. Write B and b across the top and B and b down the side.
2. Fill the boxes: BB, Bb, Bb, bb.
3. BB and Bb puppies are black (B is dominant): 3 of 4 boxes. The bb puppy is chocolate: 1 of 4 boxes.
4. Ratio 3 black : 1 chocolate, or 75% black and 25% chocolate.

Answer: 3/4 (75%) black and 1/4 (25%) chocolate.

Example 2. A Chihuahua stands 20 cm at the shoulder and has a mass of 2 kg. A Great Dane stands 80 cm and has a mass of 64 kg. Find the height ratio and the mass ratio. If the two dogs had exactly the same shape, what mass ratio would you expect?

1. Height ratio = 80 cm ÷ 20 cm = 4.
2. Mass ratio = 64 kg ÷ 2 kg = 32.
3. If the shape were identical, length, width and height would all be 4 times larger, so the volume and mass would be 4 × 4 × 4 = 64 times larger.
4. The real ratio (32) is smaller than 64 because the dogs are not the same shape: a Great Dane is built leaner and longer-legged than a Chihuahua.

Answer: Height ratio 4; mass ratio 32. Same-shape dogs would give a mass ratio of 64, but the Great Dane's leaner build makes the real ratio smaller.

Example 3. Two healthy-looking dogs each carry one copy of a recessive allele (d) for an inherited eye disease (genotype Dd). If they are bred, what are the chances a puppy will have the disease, be a carrier, or be clear? In a litter of 8, how many affected puppies would you expect on average?

1. Cross Dd × Dd. The boxes are DD, Dd, Dd, dd.
2. Affected (dd): 1 of 4 = 25%. Carriers (Dd): 2 of 4 = 50%. Clear (DD): 1 of 4 = 25%.
3. Expected affected in a litter of 8 = 8 × 1/4 = 2 puppies.
4. This is why breeders DNA-test their dogs: pairing a carrier with a clear dog (Dd × DD) produces no affected puppies at all.

Answer: 25% affected, 50% carriers, 25% clear; about 2 affected puppies expected in a litter of 8.

PRACTICE

1. EASY To what species do all dog breeds belong, and how many chromosomes does a dog have?
2. EASY How is artificial selection different from natural selection?
3. EASY Name the gene linked to small body size in dogs and the gene whose extra copy causes the short legs of dachshunds and corgis.
4. MEDIUM A black Lab that carries chocolate (Bb) is bred with a chocolate Lab (bb). What percent of the puppies are expected to be chocolate?
5. MEDIUM Data reading. Typical rounded values for five breeds:
   Chihuahua: 2 kg, lives about 15 years.
   Beagle: 10 kg, about 13 years.
   Labrador retriever: 30 kg, about 12 years.
   Irish wolfhound: 55 kg, about 7 years.
   Great Dane: 60 kg, about 8 years.
   (a) Describe the relationship between mass and lifespan. (b) Predict the lifespan of a 40 kg breed. (c) Does this table prove that size causes a shorter life?
6. MEDIUM Data reading. A breed was standardized over 150 years. If a dog generation (the average age of parents when puppies are born) is about 3 years, how many generations is that? Why can breeders change dogs so much faster than wild populations change?
7. HARD Experiment design. You want to test whether a dog’s shoulder height predicts its mass. Name your independent and dependent variables, describe how you will measure each, and explain how you will make the measurements fair.
8. HARD Explain in a short paragraph why dog breeds are strong evidence for variation within a kind but do not, by themselves, settle whether all living things share one ancestor.
9. HARD Why does inbreeding make inherited diseases more common in a breed, even if no new harmful mutations appear?

10. CHALLENGE In Labradors, a second gene controls yellow color: ee dogs are yellow no matter which B alleles they have; E_ dogs show black (B_) or chocolate (bb). Two black Labs, each BbEe, are bred. What fraction of the puppies are expected to be black, chocolate and yellow?

COMMON MISTAKES

- Thinking each dog breed is a separate species. All breeds are one species and can interbreed.
- Thinking breeders create new genes whenever they want a trait. Breeders mostly sort and concentrate alleles that already exist; useful new mutations are rare and come by chance.
- Thinking "purebred" always means healthier. Narrow gene pools make inherited diseases more common unless breeders test and plan carefully.

> **Make it a game · Breed, Species or Kind?.** A parent says the name of a group (beagle, domestic dog, wolf, golden retriever, the dog kind, coyote, poodle). You answer "breed," "species" or "kind," and give one reason. Score a point for each correct answer and a bonus point if you can name a job the breed was made for. First to ten points wins.

> **Scripture.** "A righteous man regardeth the life of his beast: but the tender mercies of the wicked are cruel." (Proverbs 12:10, KJV)

People may shape animals for work and companionship, but a righteous person cares about the animal's health and life. Good breeding serves the dog as well as the owner.

Practice answers

1. The domestic dog, *Canis familiaris* (often written *Canis lupus familiaris*), with 78 chromosomes.
2. In artificial selection, people choose which animals become parents. In natural selection, the surroundings (food, weather, predators) decide which individuals survive and reproduce.
3. *IGF1* for small body size; *FGF4* for short legs.
4. The boxes are Bb, Bb, bb, bb, so 50% black and 50% chocolate.
5. (a) Heavier breeds tend to have shorter lifespans. (b) Between the Labrador (12 years) and the wolfhound (7 years), so roughly 10 to 11 years. (c) No. It shows a correlation (the two go together); other factors, such as breed-specific diseases, could be involved, so more study is needed to show cause.
6. 150 ÷ 3 = 50 generations. Breeders choose every pair of parents on purpose, keep only the dogs with the wanted traits and protect the puppies, so selection is much stronger and more consistent than in the wild.
7. Independent variable: shoulder height (cm). Dependent variable: mass (kg). Measure height at the withers with the dog standing square on a level floor; measure mass by weighing the owner with and without the dog. Make it fair by measuring every dog the same way, measuring twice and averaging, using the same tape and scale, and including as many dogs of different sizes as possible.

8. Dog breeds show that one kind holds enormous variety and that selection can reshape size, legs, coat and behavior in a few dozen generations. But every breed is still a dog: the changes adjust the size and proportions of existing parts, and all breeds can interbreed with each other and with wolves. Whether this kind of change can build entirely new body plans and organs over many generations is a separate question that breeds do not test.
9. Close relatives are likely to carry the same alleles inherited from shared ancestors. When they are bred together, puppies are more likely to receive two copies of the same recessive harmful allele (dd), so the hidden disease shows up more often.
10. Out of 16 equal combinations: black (B_E_) = 3/4 × 3/4 = 9/16; chocolate (bbE_) = 1/4 × 3/4 = 3/16; yellow (__ee) = 1/4 = 4/16. Ratio 9 black : 3 chocolate : 4 yellow.

3.3 Antibiotic Resistance

OBJECTIVES

- Tell how Alexander Fleming discovered penicillin in 1928 and how Howard Florey, Ernst Chain and their Oxford team turned it into a medicine.
- Explain how a population of bacteria becomes resistant through variation, selection and gene sharing, and calculate bacterial growth by repeated doubling.
- Read zone-of-inhibition data and explain what antibiotic resistance shows, and does not show, about change in living things.

Warm-up. Take one penny (or one dried bean). Each “round” stands for 20 minutes, the time some bacteria need to divide in ideal lab conditions. Every round, double your pile: 1, 2, 4, 8 and so on. Guess first: how many will you have after 6 rounds (2 hours)? Count it out. Then calculate how many there would be after 6 hours (18 rounds). Do you have enough pennies in the house?

Video. Coming soon. Alexander Fleming and the discovery of penicillin, how bacteria become resistant to antibiotics, and disk-diffusion (zone of inhibition) lab demonstrations; search Science History Institute, HHMI BioInteractive, university microbiology departments and Moody Science classics.

KEY TERMS

bacterium (plural bacteria)
A single-celled living thing with no nucleus. Most bacteria are harmless or helpful; a few cause disease.

antibiotic
A medicine that kills bacteria or stops them from growing. Antibiotics do not work against viruses.

antibiotic resistance
The ability of some bacteria to survive and multiply even when an antibiotic is present.

selection pressure
Anything in the surroundings, such as an antibiotic, that lets some individuals survive and reproduce better than others.

plasmid
A small ring of DNA, separate from the main chromosome, that bacteria can copy and pass to other bacteria. Many resistance genes travel on plasmids.

zone of inhibition
The clear ring around an antibiotic disk on a culture plate, where bacteria could not grow. A wider ring means the bacteria are more easily killed by that antibiotic.

CORE IDEAS

The story. In September 1928, Alexander Fleming, a Scottish doctor and bacteriologist, came back from a summer holiday to his small laboratory at St Mary's Hospital in London. Stacked on his bench were glass dishes in which he had been growing *Staphylococcus*, the bacteria that cause boils and wound infections. On one dish a blue-green mold had landed and grown, and all around it was a clear ring where the bacteria had died. Fleming grew the mold, a kind of *Penicillium*, and named the substance it gave off penicillin. He published his findings in 1929, but he could not make enough pure penicillin to treat patients. Ten years later, at Oxford, Howard Florey, Ernst Chain and Norman Heatley found a way to purify it. In February 1941 their first patient, a police constable named Albert Alexander, began to recover from a terrible infection, but the tiny supply ran out and he died. By the end of the Second World War, factories were making penicillin by the ton, and countless soldiers and civilians lived who would have died. Fleming, Florey and Chain shared the Nobel Prize in 1945.

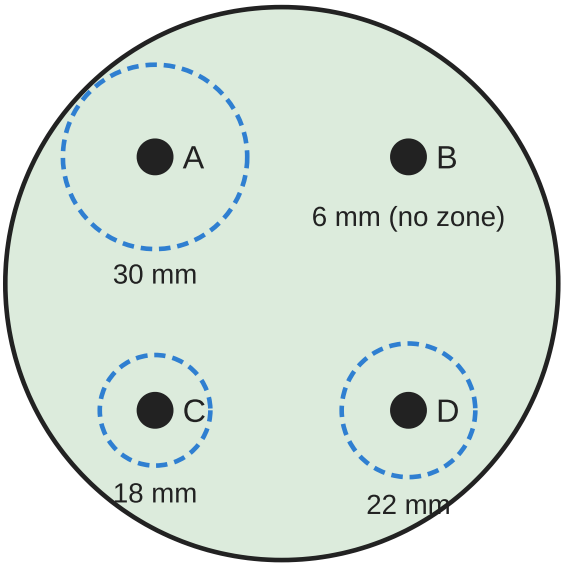
How they figured it out. Even before penicillin was widely used, Edward Abraham and Ernst Chain reported in 1940 that some bacteria make an enzyme that breaks penicillin apart. In his Nobel lecture in December 1945, Fleming warned that if people took too little penicillin, the bacteria might not be killed and could become resistant. He was right. Within a few years, penicillin-resistant *Staphylococcus* was common in hospitals. Later, scientists found bacteria carrying resistance genes in places that had never seen modern medicine, such as Lechuguilla Cave in New Mexico, sealed off deep underground. Resistance, it turned out, was not invented by the medicine. Much of it was already there.

The big idea. One infection can hold billions of bacteria, and they vary. A few may carry a gene that destroys the drug, pumps it out of the cell, or changes the part of the cell the drug attacks. The antibiotic is a **selection pressure**: it kills the susceptible bacteria and leaves the resistant ones. Because bacteria can divide as often as every 20 minutes in ideal conditions, a handful of survivors can become a whole new population in hours. Bacteria also share genes on small rings of DNA called **plasmids**, so resistance can spread from one bacterium to another, even between different species. Some resistance comes from new mutations, often small changes that alter or damage a protein the drug targets. Resistance often has a cost: when the antibiotic is gone, resistant strains frequently grow more slowly and can be outcompeted.

What changed and what didn't. What changed was the makeup of the population: resistant bacteria went from rare to common. What did not change: *Staphylococcus* stayed *Staphylococcus*, and *E. coli* stayed *E. coli*. In a famous experiment begun by Richard Lenski in 1988, twelve populations of *E. coli* have been grown for more than 75,000 generations. They remain *E. coli*, though one population gained the ability to use a food called citrate when oxygen is present, after an existing gene for taking in citrate was copied and switched on in a new way. Mainstream biologists see results like these as evolution happening before our eyes and a model for how new abilities arise. Creation biologists see them as variation within bacterial kinds, much of it from losing, rearranging or sharing genetic information that already existed. Both sides agree on the measurements.

In the world today. Because resistance is real, doctors try to prescribe antibiotics only when bacteria are the cause, and patients should take them exactly as the doctor directs, never save them for later and never share them. Antibiotics do nothing against viruses such as those that cause colds. Simple habits that Joseph Lister and Louis Pasteur championed in the 1800s, such as washing hands and keeping wounds clean, still prevent many infections before any medicine is needed.

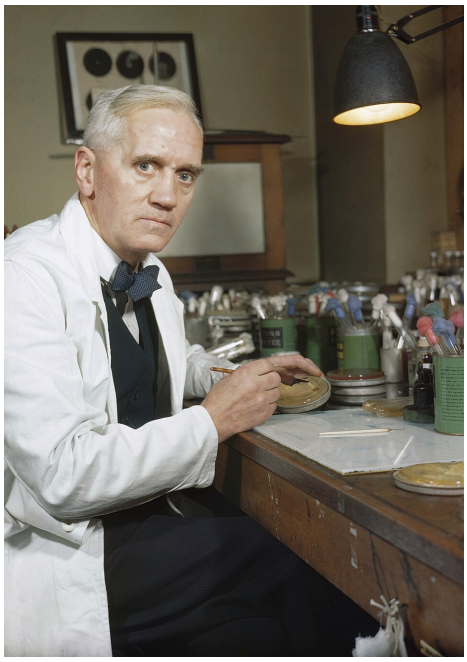
God's handiwork. Penicillin came from a mold, and streptomycin, discovered in 1943 in Selman Waksman's laboratory, came from a soil microbe. Many of our best medicines were hidden in the dirt and dust of God's creation, waiting to be found. "It is the glory of God to conceal a thing: but the honour of kings is to search out a matter" (Proverbs 25:2).



Dashed rings: clear zones where bacteria could not grow

Disk-diffusion test: the wider the clear zone, the better the antibiotic stops these bacteria. Disk B shows resistance.

PICTURE STUDY



Professor Alexander Fleming in his laboratory at St Mary's Hospital, London, Official photographer, British Ministry of Information, 1943 · Color photograph (Ministry of Information wartime color transparency) · Imperial War Museum, London (photograph TR 1468)

This color photograph was taken by a British government photographer in 1943, during the Second World War, when penicillin had become famous and people wanted to see the man who found it. Fleming sits at his crowded bench at St Mary's Hospital, where the moldy dish appeared in 1928.

Photographs like this are historical sources. They show us the real tools of a scientist: glass dishes, bottles, a microscope and a notebook. Fleming's discovery came because he looked carefully at a "spoiled" experiment instead of throwing it away.

Look closely

- Look at Fleming's hands. What is he working with, and why might a scientist hold glassware up to the light?
- List every piece of lab equipment you can identify.
- Look at the bench. Is it neat or crowded? What does that suggest about how Fleming worked?
- Look at Fleming's face and posture. What mood does the photographer capture?

Talk about it

1. Why did the government want photographs of penicillin research during the war?
2. What habit of a good scientist led Fleming to his discovery?
3. How is Fleming's lab like or unlike a science lab you have seen?

> **Safety first.** Never take, save or share antibiotics except exactly as a doctor directs. Do not grow bacteria at home without an adult who knows safe lab methods; sealed culture dishes must never be opened and must be disposed of properly. The beans in the project are game pieces, not food.

EXPERIMENT: BEAN BACTERIA: A RESISTANCE SIMULATION

You will model a population of bacteria with dried beans: white beans are susceptible, dark beans are resistant. You will test how repeated doses of an “antibiotic” change the percent of resistant bacteria.

You will need

- About 100 white dried beans (navy or great northern) and about 80 dark beans (black or kidney)
- A bowl for the “infection,” a cup for the reserve of beans, and a calculator
- Lab notebook

Steps

1. Question: How does repeated antibiotic use change the percent of resistant bacteria in a population? Write a prediction.
2. Set up the starting population: 48 white beans and 2 dark beans (50 total, 4% resistant).
3. Rules for one round: (1) Dose: remove 80% of the white beans, rounding to the nearest whole bean; dark beans are not harmed. (2) Growth: double every bean still in the bowl by adding the same number of matching beans from the reserve.
4. Variables: what you change is the number of rounds with a dose. What you keep the same is the starting population and the rules. What you measure is the number of white and dark beans and the percent dark after each round.
5. Run three rounds with doses. After each round, record white, dark and percent dark in a table. (Check: after round 1 you should have 20 white and 4 dark, about 17% resistant.)
6. Control: start again with 48 white and 2 dark, but run three rounds of growth only, with no dose. Record the percent dark each time.
7. Optional cost test: in growth-only rounds, add only half as many dark beans as you had (resistant bacteria grow more slowly without the drug). What happens to the percent dark?
8. Graph percent resistant against round number for both trials and write a conclusion.

Tips

- No bean ever changes color. Selection only changes which beans are common, just as an antibiotic does not turn a susceptible bacterium into a resistant one.
- Real bacteria also swap resistance genes on plasmids. To model that, you could swap one white bean for a dark one each round.

Check your work

- I recorded counts and percents for every round in both trials.
- My control trial shows what happens without the antibiotic.
- I can explain why the percent of resistant beans rose without any bean changing.

NATURE NOTEBOOK

1. Draw a bacterium as a rod-shaped cell. Label the cell membrane, cell wall, chromosome (DNA) and one plasmid.
2. Draw a three-panel comic: a mixed population of bacteria, the antibiotic killing the susceptible ones, and the survivors multiplying.
3. Make a timeline of antibiotic history: 1928 Fleming, 1940 penicillin-breaking enzyme reported, 1941 first patient, 1943 streptomycin, 1945 Nobel Prize.

From history. To mass-produce penicillin during the war, scientists at a United States Department of Agriculture laboratory in Peoria, Illinois, searched for a mold that made more of it. In 1943 a moldy cantaloupe from a Peoria market gave them a *Penicillium* strain that produced far more penicillin than Fleming's, and improved descendants of that strain were used to make much of the world's penicillin. The lab worker who gathered moldy fruit, Mary Hunt, earned the nickname "Moldy Mary."

WORKED EXAMPLES

Example 1. In ideal lab conditions, a bacterium divides every 20 minutes. Starting with one bacterium, how many will there be after 4 hours? After 6 hours?

1. Doublings in 4 hours = $4 \times 60 \div 20 = 240 \div 20 = 12$.
2. Number after 12 doublings = $2^{12} = 4{,}096$.
3. Doublings in 6 hours = $6 \times 3 = 18$. Number = $2^{18} = 262{,}144$.
4. In real bodies, food, space and the immune system slow this down, but the math shows why survivors can rebuild a population quickly.

Answer: 4,096 bacteria after 4 hours and 262,144 after 6 hours.

Example 2. An infection contains 10,000,000 bacteria. One in every 1,000,000 carries a resistance gene. An antibiotic kills all the susceptible bacteria but none of the resistant ones. How many survive? If the survivors then double every 20 minutes for 3 hours, how many resistant bacteria will there be, and what percent of the population is resistant?

1. Resistant bacteria at the start = 10,000,000 ÷ 1,000,000 = 10.
2. Before the drug, the resistant fraction was 10 ÷ 10,000,000 = 0.0001%.
3. Doublings in 3 hours = 180 ÷ 20 = 9, and $2^9 = 512$.
4. Resistant bacteria after 3 hours = 10 × 512 = 5,120, and since all the susceptible ones died, they make up 100% of the population.

Answer: 10 survive; after 3 hours there are 5,120, and the population is 100% resistant (up from 0.0001%).

Example 3. A lab tests four antibiotics (A, B, C, D) on one kind of bacteria using the disk method. The clear zones measure A = 30 mm, B = 6 mm (the disk itself, so no clear zone), C = 18 mm and D = 22 mm. For this sample test, use these cutoffs: 20 mm or more = susceptible, 15 to 19 mm = intermediate, 14 mm or less = resistant. Classify each and choose the best drug.

(Use the map or drawing "Measure each clear zone across its full width (diameter) in millimeters." shown earlier in this lesson.)

1. A: 30 mm is at least 20 mm, so susceptible.
2. B: 6 mm is no clear zone at all, so resistant.
3. C: 18 mm is between 15 and 19 mm, so intermediate.
4. D: 22 mm is at least 20 mm, so susceptible. A has the widest zone, so it stopped these bacteria best in this test.

Answer: A susceptible, B resistant, C intermediate, D susceptible. Antibiotic A is the best choice in this test.

PRACTICE

1. EASY Who discovered penicillin, in what year, and where?
2. EASY What is a plasmid, and why does it matter for antibiotic resistance?
3. EASY Why will an antibiotic not cure a common cold?
4. MEDIUM A bacterium divides every 30 minutes. Starting from one, how many bacteria are there after 3 hours?
5. MEDIUM Data reading. Sample hospital records show the percent of *Staphylococcus* samples resistant to penicillin: Year 1: 14%; Year 2: 38%; Year 3: 59%. (a) Describe the trend. (b) By how many percentage points did resistance rise from Year 1 to Year 3? (c) Give the most likely explanation.

6. MEDIUM Data reading. A disk test gives these clear-zone diameters: Drug P 25 mm, Drug Q 12 mm, Drug R 16 mm. Using the cutoffs from Worked Example 3 (20 mm or more susceptible, 15 to 19 intermediate, 14 or less resistant), classify each drug. Which is the dependent variable in this test?
7. MEDIUM Explain in three steps how a population of bacteria becomes resistant to an antibiotic.
8. HARD Experiment design. A supervised school lab wants to test whether garlic juice slows the growth of a harmless lab strain of bacteria. Describe the setup using disks on a culture plate: the independent variable, the dependent variable, the control, two things kept the same and the number of trials.
9. HARD Abraham and Chain reported a penicillin-breaking enzyme in 1940, before penicillin was widely used, and bacteria from isolated Lechuguilla Cave carry resistance genes. What do these facts suggest about where resistance comes from?
10. CHALLENGE With no antibiotic present, susceptible bacteria divide every 20 minutes but a resistant strain divides only every 30 minutes. You start with 100 of each. After 4 hours, how many of each are there, and what percent of the population is resistant?

COMMON MISTAKES

- Thinking a person’s body becomes resistant to antibiotics. It is the bacteria that become resistant, not the patient.
- Thinking antibiotics work against viruses such as colds and flu. They work only against bacteria.
- Thinking the antibiotic “teaches” bacteria to resist or causes the resistance gene to appear. The drug selects bacteria that already carry resistance; mutations happen by chance, not because the bacteria need them.

> **Make it a game · Survivor Bugs.** Shuffle a deck of cards: red cards are susceptible bacteria and black cards are resistant. Deal 20 cards face up as your “infection,” with only 2 black. Roll a die for each dose: on 1 to 5, remove all red cards showing except one; on a 6, the dose was skipped and nothing is removed. After each dose, double the remaining cards from the deck, matching colors. The player who explains each round correctly (“the red cards died, the black ones survived and multiplied”) scores a point. Play three doses and compare the colors at the end.

> **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 healing substances in molds and soil microbes. Fleming, Florey and Chain had the honor of searching them out, and careful use of what they found is part of loving our neighbor.

Practice answers

1. Alexander Fleming, in 1928, at St Mary’s Hospital in London.

2. A plasmid is a small ring of DNA separate from a bacterium’s main chromosome. Bacteria can copy plasmids and pass them to other bacteria, so resistance genes on plasmids can spread quickly, even between species.
3. Colds are caused by viruses, and antibiotics work only against bacteria.
4. 3 hours = 180 minutes ÷ 30 = 6 doublings. $2^6 = 64$ bacteria.
5. (a) Resistance rose steadily each year. (b) 59 − 14 = 45 percentage points. (c) As penicillin was used more, it killed susceptible bacteria and left resistant ones to multiply and spread, so the resistant share grew.
6. P susceptible, Q resistant, R intermediate. The dependent variable is the diameter of the clear zone (what is measured); the independent variable is which antibiotic is on the disk.
7. (1) The population varies: a few bacteria already carry resistance (from a mutation or a shared plasmid). (2) The antibiotic kills the susceptible bacteria, leaving the resistant ones. (3) The survivors multiply quickly, so the new population is mostly resistant.
8. Independent variable: what the paper disk is soaked in (garlic juice versus plain sterile water). Dependent variable: the diameter of the clear zone in millimeters. Control: disks soaked in sterile water only. Keep the same: the type and amount of bacteria spread on each plate, disk size, soaking time, temperature and incubation time. Run at least three plates. The plates stay sealed and are disposed of by the teacher.
9. Much resistance existed before people used antibiotics. The medicine did not create the resistance; it selected bacteria that already had it, allowing them to become common. (New mutations can add resistance too, but pre-existing genes are a major source.)
10. Susceptible: 240 ÷ 20 = 12 doublings, 100 × 4,096 = 409,600. Resistant: 240 ÷ 30 = 8 doublings, 100 × 256 = 25,600. Total = 435,200. Percent resistant = 25,600 ÷ 435,200 × 100 ≈ 5.9%. Without the drug, the slower resistant strain falls from 50% to about 6%.

3.4 What a "Kind" May Be (Baramin)

OBJECTIVES

- Explain the Hebrew word *min* ("kind"), the term baramin coined by Frank Lewis Marsh in 1941, and how creation biologists try to identify created kinds.
- Use hybridization records and chromosome counts to group species into possible kinds and explain why most mules cannot have offspring.
- Compare the created-kind view with the mainstream view of species and common descent fairly, and name a limit of the hybrid test.

Warm-up. Write these animals on eight slips of paper: horse, donkey, zebra, lion, tiger, house cat, wolf, poodle. Sort them into groups that you think "belong together." Now think: which pairs have ever produced offspring together? Draw a line between any pair you believe can. Did your lines match your groups? Keep your slips for the end of the lesson.

Video. Coming soon. Animal hybrids such as mules, zorses, ligers and wholphins, and how scientists classify species with the Linnaean ranks; search Smithsonian National Zoo, San Diego Zoo Wildlife Alliance, PBS nature programs and university biology channels.

KEY TERMS

kind (Hebrew *min*)
The Bible's word for the groups of living things God created to reproduce "after his kind" (Genesis 1). It is not the same as the modern word species.

baramin
A created kind. The word was coined in 1941 by Frank Lewis Marsh from the Hebrew *bara* ("created") and *min* ("kind").

baraminology
The study, by creation biologists, of which living things belong to the same created kind, using hybrids, anatomy and DNA.

species
In modern biology, a group of living things that can interbreed in nature and produce fertile offspring; the smallest main rank in Linnaean classification.

hybridization
The mating of two different species or varieties to produce offspring (a hybrid), such as a horse and donkey producing a mule.

family (rank)
The Linnaean rank above genus and below order, such as the cat family (Felidae) or the dog family (Canidae).

CORE IDEAS

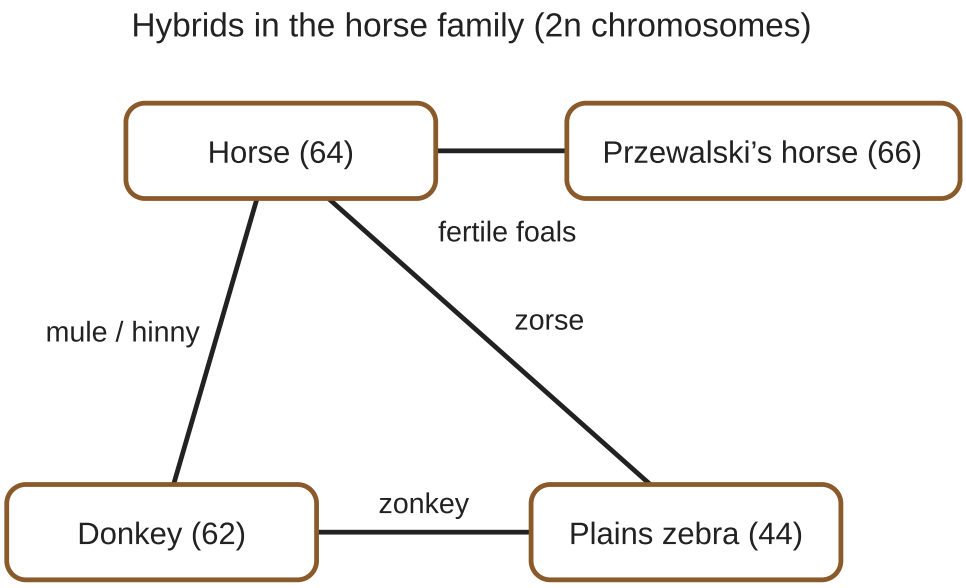
The story. In 1941 an American biology teacher named Frank Lewis Marsh published a textbook called *Fundamental Biology*. Marsh believed Genesis, and he had a problem. Genesis 1 says ten times that God made living things "after his kind" or "after their kind," but biology had no word for a created kind. The word species did not fit, because Marsh accepted that new species could form within a kind. So Marsh made a new word from two Hebrew words in Genesis: *bara*, "created," and *min*, "kind." A **baramin** is a created kind. Marsh's question is the question of this whole unit: if finches, dogs and bacteria vary so much, where are the edges of a kind?

How they figured it out. Marsh proposed a test: if two creatures can **hybridize**, producing offspring by true fertilization, they belong to the same baramin. The records are surprising. A male donkey and a female horse produce a mule. A zebra and a horse produce a zorse. A lion and a tigress produce a liger. In 1985, at Sea Life Park in Hawaii, a false killer whale and a bottlenose dolphin produced a calf called a wholphin. American bison and domestic cattle produce "beefalo," and wild polar bear and grizzly bear hybrids have been found in the Canadian Arctic. In the 1990s creation biologists such as Kurt Wise and Walter ReMine built Marsh's idea into a field called **baraminology**, and later researchers began comparing hundreds of traits and DNA sequences to see which groups cluster together and where clear gaps appear.

The big idea. Linnaeus sorted living things into nested ranks: kingdom, phylum, class, order, **family**, genus and species. Many creation biologists conclude that a created kind often lies near the family level. The cat family (Felidae, about 40 species), the dog family (Canidae, about 35 species) and the horse family (Equidae) may each be one kind, though some kinds may be narrower or broader. Within each kind lies the kind of variety you have studied: finch beaks, dog breeds, bacterial resistance. On this reading, Noah brought animals "after their kind" into the ark (Genesis 6:20), far fewer than all the species living today, and the many species we see arose afterward by variation within kinds as animals spread over the earth. Human beings are not one animal kind among others; Genesis teaches that God made man in His own image, male and female (Genesis 1:27).

Each side, fairly. Mainstream biologists define a **species** as a group that interbreeds in nature, and they see no fixed outer edge: they read hybrids, anatomy and DNA as branches of one great tree reaching back to a single common ancestor. Creation biologists read the same data as many separate trees, an orchard, with real gaps between kinds. Both agree that species vary, that new species can form and that hybrids happen. They disagree on whether all kinds share one ancestor. Some Christians hold still other views about how God made living things, and in Unit 6 you will compare these views in writing. The hybrid test also has a limit, and honest creation biologists say so: if two animals *can* hybridize, that is strong evidence they are one kind, but if they *cannot* or have never been tried, that does not prove they are different kinds. Animals can lose the ability to interbreed through small changes in timing, behavior or chromosomes.

God’s handiwork. The phrase “after his kind” describes both order and freedom. Order, because cats bear kittens and dogs bear puppies, and every farmer and breeder depends on it. Freedom, because within each kind God packed a wealth of variety that lets living things fill the earth, as He commanded. “And God said, Let the earth bring forth the living creature after his kind” (Genesis 1:24). When you sort animals into kinds, you are doing what Adam did when he named them: looking closely at God’s creatures and seeing how they belong together.



Hybrids link every member shown here, so by Marsh’s test they belong to one baramin. Numbers are chromosome counts (2n).

PICTURE STUDY



Noah’s Ark, Edward Hicks, 1846 · Oil on canvas · Philadelphia Museum of Art

Edward Hicks was a Quaker minister and sign painter from Bucks County, Pennsylvania, best known for his many paintings of *The Peaceable Kingdom* from Isaiah 11. In 1846 he painted the animals going into Noah’s ark, two by two, as the storm gathers. Hicks was a folk painter, largely self-taught, and his animals have a simple, almost toy-like charm.

Look at this painting with Marsh’s question in mind. Genesis says the animals came “after their kind.” Hicks painted the animals he knew from books and prints, but the Bible’s list is broader than any painter could show.

Look closely

- Count the pairs of animals you can see. Which ones can you name?
- Find animals that might belong to the same kind as each other in this unit’s sense.
- Look at the sky. How does Hicks show that the Flood is coming?
- Look at the ark itself. Is it shaped like a ship, a house or a box?

Talk about it

1. If the ark carried kinds rather than every species, how would that change the number of animals aboard?
2. Which animals in the painting might today have many species within their kind?
3. Why do you think Hicks painted the animals calm and orderly rather than frightened?

EXPERIMENT: MAP A KIND: A HYBRID NETWORK

You will pick one family of animals, gather real hybrid records from library books, zoo websites or encyclopedias, and draw a network to test whether its species link into one group by Marsh's test.

You will need

- A family to study: the dog family (Canidae), cat family (Felidae), horse family (Equidae), cattle and bison (Bovidae, cattle tribe), or ducks (Anatidae)
- Library books, an encyclopedia or zoo and university websites (with a parent)
- A large sheet of paper, colored pencils and a lab notebook

Steps

1. Write your question: Do the species of this family connect into one hybrid network? Write a prediction.
2. List at least six species in the family with their scientific names and, if you can find them, their chromosome numbers.
3. Research which pairs have produced hybrids. For each record, write the hybrid's name, whether it was fertile, and your source.
4. Draw each species as a circle on your paper. Draw a solid line for each documented hybrid and a dashed line for claims you could not confirm.
5. Variables: what you are testing is whether the species connect. Keep your standard the same for every pair: count only hybrids from a reliable source. Record the number of species connected to the largest group.
6. Write a conclusion: Do the species form one connected group, several groups, or is there not enough data? Remember that a missing line does not prove two species are different kinds.

Tips

- Linked hybrids connect groups: if A crosses with B and B crosses with C, all three join one network even if A and C have never been crossed.
- Zoos and wildlife parks are the source of many hybrid records, because animals from distant lands meet there.

Check your work

- My network shows at least six species and cites a source for each line.
- I separated confirmed hybrids from unconfirmed claims.
- My conclusion states what the data show and the limit of the hybrid test.

NATURE NOTEBOOK

1. Draw a mule and label which traits look like its horse mother and which look like its donkey father (ears, tail, size, mane).

2. Write the seven Linnaean ranks for the house cat: Animalia, Chordata, Mammalia, Carnivora, Felidae, *Felis*, *Felis catus*. Circle the rank where many creation biologists place the created kind.
3. Copy Genesis 1:24 in your best handwriting and draw three animals that reproduce “after his kind.”

From history. Carl Linnaeus, the Swedish botanist who gave us two-part scientific names, first taught that species were fixed as God created them. Later in life, after studying unusual plants and crossbreeds in his gardens at Uppsala, he wondered whether God had created fewer original forms and whether some species had arisen afterward by crossing. Even the great classifier saw that species were not quite as fixed as he had first thought, which is one reason creation biologists today distinguish the created kind from the species.

WORKED EXAMPLES

Example 1. A horse has 64 chromosomes and a donkey has 62. How many chromosomes does each parent put in an egg or sperm, and how many does a mule have? Why are mules almost always unable to have foals?

1. Eggs and sperm carry half the parent’s chromosomes. Horse: 64 ÷ 2 = 32. Donkey: 62 ÷ 2 = 31.
2. Mule = 32 + 31 = 63 chromosomes.
3. To make its own eggs or sperm, a cell must pair up matching chromosomes and split them evenly. With 63, an odd number made of two different sets, the chromosomes do not pair properly.
4. So the mule is healthy and strong but almost always sterile. (A very few female mules have had foals, which shows the horse and donkey are close.)

Answer: Horse gametes carry 32 and donkey gametes 31, so a mule has 63. The unmatched chromosomes cannot pair evenly to make eggs or sperm, so mules are almost always sterile.

Example 2. Use the horse-family network. Domestic horse (64 chromosomes) crosses with Przewalski's horse (66), donkey (62) and plains zebra (44); donkey crosses with plains zebra. Do all four belong to one group by Marsh's test? What does the horse and Przewalski's horse cross teach about chromosome numbers?

(Use the map or drawing "Follow each line to see which members are linked." shown earlier in this lesson.)

1. List the links: horse to Przewalski's horse, horse to donkey (mule or hinny), horse to zebra (zorse), donkey to zebra (zonkey).
2. Every member is connected to the domestic horse, so all four form one connected network.
3. By Marsh's test, all four belong to one baramin, the horse kind.
4. Horse (64) and Przewalski's horse (66) have different chromosome numbers, yet their foals (65) are fertile. A difference in chromosome number does not by itself prevent fertile hybrids.

Answer: Yes. All four are linked by hybrids, so they form one baramin by Marsh's test. The fertile horse and Przewalski's horse hybrids show that species with different chromosome numbers can still be close kin.

Example 3. Rounded counts of living species: cat family about 40, dog family about 35, horse family about 7 and bear family 8. If each family is one created kind, what is the total number of species, the number of kinds, and the average number of species per kind? If an ark carried one pair per kind instead of one pair per species, how many animals of these families would be aboard in each case?

1. Total species = 40 + 35 + 7 + 8 = 90.
2. Number of kinds = 4. Average = 90 ÷ 4 = 22.5 species per kind.
3. One pair per species = 90 × 2 = 180 animals.
4. One pair per kind = 4 × 2 = 8 animals, which is 180 ÷ 8 = 22.5 times fewer.

Answer: 90 species in 4 kinds, an average of 22.5 species per kind. One pair per species would be 180 animals; one pair per kind would be 8.

PRACTICE

1. EASY What does the word baramin mean, who coined it, and when?
2. EASY List the seven main Linnaean ranks from broadest to narrowest.
3. EASY Name the hybrid of each pair: (a) male donkey and female horse; (b) lion and tigress; (c) false killer whale and bottlenose dolphin.
4. MEDIUM A plains zebra has 44 chromosomes and a horse has 64. How many chromosomes would a zorse from these parents have?

5. MEDIUM Data reading. Hybrid records in the dog family: domestic dog × gray wolf: fertile young. Gray wolf × coyote: fertile young. Coyote × domestic dog: fertile young. Domestic dog × golden jackal: fertile young. Domestic dog × red fox: no confirmed hybrid. Which statement is best supported? (a) The red fox is proven to be a different kind. (b) Dog, wolf, coyote and golden jackal form one connected hybrid group. (c) Only dogs and wolves are related. (d) All five belong to one kind.
6. MEDIUM Data reading. Chromosome numbers (2n): dog 78, gray wolf 78, coyote 78, golden jackal 78, house cat 38, lion 38, tiger 38, domestic horse 64, Przewalski's horse 66. (a) Which animals share 78? (b) Does sharing a chromosome number prove two animals are the same kind? (c) Does a different number prove they are different kinds? Use the table to explain.
7. HARD Explain why "these two species cannot hybridize" does not prove they belong to different created kinds.
8. HARD Experiment design. A zoo wants to learn whether two species of ducks can produce fertile hybrids. Describe a careful, humane study: what pairs to set up, the control, what to measure and how to test fertility.
9. HARD In a short paragraph, compare how mainstream biologists and creation biologists read the same hybrid and DNA data.
10. CHALLENGE The cattle tribe includes domestic cattle (60 chromosomes) and American bison (60). They produce "beefalo," and some hybrids are fertile. Yak and cattle also produce hybrids. Draw (or describe) a network for cattle, bison and yak, state Marsh's conclusion, and explain one reason why a breeder might care.

COMMON MISTAKES

- Thinking "kind" in Genesis means the same thing as "species" in modern biology. Most creation biologists think a kind is usually broader, often near the family level.
- Thinking that if two animals cannot hybridize, they must be different kinds. The hybrid test can show two animals are one kind, but a failed or untried cross does not prove they are separate.
- Thinking creation biologists deny that species change. They accept variation and the formation of new species within kinds; they question only whether all kinds share one ancestor.

Make it a game · Kind Detective. A parent reads a hybrid clue ("A lion and a tigress had cubs."). You say which two animals are linked and draw the line on a growing chart of animal names. After eight clues, count how many separate groups your chart has. Score a point for each correct link, and a bonus point if you can say why an animal with no lines is "not enough data" rather than "a different kind."

Scripture. "And God said, Let the earth bring forth the living creature after his kind, cattle, and creeping thing, and beast of the earth after his kind: and it was so." (Genesis 1:24, KJV)

God set the living creatures in their kinds. Within those kinds He placed great room for variety, which is why the dog, finch and cattle families hold so many forms.

Practice answers

1. A created kind, from the Hebrew *bara* (“created”) and *min* (“kind”). Frank Lewis Marsh coined it in 1941.
2. Kingdom, phylum, class, order, family, genus, species.
3. (a) Mule. (b) Liger. (c) Wholphin.
4. 44 ÷ 2 = 22 and 64 ÷ 2 = 32, so the zorse has 22 + 32 = 54 chromosomes.
5. (b). The four are linked by fertile hybrids. (a) and (d) both go beyond the data: a missing hybrid neither proves nor disproves that the fox is in the same kind. (c) ignores the coyote and jackal records.
6. (a) Dog, gray wolf, coyote and golden jackal. (b) No; chromosome number is only one clue, and unrelated creatures can happen to share a number. Hybrid records, anatomy and DNA are also needed. (c) No; the domestic horse (64) and Przewalski’s horse (66) differ yet have fertile foals.
7. Within a kind, populations can lose the ability to interbreed through small changes in breeding season, courtship behavior, body size or chromosome arrangement. Also, many pairs have simply never been tested, or one of them is extinct. A successful hybrid is positive evidence of the same kind, but the absence of one is not proof of separate kinds.
8. Set up mixed pairs (male of species A with female of species B, and the reverse) in separate pens, plus control pairs of each species with its own kind kept in identical pens with the same food, space and season. Measure the number of eggs laid, the percent that are fertile and the percent that hatch. Raise any hybrid ducklings and pair them as adults to see whether they produce fertile eggs. Keep all birds healthy and record everything for at least two breeding seasons.
9. Both groups accept that species vary, that new species form and that hybrids occur. Mainstream biologists read similarities in anatomy and DNA as evidence that all living things are branches of one tree with a single common ancestor, with no fixed boundary between groups. Creation biologists read the same data as an “orchard” of separate trees: each created kind has varied into many species, but real gaps separate the kinds. The disagreement is not over the observations but over whether the kinds share one ancestor.
10. Lines connect cattle–bison and cattle–yak; cattle link all three into one network, so by Marsh’s test they are one baramin. A breeder might care because crossing them can combine useful traits, such as the hardiness of bison or yak with the gentleness and milk or meat of cattle.

Unit 3 review

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

1. (4 pts) Multiple choice. After the 1977 drought on Daphne Major, the average beak depth of medium ground finches increased. Which explanation is correct? (a) Each finch grew a deeper beak to crack hard seeds. (b) Finches with deeper beaks survived and bred more, so their young had deeper beaks on average. (c) The drought caused new beak genes to appear. (d) Small-beaked finches flew to other islands and turned into new species.
2. (6 pts) A finch population falls from 1,500 birds to 225 during a drought. Before the drought the average beak depth was 9.2 mm; the next generation averages 9.7 mm. (a) What percent of the birds survived? (b) By how many millimeters and by what percent did average beak depth change?
3. (5 pts) List two things that changed in the Galápagos finches and two things that did not change. Then write one sentence on how a creation biologist interprets the finches.
4. (4 pts) Multiple choice. A Chihuahua and a Great Dane (a) are different species because they look so different; (b) belong to the same species, *Canis familiaris*; (c) cannot share any genes; (d) have different chromosome numbers.
5. (8 pts) Diagram item. Draw and label a Punnett square for two black Labrador retrievers that are both Bb (B = black, dominant; b = chocolate, recessive). Label each parent, write the genotype in each box, color or label each box’s coat color, and state the expected ratio of black to chocolate puppies.
6. (5 pts) Explain why breeding closely related dogs makes inherited diseases more common, and name one way responsible breeders reduce the problem.
7. (6 pts) An infection holds 5,000,000 bacteria, and 1 in 1,000,000 is resistant to an antibiotic. The antibiotic kills all susceptible bacteria. (a) How many survive? (b) If the survivors double every 20 minutes, how many are there after 2 hours? (c) What percent of the new population is resistant?
8. (4 pts) Multiple choice. In a disk-diffusion test, antibiotic X gives a clear zone of 28 mm and antibiotic Y gives no clear zone. Which is true? (a) The bacteria are resistant to X. (b) The bacteria are resistant to Y. (c) Y is stronger than X. (d) The test shows nothing.
9. (6 pts) Fleming discovered penicillin in 1928. In 1940 Abraham and Chain reported a bacterial enzyme that breaks penicillin apart. Explain what this tells us about where resistance comes from, and explain what changed and what did not change when *Staphylococcus* became resistant.
10. (6 pts) A horse has 64 chromosomes and a donkey has 62. (a) How many chromosomes does a mule have? Show your work. (b) Why are mules almost always sterile? (c) By Marsh’s hybrid test, what does the mule tell us about horses and donkeys?
11. (6 pts) Define baramin. Then explain one limit of the hybrid test and one point on which mainstream and creation biologists agree.

UNIT PROJECT: A FIELD GUIDE TO ONE KIND

Choose one created kind you can observe or research: the dog kind, the cat kind, the horse kind, the cattle kind, the duck kind or the finch kind. Make an illustrated field guide of at least six pages. Include drawings of at least five varieties or species, a hybrid network with sources, a Punnett square for one real inherited trait, and a data table or graph of a measurement you collected (dog heights and masses, beak-model counts, or bean-simulation results). End with a one-page essay titled “What Changed and What Didn’t,” explaining the variation you found and how mainstream and creation biologists each interpret it.

- **Accuracy**: Names, chromosome numbers, hybrid records and genetics are correct, and every hybrid line has a source.
- **Data**: The table or graph has units, labeled axes and calculations (ratios or percents) done correctly.
- **Explanation**: The essay clearly separates observation from interpretation and states both views fairly and respectfully.
- **Care**: Drawings are neat and labeled like a naturalist’s, and the guide is organized and easy to read.

Answer key

1. (b). The population’s average changed through selection; no individual bird changed its beak and the drought did not create genes.
2. (a) 225 ÷ 1,500 × 100 = 15%. (b) 9.7 − 9.2 = 0.5 mm; 0.5 ÷ 9.2 × 100 ≈ 5.4% increase.
3. Changed (any two): average beak depth or width, average body size, how common each type of bird was. Did not change (any two): they remained finches; same feathers, wings and body plan; no new organs; many species still interbreed. A creation biologist sees the finches as variation within one created finch kind.
4. (b). All dog breeds are one species with 78 chromosomes.
5. Parents Bb across the top and Bb down the side; boxes BB (black), Bb (black), Bb (black), bb (chocolate). Ratio 3 black : 1 chocolate (75% : 25%). Scoring: correct parent labels 2, correct genotypes 3, correct colors 2, correct ratio 1.
6. Close relatives often carry the same recessive alleles from shared ancestors, so their puppies are more likely to receive two copies (for example dd) and show the disease. Breeders reduce it with DNA or health testing and by not pairing two carriers (for example breeding a carrier only with a clear dog).
7. (a) 5,000,000 ÷ 1,000,000 = 5. (b) 2 hours = 6 doublings; $5 \times 2^6 = 5 \times 64 = 320$. (c) 100%, since all the susceptible bacteria were killed.
8. (b). No clear zone means the bacteria grew right up to disk Y, so they are resistant to Y; the wide zone around X shows they are susceptible to X.
9. Resistance existed in some bacteria before the drug was widely used; penicillin selected those bacteria rather than creating the resistance. What changed: the share of resistant bacteria in the population rose from rare to common. What did not change: the bacteria were still *Staphylococcus*.
10. (a) 64 ÷ 2 = 32 and 62 ÷ 2 = 31; 32 + 31 = 63. (b) The two unmatched sets (an odd number) cannot pair evenly to make eggs or sperm. (c) Because they can produce a hybrid, horses and donkeys belong to the same baramin (created kind).

11. A baramin is a created kind (Hebrew *bara*, created, + *min*, kind), a word coined by Frank Lewis Marsh in 1941. Limit: if two animals cannot hybridize or have never been crossed, that does not prove they are different kinds. Agreement (any one): species vary; new species can form; hybrids occur; the measurements are the same for both sides.

UNIT 4

Design in Nature

"The heavens declare the glory of God; and the firmament sheweth his handywork" (Psalm 19:1). For thousands of years people have looked at living things and asked how their parts came to fit together so well. In 1802 William Paley put that question in a form no one has forgotten: if you found a watch lying on a heath, you would know it had a maker. In this unit you will follow his question from a watch to the human eye, to a spinning motor inside a single bacterium, and finally to the settings of the universe and the planet that make life possible.

This is a unit for careful thinking. In every lesson you will learn the science first: how gears divide time, how the cornea and lens focus light, how hydrogen ions drive a rotary motor, why ice floats. Then you will hear the design argument and its strongest critics, David Hume, Charles Darwin, Kenneth Miller and others, stated fairly and in their own words where possible, along with the replies of those who see design. You will measure, calculate, take things apart and test them, so that you can weigh the arguments with evidence in hand. Unit 6 will build on this work with a fair comparison of creation, Darwin's theory and intelligent design.

BEFORE YOU BEGIN

- Can multiply, divide and find percents and simple ratios
- Can find the area of a circle and convert between metric units (mm, cm, m; µm and nm)
- Knows what a cell is and that genes carry the instructions for building proteins (Unit 2)
- Can explain natural selection and variation within a kind using the finches and dog breeds (Unit 3)

MASTERY CHECKLIST

- I can retell Paley's watch argument and explain the difference between complexity and parts fitted together for a function.
- I can label the main parts of the eye, trace the path of light, and calculate how pupil size changes the light admitted.
- I can describe the bacterial flagellum as a rotary motor and define irreducible complexity with an example.
- I can explain what fine-tuning means and why water's density and specific heat matter for life.
- I can state the main objections to the design argument and the replies to them fairly and respectfully.
- I can design a fair test with a control, and read data tables and graphs to decide which conclusions they support.

OPTIONAL BOOKS AND RESOURCES

- **Charles Darwin, *On the Origin of Species* (1859), free at Project Gutenberg** (https://www.gutenberg.org/ebooks/1228): Free. Read Darwin's own words on the eye and on his test for "any complex organ" in Chapter VI, "Difficulties on Theory" (Lessons 4.2 and 4.3). Reading the primary source is the fairest way to know what Darwin actually claimed.
- **The Complete Work of Charles Darwin Online** (http://darwin-online.org.uk/): Free. A scholarly library of Darwin's books, letters and notes, including his autobiography, where he describes reading Paley at Cambridge (Lesson 4.1). Best used with a parent choosing the passages.
- **NASA Image and Video Library** (https://images.nasa.gov/): Free. Search "Earthrise" and "Apollo 8" for the photograph in Lesson 4.4, and "Venus" and "Mars" for pictures to compare with Earth while you study the habitable zone.

4.1 Paley's Watch (1802) ★

OBJECTIVES

- Retell William Paley's watch argument from *Natural Theology* (1802) and name its four steps: parts, fit, purpose and maker.
- Calculate gear ratios and tick rates in a watch, and count the possible arrangements of a set of parts to compare chance with careful assembly.
- Describe fairly the main objections of David Hume and Charles Darwin to the design argument and how defenders of design answer them.

Warm-up. Gather five objects: a pebble, a leaf, a pinecone, a key and a paper clip. Sort them into two piles, "made by a person" and "not made by a person." Next to each one, write the clue that told you. Which object was hardest to sort, and why? Keep your list; you will compare your clues with Paley's.

Video. Coming soon. William Paley's watchmaker argument and how a mechanical watch works (mainspring, gear train, escapement, balance wheel); search watchmaking and horology channels, museum clock and watch collections, Moody Science classics, and Christian apologetics channels that present the design argument fairly.

KEY TERMS

natural theology
Learning about God from what can be observed in nature, as opposed to learning about Him from the Bible. Paley's book took this as its title.

design argument
The argument that parts working together for a purpose in nature point to a mind that designed them. It is also called the teleological argument, from the Greek word *telos*, "purpose" or "end."

contrivance
Paley's word for an arrangement of parts made to do a job, such as the spring, wheels and hands of a watch.

function
The job a part or a system does, such as keeping time or focusing light.

analogy
Reasoning from one thing to another that is like it in important ways, such as from a watch to a living body.

inference to the best explanation
Choosing the cause that best accounts for all the evidence, the way a detective reasons from clues to the most likely culprit.

CORE IDEAS

The story. In 1802 a London bookseller published a thick book by William Paley (1743–1805), a Church of England clergyman and the Archdeacon of Carlisle, in the north of England. Its long title was *Natural Theology; or, Evidences of the Existence and Attributes of the Deity, Collected from the Appearances of Nature*. Paley was in poor health and would die three years later, but the first page of the book became one of the most famous openings in the history of science. “In crossing a heath,” he began, suppose I strike my foot against a stone and someone asks how it came to be there. I might answer that, for all I know, it had lain there forever. But suppose I find a **watch** on the ground. I would never give that answer about the watch. Why not?

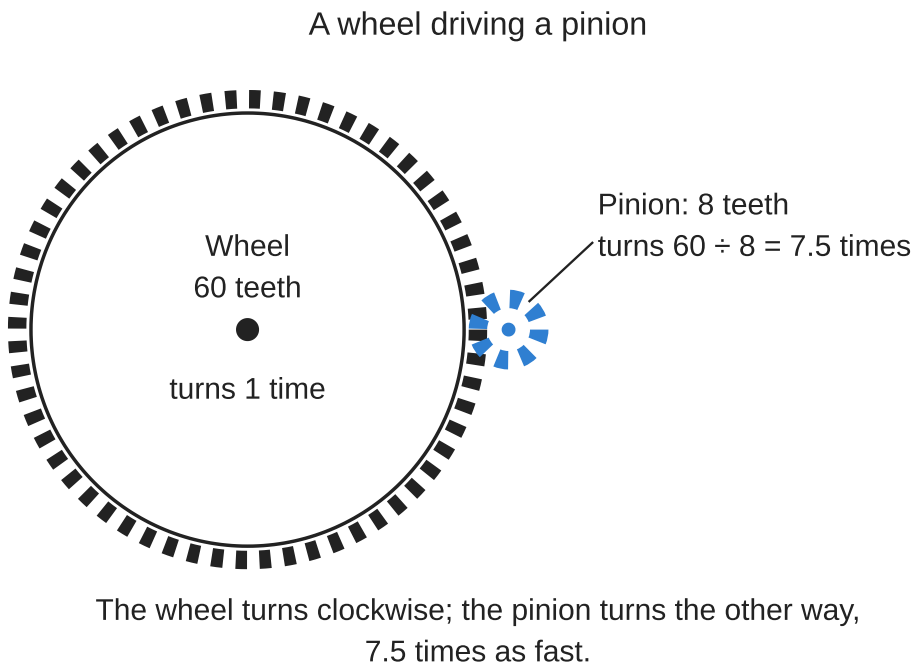
How he figured it out. Paley’s answer was that when we look inside the watch, we see something we never see in the stone: its parts are shaped and put together for a purpose. A coiled spring stores the push. A train of toothed wheels passes the motion along and divides it into seconds, minutes and hours. The hands point to the time, and a glass cover lets us read them while keeping out dust. If the parts were a different shape or size, or were put together in any other order, the watch would either not move at all or would not tell time. So, Paley concluded, the watch had a maker who understood how it would work and designed it for that use. Then he tested his own argument against objections. Would it matter if we had never seen a watch being made? No. Would it matter if the watch ran slow, or if we could not tell what one small part was for? No; a flawed or puzzling machine still shows design. What if the watch could build another watch? That, he said, would only make us admire its maker more.

The big idea. Paley’s reasoning is a **design argument**, and it has four steps. (1) Observe the parts. (2) Notice that they fit and work together to do a job, which Paley called a **contrivance**. (3) In every case where we know how such an arrangement came to be, a mind made it. (4) Living things are full of such arrangements, far finer than any watch, so they too point to a Designer. Notice that Paley did not say, “It is complicated, so God made it.” A rockslide is complicated. The clue is complexity that serves a **function**. After his opening chapters, Paley spent most of the book on living examples: the eye, which he compared with a telescope, the hinges of the joints, the muscles, and the wings and stings of insects. This kind of reasoning is an **inference to the best explanation**: we choose the cause that best accounts for what we see.

Weighing the argument. Paley’s argument has serious critics, and an honest student should know them. The Scottish philosopher David Hume, in his *Dialogues Concerning Natural Religion* (published in 1779, before Paley wrote), argued that the **analogy** between a machine and the world is weak: we have watched watches being made, but no one has ever watched a world being made. The greatest challenge came from Charles Darwin. As a student at Cambridge from 1828 to 1831, Darwin read Paley closely and later said he had hardly ever admired a book more. But in *On the Origin of Species* (1859) he proposed that natural selection, acting on small differences over many generations, could build living structures that look designed without anyone planning them. In his autobiography Darwin wrote that Paley’s argument, which had once seemed so convincing to him, failed once

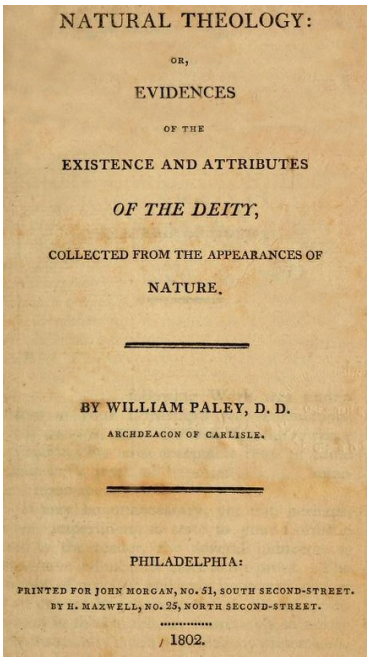
natural selection was discovered. Defenders of design answer with questions. Natural selection can sort variation that already exists, as with the finches and dogs of Unit 3, but can it build a whole new system of working parts? And selection works only on living things that already reproduce, so it cannot explain how the first living cell came to be. The next three lessons put these questions to the test with the eye, a motor inside a bacterium and the setting of the universe itself.

God's handiwork. The design argument did not begin with Paley. The psalmist sang that "the heavens declare the glory of God" (Psalm 19:1), and Paul wrote that God's eternal power is "clearly seen, being understood by the things that are made" (Romans 1:20). Paley's gift was to make that old argument concrete and to fill it with careful observations. Every time you open a watch, look at a beetle's wing case or take apart a flower, you can ask his question: what are these parts for, and how did they come to fit together so well?



A watch is full of wheel-and-pinion pairs like this one. The number of teeth decides how fast each part turns.

PICTURE STUDY



NATURAL THEOLOGY:

OR,

EVIDENCES

OF THE

EXISTENCE AND ATTRIBUTES

OF THE DEITY,

COLLECTED FROM THE APPEARANCES OF

NATURE.

BY WILLIAM PALEY, D. D.

ARCHDEACON OF CARLISLE.

PHILADELPHIA:

PRINTED FOR JOHN MORGAN, NO. 51, SOUTH SECOND-STREET.
BY H. MAXWELL, NO. 25, NORTH SECOND-STREET.

1802.

Title page of Natural Theology, William Paley (author); printed title page of the first edition, 1802 · Printed book page (letterpress) · First edition, London, 1802; copies in many university and national libraries, with scans online

Before books had colorful covers, a book introduced itself on its title page. Printers used type of different sizes so the most important words stood out, and authors often put a summary of the whole argument into a long title. Paley's title tells you exactly what he set out to do: to collect evidence for the existence and character of God from "the appearances of nature."

This book was read by students for decades. Charles Darwin studied Paley's books at Cambridge, and many naturalists of the 1800s were first drawn to nature by Paley's careful descriptions of eyes, joints and insects. When you look at this page, you are looking at the front door of one of the most influential science books of its century.

Look closely

- Find the shortest, largest words on the page. Why do you think the printer made them the biggest?
- Read the full title slowly. Which words tell you what Paley thought nature was evidence for?
- Find Paley's name and the title of his church office after it. The letters "D.D." stand for Doctor of Divinity.
- Find the city and the year. How many years after this page was printed was Darwin born? (Darwin was born in 1809.)

Talk about it

1. If you wrote a book about one living thing that amazed you, what long, old-style title would you give it?
2. Why might a book that begins with a watch on a heath still be read and argued about more than two hundred years later?
3. Paley called his evidence “appearances.” Does something that appears designed have to be designed? What would you need to know to decide?

EXPERIMENT: THE SHAKE TEST

Paley said that if the parts of a watch were put together in any other order, it would not work. You will test a simpler machine, a click pen, to see whether its parts can fall into working order by chance. Then you will compare the result with how long it takes a person who understands the pen to build it.

You will need

- A retractable click pen that you are allowed to take apart (ask a parent which one)
- A zip-top bag or a plastic jar with a lid
- A timer, a ruler and a lab notebook
- A paper towel to lay out the parts

Steps

1. Take the pen apart over the paper towel. Lay the parts in a line in the order they go together. Usually there are five: the front barrel, the spring, the ink refill, the click button parts and the back barrel. Draw and label each part and write one sentence about its job.
2. Write your question: Will shaking the pen’s parts in a bag put them together in working order?
3. Write a prediction. How many shakes do you think it would take?
4. Variables: what you change is the number of shakes. What you keep the same is the bag, the parts and the strength of each shake (one firm shake per second). What you measure is the number of correct connections (a part fitted onto the next part the right way). With five parts in a line there are four connections.
5. Run 10 trials of 100 shakes each. After each trial, open the bag without disturbing the parts and count correct connections. Record each trial in a table.
6. Now time yourself putting the pen together on purpose. Record the time in seconds.
7. Make a bar graph of correct connections for each trial. Then write three sentences: What happened when the parts were shaken? What did you have to know to build the pen? What does this suggest about Paley’s claim, and what can it not prove?

Tips

- Count a connection only if the part is fully seated and facing the right way.
- Be fair to the other side: a pen is not alive and cannot reproduce, so this test says nothing directly about natural selection. It tests only Paley’s point about parts falling

together by chance.

Check your work

- I named what I changed, what I kept the same and what I measured.
- I recorded 10 trials and graphed the results.
- I can explain what my test shows and what it does not show.

NATURE NOTEBOOK

1. Draw the inside of a mechanical watch or clock (from a real one, a library book or a museum photo). Label the mainspring, at least two gear wheels, the balance wheel and the hands, and write the job of each.
2. Make a T-chart titled “Stone or Watch?” List at least four differences Paley would point to between the two.
3. Draw an exploded view of your click pen, with the parts spread out along a line in assembly order and arrows showing how they fit together.

> **From history.** Paley’s watch was not a brand-new image. A Dutch writer, Bernard Nieuwentyt, had used a watch found in a field in a book first published in 1715 and later translated into English as *The Religious Philosopher*. What made Paley’s version last was his clear writing and the hundreds of careful observations of living things that filled the rest of his book. Paley’s other books were also read at Cambridge, and Darwin had to study his *Evidences of Christianity* to pass his degree examinations in 1831, just months before he sailed on HMS *Beagle*.

WORKED EXAMPLES

Example 1. In a watch, a wheel with 60 teeth drives a small gear, called a pinion, with 8 teeth. When the wheel turns once, how many times does the pinion turn? If the pinion's axle carries a second wheel of 64 teeth that drives another 8-tooth pinion, how many times does the last pinion turn for one turn of the first wheel?

(Use the map or drawing "Teeth on the wheel ÷ teeth on the pinion = turns of the pinion per turn of the w" shown earlier in this lesson.)

1. Each tooth of the wheel pushes one tooth of the pinion. One turn of the wheel moves 60 teeth past the pinion.
2. The pinion turns once for every 8 teeth: 60 ÷ 8 = 7.5 turns.
3. The second wheel is on the same axle, so it also turns 7.5 times. Each of its turns moves 64 teeth: 64 ÷ 8 = 8 turns of the last pinion per turn of the second wheel.
4. Multiply the two steps: 7.5 × 8 = 60 turns.
5. This is how a watch makes a hand that turns once an hour drive a hand that turns once a minute: 60 turns for 1.

Answer: The first pinion turns 7.5 times; the last pinion turns 60 times for each turn of the first wheel.

Example 2. Many mechanical watches "beat" (tick) 18,000 times per hour. How many beats is that per minute, per second and per day?

1. Per minute: 18,000 ÷ 60 = 300 beats.
2. Per second: 300 ÷ 60 = 5 beats.
3. Per day: 18,000 × 24 = 432,000 beats.
4. Check: 5 beats per second × 86,400 seconds in a day = 432,000. The two methods agree.

Answer: 300 beats per minute, 5 beats per second and 432,000 beats per day.

Example 3. A click pen has 5 parts that work only in one order along a line. If the parts were lined up in a random order, how many different orders are possible, and what is the chance of the working order? If each part could also face either of two directions, how many arrangements are there?

1. Any of the 5 parts could go first, then any of the 4 left, then 3, then 2, then 1.
2. Orders = 5 × 4 × 3 × 2 × 1 = 120. Only 1 works, so the chance is 1 in 120, about 0.83%.
3. Each part can also face 2 ways: 2 × 2 × 2 × 2 × 2 = 32 ways to face them.
4. Total arrangements = 120 × 32 = 3,840, so the chance of a working pen is 1 in 3,840, about 0.026%.
5. And this assumes the parts are already made in the right shapes. Paley's point was that the shapes themselves are fitted to one another.

Answer: 120 orders (1 in 120 chance); with two directions per part, 3,840 arrangements (1 in 3,840).

PRACTICE

1. EASY In Paley's opening, what object did he compare with the watch, and what did he say he might answer about it?
2. EASY Give the title, author and year of the book that made the watch argument famous.
3. EASY Paley said complexity alone is not the clue to design. What is the clue?
4. MEDIUM A wheel with 48 teeth drives a pinion with 6 teeth. How many times does the pinion turn when the wheel turns 3 times?
5. MEDIUM Data reading. Sample data for four watches:
   Watch A: 14,400 beats per hour; average error 30 seconds per day.
   Watch B: 18,000 beats per hour; average error 20 seconds per day.
   Watch C: 21,600 beats per hour; average error 12 seconds per day.
   Watch D: 28,800 beats per hour; average error 8 seconds per day.
   (a) How many beats per second does Watch C make? (b) Which statement is best supported? (i) In this sample, watches with higher beat rates had smaller average errors. (ii) A fast beat rate guarantees a perfect watch. (iii) Watch A was not designed. (iv) The data show no pattern.
6. MEDIUM Data reading. A student ran the Shake Test with a five-part pen: 10 trials of 100 shakes. Correct connections (out of 4) in each trial were: 0, 1, 0, 0, 0, 1, 0, 0, 0, 0. (a) In what percent of trials was there at least one correct connection? (b) How many fully assembled pens resulted? (c) Write one conclusion the data support and one they do not.
7. MEDIUM A toy has 4 parts that must go together in one order. How many orders are possible, and what is the chance that a random order works?
8. HARD Explain David Hume's objection to the design argument in your own words, and give one way a defender of design might answer it.

9. HARD Experiment design. Design a test of whether a nut, a bolt and a washer will screw together into working order if shaken in a jar. Name the independent variable, the dependent variable, three things to keep the same, how many trials you would run and what result would count as “assembled.”
10. CHALLENGE Darwin wrote that Paley’s argument failed once natural selection was discovered. Explain what Darwin meant, then give two questions a defender of design would ask in reply.

COMMON MISTAKES

- Thinking Paley’s argument is simply “it is complicated, so God made it.” Paley pointed to parts fitted together for a purpose, not to complexity alone. A pile of rocks is complicated but serves no function.
- Thinking that a flaw or a part we do not understand proves there was no designer. Paley answered this himself: a watch that runs slow, or has a part whose job we cannot guess, was still made by a watchmaker.
- Thinking the design argument began with Paley, or that Darwin ignored it. It is far older (Psalm 19:1; Romans 1:20; the Roman writer Cicero used a sundial as an example), and Darwin admired Paley and took his argument seriously enough to answer it.

Make it a game · Watch or Stone?. A parent names an object: a key, a seashell, a snowflake, a bird’s nest, a honeycomb, a quartz crystal, a bicycle, a beaver dam, an eye. You have ten seconds to say “watch” (parts fitted for a purpose) or “stone” (no sign of fitted parts) and give your clue. Tricky ones earn a bonus point if you explain them well: a snowflake is orderly but has no moving parts working toward a job, and a bird’s nest was built on purpose by the bird. Play to ten points.

Scripture. “For the invisible things of him from the creation of the world are clearly seen, being understood by the things that are made, even his eternal power and Godhead; so that they are without excuse:” (Romans 1:20, KJV)

Paul says the things that are made point beyond themselves to their Maker. Paley tried to show that idea in detail, one contrivance at a time. Whatever you think of his argument, it is good to look at the created world long enough to ask what it says about the One who made it.

Practice answers

1. A stone lying on a heath. He said that, for all he knew, it might have lain there forever; he would not give that answer about a watch.
2. *Natural Theology* by William Paley, 1802.
3. Parts that are shaped and arranged to work together for a purpose or function (a contrivance), so that changing their shape, size or order would stop them working.
4. 48 ÷ 6 = 8 pinion turns per wheel turn, so 8 × 3 = 24 turns.

5. (a) 21,600 ÷ 3,600 = 6 beats per second. (b) (i). Error falls as the beat rate rises in all four watches. (ii) goes beyond the data, since even Watch D has an error; (iii) confuses accuracy with design, as Paley himself warned; (iv) ignores a clear pattern.
6. (a) 2 of 10 trials = 20%. (b) None. (c) Supported: in 1,000 total shakes, random shaking never assembled the pen and rarely made even one connection. Not supported: that it is impossible for the parts ever to assemble by chance; the test only shows it is very unlikely in this many tries.
7. 4 × 3 × 2 × 1 = 24 orders; the chance is 1 in 24, about 4.2%.
8. Hume said the comparison between a machine and the world (or a living thing) is weak, because we have seen watches being made but have never seen a world or a living thing being made, so we cannot be sure the same kind of cause applies. A defender could answer that we often reason to causes we did not watch, as a detective or an archaeologist does, and that in every case where we do know the cause of parts fitted together for a function, it is a mind.
9. Independent variable: the number of shakes (for example 50, 100, 200). Dependent variable: whether the parts are assembled (washer on the bolt and nut threaded on at least one full turn). Keep the same: the jar, the same nut, bolt and washer, the strength and speed of shaking, and the person shaking. Run at least 10 trials for each number of shakes. “Assembled” must be defined before starting, such as the nut threaded at least one turn with the washer between it and the bolt head.
10. Darwin meant that natural selection, by keeping small helpful differences over many generations, could produce living structures that look designed without a designer planning each one, so the appearance of design would no longer require a maker. A defender would ask: (1) Has natural selection been observed building a new system of many working parts, or only sorting variation that already exists, as in finch beaks? (2) Since selection works only on living things that already reproduce, how did the first reproducing cell, with all its parts, come to be?

4.2 The Eye

OBJECTIVES

- Name the main parts of the human eye, give the job of each, and trace the path of light from the cornea to the brain.
- Use ratios and similar triangles to calculate how much more light a wide pupil admits, the ratio of rods to cones, and the size of an image on the retina.
- Explain fairly Darwin's step-by-step account of the eye, the design response, and both sides of the debate over the "backward" retina.

Warm-up. Find your blind spot. On an index card, draw a small X near the left edge and a solid dot about 6 centimeters to the right of it. Hold the card at arm's length, close your left eye and stare at the X with your right eye. Slowly bring the card toward your face. At some distance (often around 20 centimeters) the dot vanishes. Measure that distance with a ruler. Why would part of your eye be unable to see?

Video. Coming soon. How the human eye focuses light (cornea, lens, retina, rods and cones, blind spot) and how a pinhole camera works; search university anatomy and optics channels, eye-doctor education channels, Science Max, Homeschool Pop (Alternate) and Moody Science classics.

KEY TERMS

cornea
The clear, curved front window of the eye. It does about two-thirds of the bending of light that focuses an image.

iris and pupil
The iris is the colored ring of muscle in the eye; the pupil is the opening in its center. The iris widens or narrows the pupil to let in more or less light.

lens
A clear, flexible structure behind the pupil that changes shape to fine-tune the focus for near or far objects.

retina
The thin layer at the back of the eye where light is changed into nerve signals.

rods and cones
The light-sensing cells of the retina. Rods work in dim light; cones sense color and fine detail in bright light.

optic nerve
The bundle of about a million nerve fibers that carries signals from the retina to the brain. Where it leaves the eye there are no rods or cones, which makes the blind spot.

CORE IDEAS

The story. In 1604 Johannes Kepler, the imperial mathematician in Prague, published a book on light with a modest Latin title, *Ad Vitellionem Paralipomena* ("Additions to Witelo," a medieval writer on optics). Kepler is famous for discovering how the planets move, but here he solved a puzzle about the eye that scholars had argued over for centuries. Many had thought that seeing happened inside the lens. Kepler showed that the front of the eye and the lens bend the rays of light coming from each point of an object and bring them together again at a point on the **retina**, the thin layer at the back of the eye. The result is a tiny picture of the world on the retina, and it is upside down. Kepler honestly admitted he could not explain how we then see the world right side up.

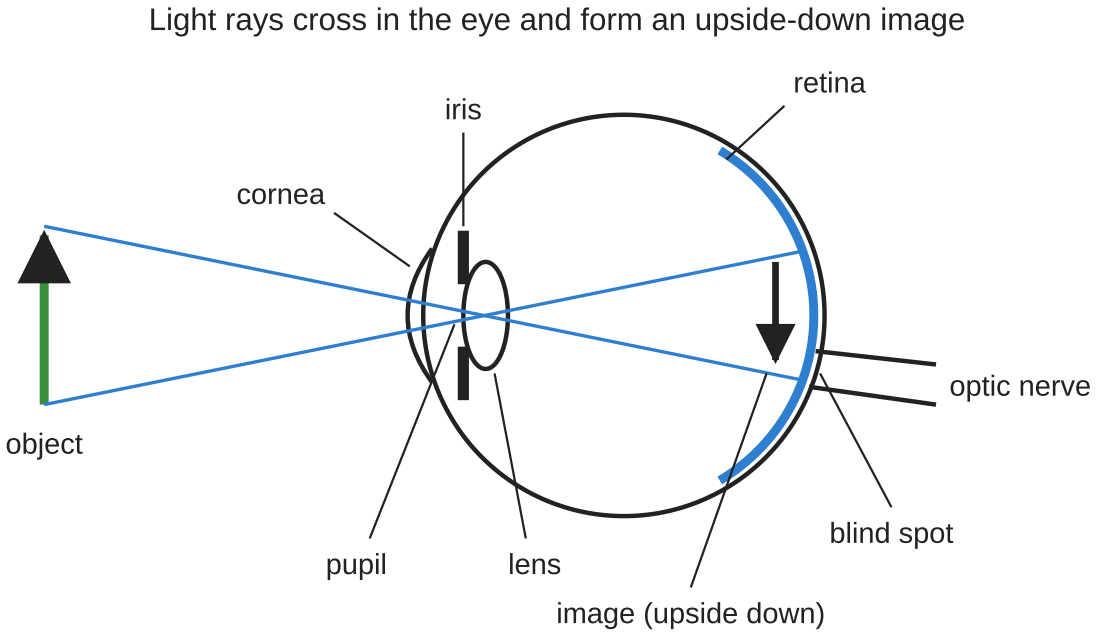
How they figured it out. Kepler's idea was soon checked by experiment. The Jesuit astronomer Christoph Scheiner carefully removed the back layers of an animal's eye and looked at the thin layer left behind: on it was a small, upside-down image of the scene in front of the eye. René Descartes described the same experiment in 1637. Today we know the path of light in detail. It first passes through the **cornea**, which does about two-thirds of the bending. Next it goes through the **pupil**, the opening in the colored **iris**, which can widen from about 2 millimeters across in bright light to about 8 millimeters in the dark. The **lens** fine-tunes the focus by changing shape. On the retina, about 120 million **rods** work in dim light and about 6 million **cones** sense color and fine detail; the cones are packed most tightly in a small central pit called the fovea. Signals leave through the **optic nerve**, and the brain turns the upside-down image into the right-side-up world we see.

The big idea. The eye is a system: many parts, each with a job, all working together. A cloudy cornea, a lens that cannot focus, a retina without rods and cones, or a cut optic nerve each means no clear sight. Helpers keep the eye working: eyelids blink about 15 to 20 times a minute, tears wash and protect the cornea, and six small muscles aim each eye so both point at the same thing. Paley gave a whole chapter of *Natural Theology* (1802) to the eye. If a telescope was plainly made to help us see, he argued, then the eye, which adjusts for brightness and distance better than any telescope of his day, was plainly made for seeing.

Two ways to read the eye. Darwin knew the eye was a hard case for his theory. In 1859 he wrote: "To suppose that the eye, with all its inimitable contrivances for adjusting the focus to different distances, for admitting different amounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I freely confess, absurd in the highest possible degree." Then he argued that the difficulty could be overcome if numerous gradations from a simple eye to a complex one could be shown, each useful to its owner, beginning with little more than a nerve coated with pigment. Biologists today often illustrate such a series with eyes of living animals: a light-sensitive spot, a cup that tells the direction of light (as in flatworms), a pinhole eye with no lens (as in the chambered nautilus), and a camera eye with a lens. Mainstream biologists see such a series as a possible path. Design advocates answer that these eyes belong to living animals, each complete for its own way of life, not to a proven line of ancestors, and that even a simple light-sensitive spot needs special light-catching proteins and a chain of chemical steps to turn light into a nerve signal.

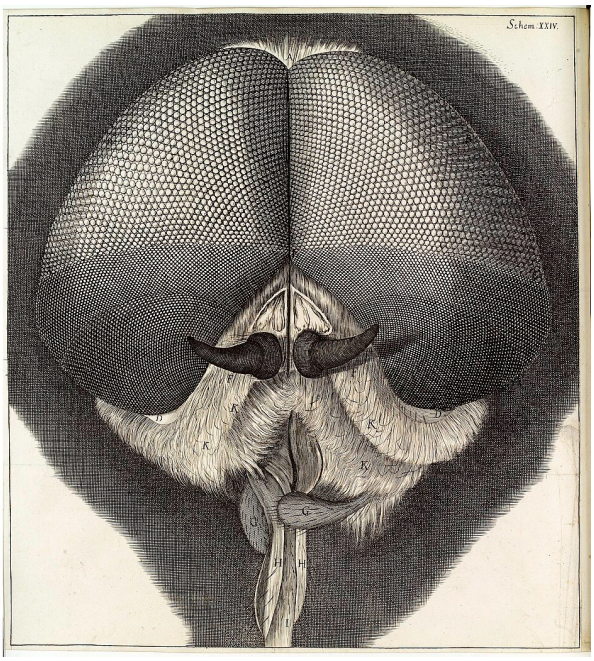
The “backward” retina. Some critics say the human eye is wired backward, because light passes through layers of nerve cells and blood vessels before it reaches the rods and cones, and the place where the nerve fibers leave the eye has no receptors at all: the blind spot. Researchers have found reasons for the arrangement. Rods and cones use energy very quickly, and facing backward puts them right against a dark pigment layer and a rich blood supply that feed them, soak up stray light and recycle the worn tips that rods shed every day. In 2007 a team of researchers in Germany reported that long cells in the retina called Müller cells act like optical fibers, guiding light through the layers to the receptors. And with two eyes, each eye covers the other’s blind spot.

God’s handiwork. The psalmist asked, “He that formed the eye, shall he not see?” (Psalm 94:9). As you read this sentence, millions of cells in your eyes are catching light and sending signals to your brain. Whatever you conclude about how the eye came to be, it deserves the careful wonder that Kepler gave it.



Light from the top of an object lands at the bottom of the retina, so the image is upside down. The brain turns it right side up.

PICTURE STUDY



Head and eyes of a drone fly, from Micrographia, Robert Hooke, 1665 · Engraving · Published in Robert Hooke, *Micrographia* (London: Royal Society, 1665); copies in many libraries, with scans online

Photo: Wellcome Collection · CC BY 4.0 (https://creativecommons.org/licenses/by/4.0) · via Wikimedia Commons

Robert Hooke was the Royal Society's curator of experiments in London. In 1665 he published *Micrographia*, the first great book of drawings made through a microscope, with large fold-out engravings of fleas, lice, mold and the cork cells that gave us the word "cell." In one observation he examined the eyes and head of a grey drone fly.

Hooke saw that a fly's eye is built very differently from ours. Instead of one lens and one retina, it is a **compound eye** made of thousands of tiny units, each with its own little lens, which looked to him like rows of pearls. Each unit catches light from one small patch of the world, and together they make a mosaic picture. A fly sees fine detail poorly but notices motion very quickly, which is why it is so hard to swat.

Look closely

- Find the two large eyes. What fraction of the whole head do they cover?
- Look at the surface of each eye. Describe the pattern of the tiny bumps.
- Find the parts of the head that are not eyes, such as the mouthparts or hairs. How did Hooke show texture with only black lines?
- Compare this eye with the human eye diagram in this lesson. Where would you find the lens in each?

Talk about it

1. Why might a fly's many-lensed eye suit its life better than an eye like ours would?

2. A camera eye and a compound eye solve the same problem in very different ways. What does that suggest to you about the variety in creation?
3. Hooke had to draw what he saw through a dim, wobbly microscope. What skills would a scientist need to make a drawing this careful?

> **Safety first.** Never look at the sun, directly or through any tube, pinhole, lens or magnifying glass; it can permanently damage your eyes in seconds. Point your viewer at a bright window scene or a lamp, not the sun. Let an adult do any cutting with a craft knife, and handle pins carefully.

EXPERIMENT: BUILD A PINHOLE EYE

Kepler said the eye forms an upside-down image on the retina. You will build a model eye from a tube, foil and wax paper, prove that the image is upside down, and test how the size of the opening (like the pupil) changes the brightness and sharpness of the image.

You will need

- A cardboard tube at least 25 centimeters long, or a tall potato-chip can
- Aluminum foil, wax paper, tape and a rubber band
- A straight pin, a thumbtack, a small nail and a pencil, for holes of different sizes
- A ruler, scissors and a lab notebook
- A dark towel or jacket to drape over your head (optional)
- A magnifying glass (optional, for the bonus step)

Steps

1. Have an adult cut the tube about 5 centimeters from one end. The short piece is the “eyeball”; the long piece is a light shield.
2. Cover the far end of the short piece with foil and make a tiny hole in the center with the straight pin. This is the “pupil.”
3. Stretch wax paper over the cut end of the short piece and hold it with tape or a rubber band. This is the “retina.” Tape the long piece back on, so the wax paper is inside the tube.
4. Look into the open end of the long piece while pointing the pinhole at a bright window scene or a lamp (never the sun). Drape a towel over your head to block extra light. Draw what you see. Is it upside down? Is left and right also swapped?
5. Write your question: How does the size of the pinhole affect the brightness and sharpness of the image? Write a prediction.
6. Variables: what you change is the hole size (pin, thumbtack, nail, pencil). What you keep the same is the scene, the time of day, the tube and the viewer. What you measure is brightness and sharpness, each rated from 1 (worst) to 5 (best). Make a fresh foil cap for each hole size, and measure each hole’s width in millimeters with a ruler.
7. Record each rating in a table and make a double bar graph of brightness and sharpness for each hole size.

8. Bonus: with the largest hole, hold the magnifying glass in front of the opening and move it slowly until the image becomes sharp. What part of the eye does the magnifying glass act like?
9. Write three sentences: What happened to brightness and to sharpness as the hole grew? Why does a real eye need both a pupil and a lens?

Tips

- Ratings are a judgment, so have two people rate each image without seeing each other’s scores, then average them.
- A small hole makes a sharp but dim image; a large hole makes a bright but blurry one. A lens lets an eye have both brightness and sharpness.

Check your work

- I showed that the image in my model eye is upside down.
- I named what I changed, what I kept the same and what I measured, and graphed my results.
- I can explain why an eye with a lens works better than a pinhole.

NATURE NOTEBOOK

1. Copy the eye diagram from memory, then check it against the figure. Label the cornea, iris, pupil, lens, retina, optic nerve and blind spot, and write each part’s job in five words or fewer.
2. Look closely at a family member’s eyes in a dim room, then have them look toward a bright window. Sketch the pupil both times and record its approximate diameter in millimeters.
3. Draw four eyes side by side, in the order of the series described in this lesson: a light-sensitive spot, a cup eye, a pinhole eye and a camera eye with a lens. Under each, write one animal that has it and what it can and cannot do.

> **From history.** Kepler’s own eyesight was poor because of smallpox in childhood, yet he did more than anyone of his time to explain how eyes and lenses work. In 1611, after Galileo turned the telescope to the sky, Kepler published another book, *Dioptrice*, which explained how telescopes form images and described a new design with two convex lenses. That design, now called the Keplerian telescope, became the pattern for most astronomical telescopes that followed.

WORKED EXAMPLES

Example 1. In bright sunlight a pupil may be 2 millimeters across; in the dark it may open to 8 millimeters. How many times more light can the wide pupil admit?

1. Light admitted depends on the area of the opening. Area of a circle = π × radius².
2. Narrow pupil: radius 1 mm, so area = 3.14 × 1² = 3.14 mm².
3. Wide pupil: radius 4 mm, so area = 3.14 × 4² = 3.14 × 16 = 50.2 mm².
4. Ratio = 50.2 ÷ 3.14 = 16. (Shortcut: the diameter is 4 times larger, and 4² = 16.)

Answer: The 8 mm pupil admits about 16 times as much light as the 2 mm pupil.

Example 2. A human retina has about 120 million rods and about 6 million cones. What is the ratio of rods to cones? What percent of the receptors are cones? If the optic nerve has about 1 million fibers, about how many receptors share each fiber, on average?

1. Ratio of rods to cones: 120,000,000 ÷ 6,000,000 = 20, so 20 to 1.
2. Total receptors: 120 million + 6 million = 126 million.
3. Percent cones: 6 ÷ 126 × 100 ≈ 4.8%.
4. Receptors per fiber: 126,000,000 ÷ 1,000,000 = 126. The retina's own nerve cells combine and process signals before they leave the eye.

Answer: Rods to cones is 20 to 1; cones are about 4.8% of receptors; about 126 receptors share each optic nerve fiber on average.

Example 3. A tree 10 meters tall stands 20 meters from you. In a simple model of the eye, light rays cross at a point about 17 millimeters in front of the retina. How tall is the image of the tree on your retina, and which way up is it?

(Use the map or drawing "The two crossing rays form two similar triangles, one outside the eye and one in" shown earlier in this lesson.)

1. The rays make two similar triangles that meet at the crossing point, so image height ÷ image distance = object height ÷ object distance.
2. Use the same units: 10 m = 10,000 mm; 20 m = 20,000 mm.
3. Image height = 17 mm × (10,000 ÷ 20,000) = 17 mm × 0.5 = 8.5 mm.
4. The rays cross, so the top of the tree lands at the bottom of the retina: the image is upside down.

Answer: About 8.5 millimeters tall, and upside down.

PRACTICE

1. EASY Which part of the eye does most of the bending of light: the lens or the cornea?
2. EASY What is the difference between rods and cones?
3. EASY Who first explained, in 1604, that the eye forms an upside-down image on the retina?
4. MEDIUM A pupil widens from 3 millimeters to 6 millimeters across. How many times more light can it admit?
5. MEDIUM Data reading.
   Flatworm (planarian): cup eye; no lens; senses the direction of light but forms no image.
   Chambered nautilus: pinhole eye; no lens; forms a dim, blurry image.
   Octopus: camera eye; has a lens; forms a sharp image.
   Human: camera eye; has a lens; forms a sharp image.
   (a) Which statement is best supported by the table alone? (i) The animals in this table with a lens form sharp images. (ii) The nautilus is the ancestor of the octopus. (iii) Flatworms cannot sense light. (iv) Pinhole eyes are sharper than camera eyes. (b) Why can the table not show by itself whether one eye type came from another?
6. MEDIUM Data reading. Sample data for one person’s pupil diameter:
   Bright sunlight: 2 mm. Indoor room: 4 mm. Dim evening: 6 mm. Dark room: 8 mm.
   (a) Describe the trend. (b) How many times more light does the pupil admit in the dark room than in the indoor room? (c) Name the independent and dependent variables.
7. MEDIUM A person 1.7 meters tall stands 10 meters away. Using 17 millimeters for the distance from the crossing point to the retina, how tall is the person’s image on the retina?
8. HARD Explain the argument that the human retina is “wired backward,” then give two reasons researchers have found for the arrangement.
9. HARD Experiment design. Design an experiment to test whether people’s blind-spot distance (the distance at which the dot vanishes in the warm-up test) depends on the spacing between the X and the dot. Name the variables, the controls and how you would record the data.
10. CHALLENGE Darwin wrote that supposing the eye was formed by natural selection “seems, I freely confess, absurd in the highest possible degree.” Did Darwin think it was impossible? Explain his argument, then explain the design response.

COMMON MISTAKES

- Thinking the lens does all the focusing. The cornea does about two-thirds of the bending; the lens adjusts the focus for near and far.
- Thinking the image on the retina is right side up, or that the eye “sees” by itself. The image is upside down, and seeing happens when the brain interprets the signals from the retina.
- Thinking that a row of simple-to-complex eyes in living animals is the same as a record of ancestors. The animals are all alive today; ordering their eyes from simple to

complex is an interpretation, not a direct observation of change.

Make it a game · Follow the Light. One player is a ray of light. A parent calls out a part of the eye (cornea, pupil, lens, retina, optic nerve, brain), and the player must step to a paper sign for that part, placed in order across the room, and say its job. Calling a part out of order is a trick: the player must say what comes before and after it. Score a point for each correct step. For a bonus, explain what happens to a ray that lands on the blind spot.

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

The psalmist reasons from the eye to its Maker: the One who made seeing possible must Himself see. Nothing is hidden from Him, and the gift of sight is one of His daily kindnesses.

Practice answers

1. The cornea, about two-thirds of the bending. The lens fine-tunes the focus.
2. Rods work in dim light and do not sense color; cones work in brighter light and sense color and fine detail.
3. Johannes Kepler, in Prague.
4. The diameter doubles, so the area grows by $2^2 = 4$. It admits 4 times as much light.
5. (a) (i). Both animals with a lens form sharp images. (ii) is not in the table; (iii) is contradicted, since flatworms sense the direction of light; (iv) is backward. (b) The table describes eyes in animals living today. It shows a range from simple to complex, but it does not show any animal changing into another; that is an interpretation, not an observation in the table.
6. (a) As the light gets dimmer, the pupil gets wider. (b) $8 \div 4 = 2$ times the diameter, so $2^2 = 4$ times the light. (c) Independent: the brightness of the surroundings. Dependent: the pupil diameter.
7. 1.7 m = 1,700 mm and 10 m = 10,000 mm. Image = $17 \times (1{,}700 \div 10{,}000) = 17 \times 0.17 \approx 2.9$ mm, upside down.
8. Critics note that light must pass through nerve cells and blood vessels before reaching the rods and cones, and that the place where the nerve fibers exit has no receptors (the blind spot). Reasons found: (1) facing the back puts the energy-hungry receptors right against the pigment layer and blood supply that feed them, absorb stray light and recycle the tips rods shed daily; (2) Müller cells guide light through the retina like optical fibers. Also, two eyes cover each other’s blind spots.
9. Independent variable: the spacing between X and dot (for example 4, 6 and 8 cm). Dependent variable: the distance from eye to card when the dot vanishes, in centimeters. Keep the same: the same eye (right eye, left closed), the size of the X and dot, the lighting, the card and the speed of moving it. Test several people with three trials each, record in a table and average. Prediction: wider spacing gives a longer vanishing distance, because the blind spot lies at a fixed angle from the center of gaze.
10. No. Darwin was admitting how hard it seems, and then he argued that if a series of small steps from a simple light spot to a camera eye could exist, each useful to its owner, natural selection could build the eye. He pointed to simpler eyes in living animals as examples of such steps. The design response is that those simpler eyes belong to separate living animals, each

complete for its own life, not to a proven line of ancestors, and that even the simplest light-sensing spot needs special proteins and a chain of chemical steps, so the starting point is itself complex.

4.3 The Bacterial Flagellum and Irreducible Complexity

OBJECTIVES

- Describe the main parts of the bacterial flagellum (filament, hook, rod, rings, rotor and stator) and explain how it works as a rotary motor powered by flowing hydrogen ions.
- Calculate rotation rates, swimming speeds in body lengths per second, and sizes in a scale model of the flagellum.
- State Michael Behe's idea of irreducible complexity, test it on an everyday machine, and describe fairly the co-option objection and the design response.

Warm-up. Pick up a stapler, a flashlight or a click pen. List every part you can see or feel. Next to each part, guess: if this one part were missing, would the object still do its main job? Put a star by any part you think could be removed without stopping it. Keep the list for the project.

Video. Coming soon. The bacterial flagellum as a rotary motor (filament, hook, basal body, proton-driven stator) and E. coli run-and-tumble swimming; search university microbiology and molecular animation channels, microscope footage of swimming bacteria, and channels presenting both the irreducible complexity argument and its critics.

KEY TERMS

bacterium
A single-celled living thing with no nucleus. *Escherichia coli* (*E. coli*), which lives in the gut, is about 2 micrometers long. The plural is bacteria.

flagellum
A long, thin structure that a cell uses to swim. A bacterial flagellum spins like a propeller. The plural is flagella.

rotary motor
A motor in which one part (the rotor) spins inside a fixed part (the stator). The bacterial flagellum is driven by one.

irreducible complexity
Michael Behe's term for a single system of several well-matched parts that all work together for its basic job, so that removing any one part makes the system stop working.

co-option
The idea that a part that once did one job could be borrowed and combined with other parts to do a new job.

gene knockout

An experiment in which scientists disable one gene and watch what the living thing can no longer do. It shows which parts a system needs.

CORE IDEAS

The story. In 1996 Michael Behe, a biochemist at Lehigh University in Bethlehem, Pennsylvania, published *Darwin's Black Box*. A "black box" is a machine you can watch working but cannot see inside. In Darwin's day the cell was a black box; many thought its inside was simple jelly. By the 1990s biochemists could see inside, and Behe argued that what they found were machines. He went back to a test Darwin himself had set in 1859: "If it could be demonstrated that any complex organ existed, which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down." Behe proposed that some cell systems are **irreducibly complex**: several well-matched parts all work together for the basic job, so removing any one part stops the system. His everyday example was a mousetrap, with a base, spring, hammer, catch and holding bar. His most famous example from biology was the bacterial **flagellum**.

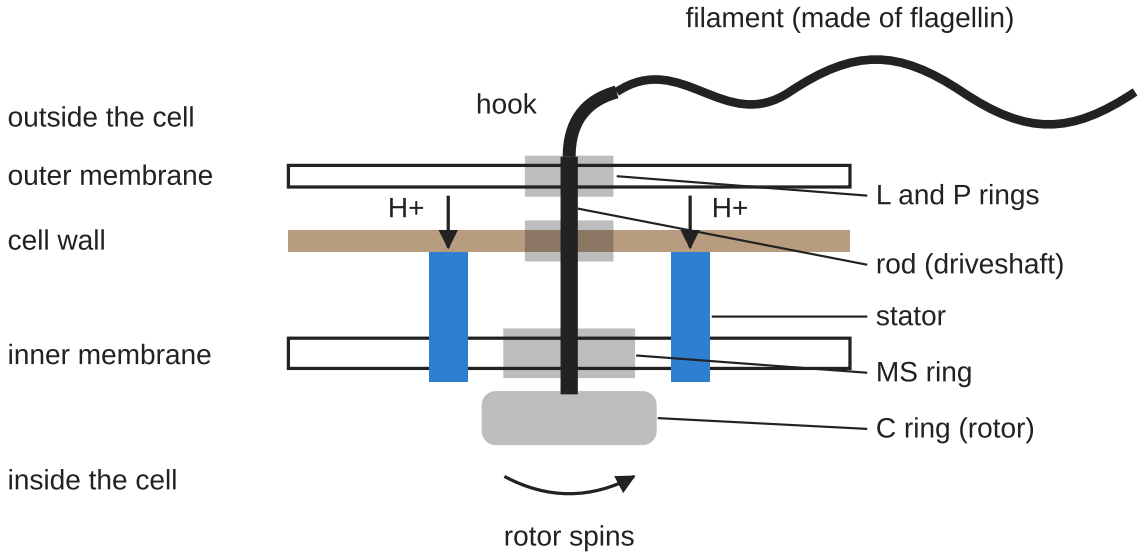
How they figured it out. Bacteria are tiny: about 500 *E. coli* cells laid end to end would span one millimeter. For a long time scientists thought bacterial flagella waved like whips. In 1973 the American biologists Howard Berg and Robert Anderson argued from the evidence then available that they rotate instead. In 1974 Michael Silverman and Melvin Simon showed it in a clever way: they fastened *E. coli* cells to a glass slide by a single flagellum, and under the microscope the whole cell spun round and round, now one way, now the other. The flagellum is driven by a true **rotary motor**, one of only a few known in living things.

The big idea. The flagellum of *E. coli* is built from about 40 kinds of proteins. The long, corkscrew filament, made of thousands of copies of a protein called flagellin, is only about 20 nanometers thick but up to about 10 micrometers long, several times longer than the cell. A short, curved hook works like a universal joint, letting the turning motion go around a bend. At the base, a rod like a driveshaft passes through rings that act like bushings in the outer membrane and cell wall. Stator units anchored to the cell wall push on the spinning rotor. The power comes from hydrogen ions (protons) flowing into the cell through the stators, somewhat like water turning a water wheel. The motor can spin about 100 turns per second and can reverse in a fraction of a second. When the flagella turn counterclockwise they bundle together and the cell swims straight (a "run"); when some turn clockwise the bundle flies apart and the cell tumbles and points a new way. Sensors on the cell tell the motor how often to reverse, steering the bacterium toward food. The flagellum even builds itself: new filament proteins travel up its hollow center and add on at the tip.

Weighing the argument. Behe pointed to **gene knockout** experiments: disable the gene for almost any core part, and the bacterium cannot swim. That, he argued, fits irreducible complexity and points to design. Many biologists disagree. Kenneth Miller of Brown University pointed out that about ten of the flagellum's proteins closely resemble the parts of a type III secretion system, a tiny needle that some disease-causing bacteria use to inject proteins into other cells. If some of the parts can do a different useful job, he argued, then parts might have been borrowed from other jobs and combined (**co-option**), so the whole

motor need not have appeared at once. Design advocates reply that showing a few parts can do another job is not the same as showing a step-by-step path to a whole working motor, with every step useful; that some gene studies suggest the needle came from the flagellum rather than the other way around; and that the parts must also be built in the right order at the right time. The debate continues, and you will meet it again in Unit 6.

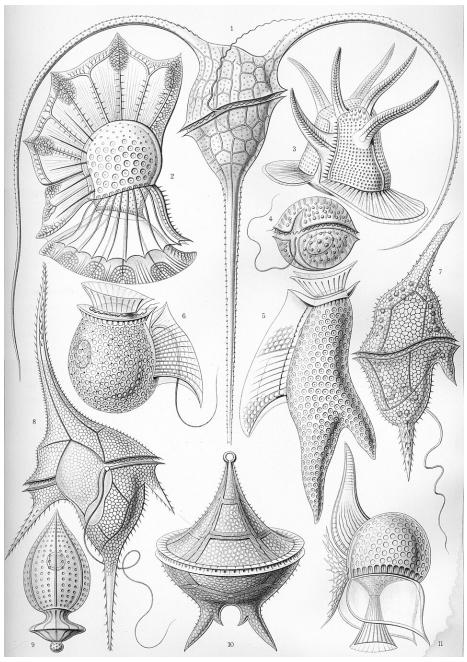
God's handiwork. Job was told, "ask now the beasts, and they shall teach thee" (Job 12:7). Today we can add the smallest living things to that list. Whether you finally agree with Behe or with his critics, a motor narrower than a wavelength of light, that spins, reverses and builds itself, is worth slowing down to admire.



Simplified, not to scale. H+ = hydrogen ions flowing into the cell.

The flagellar motor, simplified and not to scale. Hydrogen ions (H+) flowing through the stators turn the rotor, rod, hook and filament.

PICTURE STUDY



Peridinea (plate 14 of Art Forms in Nature), Ernst Haeckel, 1904 (published in parts from 1899) · Color lithograph · Ernst Haeckel, *Kunstformen der Natur* (Leipzig and Vienna: Bibliographisches Institut, 1899–1904); copies in many libraries

Ernst Haeckel was a German biologist and one of Darwin's best-known supporters, and also a gifted artist. In *Art Forms in Nature* he drew one hundred plates of living things, many of them too small to see without a microscope. This plate shows dinoflagellates, single-celled sea creatures with armored shells. Many glow at night when waves stir them.

Look closely and you will find thin threads: flagella. A dinoflagellate's flagella are different from a bacterium's. They are built inside the cell's membrane and beat or wave, while a bacterial flagellum is a stiff corkscrew outside the cell that spins like a propeller. Two very different machines do the same job of swimming.

Look closely

- Find three organisms with horns or spines. How might the shape help them float or keep from being eaten?
- Find a groove that wraps around the middle of a shell. Many dinoflagellates have a flagellum lying in that groove.
- Look at how Haeckel arranged the figures on the page. Is the pattern balanced? Why might an artist do that?
- Pick one organism and count its plates or grooves.

Talk about it

1. Haeckel saw nature as full of beautiful patterns. Do you think beauty is evidence of anything? Explain.

2. Why might two very different kinds of flagella both work well for swimming?
3. Haeckel's scientific views were very different from Paley's, but both men loved to look closely at living things. What can we learn from people we disagree with?

> **Safety first.** Use a simple flashlight with ordinary AA, C or D batteries. Never open, cut or puncture a battery, never connect its two ends with foil or wire, and do not use flashlights with built-in rechargeable batteries. Put all small parts back in a cup so they are not lost or swallowed by small children.

EXPERIMENT: THE KNOCKOUT TEST

Scientists test whether a system needs each part by knocking out one part at a time. You will do the same with a flashlight, then ask Kenneth Miller's question: could any of the removed parts do a different useful job on its own?

You will need

- A simple battery flashlight that unscrews (with a case, batteries, spring, switch, bulb or LED, reflector and clear front lens)
- A cup for small parts and a paper towel
- A lab notebook and pencil

Steps

1. Take the flashlight apart over the paper towel. Draw and label each part, and write its job in one sentence.
2. Write your question: Which parts can be removed while the flashlight still does its main job, shining a beam?
3. Before testing, write a prediction for each part: "needed" or "not needed." Define "working" ahead of time, for example: "It shines a spot of light on a wall 1 meter away."
4. Variables: what you change is which single part is left out. What you keep the same is everything else, including the same batteries and the same wall at 1 meter. What you measure is whether it shines (yes or no) and how bright the spot is (rate 0 to 5).
5. Put the flashlight together with all parts and test it. This is your control.
6. Remove one part, reassemble as well as you can and test. Record the result. Put the part back and repeat for the next part. Test every part one at a time.
7. Make a table with columns: Part removed, Still shines?, Brightness (0–5), Needed for basic job?
8. Co-option check: for each part, write one other useful job it could do on its own (for example, a battery could run a clock).
9. Write a paragraph: Which parts were needed for the basic job? Which were helpful but not needed? Is a flashlight irreducibly complex by Behe's definition? What does the co-option check add?

Tips

- Be careful to remove only one part per test, or you will not know which part caused the change.
- Some parts improve the job without being required, like the reflector, which makes the beam brighter. Behe's definition is about the basic job, so decide carefully what the basic job is.

Check your work

- I tested a control and every part one at a time.
- I recorded the results in a table and stated which parts were needed.
- I can explain both Behe's argument and the co-option objection using my flashlight.

NATURE NOTEBOOK

1. Draw the flagellar motor from the figure at a large size. Label the filament, hook, rod, rings, rotor and stator, and draw arrows showing the flow of hydrogen ions.
2. Draw two paths of an *E. coli* cell: one swimming in plain water (runs and tumbles in every direction) and one swimming toward a sugar crystal (longer runs toward the sugar).
3. Draw Behe's mousetrap with its five parts labeled. Beside it, draw one other object you think might be irreducibly complex and label its parts.

> **From history.** The first person ever to see bacteria was the Dutch cloth merchant and self-taught microscope maker Antonie van Leeuwenhoek of Delft. In the 1670s and 1680s, using tiny single-lens microscopes he ground himself, he described swarms of "little animals" in rainwater and in the scrapings from between his own teeth, and he sent his careful letters to the Royal Society in London. He could see them dart and tumble, but no microscope of his day could show the flagella that moved them.

WORKED EXAMPLES

Example 1. An *E. coli* flagellar motor spins about 100 turns per second. How many revolutions per minute (rpm) is that? A family car engine cruising on the highway may turn about 2,000 rpm. How many times faster is the flagellar motor?

1. There are 60 seconds in a minute: 100 turns per second × 60 = 6,000 turns per minute.
2. So the motor turns about 6,000 rpm.
3. Compare: 6,000 ÷ 2,000 = 3.

Answer: About 6,000 rpm, roughly 3 times as fast as a cruising car engine.

Example 2. An *E. coli* cell 2 micrometers long swims about 30 micrometers per second. How many body lengths per second is that? A strong human swimmer 1.8 meters tall swims about 2 meters per second. Compare.

1. Bacterium: 30 µm/s ÷ 2 µm = 15 body lengths per second.
2. Swimmer: 2 m/s ÷ 1.8 m ≈ 1.1 body lengths per second.
3. Ratio: 15 ÷ 1.1 ≈ 14.

Answer: The bacterium swims about 15 body lengths per second, roughly 14 times as many body lengths per second as a strong human swimmer.

Example 3. You build a scale model in which a 2-micrometer *E. coli* cell becomes 2 meters long. How much bigger is the model? In the model, how thick and how long is a filament that is really 20 nanometers thick and 10 micrometers long?

(Use the map or drawing "Use the scale factor to imagine each part one million times larger." shown earlier in this lesson.)

1. Scale factor: 2 m ÷ 2 µm. Since 1 m = 1,000,000 µm, 2 m = 2,000,000 µm, and 2,000,000 ÷ 2 = 1,000,000. The model is one million times bigger.
2. Filament thickness: 20 nm × 1,000,000 = 20,000,000 nm. Since 1 cm = 10,000,000 nm, that is 2 cm.
3. Filament length: 10 µm × 1,000,000 = 10,000,000 µm = 10 m.
4. Picture it: a 2-meter cell trailing several cords about as thick as a thumb and 10 meters long.

Answer: One million times bigger; the filament becomes about 2 centimeters thick and 10 meters long.

PRACTICE

1. EASY State Behe's idea of irreducible complexity in your own words, and name his everyday example.
2. EASY Name the three main sections of a bacterial flagellum, from the outside in.
3. EASY What powers the *E. coli* flagellar motor?
4. MEDIUM Some bacteria have flagellar motors that spin about 300 turns per second. How many rpm is that?
5. MEDIUM Data reading. Sample knockout results for *E. coli*:
   Normal cell: builds a filament; swims and tumbles.
   Flagellin gene knocked out: no filament; cannot swim.
   Hook gene knocked out: no hook or filament; cannot swim.
   Stator gene knocked out: builds a complete flagellum; cannot swim ("paralyzed").
   Steering-signal gene knocked out: builds a flagellum; swims in long runs but never

tumbles.
(a) Which results fit Behe's claim that core parts are each needed to swim? (b) Which result shows a part needed for steering but not for swimming? (c) What is the control?

6. MEDIUM Data reading. Sample data:
Bacterium A: length 2 µm; speed 30 µm/s.
Bacterium B: length 3 µm; speed 60 µm/s.
Bacterium C: length 5 µm; speed 50 µm/s.
(a) Find each speed in body lengths per second. (b) Which is fastest by actual speed, and which by body lengths? (c) Why do scientists often compare small swimmers in body lengths?
7. MEDIUM The flagellar hook is about 55 nanometers long. In the one-million-times scale model, how long is the hook?
8. HARD Explain the co-option objection to Behe's argument, using the type III secretion system, and give two replies from design advocates.
9. HARD Experiment design. Design an experiment to test whether *E. coli* swim toward sugar. You may use thin glass tubes, a microscope, a sugar solution and plain water. Name the independent and dependent variables, the control and two things to keep the same.
10. CHALLENGE Darwin wrote that his theory would "absolutely break down" if an organ were shown that "could not possibly" have formed by numerous, successive, slight modifications. Why is this test hard to settle in either direction? What kind of evidence would each side need?

COMMON MISTAKES

- Thinking a bacterial flagellum waves like a whip or a tail. It is a stiff corkscrew turned by a rotary motor at its base.
- Thinking irreducible complexity means "very complicated." It means that the basic job fails if any one of the core parts is missing; a complicated machine with many optional parts is not irreducibly complex.
- Thinking that showing some parts can do another job settles the debate either way. Co-option shows parts can be useful elsewhere; it does not by itself show a complete pathway, and the lack of a known pathway does not by itself prove there is none.

Make it a game · Knock It Out. A parent names a machine or living system: a bicycle, a mousetrap, a door lock, an eye, a flagellum, a pair of scissors. Name one part and say "knock it out!" You have ten seconds to say whether the basic job still works without that part and why. Score a point for each correct answer. A bonus point goes to the player who names a part that can be removed without stopping the job, since it shows not every part is required.

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)

Job is told to let living things be his teachers. The smallest creatures, invisible to Job, have their own lessons to teach about the hand that made them.

Practice answers

1. A system made of several well-matched parts that all work together for its basic job, so that taking away any one part makes it stop working. His everyday example was a snap mousetrap.
2. The filament (the long propeller), the hook (the flexible joint) and the basal body (the motor, with its rod, rings, rotor and stators).
3. The flow of hydrogen ions (protons) into the cell through the stator units.
4. 300 × 60 = 18,000 rpm.
5. (a) The flagellin, hook and stator knockouts: removing any one stops swimming. The stator result is especially telling, since the whole flagellum is built but cannot turn. (b) The steering-signal knockout: the cell still swims but cannot tumble to change direction. (c) The normal cell with no gene knocked out.
6. (a) A: 30 ÷ 2 = 15; B: 60 ÷ 3 = 20; C: 50 ÷ 5 = 10 body lengths per second. (b) B is fastest in both (60 µm/s and 20 body lengths per second); C is second by actual speed but slowest by body lengths. (c) Body lengths per second makes it fair to compare swimmers of very different sizes.
7. 55 nm × 1,000,000 = 55,000,000 nm = 5.5 cm (since 10,000,000 nm = 1 cm).
8. Kenneth Miller and others note that about ten flagellar proteins resemble parts of the type III secretion system, a needle some bacteria use to inject proteins into other cells. Since a subset of the parts does a different useful job, they argue, parts could have been borrowed from other systems and combined, so the whole flagellum did not need to arise at once. Replies: (1) showing that a few parts can do another job does not show a step-by-step path, each step useful, to a complete motor; (2) some gene studies suggest the needle came from the flagellum, not the reverse; also, the parts must be made in the right order at the right time.
9. Place thin tubes filled with liquid into a drop of swimming bacteria for a set time. Independent variable: what is in the tube (sugar solution vs. plain water). Dependent variable: the number of bacteria that swim into the tube, counted under the microscope. Control: the tube with plain water. Keep the same: the time (for example 30 minutes), the temperature, the tube size, the number of bacteria in each drop and the method of counting. Repeat several times.
10. It is hard to prove that something could not possibly have formed gradually, because someone can always propose a pathway not yet tested; but it is also hard to prove that it did form gradually unless a detailed path is shown. A critic of design would need a specific, step-by-step pathway in which each step is useful and could arise, ideally supported by experiments. A design advocate would need to show that every proposed pathway fails, for example because removing parts destroys function and no smaller version does anything useful. That is why the debate continues and both sides argue about where the burden of proof lies.

4.4 Fine-Tuning

OBJECTIVES

- Explain what scientists mean by fine-tuning and give examples from physics (carbon made in stars) and from life science (the properties of water and Earth's place near the sun).
- Calculate the volume change of freezing water, the energy needed to warm water and metals, and how sunlight weakens with distance.
- Compare fairly three responses to fine-tuning: design, many universes, and the anthropic principle.

Warm-up. Drop an ice cube into a clear glass of water and look at it from the side. About how much of the cube sits above the waterline: half, a quarter, or about one tenth? Now imagine that ice sank like most solids sink in their own liquid. Write two sentences about what would happen to a pond in a long, cold winter.

Video. Coming soon. Fine-tuning of the universe for life, Fred Hoyle's carbon prediction, and why ice floats (water's unusual properties); search NASA, university physics and chemistry channels, Science Max, Moody Science classics, and Christian science channels that explain the fine-tuning argument and its critics fairly.

KEY TERMS

fine-tuning
The observation that many features of nature, from the laws of physics to Earth's place near the sun, fall within narrow ranges that life requires.

physical constant
A number in the laws of nature that does not change, such as the strength of gravity or the charge of an electron.

density
How much mass is packed into a given volume: density = mass ÷ volume. Liquid water is about 1.00 g/cm^3 and ice about 0.917 g/cm^3, so ice floats.

specific heat
The energy needed to warm 1 gram of a substance by 1 °C. Water's is 4.18 joules per gram per degree, unusually high, so water warms and cools slowly.

habitable zone
The range of distances from a star where a planet's surface could be the right temperature for liquid water.

anthropic principle
The idea that we can only observe a universe that allows observers like us to exist, so we should expect to find one fit for life. The name was given by the physicist Brandon Carter in 1973.

CORE IDEAS

The story. Early in 1953 the English astronomer Fred Hoyle of Cambridge University walked into the Kellogg Radiation Laboratory at the California Institute of Technology in Pasadena with a bold prediction. Hoyle studied how stars make the elements. Carbon, the backbone of proteins, sugars, fats and DNA, forms in stars when three helium nuclei join together. By Hoyle's calculations this happened far too slowly to make the carbon we see, unless the carbon nucleus had a special energy level, a "resonance," at just the right value to speed up the reaction. Because carbon exists, Hoyle reasoned, the energy level must exist. The nuclear physicist William Fowler doubted it but let his team look. Within months they found the level almost exactly where Hoyle had said it would be.

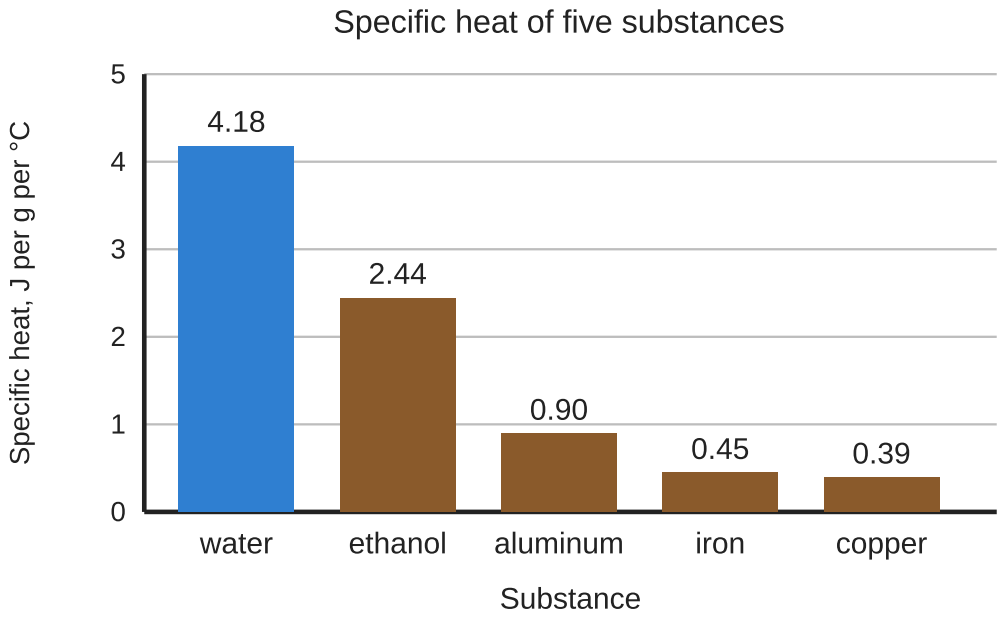
How they figured it out. Hoyle was not a Christian, but the discovery stayed with him. In 1981 he wrote: "A common sense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as with chemistry and biology, and that there are no blind forces worth speaking about in nature." A biologist had noticed something similar much earlier. In 1913 Lawrence Henderson, a biochemist at Harvard, published *The Fitness of the Environment*, arguing that the world itself seems unusually suited to life, especially water and carbon. Water has a high **specific heat**, so oceans, lakes and the water in your body change temperature slowly. It dissolves more substances than almost any other liquid, so it can carry food and wastes in blood and sap. And water is strange in one more way: unlike most substances, it expands when it freezes, so ice has a lower **density** than liquid water and floats. Lakes freeze from the top down, and the ice on top shields the water below, so fish live through the winter.

The big idea. Fine-tuning is the observation that many features of nature fall within narrow ranges that life requires. Some are **physical constants**, such as the strength of gravity and of the forces that hold atoms together; physicists have calculated that changing some of them even slightly would leave a universe without stable stars or without carbon. Others are features of our own planet. Earth orbits about 150 million kilometers from the sun, inside the **habitable zone** where water can stay liquid on the surface. Venus, closer in, is hot enough at the surface to melt lead; Mars, farther out, is a frozen desert. Earth's air is about 21 percent oxygen, enough for animals to breathe. Many scientists think our large moon helps steady the tilt of Earth's axis, which keeps the seasons regular.

Three ways to read it. Scientists agree that many of these settings are real; they disagree about what they mean. (1) **Design.** Many scientists who believe in God, and some who do not, see fine-tuning as the mark of a mind that set the dials on purpose, as Paley saw a watchmaker behind a watch. (2) **Many universes.** Some physicists propose that there may be a huge number of universes, each with different settings, and we live in one where the settings happen to allow life. Critics answer that no one has observed another universe, so the idea cannot yet be tested. (3) **The anthropic principle** says we should not be surprised to find a universe fit for life, because if it were not, we would not be here to notice. The philosopher John Leslie answered with a story: if fifty trained marksmen all fire at you and every one misses, it is not enough to say, "Of course they missed, or I would not be here to

wonder about it.” You would rightly ask why they missed. Scientists also debate how finely tuned some settings really are, and research on the question continues.

God’s handiwork. This unit began with a watch and then looked at an eye and a motor inside a single cell. Fine-tuning steps back to look at the whole stage on which life is set. Isaiah wrote that the LORD “formed the earth and made it,” and that “he created it not in vain, he formed it to be inhabited” (Isaiah 45:18). Every glass of water you drink and every breath of air you take is a small reminder that the world was made to be lived in.



Water needs more energy to warm up than other common substances, so it steadies the temperature of oceans, lakes and living bodies.

PICTURE STUDY



Earthrise, William Anders, Apollo 8 astronaut (NASA), December 24, 1968 · Color photograph · NASA; the image is in the public domain and widely available

On Christmas Eve 1968, the three astronauts of Apollo 8, Frank Borman, Jim Lovell and William Anders, became the first people to orbit the moon. As their spacecraft came around from the far side, Earth rose over the moon's horizon, and Anders grabbed a camera loaded with color film. His photograph became one of the most famous pictures ever taken.

That same evening the crew spoke to the people of Earth in a television broadcast from lunar orbit. They took turns reading the first ten verses of Genesis, beginning, "In the beginning God created the heaven and the earth." Borman closed by wishing God's blessing on "all of you on the good Earth."

Look closely

- Compare the colors of Earth with the colors of the moon. What do the blue and white tell you about Earth that the moon lacks?
- Find the line between day and night on Earth. Which part is lit by the sun?
- Look at the moon's surface in the foreground. What features can you see, and what is missing that you see every day on Earth?
- How large does Earth look here? Try covering it with your thumbnail at arm's length.

Talk about it

1. Why do you think this photograph moved so many people when it was first published?
2. Name three things Earth has that the moon does not, which make life possible.
3. The astronauts chose to read Genesis 1 from lunar orbit. Why might those words have seemed fitting at that moment?

> **Safety first.** Rubbing alcohol is flammable and poisonous to drink: use it only with an adult, away from flames and stoves, and pour it down the drain with plenty of water when finished. Use plastic, not glass, containers in the freezer, because freezing water can crack glass.

EXPERIMENT: THE WATER THAT BREAKS THE RULES

Most substances shrink when they freeze, so their solids sink in their own liquids. Water does the opposite. You will measure how much water expands when it freezes and then show why ice floats in water but not in every liquid.

You will need

- A tall, narrow, straight-sided plastic container, such as a plastic cup or a cut-down plastic bottle
- A kitchen measuring cup marked in milliliters, a ruler and a permanent marker
- Water, a freezer and a kitchen scale (if you have one)
- Two clear plastic cups, a few ice cubes and about 100 mL of rubbing alcohol (70% isopropyl), used with an adult
- A lab notebook

Steps

1. Write your question: By what percent does water’s volume grow when it freezes? Write a prediction.
2. Variables: what you change is the state of the water (liquid, then frozen). What you keep the same is the container, the amount of water and the container’s position. What you measure is the height of the water and of the ice, in millimeters.
3. Pour exactly 200 mL of water into the container. If you have a scale, weigh it. Mark the water level and measure the height from the bottom in millimeters.
4. Freeze it overnight, standing upright. Measure the height of the ice at its edge and at its highest point. If you weighed it, weigh it again: has the mass changed?
5. Calculate: percent increase = (ice height − water height) ÷ water height × 100. Water expands about 9% when it freezes; your result may be a little less if the ice bulged in the middle or pushed against the sides.
6. Float test: fill one cup half full of water and the other half full of rubbing alcohol. Drop an ice cube into each. Draw what happens.
7. Rubbing alcohol is less dense than ice, so the ice sinks in it. Water is denser than ice, so the ice floats. Write three sentences explaining your results and what would happen to fish in a pond if ice sank in water.

Tips

- A straight-sided container matters: if the sides slope, a change in height is not the same as a change in volume.

- The mass should stay the same when the water freezes. Only the volume changes, which is why the density goes down.

Check your work

- I named what I changed, what I kept the same and what I measured.
- I calculated the percent expansion and compared it with about 9%.
- I can explain why ice floats on water and why that matters for life in ponds and lakes.

NATURE NOTEBOOK

1. Draw a cross-section of a pond in winter: a layer of ice on top, cold water beneath, and fish near the bottom. Label the ice, the liquid water and the fish. Then draw the same pond as it would be if ice sank.
2. Draw the sun, Venus, Earth and Mars in a line with their distances (about 108, 150 and 228 million kilometers) and shade the habitable zone around Earth's orbit.
3. Make a three-column chart titled "Three Ways to Read Fine-Tuning": Design, Many Universes and Anthropic Principle. In each column write what the view says and one question someone might ask about it.

> **From history.** Water's power to store heat was first measured by the Scottish chemist Joseph Black at the University of Glasgow around 1761. Black noticed that ice melting in a warm room takes in a great deal of heat while its temperature stays at 0 °C, and that different substances need different amounts of heat to warm by the same number of degrees. His ideas of latent heat and of what we now call specific heat helped his young friend James Watt, the instrument maker at the university, find ways to waste less heat and fuel in steam engines.

WORKED EXAMPLES

Example 1. 100 grams of liquid water has a volume of 100 cm^3 (density 1.00 g/cm^3). When it freezes, the mass stays the same but the density drops to 0.917 g/cm^3. What is the volume of the ice, and by what percent did the volume grow? What fraction of an ice cube floats below the surface of fresh water?

1. Volume = mass ÷ density = 100 g ÷ 0.917 g/cm^3 ≈ 109.1 cm^3.
2. Increase = 109.1 − 100 = 9.1 cm^3, which is 9.1 ÷ 100 × 100 ≈ 9.1%.
3. A floating object sinks until it pushes aside its own weight of water. Fraction below the surface = density of ice ÷ density of water = 0.917 ÷ 1.00 = 0.917.
4. So about 91.7% is below the surface and about 8.3% sticks out, roughly one tenth.

Answer: About 109.1 cm^3, an increase of about 9%. About 92% of the ice floats below the surface and about 8% above.

Example 2. Use the bar graph. How much energy does it take to warm 1 kilogram of water by 10 °C? How much for 1 kilogram of iron? How many times more energy does the water need?

(Use the map or drawing "Read each bar's value, then use energy = mass × specific heat × temperature chan" shown earlier in this lesson.)

1. Energy = mass × specific heat × temperature change. 1 kg = 1,000 g.
2. Water: 1,000 g × 4.18 J/(g·°C) × 10 °C = 41,800 J.
3. Iron: 1,000 g × 0.45 J/(g·°C) × 10 °C = 4,500 J.
4. Ratio: 41,800 ÷ 4,500 ≈ 9.3.

Answer: Water needs 41,800 J and iron 4,500 J, so water needs about 9.3 times as much energy for the same warming.

Example 3. Sunlight spreads out as it travels, so its strength falls with the square of the distance. Earth is about 150 million km from the sun, Venus about 108 million km and Mars about 228 million km. How strong is sunlight at Venus and at Mars compared with Earth?

1. Strength compared with Earth = (Earth's distance ÷ planet's distance)².
2. Venus: (150 ÷ 108)² = (1.39)² ≈ 1.93, almost twice as strong as at Earth.
3. Mars: (150 ÷ 228)² = (0.658)² ≈ 0.43, less than half as strong.
4. Small changes in distance make big changes in sunlight, one reason a planet's place in its solar system matters so much for liquid water.

Answer: At Venus sunlight is about 1.9 times as strong as at Earth; at Mars it is about 0.43 times as strong.

PRACTICE

1. EASY Who predicted a special energy level in the carbon nucleus, and where and when was it found?
2. EASY Why does it matter for living things that ice floats?
3. EASY State the anthropic principle in one sentence.
4. MEDIUM Light travels about 300,000 kilometers per second. How long does sunlight take to reach Earth from 150 million kilometers away? Give the answer in seconds and in minutes and seconds.
5. MEDIUM Data reading. Use the specific heat bar graph. (a) Which substance needs the least energy to warm 1 gram by 1 °C? (b) About how many times more energy does water need than copper? (c) A metal pot and the water inside it sit on the same burner. Which warms up faster, and why?

6. MEDIUM Data reading. Data from NASA fact sheets (rounded):
   Venus: distance from sun about 108 million km; average surface temperature about 464 °C; liquid water on surface: no.
   Earth: about 150 million km; about 15 °C; yes.
   Mars: about 228 million km; about −65 °C; no.
   (a) Which statement is best supported? (i) In this table, only the planet with an average temperature between 0 °C and 100 °C has liquid surface water. (ii) Distance from the sun is the only thing that controls temperature. (iii) Mars is too hot for liquid water. (b) Venus receives about twice Earth's sunlight, yet it is hotter than a kitchen oven. What does that suggest besides distance?
7. MEDIUM 500 grams of water freezes. Using 0.917 g/cm³ for the density of ice, what is the volume of the ice?
8. HARD Explain the "many universes" response to fine-tuning and give one criticism of it.
9. HARD Experiment design. Design an experiment to compare how fast equal masses of water and dry sand warm up under a lamp. Name the independent and dependent variables, four things to keep the same and how you would record the data.
10. CHALLENGE Explain John Leslie's firing-squad story. What point does it make against using the anthropic principle to dismiss fine-tuning, and how might someone who holds the anthropic principle reply?

COMMON MISTAKES

- Thinking ice floats because it contains air bubbles. Even clear, bubble-free ice floats, because water expands as it freezes and ice is less dense than liquid water.
- Thinking fine-tuning is only about Earth. It includes the laws and constants of physics everywhere, such as the strength of gravity and the energy level in carbon that Hoyle predicted, as well as features of Earth.
- Thinking the anthropic principle explains why the universe is fit for life. It only explains why we observe a fit universe if we exist; the question of why such a universe exists at all remains.

> **Make it a game · Turn the Dial.** A parent names one setting and a direction: "Ice sinks," "Earth moves to where Mars is," "Water warms as fast as iron," "No oxygen in the air," "No moon." You have fifteen seconds to describe one way life on Earth would be harder. Score a point for each sound answer and a bonus point if you use a number from this lesson. Then switch: you turn a dial and the parent answers.

> **Scripture.** "For thus saith the LORD that created the heavens; God himself that formed the earth and made it; he hath established it, he created it not in vain, he formed it to be inhabited: I am the LORD; and there is none else." (Isaiah 45:18, KJV)

Isaiah says the earth was made with a purpose: to be lived on. Floating ice, steady oceans, breathable air and a sun at the right distance all fit that purpose.

Practice answers

1. Fred Hoyle of Cambridge predicted it, and William Fowler’s team at the Kellogg Radiation Laboratory at Caltech in Pasadena found it in 1953.
2. Lakes and ponds freeze from the top down, and the ice layer shields the water beneath from the cold air, so the water below stays liquid and fish and other creatures can live through the winter.
3. We can only observe a universe that allows observers like us to exist, so we should not be surprised that ours is fit for life.
4. 150,000,000 ÷ 300,000 = 500 seconds, which is 8 minutes 20 seconds.
5. (a) Copper (0.39 J/(g·°C)). (b) 4.18 ÷ 0.39 ≈ 10.7, about 11 times. (c) The metal pot warms faster, because metals like aluminum, iron and copper have much lower specific heats than water, so the same energy raises their temperature more.
6. (a) (i). Earth is the only one between water’s freezing and boiling points and the only one with liquid surface water. (ii) goes beyond the data; (iii) is backward, since Mars is too cold. (b) Something besides distance also matters; Venus’s very thick carbon dioxide atmosphere traps heat. A planet needs the right distance and the right atmosphere.
7. 500 ÷ 0.917 ≈ 545 cm^3, about 45 cm^3 (about 9%) more than the 500 cm^3 of liquid water.
8. It proposes that there may be a huge number of universes with different settings, so by chance some, including ours, would have settings that allow life, and we naturally find ourselves in one of those. Criticism: no one has observed any other universe, so the idea cannot yet be tested, and it explains the evidence by adding a vast number of unseen things.
9. Independent variable: the material (water or sand). Dependent variable: the temperature rise in °C after a set time, such as every 2 minutes for 20 minutes. Keep the same: the mass (for example 200 g each), the starting temperature, identical containers, the same lamp at the same distance, and the thermometer depth. Record temperatures in a table and plot both on a line graph of temperature vs. time. The sand should warm faster because its specific heat is lower.
10. If fifty trained marksmen fire at you and all miss, you would not simply say, “Of course they missed, or I would not be here to notice.” Your survival is surprising and calls for an explanation, such as that they missed on purpose. In the same way, the fact that we can only observe a life-permitting universe does not remove the need to explain why the universe permits life. A defender of the anthropic principle might reply that if there were a huge number of universes (or firing squads), some survivors would be expected by chance, so the reply leans on the many-universes idea, which has its own critics.

Unit 4 review

Answer each question. Show your work for calculations, label units, and use complete sentences for explanations. When asked about a debate, state each side fairly. The test is worth 60 points.

1. (5 pts) Multiple choice. In Paley's argument, what feature of the watch shows that it was designed? (a) It is shiny. (b) It is complicated. (c) Its parts are shaped and arranged to work together for a purpose. (d) It is old.
2. (5 pts) A watch wheel with 40 teeth drives a pinion with 8 teeth. How many times does the pinion turn when the wheel turns 6 times?
3. (5 pts) Name two critics of the design argument from this unit's first lesson and state each one's main objection in one sentence.
4. (5 pts) Multiple choice. Which part of the human eye does about two-thirds of the bending of light? (a) lens (b) cornea (c) retina (d) iris
5. (5 pts) Diagram. Draw a side view of the human eye. Label the cornea, iris, pupil, lens, retina, optic nerve and blind spot. Draw an upright arrow outside the eye and two light rays from its top and bottom that cross inside the eye, and show the image on the retina.
6. (5 pts) A pupil widens from 2.5 millimeters to 7.5 millimeters across. How many times more light can it admit? Show your reasoning.
7. (5 pts) Multiple choice. What powers the motor of the *E. coli* flagellum? (a) sunlight (b) a flow of hydrogen ions (protons) through the stator (c) the cell's heartbeat (d) water pressure from outside the cell
8. (5 pts) Define irreducible complexity. Then use these sample results to say whether they support the idea for the flagellum: when the gene for the filament, the hook or the stator is knocked out, the bacterium cannot swim; when a steering-signal gene is knocked out, it swims but never tumbles.
9. (5 pts) Explain the co-option objection to Behe's argument and give one reply from a design advocate.
10. (5 pts) 250 grams of water freezes. The density of ice is 0.917 g/cm³. What is the volume of the ice, and by how many cubic centimeters did the volume increase from the 250 cm³ of water? Why does this matter for fish in a pond?
11. (5 pts) Name the three responses to fine-tuning studied in this unit and give a one-sentence description of each.
12. (5 pts) Short essay (5–7 sentences). Choose one example from this unit (the watch, the eye, the flagellum or fine-tuning). State the design argument for it, state the strongest objection to it, and then state which you find more convincing and why. Write respectfully about the side you disagree with.

Unit project: a design case file

Choose one structure in nature and build a case file on it, the way a scientist and a detective would. Good choices include the eye, the bacterial flagellum, a bird's feather, a woodpecker's

skull and tongue, a honeybee's comb, the human hand or water's unusual properties. Your file should include a large labeled diagram, a table of parts and the job of each, a "knockout" analysis of what would happen if each main part were missing, and at least one calculation (a ratio, a scale model, a rate or a density).

Finish with a one-page written comparison. State the design reading of your structure and the natural-selection reading, each as its own supporters would put it, then give your own conclusion with reasons. Add a KJV verse that fits your structure and include photographs or data from your project in this unit.

- **Accuracy**: The diagram, labels, part functions and calculation are correct, with units shown.
- **Analysis**: The knockout analysis clearly separates parts needed for the basic job from parts that only improve it.
- **Fairness**: Both readings are stated accurately and respectfully, and the conclusion is supported by evidence rather than name-calling.
- **Care**: The case file is neat, organized and easy to follow, with a fitting Scripture verse quoted exactly.

Answer key

1. (c). Paley's clue was parts fitted together for a function; complexity alone (b) is not enough, since a rockslide is complicated.
2. 40 ÷ 8 = 5 turns of the pinion per turn of the wheel; 5 × 6 = 30 turns.
3. David Hume: the analogy between a machine and the world is weak, because we have seen watches made but never a world. Charles Darwin: natural selection acting on small differences over many generations could produce living structures that look designed without a designer.
4. (b) the cornea. The lens fine-tunes the focus.
5. A correct diagram shows the cornea as the clear bulge at the front, the iris on either side of the pupil opening, the lens just behind the pupil, the retina lining the back, and the optic nerve leaving the back with the blind spot where it joins the retina. The ray from the top of the arrow crosses to the bottom of the retina and the ray from the bottom crosses to the top, so the image is upside down. (1 point for the parts in order, 2 points for correct labels, 2 points for crossing rays and an inverted image.)
6. Light depends on area, which depends on the square of the diameter. 7.5 ÷ 2.5 = 3, and 3^2 = 9, so it admits 9 times as much light.
7. (b) a flow of hydrogen ions (protons) into the cell through the stator units.
8. Irreducible complexity (Behe): a single system of several well-matched parts that all work together for its basic job, so removing any one part stops the system working. The filament, hook and stator results support it, since removing any one of those core parts stops swimming. The steering-gene result shows that some parts add a function (changing direction) without being needed for the basic job of swimming.
9. Co-option: about ten flagellar proteins resemble parts of the type III secretion system, a needle some bacteria use to inject proteins, so parts might have been borrowed from other useful jobs and combined, and the whole motor need not have appeared at once. Reply (any one): showing a few parts can do another job is not a step-by-step path to the whole motor

with each step useful; some gene studies suggest the needle came from the flagellum; the parts must also be built in the right order.

10. 250 ÷ 0.917 ≈ 272.6 cm^3, an increase of about 22.6 cm^3 (about 9%). Because ice is less dense than water, it floats, so ponds freeze from the top down and the ice shields the liquid water below, where fish survive the winter.
11. Design: the settings were chosen on purpose by a mind. Many universes: there may be a huge number of universes with different settings, and we live in one that happens to allow life. Anthropic principle: we could only observe a universe that allows life, so we should not be surprised to find one.
12. Answers will vary. A full-credit answer states the design argument accurately (for example, the eye’s parts work together for sight, as a telescope’s do), states the strongest objection accurately (for example, Darwin’s series of simpler useful eyes), gives a reasoned conclusion based on evidence from the unit, and treats the other side fairly without mocking it.

UNIT 5

Fossils and Life's History

Fossils are the only direct record we have of creatures that lived before written history. Job was told to "speak to the earth, and it shall teach thee" (Job 12:8), and in this unit you will do exactly that: split rock with Charles Walcott in the Canadian Rockies, dissolve a *T. rex* bone with Mary Schweitzer, measure the feathers of *Archaeopteryx*, follow Neil Shubin's team to the Arctic for *Tiktaalik*, and meet a "fossil fish" hauled up alive off South Africa in 1938.

These are some of the most debated finds in all of science, so the unit trains one skill above all: **separating what we observe from how we interpret it**. You will calculate percents, ratios, half-life steps, magnifications and timeline gaps, read fossil tallies and range charts, and run experiments on preservation, decay, feathers and settling. Every lesson has a "⏳ Thinking About Time" box that gives the museum's numbers accurately, lists what is actually observed, and explains how young-earth Christians read the same evidence.

Our aim is to understand each side so well that its own holders would agree we have told it fairly. Christians have nothing to fear from careful questions. We can measure honestly, admit puzzles on every side, refuse weak arguments even when they seem to help us, and give thanks to the God who "created great whales, and every living creature that moveth" (Genesis 1:21).

BEFORE YOU BEGIN

- Can calculate percents, ratios and averages and read bar graphs (Grade 7 math and Unit 3 of this course)
- Knows the difference between a species, a breed and a created kind (Unit 3)
- Knows what proteins and DNA are (Unit 2)
- Can identify independent, dependent and controlled variables in an experiment

MASTERY CHECKLIST

- I can describe the Burgess Shale animals and explain what the "Cambrian explosion" means as a pattern in the rock layers.
- I can tell how soft tissue was found in a *T. rex* bone and explain what decay rates and half-lives tell us about it.
- I can list the mosaic traits of *Archaeopteryx* and *Tiktaalik* and explain the difference between a transitional form and an ancestor.
- I can read a fossil range chart and a fossil tally and calculate percents, ranges and averages from them.
- I can sort statements into observations and interpretations.
- I can explain fairly how mainstream scientists, young-earth creationists and intelligent-design writers each read the same fossils.

OPTIONAL BOOKS AND RESOURCES

- **Smithsonian National Museum of Natural History** (https://naturalhistory.si.edu/): Free. The museum that holds Walcott's Burgess Shale collection. Browse its online fossil exhibits and collections search for Burgess Shale animals, dinosaurs and fossil fish (Lessons 5.1–5.4). A parent should preview, since exhibit text assumes the mainstream ages; use it to practice reading the museum's words in the ⏳ boxes.
- ***On the Origin of Species* by Charles Darwin, first edition (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/1228): Free. Read Darwin's own words on the missing early fossils in the chapter "On the Imperfection of the Geological Record" (Lesson 5.1). Reading a scientist in his own words is the fairest way to understand him.

5.1 The Cambrian Explosion ★

OBJECTIVES

- Tell how Charles Doolittle Walcott found the Burgess Shale in 1909 and describe at least three of its animals, including Marrella, Opabinia and Hallucigenia.
- Explain what the “Cambrian explosion” means as a pattern in the rock layers, and calculate percents, scale sizes and time fractions from fossil data.
- Separate what is observed in Cambrian rocks from how mainstream scientists, intelligent-design writers and young-earth creationists each interpret it.

Warm-up. Take a slice of bread and press a coin, a key and a leaf firmly into it, then lift them out. Do the same in a handful of dry rice poured on a plate. Which material kept the sharper print? Which details (letters on the coin, veins on the leaf) survived? Write one sentence predicting what kind of mud would preserve the finest details of a soft animal.

Video. Coming soon. Burgess Shale and the Cambrian explosion: Marrella, Opabinia, Hallucigenia, Anomalocaris and trilobites; search the Smithsonian National Museum of Natural History, the Royal Ontario Museum Burgess Shale pages, Parks Canada Yoho National Park, and museum fossil-collection footage.

KEY TERMS

Cambrian explosion
A museum and textbook name for the pattern in which most major groups of animals appear suddenly in the rock layers labeled “Cambrian,” with few clear forerunners in the layers beneath.

Burgess Shale
A layer of fine, dark shale high in the Canadian Rockies of British Columbia, found by Charles Walcott in 1909, famous for animals preserved with their soft parts.

phylum
A large group of animals that share one basic body plan, such as arthropods (jointed legs and an outer skeleton), mollusks or chordates. The plural is phyla.

body plan
The basic layout of an animal: its symmetry, segments, skeleton, gut, limbs and nerve cord.

exceptional preservation
Fossils that keep soft parts such as guts, gills, muscles or eyes, not only shells and bones. It usually requires very rapid burial in fine sediment with little oxygen.

reconstruction
A scientist’s drawing or model of what a whole living animal looked like, built from flattened or broken fossils. It is an interpretation that can be corrected.

CORE IDEAS

The story. In late August 1909, Charles Doolittle Walcott, the Secretary of the Smithsonian Institution in Washington, was hunting fossils with his family on a ridge between Mount Field and Mount Wapta, near the railroad town of Field, British Columbia. Splitting slabs of fine, dark shale, he found flattened animals shining like silvery films on the rock. They were not only shells. They had legs, gills, guts and feelers. Walcott returned in 1910 and opened a quarry on the slope. He and his family came back for several more summers, the last in 1924, and shipped about 65,000 specimens to Washington, where most of them are still kept at the National Museum of Natural History. The layer became known as the **Burgess Shale**.

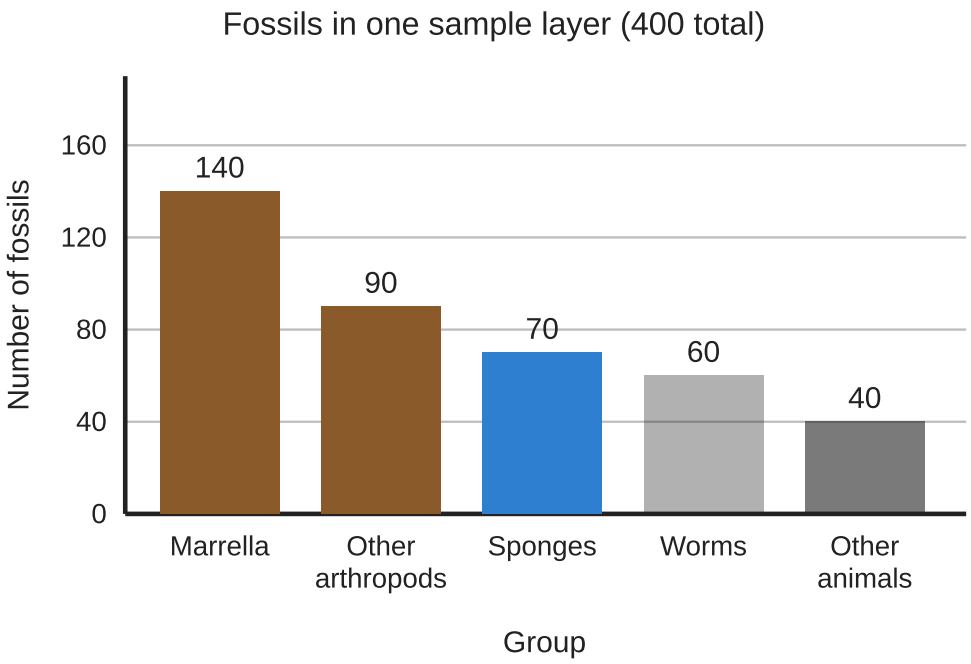
How they figured it out. Walcott was a busy administrator, and he fit most of his animals into groups he already knew. In the 1960s and 1970s, Harry Whittington and his students Simon Conway Morris and Derek Briggs at the University of Cambridge looked again. With fine needles they chipped away rock layer by layer and drew each specimen under the microscope. They found strange creatures. *Opabinia*, only a few centimeters long, had five eyes on stalks and a long, flexible nozzle tipped with a claw. *Marrella*, the "lace crab," is the most common animal in the quarry; collectors have gathered more than 25,000 of them. *Hallucigenia* was first drawn in 1977 walking on stiff spines with soft tentacles on its back. Better fossils from China showed in 1991 that it had been drawn upside down, and in 2015 scientists finally identified which end was its head. The lesson is worth remembering: the fossil is the observation, but the **reconstruction** is an interpretation, and interpretations can be corrected.

The big idea. The Burgess Shale is one window on a larger pattern. In layers labeled "Cambrian" around the world, including the Chengjiang beds of Yunnan, China, found by Hou Xianguang in July 1984, most of the major animal **phyla** appear suddenly and fully formed: arthropods with jointed legs, sponges, mollusks, worms, and even simple chordates such as *Pikaia*. Trilobites already had compound eyes with lenses made of the mineral calcite. In the layers beneath, animal fossils are rare. There are some strange soft-bodied forms, called the Ediacaran fossils, that look like fronds, discs and quilted pads, and there are mats left by microbes. But the long series of in-between forms leading up to each **body plan** has not been found. Darwin knew of this gap. In *On the Origin of Species* (1859) he wrote of the missing earlier fossils: "The case at present must remain inexplicable; and may be truly urged as a valid argument against the views here entertained."

How each side reads it. Everyone agrees on the observations. Mainstream scientists say the animal groups did branch from common ancestors, but quickly, and they propose reasons: a rise in oxygen, the first eyes and predators setting off an "arms race," and new genes that control body layout. They add that earlier ancestors may have been tiny and soft and seldom fossilized. Critics answer that the Burgess Shale and the Ediacaran beds show soft bodies *can* be preserved. Intelligent-design writers, such as Stephen Meyer in *Darwin's Doubt* (2013), argue that so many new body plans appearing at once points to a designing mind supplying new information. Young-earth creationists read the sudden appearance as distinct kinds created fully formed, and the Cambrian layers as among the first sea-floor communities buried by the Flood.

Try it and see. Fine mud is the secret of the Burgess Shale. Most scientists agree that its animals were buried very quickly by underwater flows of mud, sealed away from scavengers and from most of the oxygen that decay needs. In this lesson's project you will press objects into fine and coarse materials and count how many details each one keeps, just as a paleontologist judges how much a rock layer can record.

God's handiwork. The first well-preserved animals we find are not crude. They have eyes, jointed legs, gills and guts, all working together. The psalmist looked at the sea and said, "So is this great and wide sea, wherein are things creeping innumerable, both small and great beasts" (Psalm 104:25). The Burgess Shale is a gallery of those creeping things, and it invites us to wonder at the One who made them.



Sample data: what one layer of a Burgess-type quarry might yield. Marrella really is the most common animal in Walcott's quarry.

⏳ Thinking About Time

What the sign says. What the sign says: museum signs and textbooks say the Cambrian period began about 539 million years ago (often rounded to 540), that most major animal groups appeared within roughly 20 to 25 million years, and that the Burgess Shale is about 508 million years old.

What we observe. What we observe: layers labeled Cambrian contain a sudden abundance of complex animals with eyes, legs, gills and guts; the layers below hold few animal fossils (mostly soft Ediacaran forms and microbial mats); and many Cambrian animals are preserved with soft parts, which requires very rapid burial in fine mud.

How Christians read it. How Christians read it: young-earth creationists read the Cambrian layers as among the first deposits of the Flood, when "the fountains of the

great deep” broke up and buried sea-floor creatures quickly, and they see the sudden, fully formed body plans as distinct kinds made by God. Some other Christians accept the mainstream ages but still see the explosion as evidence of design.

Try it. On a strip of paper, draw the Burgess Shale layer and the layers below it, and write one observation and one interpretation beside each.

Genesis 7:11

PICTURE STUDY



Charles D. Walcott with his son Sidney and daughter Helen at the Burgess Shale quarry, Photographer of the Walcott expeditions (Smithsonian Institution Archives), about 1913 · Black-and-white photograph · Smithsonian Institution Archives, Washington, D.C.

Walcott kept careful photographs and diaries of his summers in the Canadian Rockies. His wife Helena and his children often worked beside him, climbing to the quarry high on the ridge, splitting slabs and wrapping specimens for the long trip by pack horse and train back to Washington. Photographs like this one show what real fieldwork looked like more than a century ago: hammers, chisels, notebooks and a great deal of patient labor.

Look at this photograph the way a historian of science would. What tools did they have? What did they not have? How did they get heavy rock off a mountain?

Look closely

- Find the quarry face. How thick do the shale layers look?
- Look for tools: hammers, chisels, sacks or boxes. What is each person doing?
- Look at the slope and the mountains behind. How do you think the slabs were carried down?

- Look at the clothing. What does it tell you about the date and about the conditions?

Talk about it

1. Why would a family spend its summers splitting rock on a cold mountainside?
2. Walcott collected about 65,000 specimens. Why is a large collection more useful to a scientist than a few beautiful fossils?
3. What would you add to a field notebook so that a scientist 100 years later could still use your specimens?

> **Safety first.** Plaster of Paris gets warm as it sets and its dust should not be breathed: mix it outdoors or in a ventilated room, wear a dust mask and gloves, never cast a hand or body part in it, and never pour leftover plaster down a drain.

EXPERIMENT: FINE MUD OR COARSE SAND? A PRESERVATION EXPERIMENT

The Burgess Shale kept legs, gills and guts because its animals were buried in very fine mud. You will test whether fine material records more detail than coarse material by pressing the same objects into each, casting the prints in plaster and counting the details that survive.

You will need

- Three shallow plastic containers (such as clean yogurt-cup lids or small food tubs)
- Fine material: modeling clay or smooth homemade salt dough
- Medium material: clay kneaded with 2 spoonfuls of fine sand
- Coarse material: damp coarse sand or aquarium gravel packed firmly
- Three test objects with fine detail: a fern or tree leaf with clear veins, a coin, a small seashell
- Plaster of Paris, water, a disposable cup and stirring stick, a metric ruler, a hand lens, a lab notebook

Steps

1. Write your question: Does the grain size of the sediment change how many details of an object are preserved?
2. Write a prediction: rank the three materials from most detail to least.
3. Variables. What you change: the material (fine, medium, coarse). What you keep the same: the objects, how hard you press (press each with the same stack of three books for 30 seconds), the depth of material (about 2 cm) and the plaster recipe. What you measure: the number of visible details in a 1 cm by 1 cm square on each cast.
4. Press each object into each material, then lift it out carefully.
5. Mix plaster following the package directions and pour a layer about 1 cm thick over each print. Let it harden at least one hour, then lift the casts out.
6. With a hand lens, mark a 1 cm square on each cast in the same place (for the leaf, beside the midrib). Count the vein lines, coin letters or shell ridges you can see. Count three times and average.

7. Make a table and a bar graph of your averages. Write three sentences: Which material kept the most detail? Was your prediction right? What does this suggest about the mud of the Burgess Shale?

Tips

- Use the same counting rule for every cast; write it down before you begin so you do not change it halfway.
- If a cast breaks, record it. A broken fossil is also data about how fragile a layer is.

Check your work

- I named the variable I changed, the variables I kept the same and what I measured.
- I counted three times and averaged.
- I can explain why fine sediment and rapid burial are needed for soft-bodied fossils.

NATURE NOTEBOOK

1. Draw a reconstruction of *Opabinia* at three times life size from a museum picture or library book: five eyes, the long nozzle with its claw, and the body segments with flaps. Label each part and write the scale (3×).
2. Draw *Hallucigenia* twice: once as it was drawn in 1977 and once as it is drawn today. Under the drawings write: “The fossil did not change. The interpretation did.”
3. Make a two-column page titled “Cambrian Rocks”: Observations (left) and Interpretations (right). Put at least four items in each column.

> **From history.** Walcott was one of the most powerful scientists in America: Secretary of the Smithsonian from 1907 until his death in 1927, and a founder of the National Advisory Committee for Aeronautics, the agency that later became NASA. Yet he still spent his summers swinging a hammer in the mountains. A popular story says he found the Burgess Shale when his wife’s horse slipped and turned over a slab, but his own diary tells a plainer story of careful searching along the ridge, and historians treat the horse tale as a legend.

WORKED EXAMPLES

Example 1. An *Opabinia* fossil is 6.0 cm long, and its nozzle measures 1.8 cm. You want a drawing at 4× scale. How long should the body be on your drawing, how long the nozzle, and what fraction of the body length is the nozzle?

1. Drawing length = real length × scale = 6.0 cm × 4 = 24 cm.
2. Nozzle on drawing = 1.8 cm × 4 = 7.2 cm.
3. Fraction = nozzle ÷ body = 1.8 ÷ 6.0 = 0.30, or 30%.
4. Check with the drawing: 7.2 ÷ 24 = 0.30. A scale drawing keeps every ratio the same.

Answer: Body 24 cm, nozzle 7.2 cm; the nozzle is 30% of the body length at any scale.

Example 2. Use the bar graph of 400 fossils from one sample quarry layer. What percent are *Marrella*? What percent are arthropods of any kind (Marrella plus other arthropods)? What is the ratio of arthropods to sponges?

(Use the map or drawing "Sample data from one layer. Read each bar against the axis." shown earlier in this lesson.)

1. Read the bars: Marrella 140, other arthropods 90, sponges 70, worms 60, other animals 40. Check the total: 140 + 90 + 70 + 60 + 40 = 400.
2. Marrella: 140 ÷ 400 × 100 = 35%.
3. All arthropods: 140 + 90 = 230; 230 ÷ 400 × 100 = 57.5%.
4. Ratio of arthropods to sponges: 230 : 70. Divide both by 10: 23 : 7, or about 3.3 to 1.

Answer: Marrella 35%; all arthropods 57.5%; arthropods to sponges 23 : 7 (about 3.3 : 1).

Example 3. Using the textbook's own numbers, why do scientists call it an "explosion"? The textbook gives Earth's history as about 4,500 million years and says most animal phyla appeared within about 20 million years. If the whole textbook history were squeezed into one 24-hour day, how many minutes would the 20-million-year window take?

1. Fraction of the textbook history = 20 ÷ 4,500 ≈ 0.0044, which is about 0.44%.
2. Minutes in a day = 24 × 60 = 1,440 minutes.
3. Window = 0.0044 × 1,440 ≈ 6.4 minutes.
4. So even on the mainstream timeline, most animal body plans appear in a very short slice. That is why the word "explosion" is used. A young-earth reading shortens the time much further, to part of a single year of the Flood for the burial.

Answer: About 0.44% of the textbook history, or about 6 minutes of a 24-hour day; on either reading the appearance is sudden.

PRACTICE

1. EASY Who found the Burgess Shale, in what year, and in what province of Canada?
2. EASY What is a phylum? Give two examples of animal phyla found in Cambrian rocks.
3. EASY Name two unusual features of *Opabinia*.
4. MEDIUM Why do most scientists of every view agree that the Burgess Shale animals were buried very quickly?
5. MEDIUM *Hallucigenia* was drawn upside down in 1977 and corrected in 1991. Explain the difference between a fossil and a reconstruction using this example.
6. MEDIUM Data reading. A sample sorting of fossils by layer gives these counts of animal phyla present: Layer 1 (lowest): 0 phyla; Layer 2: 1; Layer 3: 2; Layer 4 (lowest Cambrian): 9; Layer 5: 14; Layer 6: 15. Between which two layers is the largest jump? Which statement is best supported? (a) The number of phyla grew steadily. (b) Most phyla first appear within a few layers. (c) Phyla disappear upward. (d) No pattern.
7. MEDIUM Data reading. In the sample graph, Marrella is 140 of 400 fossils. If a second layer of 250 fossils has the same proportions, how many Marrella would you expect? How many sponges (70 of 400 in the first layer)?
8. HARD Experiment design. You want to test whether low oxygen slows the decay of soft animals. Using small shrimp from the grocery store, design an experiment: name the independent variable, dependent variable, at least three controlled variables, and how you would keep it safe.
9. HARD Darwin wrote in 1859 that the lack of earlier fossils "may be truly urged as a valid argument against the views here entertained." What problem was he admitting, and what two kinds of answers have been given since?
10. CHALLENGE A classmate says, "The Burgess Shale proves the soft-bodied ancestors could never have been fossilized." Another says, "The Burgess Shale proves the ancestors

were never there.” Explain why each claim goes too far, and write one careful sentence that sticks to the evidence.

COMMON MISTAKES

- Thinking the Cambrian “explosion” was a literal blast. It is a name for a pattern in the rock layers: many animal groups appearing suddenly.
- Thinking the Cambrian animals were simple blobs. Many had compound eyes, jointed legs, gills, guts and nerve cords.
- Treating a museum reconstruction as an observation. The flattened fossil is the observation; the drawing of the living animal is an interpretation that has sometimes been corrected.

Make it a game · Observation or Interpretation?. A parent reads a statement aloud, such as “Opabinia had five eyes,” “The Burgess animals were buried by a mudflow,” “This fossil is 508 million years old,” or “Trilobite lenses are made of calcite.” Say “Observation!” or “Interpretation!” and give a reason. Score a point for each correct call with a good reason. Bonus point: turn an interpretation into a question a scientist could test.

Scripture. “So is this great and wide sea, wherein are things creeping innumerable, both small and great beasts.” (Psalm 104:25, KJV)

The Burgess Shale animals were sea creatures, many small and creeping. The psalmist’s wonder at the life of the sea fits a gallery of five-eyed, many-legged animals as well as it fits whales.

Practice answers

1. Charles Doolittle Walcott, Secretary of the Smithsonian Institution, in 1909, in British Columbia.
2. A phylum is a large group of animals sharing one basic body plan. Examples: arthropods (trilobites, Marrella), sponges, mollusks, segmented worms (annelids), chordates (Pikaia).
3. It had five eyes on stalks and a long, flexible nozzle tipped with a claw (also flaps along the sides of its body).
4. Their soft parts (legs, gills, guts) are preserved. Soft tissue rots or is eaten within days, so the animals must have been sealed in fine mud quickly, away from scavengers and most oxygen.
5. The fossil is the observed specimen in the rock and did not change. The reconstruction is a scientist’s interpretation of how the living animal looked. Better fossils from China showed the spines belonged on the back and the tentacle-like parts were legs, so the interpretation was corrected.
6. The largest jump is from Layer 3 to Layer 4 (2 to 9, an increase of 7). (b) is best supported: most phyla appear within Layers 4 and 5. (a) is wrong because the growth is sudden, not steady.
7. Marrella: 35% of 250 = 87.5, about 88. Sponges: 70 ÷ 400 = 17.5%, and 17.5% of 250 = 43.75, about 44.

8. Independent variable: oxygen (shrimp in a jar of boiled, cooled water sealed with a layer of oil versus shrimp in an open jar of the same water). Dependent variable: decay, measured as days until the shell softens or the body falls apart, or change in mass. Controls: same kind and size of shrimp, same amount of water, same temperature, same light, same number of shrimp. Safety: keep jars sealed or covered, wear gloves, never eat the samples, and throw them out sealed at the end.
9. He admitted that if animals descended slowly from earlier forms, there should be many ancestors in the layers below, but they were missing. Mainstream answers: the ancestors were tiny and soft and seldom fossilized, and the branching happened quickly because of oxygen, predators and new genes. Design and creation answers: the body plans appear suddenly because they were designed or created as distinct kinds.
10. The Burgess Shale shows soft bodies can be preserved under special conditions, so the first claim is wrong, but special conditions are rare, so missing fossils cannot prove ancestors never lived. Careful sentence: “In the layers we have searched, complex animal body plans appear suddenly, and soft-bodied preservation is possible but rare, so the gap is a real pattern that each view must explain.”

5.2 Dinosaur Soft Tissue ★

OBJECTIVES

- Tell how Mary Schweitzer and her team found stretchy vessels and cell-like structures inside a *Tyrannosaurus rex* thigh bone (published 2005), and how protein fragments were later tested.
- Use half-life steps, magnification and decay-rate data to reason about how long soft tissue and molecules can last.
- Explain the questions soft tissue raises for the mainstream timeline, the explanations offered (iron preservation, biofilm), and how young-earth creationists read the find.

Warm-up. Look at a chicken drumstick bone from dinner (washed and dried). Find the hard outer bone and, if it is broken, the spongy bone inside. Now drop one piece into a jar of vinegar and leave it there for the rest of the unit. Predict: what will the vinegar remove, and what will be left?

Video. Coming soon. Mary Schweitzer and soft tissue in Tyrannosaurus rex bone (MOR 1125), collagen in dinosaur fossils and how bone is demineralized in the lab; search the Smithsonian, Museum of the Rockies, North Carolina State University, PBS NOVA-style science programs and university lab footage.

KEY TERMS

soft tissue
Body material that is not hard bone or shell, such as blood vessels, cells, skin, muscle and the proteins that make them.

collagen
The most common protein in bone, skin and tendons, made of long fibers that give bone its toughness. Gelatin is collagen that has been boiled and broken down.

demineralize
To dissolve away the hard minerals in bone with a mild acid or chemical, leaving behind any softer material that was inside.

medullary bone
A special layer of bone that female birds build inside their leg bones to store calcium for eggshells; it is laid down only around the time of egg laying.

decay rate
How fast a material breaks down over time, often given as a half-life: the time for half of it to break down.

biofilm
A slimy film made by colonies of bacteria. Some scientists have proposed that biofilm, not original tissue, made some of the structures found in fossil bone.

CORE IDEAS

The story. In 2000, Bob Harmon, a field worker for Jack Horner's crew from the Museum of the Rockies, spotted a *Tyrannosaurus rex* skeleton weathering out of a cliff in the Hell Creek rocks of eastern Montana. The specimen got the catalog number MOR 1125. It sat in a remote canyon, and the plaster jacket around the hind leg was too heavy for the helicopter that was to lift it out, so the crew had to break the thigh bone into pieces. Those broken fragments went to paleontologist Mary Higby Schweitzer, then at North Carolina State University. She placed bits of the inner bone in a mild chemical that slowly dissolves bone mineral. When the mineral was gone, something remained: flexible, see-through, branching tubes that looked like blood vessels, and inside them small round and oval structures. Some looked like the bone cells called osteocytes, with their thin branches still visible. The team published the find in the journal *Science* in March 2005.

How they figured it out. Schweitzer had been surprised before. In the early 1990s, as a graduate student at Montana State University, she had seen tiny red, round structures in a thin slice of another *T. rex* bone. Her adviser Jack Horner told her to try to prove they were not what they looked like. That attitude guided the later work. In June 2005 the team reported that MOR 1125 had **medullary bone**, the calcium-storage bone that female birds make when laying eggs, so this *T. rex* was probably a female. In 2007 and 2009, Schweitzer and chemist John Asara used mass spectrometry, an instrument that weighs molecular fragments, to read short pieces of **collagen** protein from MOR 1125 and from a duck-billed dinosaur, *Brachylophosaurus*. They also used antibodies, proteins that stick only to particular molecules, to test the vessels and cells. Other laboratories have since reported similar structures in other dinosaur bones.

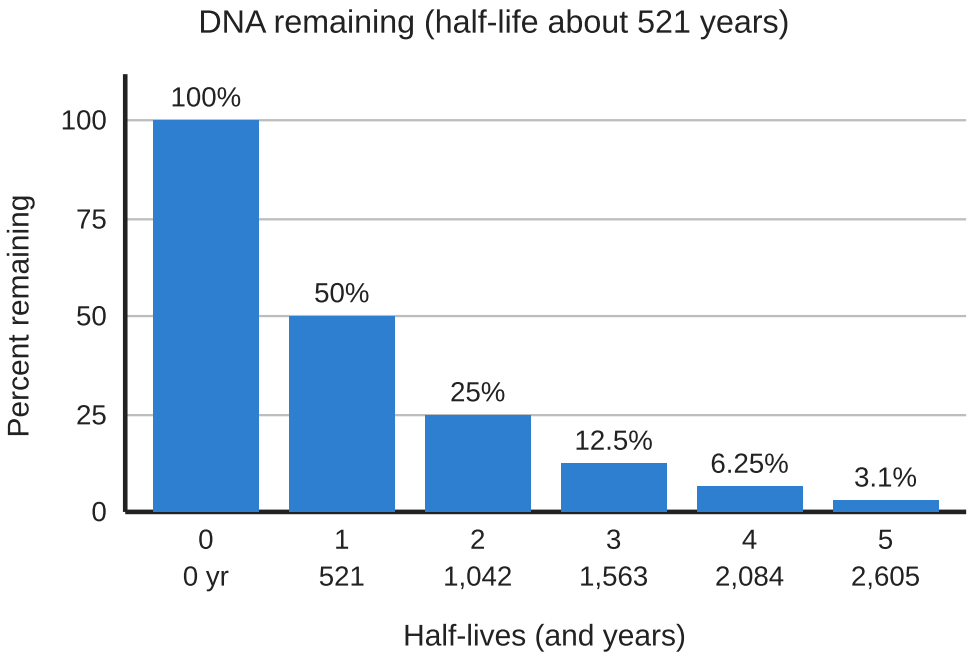
The big idea. Soft tissue and proteins normally break down. Bacteria eat them, water and oxygen attack them, and even in a sealed bone molecules fall apart by themselves over time. Scientists describe that with a **decay rate**. For example, a 2012 study of bones of the moa, a large extinct bird of New Zealand, estimated that DNA in bone has a half-life of about 521 years at the temperature of those burial sites. Proteins such as collagen last longer than DNA, but before 2005 most paleontologists did not expect any original soft material to survive for the tens of millions of years the textbooks assign to dinosaur bones. That is why the find surprised so many people, and why it was checked so carefully.

How each side reads it. Some scientists first suggested that the "vessels" were **biofilm** made by bacteria that had crept into the bone, but the protein results pointed to animal collagen. Schweitzer, who has said she is a Christian and who accepts the mainstream ages, proposed a preservation explanation: iron from the animal's blood may act like a chemical preservative, linking proteins together much as the embalming chemical formaldehyde does. In a 2013 test, ostrich blood vessels soaked in a solution rich in red blood cells showed little sign of decay after about two years, while untreated vessels began decaying within days. Mainstream scientists think chemistry like this, together with quick burial and sealing in sandstone, explains the survival. Young-earth creationists answer that the simplest reading of fragile, stretchy tissue and readable protein is that the bones are thousands of years old,

not millions, and were buried rapidly in the Flood. Both sides agree on the observations; they disagree about whether preservation chemistry can stretch decay over so much time.

Try it and see. You cannot test a dinosaur bone at home, but you can test decay. Gelatin is broken-down collagen, the same family of protein Schweitzer's team detected. In this lesson's project you will make gelatin cubes and measure how fast they spoil under different conditions. Watch your vinegar-soaked chicken bone too: the acid dissolves the mineral and leaves the rubbery collagen behind, which is a kitchen version of demineralizing.

God's handiwork. God spoke to Job of a great beast whose "bones are as strong pieces of brass" (Job 40:18). Bone is a marvel of design: hard mineral woven around tough, flexible collagen, laced with vessels and living cells. Discoveries like Schweitzer's remind us that creation still holds surprises, and that honest scientists, Christian or not, must follow the evidence carefully and admit when it is unexpected.



Halving steps using the 2012 estimate of a 521-year half-life for DNA in moa bone. Each bar is half the one before.

⏳ Thinking About Time

What the sign says. What the sign says: museum signs and textbooks say the Hell Creek rocks that held MOR 1125 are about 66 to 68 million years old, and that this *T. rex* lived about 68 million years ago.

What we observe. What we observe: after the bone mineral is dissolved, flexible branching vessels and cell-like structures remain; protein fragments matching collagen have been read by mass spectrometry and detected with antibodies; and laboratory decay rates show proteins and DNA break down steadily over time.

How Christians read it. How Christians read it: young-earth creationists read the survival of soft tissue and protein as strong evidence that dinosaur bones are thousands, not millions, of years old, buried quickly in the Flood. Other Christians, including Schweitzer herself, accept the mainstream ages and expect that preservation chemistry such as iron cross-linking will explain the find.

Try it. Draw two timelines for MOR 1125, one using the museum date and one using a young-earth reading, and mark on each what would need to be explained.

Job 40:15

PICTURE STUDY



Leaping Laelaps, Charles R. Knight, 1897 · Watercolor · American Museum of Natural History, New York

Charles R. Knight was the most famous painter of prehistoric animals in America. Working with the paleontologist Edward Drinker Cope, he painted this scene of two *Laelaps* (today called *Dryptosaurus*), meat-eating dinosaurs whose bones had been found in New Jersey. Most artists of his day showed dinosaurs as slow, dragging lizards. Knight made them leap.

Knight could see only bones. The skin, muscles, color and behavior all came from his study of living animals and his imagination. Soft-tissue discoveries like Schweitzer's are exciting partly because they let scientists test a little more of what used to be left to the artist.

Look closely

- Find the attacking dinosaur in the air. How does Knight show speed and power?
- Look at the dinosaurs' skin. Do you see scales, feathers or plain skin? Where would Knight have gotten that idea?

- Look at the tails and legs. Do the animals look slow and heavy or quick and agile?
- Look at the background. What kind of place did Knight imagine?

Talk about it

1. Which parts of this painting are based on bones, and which are interpretation?
2. What kind of fossil find would let a scientist test the skin or color of a dinosaur?
3. Why do you think this painting was so different from other dinosaur pictures of 1897?

> **Safety first.** Gelatin samples will spoil and may grow mold: never taste them, keep each one in a closed, labeled container, wear gloves or wash hands after handling, and throw the containers away without opening them if mold appears. Ask an adult to pour the hot water when making the gelatin.

EXPERIMENT: HOW FAST DOES COLLAGEN SPOIL? A GELATIN DECAY EXPERIMENT

Gelatin is collagen that has been boiled and broken down. You will make identical gelatin cubes and store them under different conditions to measure how temperature, salt and acid change the decay rate. This tests the same kind of question scientists ask about dinosaur soft tissue: what slows decay, and by how much?

You will need

- One packet of unflavored gelatin, hot and cold water, a small baking pan, a knife (adult help)
- Eight small clear containers with lids, masking tape and a marker for labels
- Table salt and white vinegar
- A kitchen scale that reads to 1 gram (or 0.1 gram if you have one), a metric ruler, a hand lens
- A lab notebook

Steps

1. Write your question: Do cold, salt or vinegar slow the decay of gelatin compared with room temperature?
2. Write a prediction ranking the four conditions from slowest decay to fastest.
3. Make the gelatin following the packet (adult pours the hot water). When firm, cut eight cubes about 2 cm on each side.
4. Variables. What you change: the storage condition. Two cubes each: (A) room temperature, plain (the control); (B) refrigerator, plain; (C) room temperature, coated in salt; (D) room temperature, with 1 spoonful of vinegar poured over. What you keep the same: cube size, container type, lids on, time between checks, the same light. What you measure: mass in grams, and the day mold or cloudiness first appears.
5. Weigh each cube on day 0 (before adding salt or vinegar) and record it. Check and weigh daily for 7 to 10 days, lifting lids only long enough to weigh (or weigh the closed container and subtract the empty container’s mass).

6. Record observations: color, clarity, smell (from a distance), firmness and the first sign of mold.
7. Calculate the percent mass change for each cube and graph mass against day for the four conditions. Write a conclusion: Which condition slowed decay most? What would preserve protein longest in a buried bone?

Tips

- Two cubes per condition lets you see whether a result repeats. Average the pair.
- Weighing the closed container avoids opening moldy samples. Write down the empty container mass first.

Check your work

- I set up a control and changed only one thing at a time.
- I recorded mass and first-mold day for every cube and calculated percent change.
- I can explain why a find of soft tissue raises questions about how long it has been buried.

NATURE NOTEBOOK

1. Draw a cross-section of a leg bone: the hard outer bone, the spongy bone, the marrow space and, for a female bird or the MOR 1125 *T. rex*, a thin layer of medullary bone. Label each part.
2. After a week, draw your vinegar-soaked chicken bone. Bend it gently and record what happens. Label what the vinegar removed (mineral) and what remained (collagen).
3. Make a timeline from 2000 to 2013 with five dated events from this lesson: the discovery of MOR 1125, the March 2005 paper, the medullary bone report, the collagen sequences, and the iron preservation test.

> **From history.** Mary Schweitzer came to paleontology late. She was a mother of three working as a substitute teacher when she sat in on a dinosaur class taught by Jack Horner at Montana State University and asked to volunteer in his lab. She went on to earn her doctorate and to found a new field of study sometimes called molecular paleontology. Her discovery led many museums to look again at bones in their drawers that had never been tested for soft tissue.

WORKED EXAMPLES

Example 1. A 2012 study estimated that DNA in bone has a half-life of about 521 years at the temperature of the moa burial sites. What fraction of the DNA would remain after 10 half-lives, and how many years is that? How many half-lives until less than one part in a million remains?

(Use the map or drawing "Each 521-year step halves what is left." shown earlier in this lesson.)

1. Each half-life cuts the amount in half: 1 → 1/2 → 1/4 → 1/8 → ... After n half-lives the fraction left is $(1/2)^n$.
2. After 10 half-lives: $(1/2)^{10}$ = 1/1,024, about 0.098%, or roughly one part in a thousand.
3. Time = 10 × 521 years = 5,210 years.
4. One part in a million: 2^{20} = 1,048,576, which is just over one million, so 20 half-lives are needed. Time = 20 × 521 = 10,420 years.
5. Note: this estimate is for DNA, not collagen, and decay is slower when colder. Collagen lasts much longer than DNA, but it still decays steadily.

Answer: After 10 half-lives (5,210 years) about 1/1,024 remains; after 20 half-lives (10,420 years) less than one part in a million remains.

Example 2. A microscope photograph is printed at 400× magnification. On the print, one vessel is 20 mm wide and a cell-like structure inside it is 4 mm long. What are their real sizes in micrometers (1 mm = 1,000 µm)?

1. Real size = size on the print ÷ magnification.
2. Vessel: 20 mm ÷ 400 = 0.05 mm. In micrometers: 0.05 × 1,000 = 50 µm.
3. Cell-like structure: 4 mm ÷ 400 = 0.01 mm = 10 µm.
4. Check: the structure is 4 ÷ 20 = 1/5 the vessel width both on the print and in real life (10 ÷ 50 = 1/5).

Answer: The vessel is about 50 µm wide and the structure is about 10 µm long, smaller than the width of a human hair.

Example 3. Sample data from the gelatin project. Each cube started at 20.0 g. After 6 days: room temperature (control) 14.0 g, salt-coated 17.0 g, refrigerator 19.4 g. Find the percent mass lost and the average loss per day for each.

1. Control: lost 20.0 − 14.0 = 6.0 g. Percent = 6.0 ÷ 20.0 × 100 = 30%. Per day = 6.0 ÷ 6 = 1.0 g/day.
2. Salt: lost 3.0 g. Percent = 3.0 ÷ 20.0 × 100 = 15%. Per day = 0.5 g/day.
3. Refrigerator: lost 0.6 g. Percent = 0.6 ÷ 20.0 × 100 = 3%. Per day = 0.1 g/day.
4. Compare: the refrigerator cube lost mass 1.0 ÷ 0.1 = 10 times more slowly than the control. Conditions can change a decay rate a great deal, which is why both sides of the soft-tissue debate argue about burial conditions.

Answer: Control 30% (1.0 g/day); salt 15% (0.5 g/day); refrigerator 3% (0.1 g/day). Cold slowed the loss tenfold.

PRACTICE

1. EASY What did Mary Schweitzer’s team find after dissolving the mineral from pieces of the MOR 1125 *T. rex* thigh bone?
2. EASY Why was the MOR 1125 thigh bone broken before it reached the lab?
3. EASY What is medullary bone, and what did finding it suggest about MOR 1125?
4. MEDIUM A sample protein has a half-life of 1,000 years. What fraction remains after 3,000 years? After 6,000 years?
5. MEDIUM Data reading. A sample table of first-mold day for gelatin cubes: room temperature 3 days; vinegar 6 days; salt 9 days; refrigerator 15 days. Which condition slowed decay most, and how many times longer did it last than the control? Which statement is best supported? (a) Salt is the best preservative. (b) Cold slowed decay more than salt or vinegar did. (c) Vinegar speeds decay. (d) All conditions decayed at the same rate.
6. MEDIUM Data reading. Look at the half-life bar graph. What percent of DNA remains after 3 half-lives, and how many years is that? Between which two bars is the drop in percentage points largest, and why?
7. MEDIUM What is the difference between the biofilm explanation and the iron explanation for the MOR 1125 structures?
8. HARD Experiment design. Design a test of whether iron slows the decay of gelatin. Name the independent variable, the dependent variable, the control group, three controlled variables and one safety rule.
9. HARD Explain in three or four sentences why both a mainstream scientist and a young-earth creationist might call the MOR 1125 find important.
10. CHALLENGE In the 2013 test, ostrich vessels in a solution rich in red blood cells showed little decay after about two years, while untreated vessels began decaying within days. What does this experiment show, and what does it not show? Name one more test that would help.

COMMON MISTAKES

- Thinking Schweitzer found dinosaur DNA or living cells. She found flexible vessels, cell-like structures and protein fragments; no dinosaur DNA has been confirmed.
- Thinking fossil bone is always pure rock. Many fossil bones keep their original bone mineral and spaces, and some have been found to hold traces of original protein.
- Thinking a decay rate is fixed no matter what. Temperature, water, oxygen and chemicals such as iron and salt can change how fast tissue breaks down.

Make it a game · Half-Life Countdown. Start with 64 dried beans in a bowl, standing for molecules. Each round is one half-life: remove exactly half and say the number of years aloud (521, 1,042, 1,563 ...). Before each round, predict how many beans will be left. Score a point for every correct prediction. When you reach 1 bean, say how many half-lives and years it took (6 half-lives, 3,126 years).

Scripture. “His bones are as strong pieces of brass; his bones are like bars of iron.” (Job 40:18, KJV)

God described the bones of behemoth as brass and iron. Real bone is even more remarkable: mineral and protein woven together and laced with vessels, a design scientists are still learning to read.

Practice answers

1. Flexible, transparent, branching vessels like blood vessels, and small round and oval structures inside them, some resembling bone cells (osteocytes) with branches.
2. The plaster jacket around the leg was too heavy for the helicopter lifting it out of the remote site, so the crew broke the bone into pieces.
3. A calcium-storage bone that female birds make inside their leg bones when laying eggs. It suggested MOR 1125 was a female.
4. 3,000 years is 3 half-lives: $(1/2)^3 = 1/8$ (12.5%). 6,000 years is 6 half-lives: $(1/2)^6 = 1/64$ (about 1.6%).
5. The refrigerator, lasting $15 \div 3 = 5$ times longer than the control. (b) is best supported. (a) is wrong because cold beat salt; (c) is wrong because vinegar lasted longer than the control; (d) ignores the data.
6. 12.5% remains after 3 half-lives, which is $3 \times 521 = 1{,}563$ years. The largest drop (50 percentage points) is from 0 to 1 half-life, because each step removes half of what is left, and there is the most to lose at the start.
7. The biofilm explanation says the vessel-like structures were made later by bacteria growing inside the bone, so they are not original dinosaur tissue. The iron explanation accepts they are original tissue and proposes that iron from blood helped cross-link and preserve the proteins.
8. Independent variable: whether iron is present (for example, gelatin cubes resting on a clean steel nail or iron washer versus without). Dependent variable: days until mold appears, or percent mass lost. Control: identical cubes with no iron. Controlled variables: cube size, temperature, container and lid, light, time between checks. Safety: never taste samples;

dispose of moldy containers without opening them; do not use iron pills, which are dangerous to young children.

9. Both agree it is surprising that flexible vessels and collagen fragments survived. For the mainstream scientist, it opens a new field: studying ancient proteins and discovering what chemistry can preserve tissue for very long times. For the young-earth creationist, it is evidence that the bones may be far younger than the textbook ages. In both cases, careful tests of decay rates under real burial conditions are needed.
10. It shows iron-rich blood can greatly slow decay over at least two years in the lab. It does not show that tissue would last tens of millions of years, because the experiment covered only two years and decay over longer spans must be estimated by extending the trend. A helpful test: measure decay rates at several temperatures and over longer times, or test bones buried in real sandstone conditions, to see whether the slowdown continues.

5.3 Transitional-Fossil Claims: Archaeopteryx and Tiktaalik

OBJECTIVES

- Tell the discovery stories of *Archaeopteryx* (Germany, 1861) and *Tiktaalik* (Canadian Arctic, 2004) and list the features that make each a "mosaic" of traits.
- Measure and compare feather vane ratios, tally mosaic traits and use textbook dates to calculate the gap between fossils.
- Define a transitional form, explain the difference between an ancestor and a relative, and state fairly how mainstream scientists and creationists read these two fossils.

Warm-up. Take two feathers from a craft store bag or a pillow (or look at a picture of a bird's wing feather). Hold each one up and look at the shaft. Is the shaft in the middle, or off to one side? Gently drop each one from shoulder height and watch how it falls. Write one sentence guessing why some feathers are lopsided.

Video. Coming soon. Archaeopteryx specimens from the Solnhofen limestone and Tiktaalik roseae from Ellesmere Island; search the Natural History Museum (London), the Museum für Naturkunde Berlin, the University of Chicago (Neil Shubin), the Academy of Natural Sciences of Philadelphia, and museum fossil footage.

KEY TERMS

transitional form
A fossil with a mix of features from two groups, such as reptiles and birds or fish and four-legged animals, that mainstream scientists propose shows a step between them.

mosaic
An organism that combines traits usually found in different groups, like the tiles of a mosaic picture, without being halfway in every trait.

Archaeopteryx
A feathered animal about the size of a raven, found in fine limestone near Solnhofen, Germany, with wings and flight feathers but also teeth, clawed fingers and a long bony tail.

Tiktaalik
A large fossil fish found on Ellesmere Island in the Canadian Arctic in 2004, with gills, scales and fins but also a flat head, a neck and sturdy bones inside its front fins.

tetrapod
An animal with a backbone and four limbs (or descended from such animals), including amphibians, reptiles, birds and mammals.

asymmetrical feather
A feather whose shaft is off center, with a narrow leading vane and a wide trailing vane. Flying birds have them in their wings; they help the feather work like a small wing.

CORE IDEAS

The story. The limestone quarries around Solnhofen in Bavaria, Germany, split into thin, smooth slabs so fine that printers used them for lithography. In 1861 a single fossil feather was found there, and the paleontologist Hermann von Meyer gave it the name *Archaeopteryx*, "ancient wing." That same year a nearly complete skeleton with feathers turned up near Langenaltheim. A local doctor, Karl Häberlein, sold it in 1862 to the British Museum in London for £700, and Richard Owen described it in 1863. In the 1870s a second, even finer skeleton was found near Eichstätt. A well-known story says the farmer who found it sold it to buy a cow. Berlin's natural history museum bought it in 1881, and it is still there. With its wings spread and its head thrown back, the "Berlin specimen" is one of the most famous fossils in the world. About a dozen skeletons are known today.

How they figured it out. *Archaeopteryx* had feathered wings with **asymmetrical** flight feathers like those of flying birds, and a wishbone. But it also had teeth in its jaws, three separate clawed fingers on each wing and a long, bony tail. In 1868 Thomas Huxley, Darwin's strongest defender, compared it with small meat-eating dinosaurs and argued that birds and dinosaurs were related. Nearly a century and a half later, a team led by Neil Shubin, Edward Daeschler and Farish Jenkins went looking for a different "in-between" animal: a fish on its way, they proposed, to walking on land. They reasoned that it should lie in freshwater stream rocks of a certain textbook age, exposed where nothing covered them. Geological maps pointed to Ellesmere Island in the Canadian Arctic. They searched there for four summers starting in 1999, and in July 2004 they found the flat head of a large fish poking out of the rock. They published it in *Nature* in April 2006 and named it *Tiktaalik roseae*; with help from the elders of Nunavut, they chose *tiktaalik*, an Inuktitut word for a large freshwater fish.

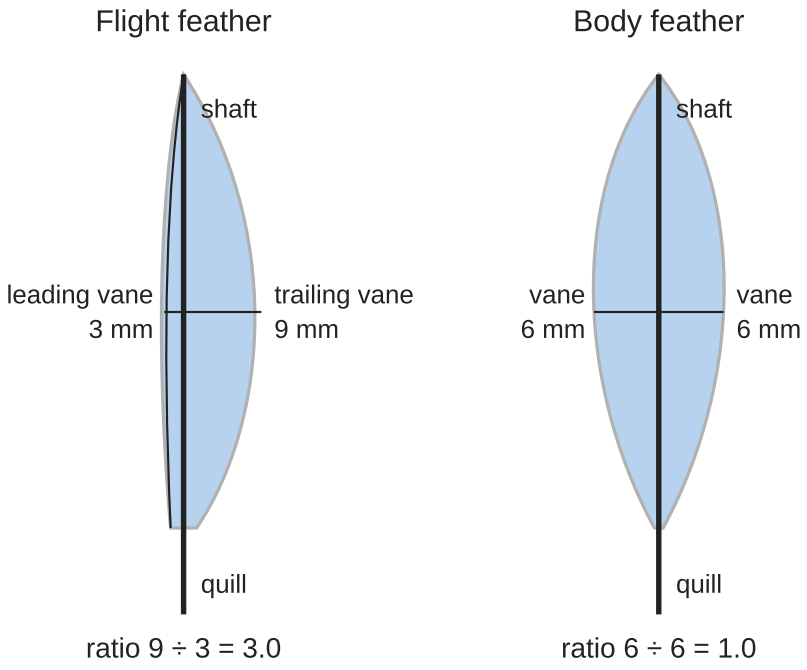
The big idea. *Tiktaalik* had gills, scales and fins with fin rays, like a fish. But it had a flat, crocodile-like head with eyes on top, a neck that let it turn its head, sturdy ribs, and inside each front fin bones that match a shoulder, elbow and wrist. Mainstream scientists call *Archaeopteryx* and *Tiktaalik* **transitional forms**. Notice what that does and does not mean. A transitional form is a **mosaic**: some traits like one group, some like another. It need not be a direct ancestor. Even mainstream scientists describe *Tiktaalik* as a relative of the first **tetrapods**, not necessarily their great-grandparent. That matters, because in 2010 scientists reported four-toed trackways in the Zachełmie quarry of Poland in rocks their textbooks date older than *Tiktaalik*. Since 1996, China has also yielded many small dinosaurs with feathers. Most carry textbook dates younger than *Archaeopteryx*, which critics call a "temporal paradox"; mainstream scientists answer that a few, such as *Anchiornis*, are dated older.

How each side reads them. Mainstream scientists see these fossils as strong evidence that birds descended from dinosaurs and four-legged animals from fish, and they point out that the *Tiktaalik* team predicted where and in what rocks to look before they found it. Creation scientists read the same bones differently. Many classify *Archaeopteryx* as a true bird with unusual features, noting that some living birds have wing claws (hoatzin chicks and ostriches) and that other fossil birds had teeth. They read *Tiktaalik* as a fish, one of many created kinds, with sturdy fins suited to shallow water, and they note that the older

trackways weaken the claim that it stands in a line leading to land animals. Design writers add that a Maker who reuses good patterns across many creatures would also produce mosaics. All sides agree on the bones; the argument is over what the mixture of traits means.

Try it and see. You can test one of the key observations yourself. A flight feather's shaft runs off center; a body feather's runs closer to the middle. In this lesson's project you will measure the vanes of many feathers and calculate a ratio, the same kind of measurement scientists used to argue that *Archaeopteryx* had true flight feathers.

God's handiwork. A single flight feather has a shaft, hundreds of barbs and thousands of tiny hooked barbules that zip the vane together. Job was told, "But ask now the beasts, and they shall teach thee; and the fowls of the air, and they shall tell thee" (Job 12:7). Whatever we conclude about how these creatures are related, a feather teaches the engineering of its Maker.



An asymmetrical flight feather (left) and a symmetrical body feather (right), with sample vane widths measured across the widest part.

⏳ Thinking About Time

What the sign says. What the sign says: museum signs date *Archaeopteryx* to the Late Jurassic, about 150 million years ago, and *Tiktaalik* to the Late Devonian, about 375 million years ago. Textbooks place the Zachełmie trackways at about 395 million years and many feathered Chinese dinosaurs at about 160 to 120 million years.

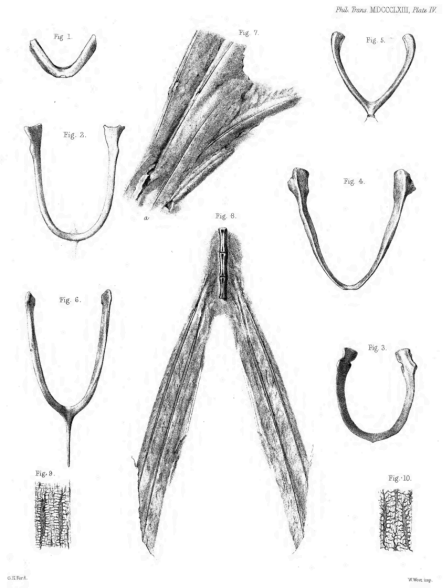
What we observe. What we observe: *Archaeopteryx* skeletons in fine limestone with feathers, teeth, three clawed fingers and a long bony tail; *Tiktaalik* skeletons in stream sandstones with gills, scales, fins, a neck and sturdy fin bones; and four-toed trackways in a Polish quarry in layers placed below *Tiktaalik*.

How Christians read it. How Christians read it: young-earth creationists read these fossils as buried in the Flood, with *Archaeopteryx* a bird and *Tiktaalik* a fish, each part of a created kind rather than a step between kinds; the order of layers is read as the order of burial, not long ages. Some other Christians accept the mainstream ages, and a few accept common descent as the way God worked.

Try it. Make a paper timeline using the textbook numbers and place *Tiktaalik*, the Zachełmie tracks and *Archaeopteryx* on it; then write beside it how a young-earth reading would relabel the same order.

Genesis 1:21

PICTURE STUDY



The London specimen of Archaeopteryx, plate from Richard Owen's 1863 description, Lithograph prepared for Richard Owen, 1863 · Lithograph · Published in the *Philosophical Transactions of the Royal Society of London*, 1863; the fossil is at the Natural History Museum, London

Before photographs could be printed in scientific journals, fossils were shown by careful drawings turned into lithographs. This plate shows the first *Archaeopteryx* skeleton exactly as it lay in the stone, with its scattered bones and the prints of its feathers. Most of the head was missing from this specimen, which is one reason the later Berlin specimen caused such excitement.

Richard Owen was the leading anatomist of Victorian Britain and the man who coined the word "dinosaur" in 1842. He described *Archaeopteryx* as a bird. Others, like Thomas Huxley, looked at the same plate and saw reptile features. One picture, two readings.

Look closely

- Find the tail. How can you tell it was made of bones, with feathers attached along each side?
- Find the wing feathers. Which way do they spread from the arm bones?
- Look for the clawed fingers. How many can you find?
- What is missing from this specimen that a scientist would most want to see?

Talk about it

1. Which features in this plate look like a bird's? Which look like a reptile's?
2. Why might two scientists looking at the very same plate reach different conclusions?
3. What is the advantage of a careful drawing over a photograph? What is the danger?

> **Safety first.** In the United States, federal law protects the feathers of almost all wild native birds, so do not collect wild bird feathers; photograph them instead and use feathers from domestic birds or craft stores. Wash your hands after handling any feathers.

EXPERIMENT: THE FEATHER ASYMMETRY SURVEY

Is there a measurable difference between wing feathers and body feathers? You will measure the two vanes of many feathers, calculate an asymmetry ratio for each and test the hypothesis that flight feathers are more lopsided than body feathers.

You will need

- At least 10 feathers from domestic birds: craft-store feathers, a few from a pillow, or molted feathers from chickens, ducks, geese, turkeys or a pet parakeet (label which are wing and which are body feathers if you know)
- A metric ruler marked in millimeters, a hand lens, a sheet of dark paper
- A lab notebook and a calculator

Steps

1. Write your question: Do wing (flight) feathers have a higher vane ratio than body feathers?
2. Write a hypothesis and a prediction, such as "Wing feathers will have an average ratio above 2; body feathers will be near 1."
3. Variables. What you change: the type of feather (wing or body). What you keep the same: where you measure (at the widest point of the vane), the ruler, and the person measuring. What you measure: the width of the narrow (leading) vane and the wide (trailing) vane, in millimeters.
4. Lay each feather on dark paper. Measure both vanes at the widest point, straight out from the shaft to the edge.
5. Calculate the ratio for each: wide vane ÷ narrow vane. A ratio of 1.0 means perfectly symmetrical.

6. Record a table: feather number, type, narrow vane (mm), wide vane (mm), ratio. Average the ratios for each type.
7. With a hand lens, look at a vane up close. Gently separate two barbs, then stroke them back together. Draw what you see. Write a conclusion: Was your hypothesis supported? What does a high ratio suggest about a feather's job?

Tips

- Measure each feather twice and use the average; vanes are easy to misjudge by a millimeter.
- Note any feather that is damaged or curled. Leave it out of the averages and say why.

Check your work

- I measured at least 10 feathers the same way and calculated each ratio.
- I compared the average ratios of the two groups.
- I can explain why asymmetrical flight feathers in *Archaeopteryx* are important evidence.

NATURE NOTEBOOK

1. Draw a large flight feather and label the quill, shaft, leading vane, trailing vane and barbs. Add a close-up circle showing barbs and hooked barbules.
2. Make a two-column chart titled "*Archaeopteryx*: a Mosaic" with "Like a bird" and "Like a reptile" columns, at least four items in each.
3. Draw the front fin bones of *Tiktaalik* beside the bones of your own arm, and label the matching parts (upper arm, two forearm bones, wrist). Write one observation and one interpretation under the drawing.

> **From history.** In 1985 the famous astronomer Fred Hoyle and several colleagues claimed that the feathers of the London *Archaeopteryx* had been faked by pressing feathers into a thin layer of paste on the stone. Scientists at the British Museum (Natural History) examined the two halves of the slab and showed that fine cracks and small mineral features ran continuously through the feather areas and matched on both halves, which a forger could not have done. The specimen is genuine. Honest Christians and honest skeptics alike can learn from this: test a claim before repeating it.

WORKED EXAMPLES

Example 1. On the feather diagram, the flight feather's leading vane is 3 mm wide and its trailing vane is 9 mm wide; the body feather's vanes are 6 mm and 6 mm. Calculate each feather's asymmetry ratio and say which is more lopsided.

(Use the map or drawing "Read the vane widths from the labels." shown earlier in this lesson.)

1. Asymmetry ratio = wide vane ÷ narrow vane.
2. Flight feather: 9 mm ÷ 3 mm = 3.0.
3. Body feather: 6 mm ÷ 6 mm = 1.0 (perfectly symmetrical).
4. The flight feather's trailing vane is three times as wide as its leading vane. *Archaeopteryx* flight feathers are clearly asymmetrical in this way, which is why most scientists think it could fly or at least glide.

Answer: Flight feather ratio 3.0; body feather ratio 1.0; the flight feather is far more asymmetrical.

Example 2. Tally *Archaeopteryx*'s traits: feathers, feathered wings, asymmetrical flight feathers, wishbone, teeth, three clawed fingers, long bony tail, and no bony beak. Sort them into "like living birds" and "unlike living birds." What percent are bird-like? Then explain why the tally alone cannot settle whether it is a bird.

1. Like living birds: feathers, feathered wings, asymmetrical flight feathers, wishbone = 4 traits.
2. Unlike living birds: teeth, three clawed fingers, long bony tail, no bony beak = 4 traits.
3. Percent bird-like = 4 ÷ 8 × 100 = 50%.
4. But not all traits weigh the same. Some living birds have wing claws (hoatzin chicks, ostriches), and other fossil birds had teeth, so those traits do not rule out a bird. Mainstream scientists stress features shared with small dinosaurs; creation scientists stress feathers and flight. The count depends on which traits you choose and how you weigh them.

Answer: 4 of 8 traits (50%) are like living birds; classification depends on how scientists weigh the traits, not only on a count.

Example 3. Using the textbook's numbers, the Zachełmie trackways are dated about 395 million years and *Tiktaalik* about 375 million years. How much older are the tracks on that timeline? On a classroom timeline with 1 cm for every 5 million years, how far apart would you place them?

1. Difference = 395 − 375 = 20 million years.
2. Timeline distance = 20 ÷ 5 = 4 cm, with the tracks placed further back in time than *Tiktaalik*.
3. On the mainstream timeline, animals with feet were already walking 20 million years before *Tiktaalik*, so *Tiktaalik* cannot be the direct ancestor of those walkers. Mainstream scientists reply that it is a late-surviving relative of the true ancestors.
4. On a young-earth reading, the layers record the order of burial, so the same tracks show that four-footed animals were present when the lower layers were laid down.

Answer: 20 million years on the textbook timeline, or 4 cm on a 1 cm = 5 million year chart; the tracks lie below *Tiktaalik*, which is why it is called a relative rather than an ancestor.

PRACTICE

1. EASY Where and in what kind of rock were the *Archaeopteryx* fossils found?
2. EASY Name three features of *Tiktaalik* that are like a fish and three that are not usually found in fish.
3. EASY Who led the team that found *Tiktaalik*, where, and in what year?
4. MEDIUM A feather's vanes measure 4 mm and 10 mm. What is its asymmetry ratio? Is it more likely a wing feather or a body feather?
5. MEDIUM Data reading. A student's feather survey gives these average ratios: chicken body feathers 1.1; chicken wing feathers 1.6; duck wing feathers 2.8; goose wing feathers 3.1. Which statement is best supported? (a) All feathers are symmetrical. (b) Wing feathers of strong fliers were the most asymmetrical. (c) Body feathers are more asymmetrical than wing feathers. (d) Chickens fly better than ducks.
6. MEDIUM Data reading. Textbook dates in millions of years: Zachełmie tracks 395; *Tiktaalik* 375; *Anchiornis* (a feathered dinosaur) 160; *Archaeopteryx* 150; *Microraptor* (a feathered dinosaur) 120. The mainstream claim is fish → four-legged walkers, and feathered dinosaurs → birds. Which pair fits that order, and which two finds come "out of order"? By how much?
7. MEDIUM What is the difference between calling a fossil a "transitional form" and calling it an "ancestor"?
8. HARD Experiment design. You want to test whether asymmetrical feathers fall more slowly when dropped edgewise than symmetrical feathers of the same mass. Name the independent and dependent variables, three controlled variables, and the number of trials.

9. HARD Mainstream scientists praise the *Tiktaalik* team for predicting where to look. Explain the prediction, and explain one reason a creation scientist might say the success does not prove common descent.
10. CHALLENGE Write a short paragraph explaining what the word “mosaic” helps us see about *Archaeopteryx*, and why scientists on different sides can agree on the fossil but disagree about its meaning.

COMMON MISTAKES

- Thinking a transitional form must be halfway in every trait, such as a skin covering that is half scale and half feather. Real claimed transitions are mosaics of complete traits.
- Assuming a transitional fossil is a proven direct ancestor. Even mainstream scientists usually call *Tiktaalik* and *Archaeopteryx* relatives on side branches.
- Believing the *Archaeopteryx* fossils are forgeries. That claim was made in the 1980s and was tested and rejected; good arguments, on any side, must rest on true facts.

Make it a game · Bird, Reptile or Both?. A parent calls out a trait: feathers, teeth, wishbone, long bony tail, wing claws, scales, beak, lays eggs. You answer “bird,” “reptile” or “both” and name a living animal that has it. Score a point for each correct answer. Bonus points for spotting traits that both groups share (laying eggs, scales on bird legs) or birds with surprising traits (hoatzin chicks with wing claws).

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)

This lesson studies a fowl of the air and a fish of the waters, both found by speaking to the earth with hammers and chisels. Job was told that creatures teach those who ask, and careful study is a way of asking.

Practice answers

1. In fine-grained limestone quarries around Solnhofen in Bavaria, southern Germany (the same stone used for lithograph printing).
2. Fish-like: gills, scales, fins with fin rays. Not usually in fish: a flat crocodile-like head with eyes on top, a neck, sturdy ribs, and shoulder, elbow and wrist-like bones in the front fins.
3. Neil Shubin, Edward Daeschler and Farish Jenkins, on Ellesmere Island in the Canadian Arctic (Nunavut), in July 2004 (published 2006).
4. 10 ÷ 4 = 2.5. It is strongly asymmetrical, so it is more likely a wing (flight) feather.
5. (b). Duck and goose wing feathers, from strong fliers, had the highest ratios. Chicken wing feathers, from a weak flier, were less lopsided, and body feathers were nearly symmetrical.
6. *Anchiornis* (160) is 10 million years older than *Archaeopteryx* (150), which fits the dinosaur-to-bird order. Out of order: the Zachełmie walkers (395) are 20 million years older than *Tiktaalik* (375), and *Microraptor* (120) is 30 million years younger than *Archaeopteryx*. Neither *Tiktaalik* nor *Microraptor* can be a direct ancestor of the animal it is compared with, so mainstream scientists call them relatives.

7. A transitional form has a mosaic of traits between two groups. An ancestor is the actual parent line from which later animals came. A fossil can be transitional in its traits without being anyone’s ancestor; it could be a side branch, a cousin, or (in a creation reading) a separate kind.
8. Independent variable: the feather’s asymmetry (high-ratio wing feather versus low-ratio body feather). Dependent variable: time to fall a set distance, such as 2.0 m. Controlled: feather mass and length (choose feathers of similar mass), drop height, how the feather is held and released, indoor still air. Run at least five trials per feather and average them.
9. The team predicted that a fish with land-animal features would be found in freshwater rocks of a certain textbook age, exposed at the surface, and they searched Ellesmere Island and found it. A creation scientist might answer that the prediction mainly used the known order of fossils in layers (fish below, tetrapods above), which both views accept, and that the older Zachełmie tracks show *Tiktaalik* was not in fact on the path to land animals.
10. A mosaic combines whole traits from different groups (full feathers and wings, but also teeth and a bony tail) rather than being halfway in each trait. Everyone can see and measure the same traits. Mainstream scientists read the mix as a step from small dinosaurs to birds; creation scientists read it as a bird kind with unusual features, since some birds have claws and some fossil birds had teeth. The disagreement is not about the bones but about the history behind them.

5.4 How Each Side Reads the Fossils

OBJECTIVES

- Tell the story of the living coelacanth found off South Africa in 1938 and explain what “living fossils” and stasis show about reading the fossil record.
- Read a fossil range chart and a fossil tally, calculating percents, ranges and averages, and separate each observation from its interpretation.
- State accurately and respectfully how mainstream scientists, young-earth creationists and intelligent-design writers each read the Cambrian explosion, dinosaur soft tissue and transitional-fossil claims.

Warm-up. Look at an optical-illusion picture (the duck-rabbit drawing or the vase-faces drawing, easy to find in a library book). Write down what you see first. Then make yourself see the other picture. The lines on the paper never changed. What changed? Write one sentence about how this might apply to scientists looking at the same fossil.

Video. Coming soon. The 1938 coelacanth discovery and living coelacanths filmed by submersible, plus how fossils are sorted into rock layers; search the Smithsonian, South African fish and ocean research institutes, nature documentary footage of coelacanths, and sedimentation demonstrations from university geology departments.

KEY TERMS

observation
Something measured or seen that anyone with the right tools can check, such as the shape of a bone or the order of layers in a cliff.

interpretation
An explanation of what observations mean, especially about past events no one saw, such as how long ago an animal lived or what it descended from.

living fossil
A living organism that looks very much like its fossil relatives, such as the coelacanth, horseshoe crab or ginkgo tree.

stasis
The common pattern in which a fossil species appears and stays nearly the same throughout the layers where it is found.

punctuated equilibrium
An idea proposed by Niles Eldredge and Stephen Jay Gould in 1972: species stay the same for long periods and change quickly in small, isolated groups, so in-between forms are seldom fossilized.

ecological zonation
A Flood-geology idea that the order of fossils in the layers partly reflects where creatures lived before the Flood, with sea-floor creatures buried first and upland creatures later.

CORE IDEAS

The story. On December 22, 1938, Marjorie Courtenay-Latimer, the young curator of the small museum in East London, South Africa, went down to the docks to look over the catch of the fishing trawler *Nerine*. Under a pile of sharks and rays she saw a blue fin. She later described the fish as the most beautiful she had ever seen: about 1.5 meters long, steel blue with silvery flecks, with heavy scales and strange fleshy, limb-like fins. She could not identify it, so she sketched it and sent the drawing to J. L. B. Smith, a chemistry lecturer and fish expert at Rhodes University College in Grahamstown. When Smith finally saw the fish in February 1939, he recognized a coelacanth, a group known until then only from fossils. He named it *Latimeria chalumnae*, after her and the Chalumna River near where it was caught. More were found near the Comoro Islands beginning in 1952, and a second species was recognized in Indonesia in the late 1990s.

How they figured it out. The coelacanth teaches a lesson about reading rocks. Its fossils were known from many layers, but none from the uppermost layers, so scientists had concluded it died out with the dinosaurs. The absence of fossils had been read as the absence of the animal. Both sides learned from that. Many groups of living things, from horseshoe crabs to ginkgo trees, look much like their fossils. And many fossil species show **stasis**: they appear and stay nearly the same through every layer where they are found. In 1972 Niles Eldredge and Stephen Jay Gould proposed **punctuated equilibrium**, the idea that species stay stable for long periods and change rapidly in small groups, to explain why the fossil record shows stasis and few in-between forms.

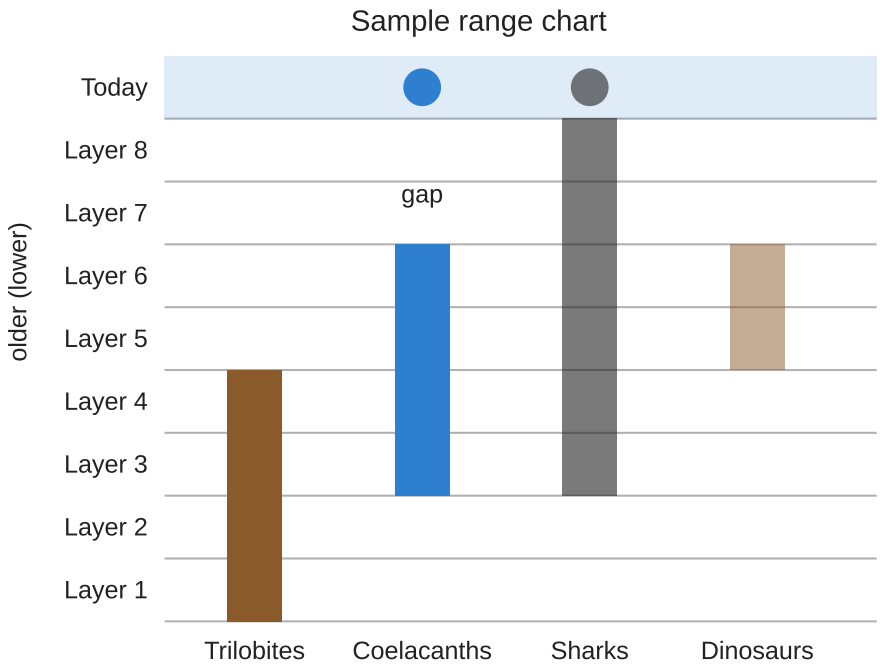
The big idea. In this unit you have met three famous kinds of evidence: the sudden appearance of animal body plans in the Cambrian, soft tissue in dinosaur bone, and mosaic fossils such as *Archaeopteryx* and *Tiktaalik*. Scientists of every view agree on the **observations**: the bones, the layers, the measurements. They disagree about **interpretations**, because no one watched the past happen. Each person reads the evidence inside a framework, a set of starting beliefs about how long the earth has existed and how living things came to be. Like the duck-rabbit drawing, the same lines can be read two ways. Good science asks which reading explains the most evidence with the fewest special assumptions, and which makes predictions that can be checked.

How each side reads them. Mainstream scientists read the layers as a record of long ages and the fossils as branches of one family tree: the Cambrian explosion as rapid branching, soft tissue as remarkable chemistry, and mosaics as transitions. Young-earth creationists read the layers mostly as the work of the Flood, with the order of fossils reflecting the order of burial (**ecological zonation**, and how well creatures could flee rising water). They read the Cambrian as created kinds appearing fully formed, soft tissue as evidence of a young age, stasis as kinds staying true to their kind, and mosaics as creatures God made with a mix of traits. Intelligent-design writers, who hold various views about age, argue that sudden new body plans require new information best explained by a designing mind. Some Christians accept the mainstream ages and see God working through long processes. Each side also has puzzles: the mainstream view must explain the missing Cambrian ancestors

and long-lasting tissue; the young-earth view must explain why the fossil order is so consistent worldwide and why radiometric dates come out old.

Try it and see. A fair student can state the other side's view so well that its holders would say, "Yes, that is what we believe." In this lesson's project you will also test a process both views care about: how objects of different shape and weight settle when they are dropped together into water. Then you will write each view's reading of your own results.

God's handiwork. Proverbs warns that the first person to tell his side always sounds right, until his neighbor comes and questions him (Proverbs 18:17). Christians have nothing to fear from careful questions, because all truth is God's truth. We can measure honestly, admit puzzles, refuse bad arguments even when they seem to help our side, and speak respectfully to those who disagree.



Sample range chart. Each bar shows the layers in which a group's fossils are found. The coelacanth bar has a gap: no fossils in layers 7 and 8, yet it is alive today.

⏳ Thinking About Time

What the sign says. What the sign says: museum signs say the animal fossil record spans about 540 million years and that coelacanths were thought to have died out about 66 million years ago, at the end of the Cretaceous, until one was caught alive in 1938.

What we observe. What we observe: fossils occur in a consistent general order in rock layers; many species show stasis; coelacanth fossils are absent from the uppermost layers, yet coelacanths live today; and many fossils needed rapid burial to form.

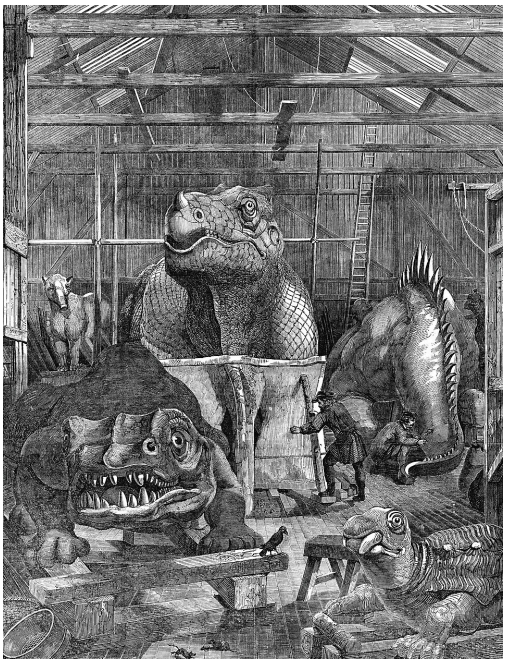
How Christians read it. How Christians read it: young-earth creationists read most fossil-bearing layers as deposited during the year-long Flood, so the gap between the last

fossil coelacanth and today is short, and the living fish shows that missing fossils do not mean missing animals. Other Christians hold old-earth views, and some accept common descent, while agreeing that God is the Creator.

Try it. Ask a parent or friend to explain one fossil from this unit using a view different from yours, then tell it back until they agree you have it right.

Genesis 7:19

PICTURE STUDY



Benjamin Waterhouse Hawkins's studio at Sydenham, After Philip Henry Delamotte (as credited on Wikimedia Commons), 1853 · Black-and-white engraving of the workshop · Made at Sydenham, south London, in 1853; widely reproduced and in the public domain

In 1853 the sculptor Benjamin Waterhouse Hawkins was building life-size models of extinct animals for the park of the Crystal Palace in south London, with the anatomist Richard Owen advising him on their shapes. The photographer Philip Henry Delamotte, who recorded the building of the new Crystal Palace, recorded Hawkins's workshop while the models were being made, and this engraved view of it has been printed ever since. On New Year's Eve 1853 about twenty scientists and supporters even ate dinner inside the mold of the *Iguanodon*, with Owen at the head of the table. The finished models still stand in the park today.

Hawkins's *Iguanodon* was a heavy, four-legged beast with a horn on its nose. In 1878 coal miners at Bernissart in Belgium found dozens of complete *Iguanodon* skeletons, and they showed that the "horn" was really a spike on the thumb. The bones of 1853 had not changed. The reading of them had.

Look closely

- Find the largest model. What kind of animal do you think it is meant to be?
- Look for signs that the work is unfinished. What tools, frames or rough surfaces can you see?
- Look at the size of the models compared with the room or with any people. How big were these animals imagined to be?
- Choose one model. Is it standing on two legs or four? What would a sculptor need to know to decide?

Talk about it

1. Which parts of Hawkins's models came from bones, and which were interpretation?
2. What new evidence changed the reading of *Iguanodon*, and what does that teach about holding interpretations humbly?
3. If you could build a life-size model of one fossil from this unit, which would you choose, and which parts would you have to guess?

> **Safety first.** Use a plastic jar or bottle if you can; if you use glass, carry it with two hands and set it on a towel. Wipe up spilled water right away so no one slips, and pour the sediment out in the yard or the trash, not down the drain.

EXPERIMENT: THE SETTLING JAR: HOW DO MIXED OBJECTS SORT IN WATER?

Both mainstream geologists and Flood geologists ask how moving water sorts sediment and buried creatures. You will drop a mix of sediment and model "fossils" into a jar of water, measure where each settles, and then write how each view would read your results.

You will need

- A tall clear jar or bottle with a lid, about 1 liter
- Sediment: 1 cup of mixed soil, sand and small gravel
- Model "fossils": 5 small shells or pasta shells, 5 dried beans, 5 small flat plastic pieces (cut from a lid), 5 sunflower seeds
- Water, a metric ruler, masking tape, a timer and a lab notebook

Steps

1. Write your question: Do objects of different density and shape settle at different levels when they sink together?
2. Write a prediction: list the four "fossil" types in the order you expect them to settle, bottom to top.
3. Variables. What you change: the object type. What you keep the same: the amount of sediment, the amount of water, how long and how hard you shake (10 seconds), and the settling time. What you measure: the height of each object above the bottom of the jar, in millimeters, after 30 minutes.
4. Put the sediment and objects in the jar, fill it with water to 3 cm below the top, close it tightly and shake for 10 seconds. Set it down and start the timer.

5. Watch the first minute closely and write what settles first. After 30 minutes, put a strip of tape up the side and mark the layers. Measure the height of each object you can see.
6. Repeat the whole trial two more times. Make a table and average each object's height.
7. Write two paragraphs: (1) What I observed. (2) How a mainstream geologist and a Flood geologist would each use this result, and what this small jar cannot show about real rock layers.

Tips

- Some objects will float at first. Record that too; floating and sinking matter for buried creatures.
- Remember the limits of a model: a 1-liter jar is not an ocean basin. Say what your model can and cannot test.

Check your work

- I ran three trials and averaged the heights.
- I kept my observations separate from my interpretations.
- I described each view fairly, in words its holders would accept.

NATURE NOTEBOOK

1. Draw the duck-rabbit illusion (or another two-way picture) and beside it a fossil from this unit. Under each write: "Same lines, two readings."
2. Draw a coelacanth from a photograph or museum book, about 15 cm long (a 1 : 10 scale of the 1.5 m fish). Label its lobed fins, tail and heavy scales.
3. Make a three-column chart titled "One Fossil, Three Readings." Choose one fossil from this unit and fill in the observation, the mainstream reading and the creation reading.

> **From history.** J. L. B. Smith spent fourteen years hoping for a second coelacanth. He printed a reward leaflet in English, French and Portuguese with a picture of the fish and spread it along the coast of East Africa. In December 1952 a fisherman in the Comoro Islands brought one to a ship's captain who had a leaflet, and Smith flew there in a South African Air Force plane provided by Prime Minister D. F. Malan to collect it. Today scientists study living coelacanths with submersibles, filming them drifting near cliffs and caves in deep water.

WORKED EXAMPLES

Example 1. Use the sample range chart. (a) In which layers are coelacanth fossils found? (b) Which groups are found together in layer 4? (c) If you had studied only layers 7 and 8, what would you have wrongly concluded about coelacanths?

(Use the map or drawing "Read across a layer to see which groups were found together." shown earlier in this lesson.)

1. Read the coelacanth bar: it runs from layer 3 to layer 6, then a dot marks it alive Today. No fossils appear in layers 7 or 8.
2. Layer 4: draw a line across at layer 4. It crosses the trilobite, coelacanth and shark bars, but not the dinosaur bar (layers 5 and 6).
3. With only layers 7 and 8, you would find sharks but no coelacanths and might conclude coelacanths had died out. The living fish shows that no fossils in a layer does not prove no animals at that time.
4. Both views use this lesson: mainstream scientists treat gaps as an incomplete record; creationists add that missing fossils cannot prove an animal's history either way.

Answer: (a) Layers 3 to 6 (and alive today). (b) Trilobites, coelacanths and sharks. (c) That coelacanths were extinct, which the living fish shows is false.

Example 2. Sample data. A class sorts 500 fossils from a road cut: 470 marine invertebrates (shells, corals, trilobites), 18 plant fossils, 8 fish and 4 land animals with backbones. What percent is each group? What is one observation everyone agrees on, and how might each side read it?

1. Check the total: 470 + 18 + 8 + 4 = 500.
2. Marine invertebrates: 470 ÷ 500 × 100 = 94%. Plants: 18 ÷ 500 × 100 = 3.6%. Fish: 8 ÷ 500 × 100 = 1.6%. Land vertebrates: 4 ÷ 500 × 100 = 0.8%.
3. Observation: most fossils in this sample are sea creatures, and land animals with backbones are rare. (This matches the real fossil record in general.)
4. Mainstream reading: shallow seas covered the land many times over long ages and preserved sea life best. Flood reading: the Flood began with the sea floor and buried vast numbers of marine creatures; land animals were fewer, floated or fled, and were seldom buried whole.

Answer: 94% marine invertebrates, 3.6% plants, 1.6% fish, 0.8% land vertebrates; both views agree sea creatures dominate, but they explain it differently.

Example 3. Sample data. The length of one fossil clam species is measured in five layers, from bottom to top: 41 mm, 40 mm, 42 mm, 41 mm, 40 mm. Find the average and the range. Is this change or stasis?

1. Average = (41 + 40 + 42 + 41 + 40) ÷ 5 = 204 ÷ 5 = 40.8 mm.
2. Range = largest − smallest = 42 − 40 = 2 mm.
3. As a percent of the average: 2 ÷ 40.8 × 100 ≈ 4.9%. The size wobbles slightly with no steady trend up or down.
4. This is stasis. Mainstream scientists explain it with ideas like punctuated equilibrium; creationists read it as a kind staying true to its kind.

Answer: Average 40.8 mm, range 2 mm (about 5% of the average), with no trend: stasis.

PRACTICE

1. EASY Who first recognized the 1938 coelacanth as unusual, and who identified it?
2. EASY Label each as observation (O) or interpretation (I): (a) *Archaeopteryx* had teeth. (b) *Archaeopteryx* descended from dinosaurs. (c) Trilobite fossils are found below dinosaur fossils. (d) The MOR 1125 bone is 68 million years old.
3. EASY What is stasis, and what idea did Eldredge and Gould propose in 1972 to explain it?
4. MEDIUM Data reading. Using the sample range chart, which group has the longest range in the layers, and how many layers does it span? Which group appears in the fewest layers?
5. MEDIUM Data reading. In the settling-jar sample data, average heights above the jar bottom were: beans 4 mm, shells 9 mm, sunflower seeds 31 mm, flat plastic pieces 26 mm; gravel formed the bottom layer and fine silt the top layer. Which statement is best supported? (a) Objects settle in random order. (b) Denser, rounder objects settled lower than light or flat objects. (c) Every object settled at the same height. (d) The jar proves the Flood laid down all rock layers.
6. MEDIUM A fossil snail is measured in four layers at 18 mm, 18 mm, 19 mm and 17 mm. Find the average and the range.
7. MEDIUM Give one puzzle that the mainstream view must explain and one puzzle that the young-earth view must explain.
8. HARD Experiment design. Design a test of whether animals that can swim or float are buried higher in a settling jar than animals that sink at once. Describe your model “animals,” the independent and dependent variables, controls and number of trials.
9. HARD What does the living coelacanth teach about arguments from missing fossils? Give one way each side has used this lesson.
10. CHALLENGE Write a paragraph that fairly explains how a mainstream scientist and a young-earth creationist read *Tiktaalik*. Each description should be one its holders would accept, and your paragraph should end with one question both sides could test.

COMMON MISTAKES

- Thinking scientists who disagree must be looking at different evidence. Usually they agree on the bones and layers and disagree about interpretations.
- Treating an absence of fossils as proof that an animal did not exist. The coelacanth showed otherwise.
- Thinking the best way to defend a view is to make the other side look foolish. A fair thinker states the other view in its strongest form, then weighs the evidence.

Make it a game · Switch Sides. A parent names a fossil from this unit: a trilobite, Opabinia, MOR 1125, Archaeopteryx, Tiktaalik or the coelacanth. You give one observation about it, then explain it first the way a mainstream scientist would and then the way a young-earth creationist would. The parent scores a point if each reading is fair enough that its holders would agree. Switch roles and let the parent try.

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

Every argument sounds good until someone tests it. In science and in friendship, listen to both sides, search out the evidence and be willing to change your mind about an interpretation.

Practice answers

1. Marjorie Courtenay-Latimer, curator of the East London museum in South Africa, noticed it and sketched it; J. L. B. Smith of Rhodes University College identified it as a coelacanth and named it *Latimeria chalumnae*.
2. (a) O. (b) I. (c) O. (d) I (it is an interpretation based on dating methods and assumptions).
3. Stasis is the pattern of fossil species staying nearly the same through the layers where they appear. Eldredge and Gould proposed punctuated equilibrium: long periods of stability broken by rapid change in small, isolated groups.
4. Sharks have the longest range, layers 3 to 8, which is 6 layers (and they are alive today). Dinosaurs appear in the fewest, layers 5 and 6, which is 2 layers.
5. (b). Beans and shells (dense, compact) settled lowest; seeds and flat pieces settled higher. (d) goes too far: a small jar can show that water sorts objects, but it cannot by itself prove how real rock layers formed.
6. Average = 72 ÷ 4 = 18 mm. Range = 19 − 17 = 2 mm. This little variation with no trend is stasis.
7. Mainstream: the missing ancestors of the Cambrian body plans, or how soft tissue and protein survived tens of millions of years. Young-earth: why the fossil order is so consistent worldwide, or why radiometric dating methods give very old ages.
8. Model animals: objects of equal size but different buoyancy, such as small sealed foil packets with and without air trapped inside, or modeling-clay shapes with and without a bit of cork. Independent variable: buoyancy (floats briefly versus sinks at once). Dependent variable: final height above the jar bottom in millimeters. Controls: same sediment amount and mix, same water level, same shaking time, same settling time. Run at least three trials and average.

9. Missing fossils in a layer do not prove an animal was absent at that time, because coelacanths have no fossils in the upper layers yet are alive. Mainstream scientists use this to say gaps in the record (like missing Cambrian ancestors) may be gaps in preservation. Creationists use it to say the fossil record cannot prove long ages or extinctions, and that creatures can stay unchanged after their kind.
10. A good answer: A mainstream scientist reads *Tiktaalik* as a close relative of the fish that gave rise to four-legged animals, pointing to its neck, flat head and limb-like fin bones, and to the successful prediction of where it would be found. A young-earth creationist reads it as a created kind of fish with sturdy fins suited to shallow water, buried in the Flood, and notes that the older-looking Zachełmie trackways show it was not on a line leading to land animals. A testable question: Could *Tiktaalik*'s fin bones and shoulder actually support its body weight out of water, as tested with models or computer simulations of its skeleton?

Unit 5 review

Answer each question. Show your work for calculations and use complete sentences for explanations. When a question asks how a view reads the evidence, state that view fairly, in words its holders would accept. The test is worth 60 points.

1. (5 pts) Multiple choice. The Burgess Shale is famous mainly because (a) it holds the oldest dinosaur bones, (b) its animals are preserved with soft parts such as legs, gills and guts, (c) it is made of volcanic glass, (d) it contains only plant fossils.
2. (5 pts) What does “Cambrian explosion” mean? Give one mainstream explanation for it and one creation or design explanation.
3. (5 pts) In a sample of 600 Burgess-type fossils, 210 are *Marrella*. What percent is that? If arthropods of all kinds total 360, what is the ratio of arthropods to all other fossils?
4. (5 pts) Describe what Mary Schweitzer’s team found in the MOR 1125 *T. rex* bone, and how they found it.
5. (5 pts) A molecule has a half-life of 521 years. What fraction remains after 2,084 years? Show the halving steps.
6. (5 pts) Explain the iron preservation idea and why young-earth creationists still see soft tissue as evidence for a young age.
7. (5 pts) Multiple choice. Which of these traits of *Archaeopteryx* is NOT found in any living adult bird? (a) feathers (b) wishbone (c) teeth (d) asymmetrical flight feathers.
8. (5 pts) Where and when was *Tiktaalik* found? List two fish-like features and two features not usually found in fish. Why do even mainstream scientists call it a relative rather than a direct ancestor of four-legged animals?
9. (5 pts) Diagram item. Draw a flight feather whose leading vane is 2 mm wide and trailing vane is 7 mm wide. Label the quill, shaft, leading vane and trailing vane, write each width, and calculate the asymmetry ratio.
10. (5 pts) Label each statement O (observation) or I (interpretation): (a) The coelacanth caught in 1938 was about 1.5 meters long. (b) Coelacanths died out 66 million years ago. (c) Trilobite fossils lie below dinosaur fossils in the layers. (d) The Cambrian layers were laid down by the Flood. (e) Some Burgess Shale fossils show guts.
11. (5 pts) Data reading. A range chart shows: Group A in layers 1–3; Group B in layers 2–5 and alive today; Group C in layers 4–6. (a) Which groups are found together in layer 3? (b) Which group has no fossils in layer 6 but is alive today? (c) What wrong conclusion might someone draw from layer 6 alone?
12. (5 pts) In a short paragraph, explain how a mainstream scientist and a young-earth creationist each read the general order of fossils in the rock layers, and name one puzzle each view must explain.

Unit project: my fossil evidence gallery

Make a small museum display, on a trifold board or in a bound notebook, with four “exhibit cards,” one for each lesson: a Burgess Shale animal, the MOR 1125 *T. rex*, *Archaeopteryx* or *Tiktaalik*, and the coelacanth. Each card has a careful labeled drawing, the discovery story

(who, where, when), a list of observations, and a "⏳ Thinking About Time" box giving the museum date, what we observe, and the young-earth reading.

Beside the cards, include the data and graph from one of your unit experiments (preservation casts, gelatin decay, feather survey or settling jar) and a one-page "fair comparison" essay that explains one fossil from the mainstream view and the creation view so fairly that a holder of each would agree, ending with a question that could be tested.

- **Accuracy**: Names, places, dates and features are correct, and every museum date is clearly labeled as the museum's or textbook's claim.
- **Observation and interpretation**: Each card separates what is observed from how it is interpreted, and the experiment report states variables, trials and averages correctly.
- **Fairness**: The essay states each view in words its holders would accept, admits a puzzle for each side and uses no mocking or weak arguments.
- **Care**: Drawings are labeled, neat and to scale where stated, and the display is clear enough for a visitor to understand without help.

Answer key

1. (b). Its animals are preserved with soft parts, which requires very rapid burial in fine mud.
2. It names the pattern in which most major animal groups (phyla) appear suddenly in the layers labeled Cambrian, with few clear forerunners below. Mainstream: rapid branching from common ancestors, driven by rising oxygen, predators and new genes, with earlier ancestors small and seldom preserved. Creation or design: distinct kinds or body plans were created or designed fully formed; young-earth creationists read the layers as early Flood burial of sea-floor life.
3. 210 ÷ 600 × 100 = 35%. Other fossils = 600 − 360 = 240. Ratio 360 : 240 = 3 : 2 (1.5 to 1).
4. They dissolved the bone mineral from fragments of the thigh bone with a mild chemical (demineralizing). Flexible, transparent, branching vessels remained, with small round and oval structures inside, some resembling bone cells. Later, protein fragments matching collagen were detected by mass spectrometry and antibodies.
5. 2,084 ÷ 521 = 4 half-lives. 1 → 1/2 → 1/4 → 1/8 → 1/16. One sixteenth (6.25%) remains.
6. Iron from the animal's blood may cross-link proteins, like a chemical preservative, slowing decay; in a lab test, ostrich vessels in iron-rich blood solution showed little decay after about two years while untreated vessels decayed within days. Young-earth creationists answer that two years is far from tens of millions of years, and that fragile, stretchy tissue and readable protein are most simply explained if the bones are only thousands of years old.
7. (c) Teeth. No living bird has teeth, though some fossil birds did.
8. On Ellesmere Island in the Canadian Arctic, in July 2004 (published 2006), by Shubin, Daeschler and Jenkins. Fish-like: gills, scales, fins with fin rays. Not usually in fish: a neck, a flat head with eyes on top, shoulder, elbow and wrist-like fin bones, sturdy ribs. Four-toed trackways from Zachełmie, Poland, lie in layers textbooks date older than *Tiktaalik*, so it cannot be the direct ancestor of those walkers.
9. The drawing shows the shaft off center, with the narrow vane on the leading side and the wide vane on the trailing side, the quill at the base, and each part labeled with its width. Ratio = 7 ÷ 2 = 3.5, strongly asymmetrical like the flight feathers of flying birds and *Archaeopteryx*.

10. (a) O. (b) I (and shown wrong by the living fish). (c) O. (d) I. (e) O.
11. (a) Groups A and B. (b) Group B. (c) That Group B had died out, when in fact it lives today; missing fossils do not prove absence, as with the coelacanth.
12. A mainstream scientist reads the order as a record of long ages, with lower layers older and life branching over time. A young-earth creationist reads most fossil layers as laid down during the Flood, with the order reflecting the order of burial: sea-floor creatures first, then creatures from higher habitats, and those able to swim or flee buried later. Mainstream puzzle: the sudden Cambrian appearance or long-lasting soft tissue. Young-earth puzzle: why the order is so consistent worldwide, or why radiometric dates come out old.

UNIT 6

Origins Fairly Told

Where did living things come from? Every science textbook, museum hall and nature program gives an answer, and so does the first chapter of the Bible. In this unit you will study three accounts of origins side by side: **creation as Genesis tells it**, **Darwin's theory of evolution by natural selection** and **intelligent design**. You will begin with Genesis 1 and 2, whose opening verses were read aloud from orbit around the Moon by the crew of Apollo 8 in 1968. Then you will follow Charles Darwin from his "I think" notebook sketch of 1837 to *On the Origin of Species* in 1859, and Phillip Johnson, Michael Behe, William Dembski and Stephen Meyer as they made the modern case for design.

The goal of the unit is fairness. "Thou shalt not bear false witness against thy neighbour" (Exodus 20:16) applies to the way we describe other people's ideas. You will learn to state each view in words its own supporters would accept, to sort what is observed today from what is inferred about the unobserved past, and to keep numbers of years attributed to those who claim them. Along the way you will add up the genealogies of Genesis 5, model natural selection with beetles and paper dots, calculate the odds of a DNA sequence arising by chance, and count the generations in Richard Lenski's long-running bacteria experiment.

The unit ends with a written comparison of the three accounts, the kind of careful, respectful essay a high-school biology student, a debater or a college applicant may one day need to write. You will see that a Christian can hold firmly to Genesis and still describe Darwin accurately, weigh evidence honestly and disagree with meekness.

BEFORE YOU BEGIN

- Can explain natural selection and variation within a kind using Darwin's finches or dog breeds (Unit 3)
- Can describe the design argument and irreducible complexity (Unit 4)
- Can tell an observation from an interpretation of fossils and rock layers (Unit 5)
- Can calculate percents, averages and powers such as 2^{10}

MASTERY CHECKLIST

- I can describe the order of the six days in Genesis 1, including the forming-and-filling pattern, and explain "after his kind" and the image of God.
- I can state Darwin's theory accurately in five parts and sort which parts are observed today and which are inferred.
- I can state the central claim of intelligent design, explain specified complexity, and describe the main criticisms and replies.
- I can calculate probabilities, percent changes and generation counts used in the origins debate.
- I can write a fair comparison of the three accounts, without loaded words, with every interpretation and every age attributed to those who hold it.

OPTIONAL BOOKS AND RESOURCES

- **The King James Bible (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/10): Free. Use it for Genesis 1–11 in Lesson 6.1, for counting phrases such as “after his kind,” and for checking every Scripture quotation in your essay.
- ***On the Origin of Species* by Charles Darwin (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/1228): Free. A primary source for Lessons 6.2 and 6.4. Read passages from the last chapter, “Recapitulation and Conclusion,” to hear Darwin state his own theory before you summarize it.
- **Darwin Online** (http://darwin-online.org.uk/): Free. Scholarly site with Darwin’s complete published works and many of his notebooks and manuscripts, including images of Notebook B. Best for older students with a parent choosing the passages.

6.1 Creation in Genesis ★

OBJECTIVES

- Read Genesis 1 and 2 closely and describe the order of the six days of creation, including the pattern of forming (days 1–3) and filling (days 4–6).
- Explain what Genesis teaches about living things reproducing “after their kind” and about man being made in the image of God, male and female.
- Use the numbers in Genesis 5 and 11 to calculate the years from creation to the Flood and to graph and interpret lifespans, and state fairly how Christians read the days of creation.

Warm-up. Fold a sheet of paper into six boxes and number them 1 to 6. Without opening a Bible, write in each box what you think God made on that day. Now open to Genesis 1 and check yourself. How many did you place correctly? Look at days 1 and 4 side by side. What do you notice?

Video. Coming soon. The Apollo 8 Christmas Eve 1968 reading of Genesis 1 from lunar orbit and the Earthrise photograph; search NASA archival footage, Smithsonian National Air and Space Museum, Moody Science classics and reverent KJV readings of Genesis 1 and 2.

KEY TERMS

create
To bring into being. In Genesis 1 the Hebrew word *bara* (“created”) always has God as the one who acts; it marks three key points: the heaven and the earth (verse 1), the creatures of the sea and air (verse 21) and man (verse 27).

kind
A group of living things God made to reproduce “after his kind.” A created kind is often broader than a modern species (see Lesson 3.4).

image of God
The special likeness to God given to human beings alone, male and female (Genesis 1:27), which sets people apart from animals and gives every person dignity.

forming and filling
The pattern of Genesis 1: on days 1–3 God forms spaces (light, sky and waters, land), and on days 4–6 He fills them (lights, swimmers and fliers, land animals and man).

genealogy
A written family record of parents and children. The genealogies in Genesis 5 and 11 also give each father’s age when his son was born and his age at death.

worldview
The set of beliefs through which a person reads evidence and answers big questions such as “Where did we come from?”

CORE IDEAS

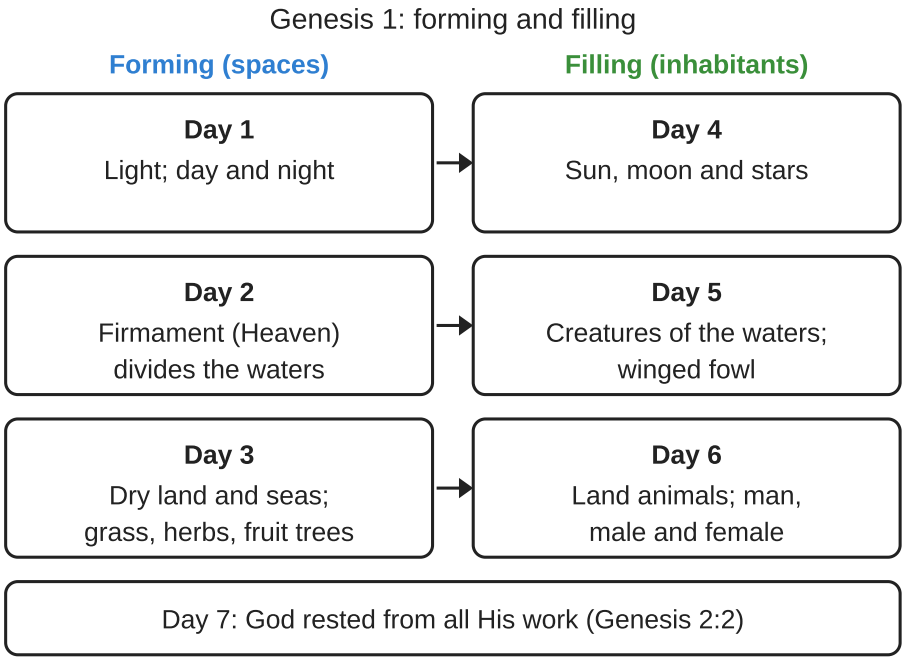
The story. On December 24, 1968, three American astronauts became the first people ever to circle the Moon. Frank Borman, Jim Lovell and Bill Anders had flown Apollo 8 about 384,000 kilometers from home. That day Anders snapped the color photograph later called *Earthrise*: a blue and white Earth rising over the gray lunar horizon. That evening, in a television broadcast watched by one of the largest audiences in history up to that time, the crew took turns reading the first ten verses of the Bible. Anders began, "In the beginning God created the heaven and the earth." Lovell read on through the first evening and morning and the firmament, Borman read of the gathering of the waters, and he closed by wishing a Merry Christmas to "all of you on the good Earth." Of all the words they could have chosen for that moment, they chose Genesis 1.

How they figured it out. Careful readers, from ancient Hebrew scholars to students today, have noticed that Genesis 1 is written with clear order. Each day closes with a refrain: "the evening and the morning were the first day," and so on through the sixth. On the first three days God *forms* spaces: light and darkness (day 1), the firmament that divides the waters, which He called Heaven (day 2), and the dry land and seas with grass, herbs and fruit trees (day 3). On the next three days He *fills* them: the sun, moon and stars (day 4) fill the light of day 1; the creatures of the waters and the winged fowl (day 5) fill the waters and sky of day 2; and the land animals and man (day 6) fill the land of day 3. Seven times God sees that what He made is good, and the seventh time it is "very good" (Genesis 1:31). The phrase "after his kind" or "after their kind" appears ten times, all for plants and animals. It is never used of man.

The big idea. Genesis 1 and 2 teach several things that shape all of biology. First, God is the Creator, separate from what He made: the sun and the sea are things, not gods. Second, creation is orderly, which is why it can be studied. Third, living things were made to reproduce "after their kind": offspring resemble their parents. Fourth, man is different from the animals: "So God created man in his own image, in the image of God created he him; male and female created he them" (Genesis 1:27). Genesis 2 then gives a close-up of the sixth day: "the LORD God formed man of the dust of the ground, and breathed into his nostrils the breath of life; and man became a living soul" (Genesis 2:7), and He made the woman from a rib taken from the man's side. Genesis 3 tells how sin entered the world, bringing death and thorns, and Genesis 6–9 records the Flood, which this course treats as real history.

In the world today. Genesis is not written like a lab report, but it makes claims about real history, and those claims touch science. Biology confirms the pattern of reproduction after kinds every day: radish seeds grow radishes, robins hatch robins, and the finches and dogs of Unit 3 vary a great deal while staying finches and dogs. Many founders of modern science, including Kepler, Boyle, Newton, Linnaeus and Faraday, believed the world was orderly because a wise Creator made it, and that belief gave them confidence that nature could be understood. In this unit you will study three accounts of origins. Genesis is the first one you must be able to state accurately, in its own words, before you compare it with any other.

God's handiwork. The *Earthrise* photograph shows what the astronauts saw: one small, bright world full of water and life, hanging in black space. Genesis says that world was made on purpose, filled on purpose and called "very good." The psalmist, looking at the same creation from the ground, wrote, "O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches" (Psalm 104:24). Every lesson in biology, from cells to whales, is a closer look at those manifold works.



Days 1–3 form the spaces; days 4–6 fill them. Day 1 pairs with day 4, day 2 with day 5, and day 3 with day 6.

⏳ Thinking About Time

What the sign says. Science textbooks and museum signs say the universe began about 13.8 billion years ago, the earth formed about 4.5 billion years ago, and life appeared and changed gradually over more than 3.5 billion years, with human beings arriving only near the very end.

What we observe. No human observed the beginning. What we have today is the text of Genesis, with six numbered days each marked by "the evening and the morning"; living things that reproduce after their kind; and rocks, fossils and starlight that every scientist measures and then interprets. Long ages come from interpreting those measurements using assumptions about how fast things happened in the unobserved past.

How Christians read it. Young-earth creationists read Genesis 1 as six ordinary days, since each day is numbered and has an evening and a morning, and Exodus 20:11 bases our seven-day week on them. Adding the ages in Genesis 5 and 11 places creation only thousands of years ago, and the Flood explains much of the rock and fossil record. Some Christians hold other views, such as reading the days as long ages. All of them confess that God is the Creator.

> **Try it.** Read Genesis 1 aloud and underline every numbered day and every "evening and the morning." How many of each do you find?
>
> *Exodus 20:11*

PICTURE STUDY



The Garden of Eden, Thomas Cole, 1828 · Oil on canvas · Amon Carter Museum of American Art, Fort Worth, Texas

Thomas Cole (1801–1848) was born in England and came to America as a young man. He painted the wild forests and rivers of New York so beautifully that he is remembered as the founder of the Hudson River School, the first great group of American landscape painters. In 1828 he painted *The Garden of Eden* and a companion picture, *Expulsion from the Garden of Eden*, which hangs today in the Museum of Fine Arts, Boston.

No one has a photograph of Eden, so Cole painted from Genesis 2 and his imagination. He wanted to show the world as God first made it, before sin and thorns: well watered, full of trees "pleasant to the sight, and good for food" (Genesis 2:9), and filled with light. Notice how small he made the people.

Look closely

- Find the two tiny human figures. How large are they compared with the trees and mountains? Why might Cole have painted them so small?
- Find all the water you can: the falls, the pools, the river. Genesis 2:10 says a river went out of Eden to water the garden.
- Look at the light. Where is it brightest, and what mood does it give the whole picture?
- Look at the plants. Can you find trees of more than one kind?

Talk about it

1. Which parts of Genesis 1 and 2 can you see in this painting? Which parts could a painter never show?
2. Cole painted a second picture of Adam and Eve leaving the garden. How do you think its colors and mood would differ from this one?
3. Is this painting a piece of science, a piece of art, or both? Explain.

> **Safety first.** Wash your hands after handling potting soil. Seeds sold for planting are sometimes coated with chemicals, so never eat them, and keep them away from small children and pets.

EXPERIMENT: AFTER ITS KIND: A SEED EXPERIMENT

Genesis says plants bring forth seed “after his kind.” You will plant three kinds of seeds, record what grows from each, and measure how much the seedlings of the same kind vary. This is a real experiment with numbers, a table and a graph.

You will need

- 10 seeds each of three kinds, such as radish, bush bean and sunflower
- 30 small cups or an egg carton with holes punched in the bottom, plus a tray
- Potting soil, water, a sunny window and masking tape for labels
- A metric ruler (millimeters), a lab notebook and a pencil

Steps

1. Write your question: Does each kind of seed produce its own kind of plant, and how much do plants of the same kind differ in height?
2. Write a prediction for each kind of seed.
3. Set up your variables. What you change: the kind of seed. What you keep the same: soil, cup size, planting depth (about 1 cm), water (the same amount each day), light and temperature. What you measure: whether each seed sprouts, what kind of seedling it is, and its height in millimeters.
4. Label every cup with the seed kind and a number (Radish 1, Radish 2 …). Plant one seed per cup and water each cup the same amount.
5. Rule a table with a row for each cup and columns for day 3, 5, 7 and 10. Measure each seedling from the soil to the top of its highest leaf and record the height in millimeters.
6. On day 10, find for each kind: the number that sprouted, the percent that sprouted, the tallest and shortest seedling, and the average height.
7. Make a bar graph of the average height for each kind, and write three sentences: What came up from each kind of seed? How much did plants of the same kind vary? Did any seed bring forth a different kind?

Tips

- Radishes sprout fastest, often within 3 to 5 days, so they are a good choice if you have only a short time.
- Measure at the same time of day each time, and keep the ruler straight up from the soil.
- Variation in height within one kind is expected. That is the variety God built into each kind, and it is what you will study in Lesson 6.2.

Check your work

- I named what I changed, what I kept the same and what I measured.
- I recorded heights in millimeters, computed percents and averages, and made a bar graph.
- I can explain how my results connect to the phrase “after his kind” and to variation within a kind.

NATURE NOTEBOOK

1. Copy the forming-and-filling chart into your notebook from memory, then check it against Genesis 1. Add the verse number where each day ends.
2. Sketch one of your seedlings on day 10 at actual size. Label the seed leaves, the true leaves, the stem and the soil line, and write its height in millimeters.
3. Draw a timeline of the Apollo 8 mission: launch (December 21, 1968), arrival at the Moon (December 24), the Genesis reading (Christmas Eve) and splashdown (December 27).

> **From history.** The Apollo 8 Genesis reading was remembered for years. In 1969 the United States Post Office issued a 6-cent stamp showing the Earth rising over the Moon, as in the *Earthrise* photograph, with the words “In the beginning God…” printed beside it. Jim Lovell later flew on Apollo 13, the mission that returned safely in April 1970 after an oxygen tank exploded on the way to the Moon.

WORKED EXAMPLES

Example 1. In Genesis 1:11–25, the phrase “after his kind” or “after their kind” appears 1 time in verse 11, 2 times in verse 12, 2 times in verse 21, 2 times in verse 24 and 3 times in verse 25. Find the total. What fraction and what percent of the uses are about plants (verses 11–12), and what percent are about animals?

1. Total = 1 + 2 + 2 + 2 + 3 = 10.
2. Plants (verses 11 and 12): 1 + 2 = 3. Fraction = 3/10. Percent = 3 ÷ 10 × 100 = 30%.
3. Animals (verses 21, 24 and 25): 2 + 2 + 3 = 7. Fraction = 7/10. Percent = 70%.
4. Check: 30% + 70% = 100%. Notice that the phrase is not used in verses 26–28, where man is made in the image of God.

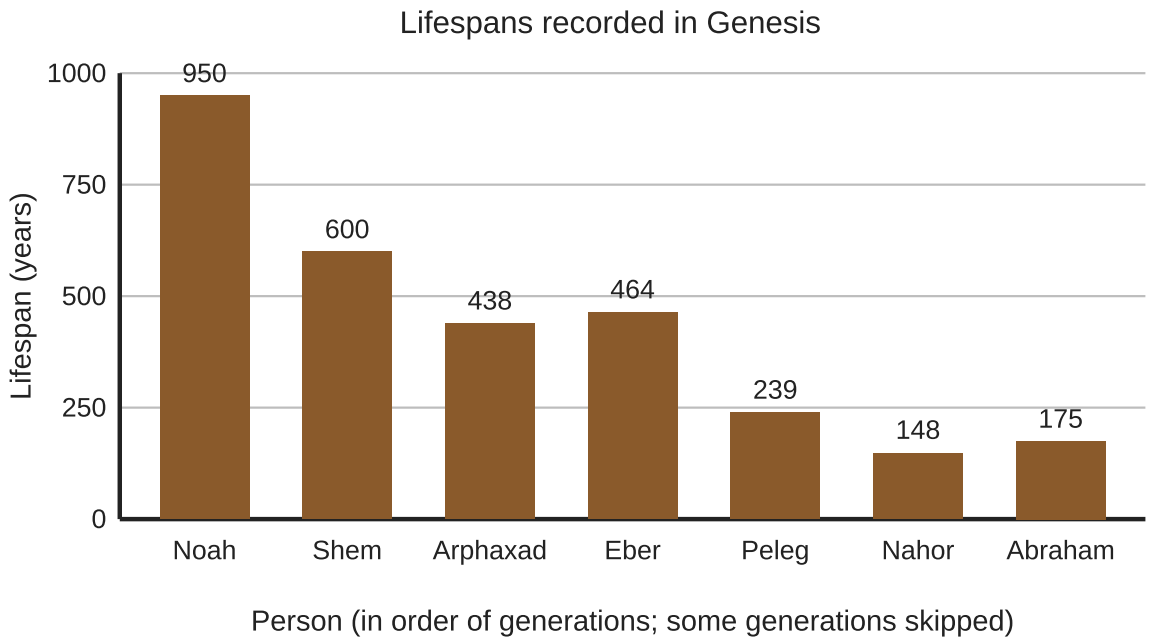
Answer: 10 uses in all: 3 about plants (30%) and 7 about animals (70%), and none about man.

Example 2. Genesis 5 gives each father’s age when his son was born: Adam 130, Seth 105, Enos 90, Cainan 70, Mahalaleel 65, Jared 162, Enoch 65, Methuselah 187, Lamech 182. Genesis 7:6 says Noah was 600 when the Flood came. Using these numbers, how many years passed from the creation of Adam to the Flood?

1. Add the fathers’ ages in order, keeping a running total: 130, then 130 + 105 = 235, then + 90 = 325, then + 70 = 395, then + 65 = 460.
2. Continue: 460 + 162 = 622, then + 65 = 687, then + 187 = 874, then + 182 = 1,056. So Noah was born in year 1,056 after creation.
3. Add Noah’s age at the Flood: 1,056 + 600 = 1,656.
4. Check with Methuselah: he was born in year 687 and lived 969 years (Genesis 5:27). 687 + 969 = 1,656, the very year of the Flood.

Answer: 1,656 years from creation to the Flood, using the numbers in the Hebrew text that the KJV translates. (The ancient Greek translation called the Septuagint gives larger numbers for several fathers, so readers who follow it get a longer total.)

Example 3. The bar graph shows the lifespans recorded in Genesis for Noah and several of his descendants. By what percent did the recorded lifespan fall from Noah (950 years) to Abraham (175 years)? By what percent did it fall from Eber (464 years) to his son Peleg (239 years)?



Lifespans recorded in Genesis 9, 11 and 25, in order of generations.

1. Noah to Abraham: decrease = 950 − 175 = 775 years. Percent decrease = 775 ÷ 950 × 100 ≈ 81.6%.
2. Eber to Peleg: decrease = 464 − 239 = 225 years. Percent decrease = 225 ÷ 464 × 100 ≈ 48.5%.
3. So Peleg's recorded lifespan is about half of his father's, a sharp drop in one generation.
4. Notice the overall pattern: lifespans fall quickly in the generations after the Flood and then level off near 150 to 200 years by the time of Abraham.

Answer: About an 81.6% drop from Noah to Abraham, and about a 48.5% drop from Eber to Peleg.

PRACTICE

1. EASY On which day did God make the sun, moon and stars? Which earlier day does that day "fill"?
2. EASY Quote Genesis 1:27 and name two things it teaches about human beings.
3. EASY What does the phrase "after his kind" tell us about how living things reproduce? Is the phrase ever used of man in Genesis 1?

4. MEDIUM Adam was 130 when Seth was born, Seth was 105 when Enos was born, and Enos was 90 when Cainan was born. In what year after creation was Cainan born?
5. MEDIUM Data reading. Use the lifespan bar graph (Noah 950, Shem 600, Arphaxad 438, Eber 464, Peleg 239, Nahor 148, Abraham 175). Which statement is best supported by the graph? (a) Every person lived a shorter life than his father. (b) Recorded lifespans fell sharply after the Flood and leveled off below 250 years by Peleg's time. (c) Lifespans dropped by exactly the same number of years each generation. (d) Abraham lived the shortest life of anyone on the graph.
6. MEDIUM Data reading. A student's seed experiment gave these results after 10 days.
   Radish: 20 planted, 18 sprouted, all radish seedlings, heights 35–62 mm.
   Bean: 20 planted, 15 sprouted, all bean seedlings, heights 80–140 mm.
   Sunflower: 20 planted, 12 sprouted, all sunflower seedlings, heights 60–110 mm.
   (a) What percent of radish seeds sprouted? (b) Which statement is best supported: (i) seeds sometimes grow into a different kind of plant; (ii) every seed that sprouted produced its own kind, but plants of the same kind varied in height; (iii) bean seedlings always reach 140 mm in 10 days?
7. MEDIUM Methuselah was born in year 687 after creation and lived 969 years. In what year did he die? What happened that same year?
8. HARD In three or four sentences, explain the forming-and-filling pattern of Genesis 1 and give all three pairs of days.
9. HARD Experiment design. You want to know whether larger bean seeds grow into taller seedlings. Name the independent variable, the dependent variable, four things to keep the same and how many seeds you would use.
10. CHALLENGE Exodus 20:11 says, "For in six days the LORD made heaven and earth, the sea, and all that in them is, and rested the seventh day." Explain why young-earth creationists see this verse as strong support for reading the days of Genesis 1 as ordinary days. Then state, fairly, one other view some Christians hold.

COMMON MISTAKES

- Thinking Genesis teaches that living things can never change. Genesis says living things reproduce "after their kind," and a created kind has room for great variety, as finches and dog breeds show (Unit 3).
- Thinking a "kind" in Genesis is the same as a "species" in a textbook. A kind is often broader, perhaps a whole family of similar species that can still interbreed or once could.
- Thinking Genesis 2 is a second creation story that contradicts Genesis 1. Genesis 2 is a close-up of the sixth day and the garden, telling in more detail how God made the man and the woman.

> **Make it a game · Day by Day.** A parent calls out something from Genesis 1: a whale, the stars, a fruit tree, the firmament, cattle, an eagle, dry land, man. You have five seconds to name the day it was made and its forming-or-filling partner day (for example, "Eagle: day

5, partner day 2”). Score a point for each right answer. Bonus point: say “after his kind” for every plant or animal, and “image of God” for man.

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

The first verse of the Bible was the first verse ever read aloud from orbit around the Moon. Before Genesis tells how or in what order, it tells who: everything that exists was made by God.

Practice answers

1. Day 4. It fills day 1, when God made light and divided the day from the night.
2. “So God created man in his own image, in the image of God created he him; male and female created he them.” It teaches that people are made in the image of God (unlike the animals) and that God made them male and female.
3. Plants and animals reproduce offspring of the same kind as the parents. The phrase is never used of man; instead man is made in God’s image.
4. 130 + 105 + 90 = 325. Cainan was born in year 325 after creation.
5. (b). (a) is false because Eber (464) lived longer than his father Salah (433) and longer than Arphaxad (438) before him; (c) is false because the drops are uneven; (d) is false because Nahor (148) lived fewer years than Abraham (175).
6. (a) 18 ÷ 20 × 100 = 90%. (b) Statement (ii). Every seedling matched its seed, and each kind showed a range of heights. Statement (i) is contradicted by the data, and (iii) ignores the range of 80–140 mm.
7. 687 + 969 = 1,656. That is the year of the Flood, using the Genesis 5 numbers (Noah was born in year 1,056 and was 600 at the Flood).
8. On days 1–3 God formed spaces, and on days 4–6 He filled them with inhabitants. Day 1 (light, day and night) is filled on day 4 by the sun, moon and stars. Day 2 (the firmament dividing the waters) is filled on day 5 by the creatures of the waters and the winged fowl. Day 3 (dry land, seas and plants) is filled on day 6 by the land animals and man; then on day 7 God rested.
9. Independent variable: seed size (weigh each seed on a kitchen scale in grams and sort into a small group and a large group). Dependent variable: seedling height in millimeters after 10 days. Keep the same: the kind and variety of bean, soil, cup size, planting depth, amount of water, light and temperature. Use at least 10 seeds in each group and compare the average heights.
10. In Exodus 20 God commands Israel to work six days and rest on the seventh because He made everything in six days and rested on the seventh. The comparison makes most sense if the creation days are the same kind of days as Israel’s work week, which agrees with the numbered days and the “evening and the morning” in Genesis 1. Some other Christians read the days as long ages (the day-age view) or as a literary framework, and they believe the earth is very old while still confessing that God created all things.

6.2 Darwin's Theory, Stated Accurately

OBJECTIVES

- Tell how Charles Darwin developed and published his theory, from his 1837 notebook sketch and his reading of Malthus in 1838 to Wallace's letter, the Linnean Society meeting of 1858 and *On the Origin of Species* in 1859.
- State the parts of Darwin's theory accurately (variation, inheritance, overproduction, natural selection and descent with modification from common ancestors) and sort which parts are observed today and which are inferred.
- Model natural selection with numbers and graphs, and correct common misstatements of the theory made by supporters and critics alike.

Warm-up. In one sentence, write what you think the word "evolution" means. Then ask two family members to do the same without looking at yours. Compare the three sentences. Do they mean the same thing? Circle any that mention monkeys, chance or "survival of the fittest." Keep your sentences; you will check them at the end of the lesson.

Video. Coming soon. Charles Darwin's life, Down House, the voyage of the Beagle and the parts of natural selection explained simply; search the Natural History Museum (London), Cambridge University Library's Darwin collections, Smithsonian, HHMI BioInteractive and Homeschool Pop (Alternate), and preview for content.

KEY TERMS

natural selection
The process in which individuals whose inherited traits suit their surroundings survive and reproduce more, so those traits become more common in later generations.

overproduction
The fact that living things produce more offspring than can possibly survive and reproduce, so there is a struggle for food, space and safety.

mutation
A change in the DNA sequence of a gene. Mutations are a source of new variation; most are neutral or harmful, and a few are helpful in a given setting.

descent with modification
Darwin's phrase for the idea that living things change over generations as they descend from their ancestors.

common descent
The claim that different species share ancestors; in its largest form, that all living things descended from one original form.

scientific theory

A broad explanation that ties many observations together and can be tested. It is more than a guess, but each of its claims must still be checked against evidence.

CORE IDEAS

The story. In July 1837, nine months after HMS *Beagle* came home, 28-year-old Charles Darwin opened a small notebook he labeled “B” and began writing private thoughts about how species might change. On one page he wrote the words “I think” and drew a little branching tree. In the autumn of 1838 he read Thomas Malthus’s *Essay on the Principle of Population*, which argued that populations tend to grow faster than their food supply. Darwin saw that in such a struggle, helpful variations would tend to be preserved. For twenty years he gathered evidence quietly at Down House, his home in Kent, breeding fancy pigeons and writing to naturalists around the world. Then in June 1858 a letter arrived from Alfred Russel Wallace, a collector working in the islands of what is now Indonesia, describing nearly the same idea. Friends arranged for both men’s papers to be read together at the Linnean Society of London on July 1, 1858. On November 24, 1859, the publisher John Murray released *On the Origin of Species*, and booksellers ordered the whole first printing of 1,250 copies almost at once.

How they figured it out. Darwin built his case from three sources. From breeders he learned that by choosing which pigeons mate, fanciers had produced pouters, fantails and tumblers, all of which he argued came from the wild rock dove. He called this *artificial selection* and reasoned that nature could select too. From Malthus he took **overproduction**: far more young are born than can survive. From the geologist Charles Lyell, whose *Principles of Geology* he read aboard the *Beagle*, he took the idea that slow processes acting over vast ages shaped the earth, and he applied it to living things. As a Cambridge student training for the ministry, Darwin had also read and admired William Paley’s *Natural Theology* (Unit 4). His theory set out to explain the way living things fit their surroundings by natural causes alone.

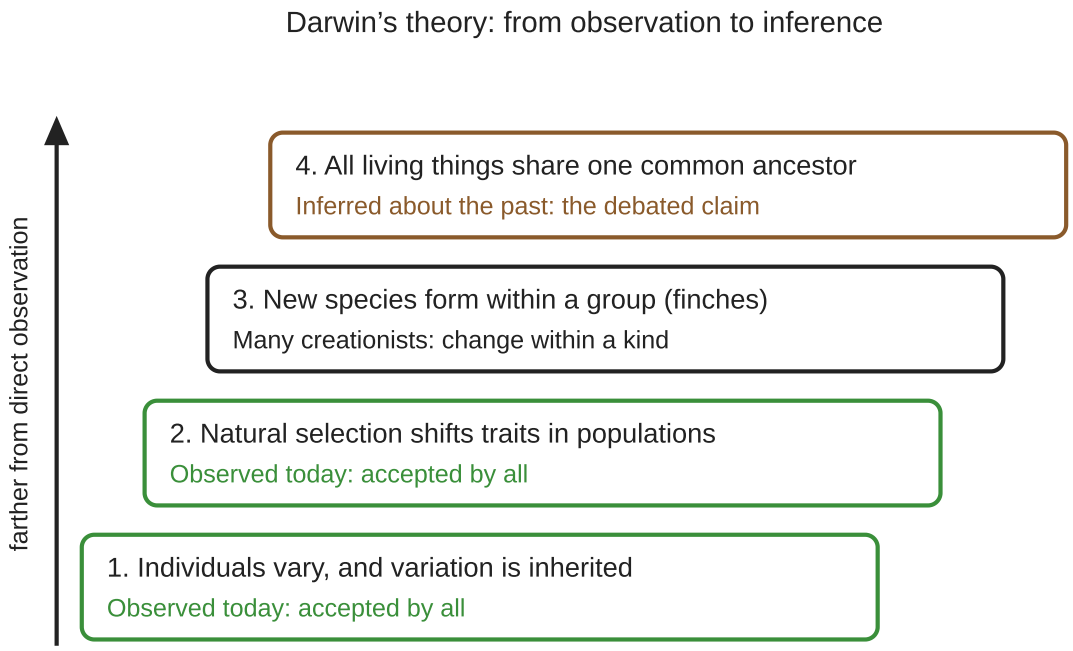
The big idea. Stated accurately, Darwin’s theory has five parts. (1) **Variation:** individuals of a species differ. (2) **Inheritance:** many of those differences are passed to offspring. (3) **Overproduction:** more young are born than can survive. (4) **Natural selection:** individuals with helpful variations survive and reproduce more, so their traits become more common. (5) **Descent with modification:** over very long ages, small changes add up to new varieties, then new species, and in the end every living thing. Darwin wrote that “probably all the organic beings which have ever lived on this earth have descended from some one primordial form, into which life was first breathed.” Darwin did not know where variation came from or how inheritance worked; Mendel’s pea results of 1866 went unnoticed until 1900. In the 1930s and 1940s biologists joined natural selection to Mendel’s genetics and to **mutation**, forming what is called the modern synthesis.

What the theory does not say. Darwin’s theory does not explain how the first life began; it starts with life already present. Darwin did not say people came from monkeys; in *The Descent of Man* (1871) he argued that humans and apes share common ancestors. The theory is not “pure chance”: mutations happen without regard to what the creature needs,

but selection is not random, since the surroundings sort which variations survive. And "survival of the fittest" was coined by Herbert Spencer in 1864; Darwin added it to the fifth edition of the *Origin* in 1869. "Fittest" means best at leaving offspring, not strongest.

In the world today. A fair student sorts the claims, as in the diagram. Variation, inheritance and natural selection are observed today, in finch beaks and resistant bacteria (Unit 3), and creation biologists accept them. The formation of new species within a group, such as the Galápagos finches, is accepted by many creationists as change within a created kind. The largest claim, that all living things share one ancestor, is an inference from present-day evidence such as similar anatomy, shared DNA and the order of fossils. That is the claim the rest of this unit weighs.

God's handiwork. The ninth commandment says, "Thou shalt not bear false witness against thy neighbour" (Exodus 20:16). That includes describing other people's ideas. A Christian who disagrees with Darwin should be able to state his theory so clearly that a Darwinian biologist would say, "Yes, that is what we mean." Only then is a disagreement honest.



Darwin's theory sorted from what is observed (bottom) to what is inferred (top).

⏳ Thinking About Time

What the sign says. Biology textbooks say all living things share a common ancestor that lived more than 3.5 billion years ago, and that natural selection and other natural processes acting over that time produced every kind of plant and animal, including human beings.

What we observe. We observe variation, inheritance, overproduction and natural selection today, changing the traits of populations within a few years (finch beaks, resistant bacteria). We observe that living things share much of their DNA and that fossils

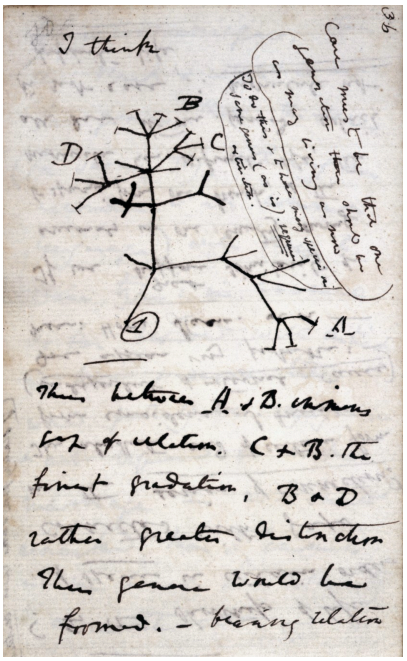
lie in an order in the rock layers. We do not observe the deep past directly; common descent of all life is an inference from these present-day observations.

How Christians read it. Young-earth creationists accept natural selection as real but see it working within created kinds over thousands of years, often sorting or removing genetic variety rather than building new kinds. They read shared DNA as the mark of one Creator using a common design, and much of the fossil order as a result of the Flood. Some Christians accept common descent and believe God worked through it.

Try it. Draw two pictures side by side: Darwin's single branching tree, and an "orchard" of separate small trees, one for each created kind. Label what each picture claims.

Genesis 1:24

PICTURE STUDY



The "I think" tree sketch, from Darwin's Notebook B, Charles Darwin, 1837 · Ink on paper, in a small handwritten notebook · Cambridge University Library, Cambridge, England

This tiny drawing, made by a 28-year-old Charles Darwin in a private notebook, has become one of the most famous sketches in the history of science. Darwin was trying to picture how species might be related. He drew a starting point, marked with a circled 1, and lines that branch and branch again. Some branches end in letters, which stand for living species; others stop short, which stand for lines that died out.

Darwin did not publish this drawing. Twenty-two years later the only illustration in *On the Origin of Species* was a much larger, more careful branching diagram built on the same idea. Look at it the way a historian would: you are seeing a thought being born, in quick handwriting, not a finished argument.

Look closely

- Find the words “I think” at the top. Why might a scientist write those words before drawing?
- Find the starting point of the tree. How many times does the first line split before it reaches the letters?
- Find the letters A, B, C and D. Which two look most closely related on the tree? How can you tell?
- Find the branches that stop without a letter. What might they stand for?

Talk about it

1. Is this drawing an observation or an interpretation? Explain.
2. How would a creation biologist redraw this picture to show separate created kinds, each with its own branches?
3. Why do you think a quick private sketch like this became so famous?

EXPERIMENT: PAPER DOT PREDATORS: A NATURAL SELECTION MODEL

You will act as a hungry bird hunting “insects” made of paper dots on a patterned background. Some dots blend in and some stand out. Over several generations you will measure how the mix of colors changes. This models natural selection: watch carefully for what changes and what does not.

You will need

- A hole punch
- Two kinds of paper for dots: a sheet of newspaper (printed dots) and a sheet of bright solid-colored paper
- A full sheet of newspaper as the background, and a second background of solid-colored paper
- Tweezers, a timer and a lab notebook with a data table

Steps

1. Write your question: On a newspaper background, how will the percent of newspaper-colored dots change over three generations of “predation”?
2. Write your prediction.
3. Variables. What you change: the background (newspaper first, then solid color as a second test). What you keep the same: the starting number of dots (25 of each), the hunting time (15 seconds), the hunter, picking one dot at a time with tweezers, and the reproduction rule. What you measure: the number of each color that survives.
4. Generation 0: punch 25 newspaper dots and 25 colored dots. Have a helper scatter all 50 on the newspaper background while you look away.
5. Hunt: for 15 seconds, pick up dots one at a time with tweezers. Count the survivors of each color left on the sheet and record them.

6. Reproduce: for each surviving dot, add one new dot of the same color. Record the new totals and the percent that are newspaper dots. Scatter them again and hunt again.
7. Run three generations. Then repeat the whole test on the solid-colored background. Make a bar graph of the percent of newspaper dots in each generation for both backgrounds.

Tips

- The helper should scatter the dots evenly, not in a pile, and the hunter should not watch where they land.
- Notice that no dot ever changed color. Selection only changed how common each color was. Write down what a new color would require that this model does not have.

Check your work

- I named what I changed, what I kept the same and what I measured.
- I recorded counts, calculated percents for each generation and made a bar graph.
- I can explain what changed (the mix of colors) and what did not (no new kind of dot appeared), and how this connects to Darwin's theory.

NATURE NOTEBOOK

1. Copy Darwin's "I think" tree into your notebook. Beside it, draw an orchard of four separate small trees, and label each picture with the claim it makes.
2. Draw the claim ladder from memory, with all four steps, and color the steps that creation biologists and Darwinian biologists both accept.
3. Make a timeline from 1809 to 1871 with these events: Darwin's birth (1809), the *Beagle* sails (1831) and returns (1836), Notebook B (1837), Malthus (1838), the Linnean Society meeting (1858), the *Origin* (1859), Mendel's paper (1866) and *The Descent of Man* (1871).

> **From history.** Darwin's Notebook B, with the "I think" sketch, and another notebook were found to be missing from Cambridge University Library in 2001, after being taken out to be photographed. For twenty years no one knew where they were. In March 2022 they were returned anonymously, left in a pink gift bag on the floor outside the librarian's office, along with a note wishing her a happy Easter. Both notebooks were undamaged.

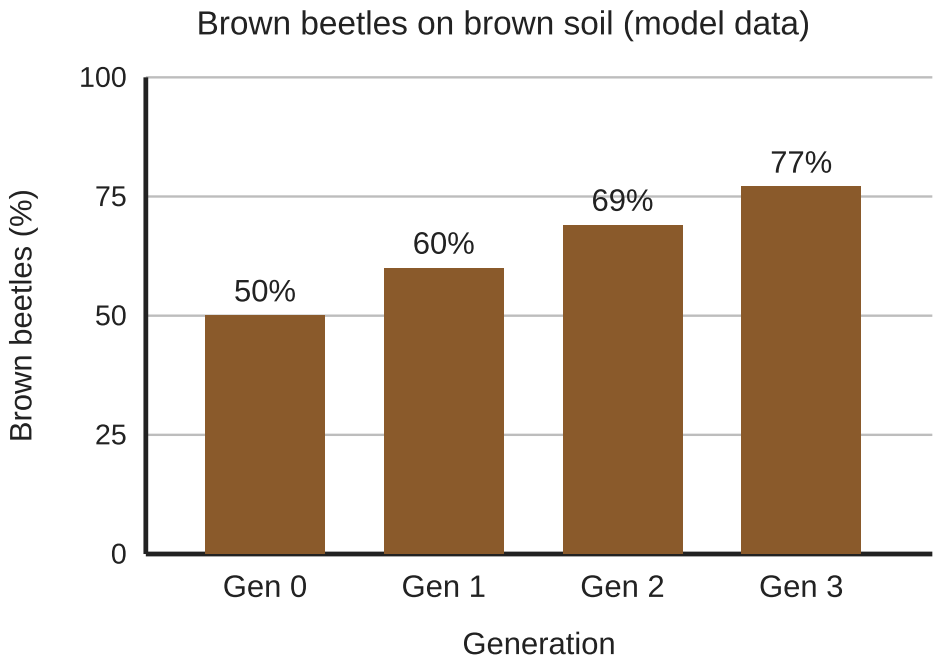
WORKED EXAMPLES

Example 1. Overproduction. Suppose a population of beetles starts with 2 and doubles every generation, with no deaths except old age. How many beetles would there be after 10 generations? After 20 generations? What does this show?

1. Doubling once multiplies by 2, so after n generations the number is 2×2^{n}.
2. After 10 generations: $2 \times 2^{10} = 2 \times 1{,}024 = 2{,}048$ beetles.
3. After 20 generations: $2 \times 2^{20} = 2 \times 1{,}048{,}576 = 2{,}097{,}152$ beetles, more than two million.
4. Real populations do not grow like this for long because food and space run out and most young die. This is the overproduction Darwin took from Malthus.

Answer: 2,048 after 10 generations and 2,097,152 after 20. Populations can multiply far faster than their food supply, so most young cannot survive.

Example 2. A field has 100 beetles: 50 green and 50 brown. On brown soil, birds eat 40% of the green beetles and 10% of the brown ones each generation. Each survivor then leaves 2 offspring of its own color (and the parents die). What percent of the beetles are brown after the birds hunt in generation 1? In generation 2?



Model data: the share of brown beetles rises each generation as birds catch more of the green ones.

1. Generation 1 survivors: green 50 × 0.60 = 30; brown 50 × 0.90 = 45. Total = 75. Percent brown = 45 ÷ 75 × 100 = 60%.
2. Offspring: green 30 × 2 = 60; brown 45 × 2 = 90.
3. Generation 2 survivors: green 60 × 0.60 = 36; brown 90 × 0.90 = 81. Total = 117. Percent brown = 81 ÷ 117 × 100 ≈ 69%.
4. Continuing the same steps gives about 77% brown in generation 3. Brown rises each generation, but no beetle ever changes color and no new color appears.

Answer: 60% brown after generation 1 and about 69% after generation 2 (about 77% after generation 3).

Example 3. Where does new variation come from? Suppose a gene has a mutation rate of 1 in 100,000 per copy per generation. A population has 1,000,000 animals, each with 2 copies of the gene. (a) How many new mutations in this gene appear each generation? (b) If only 1 in 1,000 such mutations is helpful, how many generations would pass, on average, between helpful mutations in this gene? (Sample numbers for practice.)

1. Copies of the gene = 1,000,000 × 2 = 2,000,000.
2. New mutations = 2,000,000 × 1/100,000 = 20 per generation.
3. Helpful mutations per generation = 20 × 1/1,000 = 0.02.
4. Generations per helpful mutation = 1 ÷ 0.02 = 50.

Answer: (a) 20 new mutations per generation. (b) About one helpful mutation every 50 generations. Both sides of the origins debate use calculations like this: one side to show how variation arises, the other to ask whether enough helpful mutations could arise to build entirely new organs.

PRACTICE

1. EASY Who reached nearly the same idea as Darwin, and how did both men's ideas first become public?
2. EASY List the five parts of Darwin's theory in order.
3. EASY Who coined the phrase "survival of the fittest," and what does "fittest" mean in biology?
4. MEDIUM A classmate says, "Darwin taught that people came from monkeys, and evolution explains how life started." Correct both parts of this statement accurately.
5. MEDIUM A pair of fish produces 3,000 eggs over their lives. If the population stays the same size from generation to generation, on average how many of those eggs survive to become breeding adults? What percent is that?
6. MEDIUM Data reading. Use the beetle bar graph (brown: 50%, 60%, 69%, 77% in generations 0–3). Which statement is best supported? (a) Green beetles turned brown to hide from birds. (b) The share of brown beetles rose each generation, but by a smaller amount each time. (c) After generation 3 all the beetles will be brown. (d) Birds prefer to eat brown beetles.
7. MEDIUM Data reading. Sample data shaped like the peppered moth records from near Manchester, England, show the percent of dark moths: 1848, about 1%; 1895, about 95%; 1960, about 90%; 2000, about 10%. Soot from coal smoke darkened tree bark in the 1800s; clean-air laws in the 1950s reduced it. (a) In which period did the share of dark moths rise? (b) Which statement is best supported: (i) the moths became a new kind of insect; (ii) the proportion of dark and light moths shifted with the color of the trees, and both forms stayed peppered moths; (iii) the moths caused the soot?
8. HARD Sort each statement as observed today (O) or inferred about the past (I): (a) finch beaks grew deeper on average after a drought; (b) bacteria can become resistant to an antibiotic in a laboratory; (c) whales and land mammals share a common ancestor; (d)

children inherit traits from their parents; (e) all life descended from one primordial form.

9. HARD Experiment design. Using the paper dot model, design a test of whether background color affects which dot color survives. Give the independent variable, the dependent variable, three controlled variables and how you would make the test fair.
10. CHALLENGE Write a three- or four-sentence summary of Darwin's theory that a Darwinian biologist would accept as accurate. Do not agree or disagree with it; just state it.

COMMON MISTAKES

- Saying Darwin taught that people came from monkeys. He argued that humans and apes share common ancestors.
- Calling evolution "pure chance." Mutations occur without regard to need, but natural selection is not random: the surroundings decide which variations survive.
- Treating "natural selection is observed" as if it meant "common descent of all life is observed." Natural selection within populations is observed and accepted by creation biologists; universal common descent is an inference about the unobserved past.

> **Make it a game · Accurate or Not?.** A parent reads statements about Darwin's theory, some accurate and some common mistakes ("Darwin said we came from chimpanzees," "Natural selection needs variation," "Darwin explained how life began," "Survival of the fittest means the strongest win"). Give a thumbs up for accurate or a thumbs down for not. For each thumbs down, fix the statement in one sentence to score a point. Then switch, and you write five statements for your parent.

> **Scripture.** "Thou shalt not bear false witness against thy neighbour." (Exodus 20:16, KJV)

Bearing false witness includes misstating what other people believe. Describe Darwin's theory the way a fair-minded Darwinian would, and you will be ready to weigh it honestly.

Practice answers

1. Alfred Russel Wallace. Their papers were read together at the Linnean Society of London on July 1, 1858.
2. Variation, inheritance, overproduction, natural selection and descent with modification (over long ages, from common ancestors).
3. Herbert Spencer, in 1864 (Darwin added it to the fifth edition of the *Origin* in 1869). "Fittest" means best at surviving and leaving offspring in a given setting, not strongest or fastest.
4. Darwin argued that humans and apes share common ancestors (*The Descent of Man*, 1871), not that people descended from any living monkey. His theory also does not explain how the first life began; it begins with life already present.
5. On average 2, enough to replace the two parents. 2 ÷ 3,000 × 100 ≈ 0.067%, or about 1 egg in 1,500.
6. (b). The increases are 10, 9 and 8 percentage points. (a) is wrong because no beetle changed color; (c) goes beyond the data; (d) is the opposite of the model, where green beetles are

caught more often.

7. (a) Between 1848 and 1895. (b) Statement (ii). Both forms belong to one species and interbreed; only their proportions changed. Statement (iii) reverses cause and effect.
8. (a) O, (b) O, (c) I, (d) O, (e) I.
9. Independent variable: the background (newspaper or solid color). Dependent variable: the number or percent of each dot color that survives the hunt. Controls: the starting number of each dot color, the hunting time, the hunter, the tool (tweezers) and the reproduction rule. To make it fair, have a helper scatter the dots while the hunter looks away, run three trials for each background and average the results.
10. Sample: Darwin proposed that individuals in a population vary, that many of these variations are inherited, and that more offspring are born than can survive. Those with variations best suited to their surroundings tend to survive and reproduce more, so their traits become more common; he called this natural selection. Over very long periods, he argued, these small changes accumulate to produce new species. He concluded that all living things are probably descended from one or a few original forms.

6.3 Intelligent Design

OBJECTIVES

- State the central claim of intelligent design accurately and name its leading writers and books: Phillip Johnson (1991), Michael Behe (1996), William Dembski (1998) and Stephen Meyer (2009).
- Explain the design inference (law, chance or design, and the idea of specified complexity) and calculate simple probabilities that show how quickly possible sequences multiply.
- Describe the main criticisms of intelligent design and its supporters' answers, and explain how intelligent design differs from and relates to biblical creation.

Warm-up. Gather six things: a pebble, a pinecone, a key, a handful of dropped coins, a printed sentence cut from an old magazine, and a few letter tiles shaken onto the table. Sort them into "designed" and "not designed." For each one, write the clue you used to decide. Which object was hardest to sort, and why?

Video. Coming soon. The design argument in biology, molecular machines and the information in DNA explained for students, presented from both sides; search Discovery Institute, university biology lecture channels, HHMI BioInteractive animations of the bacterial flagellum and DNA, and SETI Institute talks on recognizing signals from intelligence.

KEY TERMS

intelligent design
The view that certain features of the universe and of living things are best explained by an intelligent cause, not by an undirected process such as natural selection.

design inference
Reasoning from the features of an object or event to the conclusion that a mind produced it, as archaeologists do with arrowheads and detectives do with clues.

specified complexity
William Dembski's term for something that is both highly improbable (complex) and matches an independent, meaningful pattern (specified), such as a written sentence.

irreducible complexity
Michael Behe's term for a system of several well-matched parts that all must be present for it to work at all, such as the bacterial flagellum (Lesson 4.3).

probability
How likely an event is, written as a fraction or decimal from 0 (impossible) to 1 (certain). The chance of a tossed coin landing heads is 1/2.

methodological naturalism

The working rule, followed by most scientists, that science should explain things only by natural causes. Intelligent design writers argue that this rule should not forbid a conclusion of design.

CORE IDEAS

The story. In 1987 Phillip E. Johnson, a law professor at the University of California, Berkeley, was spending a year in London. There he read Richard Dawkins's new book *The Blind Watchmaker* (1986) and Michael Denton's *Evolution: A Theory in Crisis* (1985). Dawkins opened with a sentence that people on both sides could agree with: "Biology is the study of complicated things that give the appearance of having been designed for a purpose." He then argued that natural selection is a "blind watchmaker" that produces that appearance without any mind. Johnson, trained to weigh arguments in court, concluded that the case for unguided evolution leaned more on philosophy than on evidence, and in 1991 he published *Darwin on Trial*. Soon others were writing about what they called **intelligent design**: the biochemist Michael Behe (*Darwin's Black Box*, 1996), the mathematician and philosopher William Dembski (*The Design Inference*, 1998) and the philosopher of science Stephen Meyer (*Signature in the Cell*, 2009).

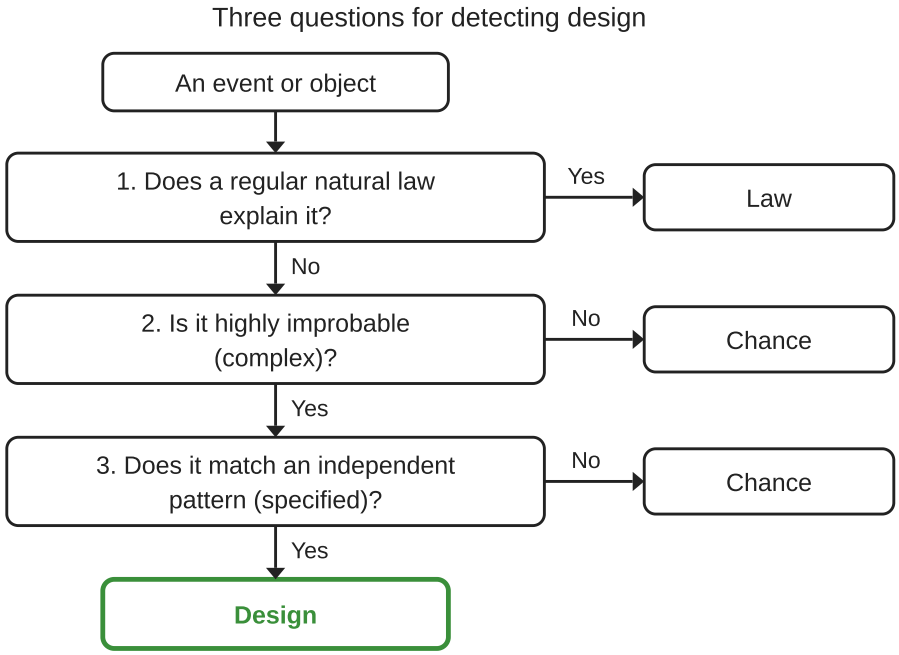
How they figured it out. Intelligent design writers point out that many sciences already detect design. Archaeologists tell a chipped arrowhead from a broken rock, detectives tell a planned crime from an accident, and radio astronomers searching for signals from other worlds have planned how they would recognize a message. Dembski described the reasoning as three questions. Can a regular natural law explain it? If not, could chance explain it? If the event is both highly improbable and matches an independent pattern, which he called **specified complexity**, the best explanation is design. A handful of scattered stones is improbable but means nothing; stones that spell your name are improbable and specified. Behe applied a test Darwin himself had set: "If it could be demonstrated that any complex organ existed, which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down." Behe argued that **irreducibly complex** machines such as the bacterial flagellum meet that test. Meyer argued that DNA stores coded information, and that in all our experience, codes come from minds.

The big idea. Stated accurately, intelligent design claims that certain features of the universe and of living things are best explained by an intelligent cause, not an undirected process such as natural selection. Just as important is what it does *not* claim. As a scientific argument, it does not name the designer. It does not say how old the earth is. It does not deny that variation and natural selection happen. Some of its writers, such as Behe, accept common descent, and not all of its writers are Christians; a few are agnostics. So intelligent design is a narrower claim than biblical creation, which names the Creator, gives the order of creation and records history from Adam to the Flood.

In the world today. Most biologists and major science organizations reject intelligent design as science. Their main objections are these: it argues from gaps ("we do not yet know how this evolved" is not the same as "it could not have evolved"); a designer cannot be tested in a laboratory; and parts of the flagellum resemble a simpler protein pump, the type

III secretion system, which might have served as a stepping stone. The biologist Kenneth Miller of Brown University, himself a Christian, has been a leading critic. Design writers answer that their argument is not from ignorance but from what we know: minds are the only cause we have seen produce codes and machines. They say design could be refuted by showing, step by step, how an undirected process built such a machine. They reply that the simpler pump may have come from the flagellum rather than the other way around. And they note that they predicted much so-called “junk DNA” would turn out to have uses; research has since found functions for some of it, though how much is still debated.

God’s handiwork. Paul wrote that “the invisible things of him from the creation of the world are clearly seen, being understood by the things that are made” (Romans 1:20). A Christian does not need intelligent design arguments to know that God created; that rests on His Word. But when a scientist looks at the coded letters of DNA or the spinning motor of a bacterium and says, “This looks designed,” the Bible says why: it was.



Dembski’s three questions for detecting design. Critics say the chart can be fooled when we simply do not yet know the natural cause.

⏳ Thinking About Time

What the sign says. Textbooks say the first living cells arose from non-living chemicals by natural processes more than 3.5 billion years ago (they say the exact way is still unknown), and that undirected natural selection then built complex systems over long ages.

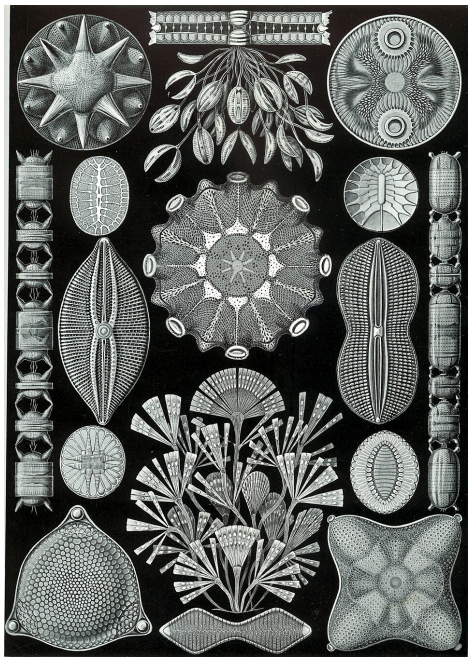
What we observe. Every living cell we can examine stores coded information in DNA and uses protein machines to read and copy it. No laboratory has produced a living cell or a working genetic code from non-living chemicals. In everyday experience, codes and machines come from minds.

How Christians read it. Young-earth creationists agree with intelligent design that life shows real design, but they go further: they name the Designer as the God of the Bible and read the history of life from Genesis, with creation in six days only thousands of years ago. Intelligent design writers themselves differ on age; many accept the textbook ages. Some Christians reject intelligent design and hold that God worked through evolution.

Try it. Spell HELLO with five letter tiles, then put the tiles in a cup, shake and pour them out in a line 20 times. Did chance ever spell a word?

Romans 1:20

PICTURE STUDY



Diatomea (diatoms), from Kunstformen der Natur (Art Forms in Nature), Ernst Haeckel, Issued 1899–1904 · Printed plate (lithograph) from a book of 100 plates · Published in Leipzig and Vienna; copies in many libraries

Diatoms are single-celled algae that live in oceans, lakes and even damp soil. Each one builds a shell of glass (silica) in two halves that fit together like a box and its lid, decorated with rows of pores and ribs too small to see without a microscope. The German zoologist Ernst Haeckel (1834–1919) drew them, along with sponges, jellyfish and other small creatures, for his book *Art Forms in Nature*.

Haeckel was the leading champion of Darwin’s theory in Germany, and he rejected belief in a personal Creator. Yet his plates are some of the most beautiful pictures of the order and symmetry of living things ever made, and people on every side of the origins debate admire them. Haeckel was also criticized, even in his own day, for some drawings of embryos that made them look more alike than they really are: a reminder that every scientist must draw what is actually there.

Look closely

- Find a round diatom and a long, narrow one. How many different shapes can you count on the page?
- Look at the patterns of dots and lines on a single shell. Are they random or orderly? How can you tell?
- Find the line of symmetry in three different diatoms.
- How did Haeckel arrange the whole page? Is the arrangement his design or nature's?

Talk about it

1. Each pattern on a diatom shell is made by a single living cell. Does that make you think more of design or of natural law? Explain your reasoning.
2. Haeckel and a Christian naturalist could both admire this plate. What would each one say about where the beauty comes from?
3. Why is it important that a scientific drawing show what is really there, even if it does not fit the artist's ideas?

EXPERIMENT: CHANCE OR MIND? A LETTER-DRAWING EXPERIMENT

Can chance spell a word? You will draw letters at random and measure how often they form a real English word, then compare longer and longer words. This tests one piece of the design argument: how quickly the odds fall as a sequence gets longer.

You will need

- 26 small slips of paper, one for each letter of the alphabet, and a cup or bag
- A lab notebook and pencil, and a dictionary for checking words
- A calculator

Steps

1. Write your question: How does the number of letters drawn affect how often chance spells a real English word?
2. Write a prediction for 3, 4 and 5 letters.
3. Variables. What you change: the number of letters drawn (3, 4 or 5). What you keep the same: the 26 slips, drawing without looking, putting each slip back after drawing it, reading the letters in the order drawn, and 50 tries for each length. What you measure: the number of tries that spell a real English word.
4. Draw 3 letters, one at a time, writing each down and putting it back before the next draw. Record whether the three letters, in order, spell a real word. Repeat 50 times.
5. Repeat with 4 letters (50 tries) and 5 letters (50 tries).
6. Calculate the percent of tries that spelled a word for each length, and make a bar graph.
7. Calculate how many different ordered sequences are possible: 26^3 = 17,576 for 3 letters, 26^4 = 456,976 for 4 letters and 26^5 = 11,881,376 for 5 letters. Write three

sentences comparing chance with a person who simply decides to write a word.

Tips

- Keep the slips the same size and shake the cup before each draw so that every letter has an equal chance.
- Have a parent check doubtful words in a dictionary. Decide before you begin whether names and abbreviations count (they should not).

Check your work

- I named what I changed, what I kept the same and what I measured.
- I recorded 50 tries for each length, calculated percents and made a bar graph.
- I can explain why longer meaningful sequences become far less likely by chance, and I can state one way critics answer the design argument.

NATURE NOTEBOOK

1. Draw the three-question design flowchart from memory. Then run three things through it: a snowflake, a sand dune ripple and a message written in the sand. Write where each one ends.
2. Sketch one diatom from Haeckel’s plate as large as your hand. Mark its line or lines of symmetry and count its rows of pores.
3. Make a two-column chart titled “What intelligent design claims / What it does not claim,” with at least three items in each column.

> **From history.** Scientists planned how to recognize a message from a mind long before intelligent design had its name. In April 1960 the astronomer Frank Drake pointed a 26-meter radio telescope at Green Bank, West Virginia, toward two nearby stars, Tau Ceti and Epsilon Eridani, listening for a signal sent by intelligent beings. He called it Project Ozma. Drake reasoned that a narrow, patterned signal, unlike the hiss of natural radio noise, would point to an intelligent sender. No such signal has ever been confirmed, but the reasoning is the same kind of design inference used by archaeologists and detectives.

WORKED EXAMPLES

Example 1. A friend tosses a fair coin 20 times and gets heads every time. What is the probability of that happening by chance? Then explain why the sequence HTTHHTHTTTHHTHTHHTTH is exactly as improbable, yet nobody suspects a trick.

1. Each toss has a probability of 1/2 of landing heads, and the tosses are independent, so multiply: $(1/2)^{20}$.
2. $2^{10} = 1{,}024$, so $2^{20} = 1{,}024 \times 1{,}024 = 1{,}048{,}576$. The probability is 1/1,048,576, about 1 in a million.
3. Any one particular sequence of 20 tosses also has a probability of 1/1,048,576.
4. The difference is the pattern. Twenty heads matches a simple pattern we could name before the tosses (specified); the mixed sequence matches no pattern anyone named in advance. Improbability alone does not point to design; improbability plus a specified pattern does.

Answer: 1 in 1,048,576. Both sequences are equally improbable, but only twenty heads is also specified, which is why it makes us suspect a two-headed coin.

Example 2. DNA uses four bases: A, T, G and C. How many different DNA sequences 12 bases long are possible? If bases were strung together at random, what is the probability of getting one particular 12-base sequence?

1. Each position has 4 choices, so the number of sequences is 4^{12}.
2. $4^{12} = (4^6)^2 = 4{,}096 \times 4{,}096 = 16{,}777{,}216$.
3. The probability of one particular sequence is 1/16,777,216, about 1 in 16.8 million.
4. Each added base multiplies the number of possibilities by 4. A typical gene is hundreds or thousands of bases long.

Answer: 16,777,216 possible sequences, so the chance of one particular sequence is about 1 in 16.8 million.

Example 3. A modest protein is a chain of 150 amino acids, and there are 20 kinds of amino acids. Estimate the number of possible chains, 20^{150}, as a power of 10. Use $2^{10} \approx 10^3$. Compare the answer with the number of atoms in the observable universe, which is often estimated at about 10^{80}.

1. Write 20 as 2×10, so $20^{150} = 2^{150} \times 10^{150}$.
2. $2^{150} = (2^{10})^{15} \approx (10^3)^{15} = 10^{45}$.
3. So $20^{150} \approx 10^{45} \times 10^{150} = 10^{195}$. (A calculator gives about 1.4×10^{195}.)
4. $10^{195} \div 10^{80} = 10^{115}$, so there are vastly more possible chains than atoms in the universe.
5. Fair note: critics answer that many different chains can do the same job and that proteins were not assembled in one random jump. Design writers reply with experiments such as Douglas Axe's 2004 study, which estimated that only about 1 chain in 10^{77} of this length folds into a working form; critics dispute that estimate.

Answer: About 10^{195} possible chains (about 1.4×10^{195}), roughly 10^{115} times the estimated number of atoms in the observable universe. The two sides disagree about how many of those chains would work.

PRACTICE

1. EASY State the central claim of intelligent design in one sentence.
2. EASY Match each writer with his book: Phillip Johnson, Michael Behe, William Dembski, Stephen Meyer. Books: *The Design Inference* (1998), *Darwin on Trial* (1991), *Signature in the Cell* (2009), *Darwin's Black Box* (1996).
3. EASY What two things must be true for something to have specified complexity? Give one example.
4. MEDIUM What is the probability of tossing 5 heads in a row with a fair coin? Of 10 heads in a row?
5. MEDIUM How many different DNA sequences 8 bases long are possible? What is the probability of one particular 8-base sequence arising at random?
6. MEDIUM Data reading. The table shows the number of possible DNA sequences for each length: 1 base, 4; 2 bases, 16; 3 bases, 64; 4 bases, 256; 5 bases, 1,024. Which statement describes the pattern? (a) Each added base adds 4 possibilities. (b) Each added base multiplies the number of possibilities by 4. (c) The number doubles with each base. (d) The number grows by 12 each time. How many sequences are possible for 10 bases?
7. MEDIUM Data reading. A student's letter-drawing experiment gave: 3 letters, 4 real words in 50 tries; 4 letters, 1 real word in 50 tries; 5 letters, 0 real words in 50 tries. (a) Find the percent of tries that spelled a word for 3 letters and for 4 letters. (b) Which conclusion is best supported: (i) chance can never spell a word; (ii) the longer the

sequence, the less often chance spelled a real word; (iii) 5-letter words are impossible to draw by chance?

8. HARD Critics call intelligent design an argument from gaps. Explain that criticism in two sentences, then give the answer intelligent design writers make in two sentences.
9. HARD Experiment design. Design an experiment to test whether people can tell real coin-toss sequences from sequences a person made up to "look random." Give the independent variable, the dependent variable, how you would avoid bias and how many sequences and testers you would use.
10. CHALLENGE Give two ways intelligent design and biblical creation agree and two ways they differ.

COMMON MISTAKES

- Thinking intelligent design is the same thing as young-earth creation. Intelligent design is a narrower argument from nature; it does not name the designer or give an age for the earth, and its writers hold different views on both.
- Thinking intelligent design denies natural selection. Design writers accept variation and natural selection; they question whether these undirected processes can build complex new systems.
- Thinking anything improbable must be designed. Every shuffled deck of cards is improbable. Design is inferred only when an improbable event also matches an independent pattern.

Make it a game · Law, Chance or Design?. A parent names something: a snowflake, a sandcastle, a crystal of salt, ripples on a beach, an arrowhead, a spider web, a footprint, a written grocery list, a pile of autumn leaves. Run it through the three questions out loud and announce Law, Chance or Design. Score a point for a good reason, not just a good answer. Spider webs and snowflakes make great arguments, so expect a lively round.

Scripture. "For the invisible things of him from the creation of the world are clearly seen, being understood by the things that are made, even his eternal power and Godhead; so that they are without excuse:" (Romans 1:20, KJV)

Paul says creation itself shows God's power. Design arguments do not prove everything Scripture teaches, but they agree with what Scripture says the things that are made reveal.

Practice answers

1. Certain features of the universe and of living things are best explained by an intelligent cause, not by an undirected process such as natural selection.
2. Johnson: *Darwin on Trial* (1991). Behe: *Darwin's Black Box* (1996). Dembski: *The Design Inference* (1998). Meyer: *Signature in the Cell* (2009).
3. It must be highly improbable (complex) and match an independent, meaningful pattern (specified). Example: a sentence written in the sand, or stones arranged to spell a name.
4. 5 heads: $(1/2)^5 = 1/32$. 10 heads: $(1/2)^{10} = 1/1{,}024$.

5. 4^8 = 65,536 sequences, so the probability is 1/65,536.
6. (b). For 10 bases: 4^{10} = 1,048,576 possible sequences.
7. (a) 3 letters: 4 ÷ 50 × 100 = 8%. 4 letters: 1 ÷ 50 × 100 = 2%. (b) Statement (ii). Statement (i) is contradicted by the 3- and 4-letter results, and (iii) goes beyond the data: 5-letter words are possible, just rare, and 50 tries were too few to find one.
8. Critics say that pointing to something we cannot yet explain by evolution and calling it designed is only an argument from present ignorance, and that science may later find a natural explanation. Design writers answer that their argument rests on what we do know: in all our experience, coded information and machines with matched parts come from minds. They add that the claim can be tested and would be refuted by a detailed, step-by-step undirected pathway.
9. Make 20 cards, each with a 20-letter sequence of H and T: 10 from real coin tosses and 10 written by a helper trying to look random. Independent variable: how the sequence was made (real tosses or made up). Dependent variable: the percent of cards each tester labels correctly. Avoid bias by shuffling the cards, marking the answers only on the back, keeping the person who made the cards out of the room, and giving every tester the same instructions and time. Use at least 5 testers and average their scores; a score near 50% means they are guessing. (Hint: people faking randomness usually avoid long runs like HHHHH.)
10. Agree: both hold that living things show real design, and both doubt that undirected natural selection can explain the origin of complex systems and coded information. Differ: biblical creation names the Creator as the God of the Bible, while intelligent design as a scientific argument does not name the designer; and biblical creation (in the young-earth reading) gives a history and timescale from Genesis, while intelligent design takes no position on the age of the earth, and some of its writers accept common descent.

6.4 A Respectful Written Comparison

OBJECTIVES

- Separate observations from interpretations, and claims from evidence, in writing about origins.
- Write a fair, organized comparison of biblical creation, Darwinian evolution and intelligent design, stating each view in words its own supporters would accept and using claim, evidence and reasoning.
- Use simple numbers (word balance, generation counts, percents and averages) to check the fairness and accuracy of a draft and to read a real case study.

Warm-up. Think of a sports team, a food or a book you do not like. Write one sentence describing it in a way that someone who loves it would agree with: no sneering, no weak points chosen on purpose. Read it aloud to a parent. Would a fan nod, or wince? Rewrite it until a fan would nod.

Video. Coming soon. How to write a compare-and-contrast essay and how to separate observation from interpretation in science; also Richard Lenski's long-term E. coli experiment explained; search Khan Academy writing lessons, university writing centers, Michigan State University and HHMI BioInteractive, and preview for content.

KEY TERMS

observation
Something measured or seen directly, which anyone with the right tools can check, such as "this fossil has feathers."

interpretation
An explanation of what observations mean, which depends on reasoning and assumptions, such as "this animal was an ancestor of birds."

claim, evidence, reasoning
A way to build a paragraph: state the claim, give the evidence that supports it, and explain the reasoning that links the evidence to the claim.

steelman
To state an opposing view in its strongest and most accurate form, the opposite of a "straw man," which is a weak version that is easy to knock down.

loaded word
A word that carries a judgment or an insult, such as "so-called" or "blind faith," used in place of a neutral description.

primary source
An original document written by the people involved, such as Genesis, Darwin's *On the Origin of Species* or Behe's *Darwin's Black Box*.

CORE IDEAS

The story. On Saturday, June 30, 1860, hundreds of people crowded into the new Oxford University Museum for a meeting of the British Association for the Advancement of Science. Bishop Samuel Wilberforce of Oxford, who had earned first-class honors in mathematics as a student, spoke against Darwin's new book. Thomas Henry Huxley, a young biologist, defended it. The most famous moment came when Wilberforce is said to have asked Huxley whether it was through his grandfather or his grandmother that he claimed descent from an ape. Huxley is said to have answered that he would rather have an ape for an ancestor than a man who used great gifts to cloud a serious question. But no one wrote down the exact words. The accounts people gave afterward differ, some were written down many years later, and each side remembered itself as the winner. Over time the day was retold as a simple tale of a brave scientist and a foolish bishop. Yet that same summer Wilberforce published a long review of the *Origin*, and Darwin wrote to his friend Joseph Hooker that it was "uncommonly clever" and picked out with skill the most doubtful parts of his book.

How they figured it out. A better model of disagreement is Darwin's friendship with Asa Gray, the leading botanist at Harvard and a devout Christian. Gray helped introduce the *Origin* to American readers and argued that natural selection could be the way God carried out His design. Darwin could not agree, and the two men argued about design for the rest of Darwin's life. Still, they wrote each other many letters, shared plant specimens, praised each other's work and stayed warm friends. Each could state the other's view fairly, and each took the other seriously.

The big idea. A respectful written comparison uses six tools. (1) Separate **observation** from **interpretation**: a feathered fossil is an observation; "ancestor of birds" is an interpretation. (2) **Steelman** each view: state it in words its own supporters would accept, as you practiced in Lessons 6.1 to 6.3. (3) Build paragraphs with **claim, evidence, reasoning**. (4) Replace **loaded words** such as "so-called," "blind faith," "fairy tale" or "just a theory" with neutral descriptions. (5) Quote **primary sources**: Genesis, the *Origin*, *Darwin's Black Box*. (6) Name the agreements first, then the real disagreements, and finally your own conclusion, clearly labeled as yours. A fair essay can still argue for a position; it simply does so honestly.

In the world today. Here is a real case to practice on. On February 24, 1988, the biologist Richard Lenski began growing twelve populations of the bacterium *E. coli* from one ancestor; for most of the years since, his team at Michigan State University kept them going, and the experiment continues today (since 2022 in Jeffrey Barrick's laboratory at the University of Texas at Austin). Every day a little of each population goes into a fresh flask, and every 500 generations samples are frozen, a living "fossil record" that can be revived and compared. The observation: around generation 31,500, one population began to use citrate, a nutrient in the flask that *E. coli* normally cannot take in when oxygen is present. Later work showed that a stretch of DNA had been copied in a way that switched on an existing citrate-carrying gene in the presence of oxygen. Mainstream biologists read this as a new ability evolving by mutation and selection, watched in real time. Behe and other critics read it as a small rearrangement that reused an existing gene, found only after more than

30,000 generations, in bacteria that are still *E. coli*. Both readings start from the same measurements.

God's handiwork. Peter told Christians to "be ready always to give an answer to every man that asketh you a reason of the hope that is in you with meekness and fear" (1 Peter 3:15). Meekness means stating the other side fairly and without scorn. Solomon adds a warning for every essay writer: the first side of a case always sounds right until someone examines it (Proverbs 18:17). Write the essay you would want an opponent to write about your own view.

Three accounts of origins compared

Question	Biblical creation	Darwinian evolution	Intelligent design
What explains living kinds?	God made them by His word (Genesis 1)	Natural selection acting on variation over ages	An intelligent cause (not named within ID)
Do all living things share one ancestor?	No: separate created kinds	Yes: one branching tree of life	Writers differ (Behe: yes)
Is natural selection real?	Yes, working within kinds	Yes: the main cause of change	Yes, but limited in what it can build
Age of the earth?	Thousands of years (young-earth reading)	About 4.5 billion years (textbook figure)	Not specified; writers differ

Agreed by all three: variation and natural selection are observed today.

A starting chart for your written comparison. Each cell is stated the way that view's supporters would state it.

⏳ Thinking About Time

What the sign says. Textbooks say the earth is about 4.5 billion years old and that life has a history of more than 3.5 billion years. You will meet these numbers in almost every mainstream source you read for your essay.

What we observe. Every writer works from the same present-day observations: the same rocks, fossils, living cells and DNA sequences, and the same laboratory results, such as the frozen samples of Lenski's bacteria. Ages of the earth and of fossils are interpretations built on those observations plus assumptions about the unobserved past.

How Christians read it. Young-earth creationists read the same evidence through Genesis: creation in six days only thousands of years ago, and a worldwide Flood. Some Christians hold an old earth with special creation, and others accept evolution as God's method. In a fair essay, attribute each age to its source ("the textbook says…", "young-earth creationists hold…") instead of stating it as plain fact or mocking it.

> **Try it.** Highlight every number of years in your essay draft. Does each one say who claims it?
>
> *Proverbs 18:17*

PICTURE STUDY



An Experiment on a Bird in the Air Pump, Joseph Wright of Derby, 1768 · Oil on canvas · The National Gallery, London

Joseph Wright of the town of Derby, England (1734–1797), loved to paint science by candlelight. In this picture a traveling lecturer shows a family and their friends what happens when air is pumped out of a glass globe with a living bird inside. Experiments like this were real: in the 1650s and 1660s Robert Boyle had used an air pump to show that animals cannot live without air. The lecturer can let the air back in and save the bird, or not. Wright leaves us at the moment of decision.

Look at the faces. Everyone in the room sees exactly the same thing, but no two people respond in the same way. That is why this painting belongs in a lesson on comparing views fairly: the same observation, many different responses.

Look closely

- Count the people. Which ones are looking at the bird, which are looking away, and which are looking at each other?
- Find the source of the light. What has the painter hidden it behind, and what does the light fall on most brightly?
- Find the window and the moon. What is the boy by the window doing?

- Look at the lecturer. Is he looking at the bird or at the viewer? What do you think he is asking?

Talk about it

1. Choose two people in the painting and describe how each one is responding to the same event. Are both responses understandable?
2. What is the observation in this scene, and what are some interpretations the people might make?
3. How is this room like a debate about origins, where everyone looks at the same evidence?

EXPERIMENT: THE FAIRNESS TEST

Do loaded words change how fair a paragraph seems, even when the facts are the same? You will write two versions of one short paragraph about origins, one with loaded words and one neutral, and have readers rate them without knowing which is which. Then you will use what you learn to plan your unit essay.

You will need

- Paper, pencil and a printer or neat handwriting
- At least six readers (family members, friends or a co-op class)
- Plain envelopes or folded cards labeled only “A” and “B”
- A lab notebook and a calculator

Steps

1. Write your question: Do readers rate a paragraph about origins as less fair when it contains loaded words, even if the facts are the same?
2. Write your prediction.
3. Write Version A (about 80 words) describing how one view reads the Galápagos finches or the Lenski bacteria, using three or four loaded words. Write Version B with exactly the same facts and the loaded words replaced by neutral ones. Keep the length within 5 words.
4. Variables. What you change: the wording (loaded or neutral). What you keep the same: the facts, the length, the topic, the instructions and the rating scale. What you measure: each reader’s fairness rating from 1 (very unfair) to 5 (very fair).
5. Give each reader both versions, but switch the order: half read A first, half read B first. Do not tell readers which is which or what you expect.
6. Record every rating in a table. Find the average rating for each version and the difference between them.
7. Write three sentences: What did you find? How sure can you be with only six readers? Which words will you avoid in your essay?

Tips

- Loaded words often hide in adjectives and adverbs: “so-called,” “merely,” “blindly,” “clearly,” “of course,” “fanatical.”
- Do not stack the deck by making Version B better written in other ways. The only difference should be the loaded words.

Check your work

- I named what I changed, what I kept the same and what I measured.
- I switched the reading order and kept readers from knowing which version was which.
- I calculated averages and can explain what my results mean and how sure I can be.

NATURE NOTEBOOK

1. Copy the comparison chart into your notebook and add one more row with a question of your own, filling in each column fairly.
2. Make a quick sketch of the arrangement of the air pump painting: draw a circle for each person and an arrow showing where each one is looking.
3. Make two columns titled “Observations” and “Interpretations” for the Lenski experiment, with at least three entries in each.

> **From history.** The friendship between Darwin and Asa Gray became part of the history of the theory itself. On September 5, 1857, Darwin wrote Gray a letter outlining his idea of natural selection. When Wallace’s paper arrived the next year, an extract from Darwin’s unpublished essay of 1844 and part of his 1857 letter to Gray were read at the Linnean Society on July 1, 1858, to show that Darwin had worked out the idea before Wallace’s letter came. A friend who disagreed with him about design held one of the key documents of his life.

WORKED EXAMPLES

Example 1. A student's essay draft has three body sections: biblical creation, 260 words; Darwinian evolution, 140 words; intelligent design, 200 words. What percent of the body does each section take up? How could the student balance the three sections without changing the total length?

1. Total body = 260 + 140 + 200 = 600 words.
2. Creation: 260 ÷ 600 × 100 ≈ 43.3%. Darwinian evolution: 140 ÷ 600 × 100 ≈ 23.3%. Intelligent design: 200 ÷ 600 × 100 ≈ 33.3%.
3. Equal balance would be 600 ÷ 3 = 200 words each.
4. Creation needs 260 − 200 = 60 fewer words; Darwinian evolution needs 200 − 140 = 60 more. Intelligent design is already balanced.

Answer: About 43.3%, 23.3% and 33.3%. Trim about 60 words from the creation section and add about 60 to the Darwinian evolution section so each has about 200 words. A view treated in far fewer words is often a view stated too weakly.

Example 2. In Lenski's experiment, each population grows about 100-fold every day before a small part is moved to a fresh flask. (a) About how many generations (doublings) is that per day? (b) About how many days would 31,500 generations take? (c) If one human generation is about 25 years, how many years would 31,500 human generations take?

1. Each generation doubles the population. $2^6 = 64$ and $2^7 = 128$, so 100-fold growth takes between 6 and 7 doublings. A calculator gives about 6.64 generations per day.
2. Days for 31,500 generations: 31,500 ÷ 6.64 ≈ 4,744 days. Divide by 365: about 13 years. (The real calendar time was a little longer, because the populations were sometimes restarted from frozen samples.)
3. Human comparison: 31,500 × 25 = 787,500 years.
4. Both readings use these numbers: one side stresses that a new ability appeared in about 13 years of lab work; the other stresses that it took more than 30,000 generations, a number of human generations far longer than recorded history.

Answer: (a) About 6.6 generations per day. (b) About 4,744 days, roughly 13 years. (c) About 787,500 years for the same number of human generations.

Example 3. A student checks one paragraph of her essay. It has 12 sentences: 7 are observations and 5 are interpretations. Of the 5 interpretations, 3 say who holds them ("Mainstream biologists read this as…") and 2 do not. What is the ratio of observations to interpretations? What percent of the interpretations are attributed? How many sentences must she fix to reach 100%?

1. Ratio of observations to interpretations = 7 : 5.
2. Attributed interpretations = 3 ÷ 5 × 100 = 60%.
3. Unattributed interpretations = 5 − 3 = 2, so she must fix 2 sentences.
4. Example fix: change "The bacteria evolved a brand-new ability" to "Lenski's team reads the change as a new ability evolving, while Behe reads it as an existing gene being switched on."

Answer: Ratio 7 : 5; 60% of interpretations are attributed; she must fix 2 sentences to reach 100%.

PRACTICE

1. EASY Label each statement as an observation (O) or an interpretation (I): (a) *Archaeopteryx* fossils show feathers and teeth. (b) *Archaeopteryx* was a step between reptiles and birds. (c) One Lenski population began using citrate around generation 31,500. (d) The citrate change shows that evolution can build any new organ.
2. EASY What is a loaded word? Give a neutral replacement for "so-called scientists."
3. EASY Who spoke on each side at the Oxford meeting of June 30, 1860, and why can we not be sure of exactly what they said?
4. MEDIUM Rewrite this sentence so that both sides would call it fair: "Evolutionists blindly worship chance, while creationists cling to fairy tales."
5. MEDIUM An essay has an introduction of 90 words, a creation section of 180, a Darwinian evolution section of 180, an intelligent design section of 120 and a conclusion of 80. (a) What is the total length? (b) What percent of the three body sections is the intelligent design section? (c) How should the body be adjusted so each view gets the same number of words, keeping the body total the same?
6. MEDIUM Data reading. Sample data shaped like the published Lenski results show the bacteria's fitness compared with their frozen ancestor (ancestor = 1.00): generation 0, 1.00; 5,000, 1.35; 10,000, 1.48; 20,000, 1.58; 50,000, 1.70. Which statement is best supported? (a) Fitness rose throughout, but most quickly in the first 5,000 generations. (b) Fitness rose by the same amount every 5,000 generations. (c) The bacteria became a new kind of organism. (d) Fitness stopped rising after generation 10,000.
7. MEDIUM Data reading. In a fairness test, six readers rated two versions of one paragraph from 1 (very unfair) to 5 (very fair). Version A (loaded words): 2, 1, 3, 2, 2, 2. Version B (neutral words): 4, 5, 4, 3, 4, 4. (a) Find each average. (b) What do the results suggest? (c) Give one reason to be cautious about the conclusion.

8. HARD Identify the claim, the evidence and the reasoning in this paragraph: “Natural selection can change a population within a few years. During the 1977 drought on Daphne Major, medium ground finches with deeper beaks survived better, and the next generation’s beaks were about 4 to 5 percent deeper on average. Because the beak change came from which birds survived to breed, this is natural selection at work.”
9. HARD Experiment design. Design a better version of the fairness test that could convince a skeptical reader. Include the independent and dependent variables, how you would prevent bias and how many readers you would use.
10. CHALLENGE Write a fair paragraph of three or four sentences comparing how mainstream biologists and young-earth creationists read the similarity between human and chimpanzee DNA. Use no loaded words and attribute every interpretation.

COMMON MISTAKES

- Thinking a fair essay cannot take a side. It can; it states every view accurately first and then labels the writer’s own conclusion clearly as a conclusion.
- Stating interpretations as if they were observations, such as writing “the fossil is 150 million years old” or “the fossil is from the Flood” without saying who holds that reading.
- Using the weakest form of the other side’s argument (a straw man). Readers who hold that view will stop listening, and the writer learns nothing.

> **Make it a game · Loaded or Level?.** A parent reads a sentence about origins, sometimes neutral, sometimes full of loaded words (“Those so-called scientists merely assume…”). Call out “Loaded!” or “Level!” For each loaded sentence, rewrite it aloud in neutral words within 15 seconds to score a point. Then trade places and write five sentences to test your parent. The player who can state the other side’s view so well that the other side would sign it wins a bonus point.

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

Any argument sounds convincing when only one side has spoken. A wise writer lets the other side speak fully and fairly before deciding, and is not afraid of being searched.

Practice answers

1. (a) O, (b) I, (c) O, (d) I.
2. A word that carries a judgment or insult in place of a neutral description. A neutral replacement: “scientists who hold this view” or simply “these scientists.”
3. Bishop Samuel Wilberforce spoke against Darwin’s theory and Thomas Henry Huxley defended it. No one recorded the exact words; the accounts differ, and some were written down many years later by people on one side.
4. Sample: “Most biologists hold that natural selection acting on random mutations explains the variety of life, while young-earth creationists hold that God created distinct kinds of living things, as Genesis describes.”

5. (a) 90 + 180 + 180 + 120 + 80 = 650 words. (b) Body = 180 + 180 + 120 = 480; 120 ÷ 480 × 100 = 25%. (c) 480 ÷ 3 = 160 each: trim 20 words from the creation section and 20 from the Darwinian section, and add 40 to the intelligent design section.
6. (a). The rise was 0.35 in the first 5,000 generations, 0.13 in the next 5,000, 0.10 in the next 10,000 and only 0.12 over the last 30,000. (b) and (d) do not match the numbers, and (c) is an interpretation the fitness data cannot show.
7. (a) A: 12 ÷ 6 = 2.0. B: 24 ÷ 6 = 4.0. (b) Readers rated the neutral version as much fairer (2.0 points higher), suggesting loaded words make writing seem unfair even when the facts are the same. (c) Only six readers took part, and they may all share similar views; a larger, more varied group would give a more reliable result.
8. Claim: natural selection can change a population within a few years. Evidence: in the 1977 drought, deeper-beaked finches survived better and the next generation's beaks were about 4 to 5 percent deeper. Reasoning: the change came from which birds survived and bred, which is the definition of natural selection.
9. Independent variable: the wording (loaded or neutral). Dependent variable: the fairness rating on a 1–5 scale. Prevent bias by keeping the facts and length the same, hiding which version is which, switching the reading order for half the readers, having someone else hand out and collect the ratings, and including readers who hold different views on origins. Use at least 20 readers, and repeat the test with a second topic to see whether the result holds.
10. Sample: Human and chimpanzee DNA sequences are very similar; textbooks often give a figure of about 98 percent, though the number depends on how the comparison is made. Mainstream biologists read this similarity as evidence that humans and chimpanzees descended from a common ancestor. Young-earth creationists read it as evidence of a common Designer who used similar plans for bodies that work in similar ways, and they point to the differences, along with Genesis 1:27, as marks of man's unique creation in God's image. Both groups begin from the same measured sequences.

Unit 6 review

Answer each question. Show your work for calculations, and use complete sentences for explanations. When you describe a view, state it the way its own supporters would. The test is worth 60 points.

1. (4 pts) Multiple choice. Which pair of days shows the forming-and-filling pattern of Genesis 1? (a) Day 1 and day 2. (b) Day 2 and day 5. (c) Day 3 and day 4. (d) Day 6 and day 7.
2. (5 pts) Using Genesis 5, the fathers’ ages at the birth of the next son are: 130, 105, 90, 70, 65, 162, 65, 187 and 182. Noah was 600 when the Flood came. How many years passed from creation to the Flood by these numbers?
3. (4 pts) Name two things Genesis 1:27 teaches about human beings, and explain how this differs from what Genesis 1 says about animals.
4. (4 pts) Multiple choice. Which statement describes Darwin’s theory accurately? (a) People descended from chimpanzees. (b) Life began by chance in a warm pond, which is the main point of the theory. (c) Individuals vary, more young are born than survive, those with helpful inherited variations leave more offspring, and over long ages this produces new species from common ancestors. (d) The strongest animals always survive.
5. (6 pts) A population has 200 moths: 100 light and 100 dark. Birds eat 50% of the light moths and 20% of the dark moths. What percent of the survivors are dark? Did any moth change color?
6. (5 pts) Name one part of Darwin’s theory that is observed today and accepted by creation biologists, and name the main claim that is inferred rather than observed. Explain the difference in one sentence.
7. (4 pts) Multiple choice. Which statement best describes intelligent design? (a) The earth is about 6,000 years old. (b) Certain features of the universe and of living things are best explained by an intelligent cause, not an undirected process such as natural selection. (c) Natural selection never happens. (d) Every improbable event is designed.
8. (5 pts) DNA has four bases. How many different 6-base sequences are possible, and what is the probability of one particular 6-base sequence arising at random?
9. (6 pts) Diagram. Draw the three-question flowchart for detecting design. Label all three questions and the four outcome boxes (Law, Chance, Chance, Design), with Yes and No on each arrow. Then run a sentence written in beach sand through your chart and show where it ends.
10. (5 pts) (a) Label as observation or interpretation: “This fossil bird has teeth in its jaws.” “This fossil bird lived 150 million years ago.” (b) Rewrite this sentence in neutral words: “Only ignorant people still believe in so-called intelligent design.”
11. (6 pts) Lenski’s bacteria go through about 6.6 generations per day. (a) About how many generations is that in one year of 365 days? (b) About how many years would 33,000 generations take? (c) Give one way mainstream biologists and one way design writers such as Behe read the citrate result.

12. (6 pts) Write a fair paragraph of four or five sentences comparing how biblical creation and Darwinian evolution answer the question, “Do all living things share one ancestor?” Use no loaded words, attribute every interpretation, and name one point both sides agree on.

UNIT PROJECT: ORIGINS FAIRLY TOLD: MY WRITTEN COMPARISON

Write a respectful comparison of 700 to 1,000 words on the three accounts of origins in this unit: creation as Genesis tells it, Darwin’s theory of evolution by natural selection, and intelligent design. Begin with what all three agree on, give each view a balanced section stated the way its own supporters would state it (with at least one primary-source quotation each), then compare them on one question of your choice, such as the finches, the Lenski bacteria or the information in DNA. End with your own conclusion, clearly labeled as yours, written with meekness.

Include with your essay: your completed comparison chart, one diagram of your own (a forming-and-filling chart, the claim ladder or the design flowchart), a word-count table showing the balance of your three body sections, and the data table and averages from your Fairness Test.

- **Accuracy**: Each view is stated correctly and in words its own supporters would accept; facts, dates, names and quotations are correct, and Scripture is quoted exactly from the KJV.
- **Evidence and reasoning**: Paragraphs use claim, evidence and reasoning; observations are kept separate from interpretations, and every age or interpretation names who holds it.
- **Fairness and tone**: No loaded words or straw men; the three body sections are balanced in length (shown in the word-count table); the writer’s own conclusion is clearly labeled and respectful.
- **Data and presentation**: The comparison chart, diagram and Fairness Test data are complete, correctly calculated and neatly presented; the essay is organized and proofread.

Answer key

1. (b). On day 2 God made the firmament dividing the waters; on day 5 He filled the waters and sky with sea creatures and winged fowl.
2. 130 + 105 + 90 + 70 + 65 + 162 + 65 + 187 + 182 = 1,056 (Noah’s birth), and 1,056 + 600 = 1,656 years.
3. People are made in the image of God, and God created them male and female. Animals are made “after their kind,” but only man is made in God’s image.
4. (c).
5. Light survivors: 100 × 0.50 = 50. Dark survivors: 100 × 0.80 = 80. Total = 130. Percent dark = 80 ÷ 130 × 100 ≈ 61.5%. No moth changed color; the proportion of colors in the population changed.
6. Observed: natural selection (or variation or inheritance) changing traits within populations, as in finch beaks or resistant bacteria. Inferred: that all living things descended from one

common ancestor. The first can be watched happening now; the second is a conclusion about the unobserved past drawn from present-day evidence.

7. (b).
8. $4^6 = 4{,}096$ sequences, so the probability is 1/4,096.
9. Chart: An event or object → (1) Does a regular natural law explain it? Yes → Law; No → (2) Is it highly improbable (complex)? No → Chance; Yes → (3) Does it match an independent pattern (specified)? No → Chance; Yes → Design. A sentence in the sand: no law of waves writes sentences (No), its letters are highly improbable by chance (Yes), and it matches the independent pattern of the English language (Yes), so it ends at Design. Award 3 points for the correct chart and labels and 3 for the worked example.
10. (a) The first is an observation; the second is an interpretation (a textbook age), which should be attributed. (b) Sample: “Intelligent design is held by some scientists and philosophers, while most biologists reject it as science.”
11. (a) $6.6 \times 365 \approx 2{,}409$, about 2,400 generations per year. (b) $33{,}000 \div 2{,}409 \approx 13.7$, about 14 years. (c) Mainstream biologists read it as a new ability evolving by mutation and selection in real time. Critics such as Behe read it as a small rearrangement that switched on an existing gene, found only after more than 30,000 generations, in bacteria that are still *E. coli*.
12. Sample: Darwinian evolution holds that all living things descended from one or a few original forms, an inference biologists draw from similar anatomy, shared DNA and the order of fossils. Biblical creation, as young-earth creationists read Genesis 1, holds that God made separate kinds of plants and animals that reproduce “after their kind,” and reads shared DNA as the mark of a common Designer. Both sides agree that variation and natural selection are observed today and can change populations, as in finch beaks. They disagree about whether those changes, extended into the past, can produce all living things from one ancestor. Award points for accuracy to both views (2), attribution and neutral wording (2), and a correct point of agreement (2).

UNIT 7

Ecology and Stewardship

On the sixth day God gave people a charge: “have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth” (Genesis 1:28). In the garden He added that the man was to “dress it and to keep it” (Genesis 2:15). In this unit you will learn the science a good steward needs: how ecosystems work, how energy flows through a food chain, how biologists count populations they cannot see all at once, and why every habitat has a limit to how many animals it can carry.

You will meet the people who did the work. Paul Kroegel guarded the pelicans of Pelican Island for a dollar a month. Frank Chapman turned a Christmas hunt into a bird count that still runs every winter. William Hornaday counted the last 1,091 bison and then helped bring them back, while refuge keepers and biologists rescued the whooping crane from just 15 birds. Aldo Leopold taught how to manage game with science, and hunters, through the Pittman–Robertson Act and the Duck Stamp, paid to restore deer, turkeys and ducks across the country. In every story you will ask the same question: **what does dominion with care look like in practice?**

Along the way you will calculate energy at each level of a pyramid, estimate populations with quadrats and mark-recapture, find doubling times for recovering species, and model the largest harvest a deer herd can sustain. Your unit portfolio is a real population study of your own.

BEFORE YOU BEGIN

- Can multiply and divide whole numbers and decimals and find a percent
- Can read a data table and a line graph
- Knows what a gene and an allele are (Units 1 and 2)
- Knows the difference between plants that make their own food and animals that eat other living things

MASTERY CHECKLIST

- I can explain what Genesis 1:28 and 2:15 teach about dominion and stewardship.
- I can classify organisms as producers, consumers and decomposers and use the 10 percent rule to calculate energy in a food chain.
- I can estimate a population with quadrats and with mark-recapture, and calculate density and growth rate.
- I can tell how the bison and the whooping crane were saved and calculate how fast their numbers grew.
- I can explain carrying capacity, limiting factors and sustained yield, and how regulated hunting helps manage game populations.
- I can read wildlife data tables critically, asking how the counts were made.

OPTIONAL BOOKS AND RESOURCES

- **eBird, from the Cornell Lab of Ornithology** (https://ebird.org/): Free with an account (a parent should set it up). Record the birds you count in your yard or a park, and see what others have counted near you. Useful for Lesson 7.2 and the portfolio.
- **The Great Backyard Bird Count** (https://www.birdcount.org/): Free. Each February families count birds for at least 15 minutes and report them. A short, real population count for Lesson 7.2.
- **William T. Hornaday's writings at Project Gutenberg** (https://www.gutenberg.org/ebooks/search/?query=Hornaday): Free. Several of Hornaday's books on American wildlife can be read online, useful background for Lesson 7.3. A parent should preview and choose passages; some descriptions of the slaughter of game are hard to read.

7.1 Dominion and Care (Genesis 1:28; 2:15) ★

OBJECTIVES

- Explain what Genesis 1:28 and 2:15 teach about dominion and stewardship, and tell how Paul Kroegel and Pelican Island (1903) show both at work.
- Identify the biotic and abiotic parts of an ecosystem and classify living things as producers, consumers and decomposers.
- Use the 10 percent rule to calculate the energy that reaches each level of an energy pyramid.

Warm-up. Look out a window at one tree (or at a houseplant if you cannot see a tree). In five minutes, make two lists: everything the tree needs to live, and everything that needs the tree. Then draw arrows between the items that depend on each other. How many arrows did you draw? Which item has the most arrows touching it?

Video. Coming soon. Pelican Island National Wildlife Refuge history and brown pelicans of the Indian River Lagoon; food webs, producers, consumers, decomposers and energy pyramids; search the U.S. Fish and Wildlife Service, Smithsonian, Homeschool Pop (Alternate), Moody Science classics and nature footage of pelicans and mangroves.

KEY TERMS

dominion
The rule over the earth and its creatures that God gave to people (Genesis 1:28). It is real authority, but it is held on God’s behalf and must be used for good.

stewardship
Managing and caring for something that belongs to someone else. People are stewards of creation, which belongs to God (Psalm 24:1).

ecosystem
All the living things in an area together with the nonliving things around them, such as sunlight, water, soil and air, working as one system.

producer
A living thing that makes its own food, usually from sunlight by photosynthesis. Plants, algae and some bacteria are producers.

consumer
A living thing that gets its energy by eating other living things. Herbivores eat plants, carnivores eat animals and omnivores eat both.

decomposer
A living thing, such as a fungus or bacterium, that breaks down dead plants and animals and returns their nutrients to the soil and water.

CORE IDEAS

The story. On March 14, 1903, President Theodore Roosevelt signed an order that set aside a small mangrove island in the Indian River Lagoon on Florida's east coast as a Federal Bird Reservation. Pelican Island was a nesting place for brown pelicans, herons and egrets, and plume hunters had been shooting the birds for feathers to decorate ladies' hats. Across the water lived Paul Kroegel, a German-born boatbuilder who had watched over the pelicans for years and sometimes rowed out to warn hunters away. Now he became the reservation's first warden, paid one dollar a month by the Florida Audubon Society. That single island was the beginning of the National Wildlife Refuge System, which today has more than 560 refuges.

The big idea. Long before 1903, the Bible gave people a job description. In Genesis 1:28 God blessed the man and the woman and told them to "have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth." In Genesis 2:15 He put the man in the garden of Eden "to dress it and to keep it." **Dominion** is real authority: people may farm, build, raise livestock, fish and hunt. But it is authority on loan. "The earth is the LORD's" (Psalm 24:1), so we are **stewards**, managers of Someone else's property who will one day give an account. To dress a garden is to work it so that it bears fruit. To keep it is to guard it. A good steward does both: uses creation wisely and protects it. Kroegel did not lock the lagoon away from people. Fishermen still worked those waters. He simply guarded the one place the pelicans needed most.

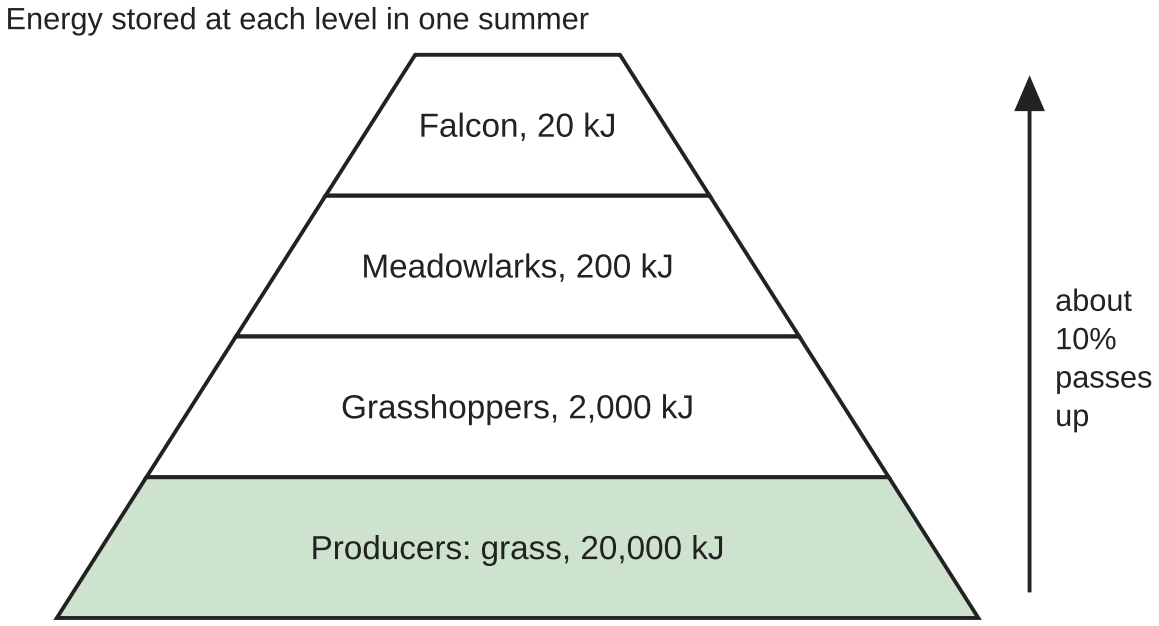
How they figured it out. To care for something well, you must understand how it works. The study of living things and their surroundings is called **ecology**. An **ecosystem** has *biotic* (living) parts and *abiotic* (nonliving) parts such as sunlight, water, soil, salt and temperature. The living parts have three jobs. **Producers**, such as mangroves, seagrass and algae, capture the sun's energy by photosynthesis. **Consumers** eat: mullet graze on algae, and pelicans dive for the mullet. **Decomposers**, mostly fungi and bacteria, break down fallen leaves, dead fish and droppings, and helpers such as crabs and worms tear the material into smaller pieces. The nutrients go back into the water and mud, where producers use them again. Matter goes around in a circle. Nothing is wasted.

Energy flows one way. Energy behaves differently from matter. It enters as sunlight and moves up the food chain, but at each step most of it is used for living (moving, growing, keeping warm) and leaves the ecosystem as heat. A useful rule of thumb, the **10 percent rule**, says that only about one tenth of the energy stored at one level is stored at the next. If the grass in a meadow stores 20,000 kJ, the grasshoppers that eat it store about 2,000 kJ, the meadowlarks that eat them about 200 kJ, and a falcon at the top about 20 kJ (see the energy pyramid). That is why there are far more blades of grass than grasshoppers, and far more grasshoppers than falcons. It also explains why top predators are few and easily harmed: they depend on every level beneath them. Protect the bottom of the pyramid, the plants and the places they grow, and you protect everything above.

God's handiwork. An ecosystem is a household run with great wisdom. The sun pours in energy, producers turn it into food, consumers pass it along, and decomposers clean up and return every nutrient to be used again. The psalmist looked at the sea and its creatures and

wrote, “These wait all upon thee; that thou mayest give them their meat in due season” (Psalm 104:27). A wise steward studies this design and works with it, the way Kroegel worked with the pelicans’ need for one quiet island. Brown pelicans still fish in the Indian River Lagoon today.

Try it and see. In this lesson’s project you will test whether decomposers work faster with water, and in your sketchbook you will survey one square meter of ground and sort what you find into producers, consumers and decomposers. You may be surprised how crowded a single square meter is.



An energy pyramid for a meadow. Each level stores only about one tenth of the energy of the level below it.

PICTURE STUDY



Ploughing in the Nivernais, Rosa Bonheur, 1849 · Oil on canvas · Musée d’Orsay, Paris

Rosa Bonheur (1822–1899) was one of the most famous animal painters of the 1800s. She studied animals constantly, sketching them on farms, at horse fairs and in markets, and kept many animals of her own so she could learn exactly how their bodies moved. The French government ordered this painting from her, and it was shown in Paris in 1849.

The scene is the Nivernais, a farming region in the middle of France famous for its strong white oxen. Bonheur shows the autumn plowing that breaks up the soil before winter. It is a picture of dominion in the good sense of Genesis 2:15: people and animals working the land together so that it will bear fruit.

Look closely

- Count the oxen in the nearest team. How many pairs are yoked together to pull one plow?
- Look at the ground behind the plows and in front of them. How does the painter show the difference between plowed and unplowed soil?
- Find the farmers. Where do they stand, and what are they doing to guide the animals?
- Look at the oxen’s heads, legs and muscles. What tells you the work is heavy?

Talk about it

1. How does this painting show people “dressing” the land? What would it look like to “keep” this field well for the next hundred years?
2. Why do you think a painter who loved animals chose to paint them working rather than resting in a pasture?
3. Which parts of this scene are biotic, and which are abiotic?

> **Safety first.** Decomposition bags will grow mold. Keep every bag sealed for the whole experiment, never open or sniff it, and throw the bags away unopened in the trash when you finish. Anyone with mold allergies or asthma should not handle the bags. Wear gloves or wash your hands well after touching soil.

EXPERIMENT: WHO BREAKS IT DOWN? A DECOMPOSER EXPERIMENT

Decomposers are the cleanup crew of every ecosystem, but they need the right conditions to work. In this small experiment you will test one question: **Does moisture make decomposers work faster?** You will measure how fast a soft, brown, decomposing spot spreads across slices of apple kept in moist soil and in dry soil.

You will need

- One apple, cut into four slices of about the same thickness
- Four zipper-top plastic sandwich bags and a permanent marker
- About 2 cups of garden soil or potting soil (not sterile seed-starting mix)
- A spoon and a small cup of water
- A metric ruler (millimeters)
- Lab notebook, pencil and graph paper
- Disposable gloves

Steps

1. Write your **question** and your **prediction** in your notebook. Will the moist bags or the dry bags show more decomposition after 8 days? Why do you think so?
2. Spread half of the soil on a tray to dry for a day. Mix the other half with water until it is damp like a wrung-out sponge but not dripping.
3. Label two bags “Moist A” and “Moist B,” and two bags “Dry A” and “Dry B.” Put 3 spoonfuls of moist soil in each Moist bag and 3 spoonfuls of dry soil in each Dry bag.
4. Press one apple slice into the soil in each bag, push out most of the air, and seal the bag. Set all four bags side by side in the same place, out of direct sunlight.
5. Name your variables. **What we change:** the moisture of the soil. **What we keep the same:** the kind of apple, slice size, amount of soil, temperature, light and time. **What we measure:** the widest soft brown or moldy spot on each slice, in millimeters.
6. Every 2 days (day 0, 2, 4, 6 and 8), measure the widest spot on each slice through the bag without opening it. Record every number in a data table.
7. Average the two Moist bags and the two Dry bags for each day. Make a line graph with day on the horizontal axis and spot size (mm) on the vertical axis, using one line for Moist and one for Dry.
8. Calculate each average rate in mm per day: the spot size on day 8 divided by 8 days.
9. Write a conclusion of three sentences: what happened, whether your prediction was right, and what it tells you about the conditions decomposers need. Then throw all bags away unopened.

Tips

- Two bags for each condition is better than one. If one slice behaves strangely, the other helps you see whether it was a fluke.
- Measure through the plastic. Opening the bags lets mold spores into the room.
- If nothing has changed by day 4, move all four bags to a warmer spot. Keep them together so the temperature stays the same for both conditions.

Check your work

- I wrote a question, a prediction, and the variables I changed, kept the same and measured.
- I recorded measurements for every bag on every measuring day and graphed the averages.
- I calculated a rate in mm per day for each condition and explained what my results show about decomposers.

NATURE NOTEBOOK

1. Mark out one square meter of lawn, garden or woods with string and four sticks. Sketch everything you find living in it, then label each thing P (producer), C (consumer) or D (decomposer). Count each kind.
2. Draw the Pelican Island food chain: sun, mangrove leaves and algae, mullet, brown pelican. Add one decomposer and draw an arrow showing where it sends the nutrients.
3. Copy Genesis 2:15 in your best handwriting. Under it, write one way your family “dresses” and one way it “keeps” the place where you live.

> **From history.** The idea that every creature has a place in a wise, balanced order is older than the word “ecology.” In 1749 Linnaeus’s circle at Uppsala in Sweden published a dissertation called *The Economy of Nature*, describing how plants, plant-eaters, predators and decay all fit together as a household arranged by the Creator. In 1866 the German zoologist Ernst Haeckel coined the word *ecology* from the Greek *oikos*, meaning house or household. Both names picture the same thing: creation as a home to be understood and well kept.

WORKED EXAMPLES

Example 1. In one summer, the grass in a meadow stores 20,000 kJ of energy. Grasshoppers eat the grass, meadowlarks eat the grasshoppers, and a prairie falcon eats meadowlarks. Using the 10 percent rule, how much energy is stored at each level? What fraction of the grass's energy reaches the falcon?

(Use the map or drawing "Each level stores about one tenth of the energy of the level below." shown earlier in this lesson.)

1. Grasshoppers (level 2): 20,000 kJ × 0.10 = 2,000 kJ.
2. Meadowlarks (level 3): 2,000 kJ × 0.10 = 200 kJ.
3. Falcon (level 4): 200 kJ × 0.10 = 20 kJ.
4. Fraction reaching the falcon: 20 kJ ÷ 20,000 kJ = 1/1,000, which is 0.1 percent.

Answer: 2,000 kJ, 200 kJ and 20 kJ. Only 1/1,000 (0.1 percent) of the grass's energy reaches the falcon.

Example 2. In a decomposer experiment, the soft brown spot on an apple slice in moist soil grew from 0 mm to 24 mm in 8 days. The spot on a slice in dry soil grew from 0 mm to 4 mm in the same 8 days. Find each rate in mm per day. How many times faster was decomposition in moist soil?

1. Rate = change in size ÷ time.
2. Moist: 24 mm ÷ 8 days = 3.0 mm per day.
3. Dry: 4 mm ÷ 8 days = 0.5 mm per day.
4. Compare: 3.0 ÷ 0.5 = 6.

Answer: Moist soil: 3.0 mm per day; dry soil: 0.5 mm per day. Decomposition was 6 times faster in moist soil, which shows that decomposers need water to work well.

Example 3. A student surveys one square meter of garden and counts 140 producers (plants), 32 consumers (insects, spiders, a slug) and 18 decomposers and their helpers (mushrooms, earthworms, pill bugs). What percent of the organisms counted fall into each group? Round to the nearest tenth of a percent.

1. Total organisms: 140 + 32 + 18 = 190.
2. Producers: 140 ÷ 190 = 0.737, which is 73.7 percent.
3. Consumers: 32 ÷ 190 = 0.168, which is 16.8 percent.
4. Decomposers: 18 ÷ 190 = 0.095, which is 9.5 percent.
5. Check: 73.7 + 16.8 + 9.5 = 100.0 percent.

Answer: Producers 73.7 percent, consumers 16.8 percent, decomposers 9.5 percent. Producers are by far the largest group, as the energy pyramid predicts. (Most decomposers, the bacteria and tiny fungi, are too small to count by eye.)

PRACTICE

1. EASY According to Genesis 2:15, what two things did God put the man in the garden to do? Explain each in your own words.
2. EASY Classify each as a producer, consumer or decomposer: oak tree, mushroom, white-tailed deer, grass, red fox, bacteria in the soil.
3. EASY Sort these parts of a pond ecosystem into biotic and abiotic: sunlight, water, a cattail, a frog, mud, algae, the water temperature.
4. MEDIUM The plants in a field store 8,000 kJ. Using the 10 percent rule, how much energy is stored by the herbivores that eat them, and by the carnivores that eat the herbivores?
5. MEDIUM A hawk sits on the fourth level of an energy pyramid (producers are level 1). If the hawks in an area store 150 kJ, about how much energy must the producers store?
6. MEDIUM Data reading. A class measured the widest decomposing spot on apple slices (mm).
   Day: 0, 2, 4, 6, 8
   Moist soil: 0, 4, 10, 16, 22
   Dry soil: 0, 1, 2, 3, 4
   (a) What variable did the class change? (b) What was the average rate for the moist slices over the 8 days? (c) If the moist trend from day 2 to day 8 continues, predict the spot size on day 10.
7. MEDIUM Data reading. Scientists estimated the energy stored in one summer at each level of a pond food chain:
   Algae: 12,000 kJ
   Water fleas: 1,150 kJ
   Small fish: 110 kJ
   Heron: 9 kJ

(a) What percent of the water fleas' energy was stored by the small fish? (b) Is the 10 percent rule a good rough estimate for this pond? Use numbers to explain.

8. HARD Some people say "dominion" in Genesis 1:28 means people may use the earth however they please. Others say people should never use animals or land at all. In 4–5 sentences, explain how Genesis 1:28 and 2:15 together answer both ideas. Use Paul Kroegel as an example.
9. MEDIUM Experiment design. Design an experiment to test whether earthworms make dead leaves break down faster. Name your independent variable, dependent variable, at least three controlled variables, and how you would make your results more reliable.
10. CHALLENGE Producers in an ecosystem store 1,000,000 kJ. Use the 10 percent rule to find how much energy would reach level 7 of a food chain. Use your answer to explain why food chains rarely have more than four or five levels.

COMMON MISTAKES

- Thinking dominion means people may use creation any way they like. Genesis 2:15 joins dominion to keeping and guarding, and the earth still belongs to the Lord.
- Thinking energy is recycled in an ecosystem the way nutrients are. Matter (carbon, nitrogen, minerals) cycles around and around, but energy flows one way, from the sun through the food chain, and leaves as heat.
- Thinking decomposers are just pests or signs of dirt. Without fungi and bacteria, dead leaves and animals would pile up and the nutrients plants need would stay locked away.

Make it a game · Pyramid Relay. Write 12 living things on index cards (for example: grass, algae, oak, grasshopper, rabbit, mullet, meadowlark, fox, pelican, falcon, mushroom, bacteria). Shuffle them face down. Players take turns drawing a card and placing it on a big paper pyramid in the right level, or in the decomposer box beside it, explaining what it eats. Score 1 point for a correct place. Then the parent calls out a starting energy (such as 50,000 kJ) and the first player to give the energy at level 3 correctly scores 2 more points. Play until the deck is gone.

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

The first job God gave a human being was gardening. To dress is to work the land so it bears fruit; to keep is to guard it. Every good steward, from a farmer to a refuge warden, does both.

Practice answers

1. To "dress it" (work it, tend it, make it fruitful) and to "keep it" (guard it, protect it from harm).
2. Producers: oak tree, grass. Consumers: white-tailed deer, red fox. Decomposers: mushroom, soil bacteria.
3. Biotic (living): cattail, frog, algae. Abiotic (nonliving): sunlight, water, mud, water temperature.

4. Herbivores: 8,000 × 0.10 = 800 kJ. Carnivores: 800 × 0.10 = 80 kJ.
5. Work backward, multiplying by 10 at each step: level 3 = 1,500 kJ, level 2 = 15,000 kJ, level 1 (producers) = 150,000 kJ.
6. (a) The moisture of the soil. (b) 22 mm ÷ 8 days = 2.75 mm per day. (c) From day 2 to day 8 the spot grew 6 mm every 2 days, so on day 10 it should be about 22 + 6 = 28 mm.
7. (a) 110 ÷ 1,150 = 0.096, about 9.6 percent. (b) Yes. Algae to fleas is 1,150 ÷ 12,000 ≈ 9.6 percent, fleas to fish ≈ 9.6 percent, and fish to heron is 9 ÷ 110 ≈ 8.2 percent. All are close to 10 percent.
8. A good answer includes: Genesis 1:28 gives people real authority to use the earth, so farming, fishing and raising animals are good. Genesis 2:15 adds that this rule includes keeping and guarding, so careless destruction is wrong. The earth belongs to God (Psalm 24:1), so people are stewards who will give an account. Kroegel did not stop people from using the lagoon, but he guarded the pelicans' nesting island, the one place they needed most. That is dominion with care: use and protect together.
9. Set up identical containers of the same soil with the same mass of the same kind of dead leaves (for example, 20 g), the same moisture, temperature and light. Add 10 earthworms to half the containers and none to the others. Independent variable: earthworms or no earthworms. Dependent variable: the mass of leaves remaining after 3–4 weeks (dried and weighed). Controlled: soil type and amount, leaf kind and mass, water, temperature, time. Reliability: use at least three containers of each kind and average the results.
10. Level 2: 100,000; level 3: 10,000; level 4: 1,000; level 5: 100; level 6: 10; level 7: 1 kJ. So much energy is lost as heat at each step that very little is left after four or five levels, not enough to support a population of large animals that must hunt over a wide area. That is why top predators are few and food chains are short.

7.2 Population Counts

OBJECTIVES

- Tell how Frank Chapman's first Christmas Bird Count (December 25, 1900) turned a holiday hunt into a scientific count, and why repeated counts matter more than one big number.
- Estimate the size of a population using quadrat sampling and the mark-recapture formula, and calculate population density.
- Calculate a population's growth rate from births, deaths, immigration and emigration, and read population data tables critically.

Warm-up. Pour a handful of dried rice onto a dark plate and spread it out. Without counting every grain, how could you estimate how many there are? Try one method: count the grains in one small square of the plate, then multiply by the number of squares the plate would hold. Then count them all (or as many as you can stand) and see how close you came.

Video. Coming soon. How wildlife biologists count animals: the Audubon Christmas Bird Count, quadrat sampling, mark-recapture with fish or turtles, aerial surveys of waterfowl; search the U.S. Fish and Wildlife Service, the National Audubon Society, the Cornell Lab of Ornithology, state wildlife agencies, Homeschool Pop (Alternate) and nature footage of passenger pigeon specimens at the Smithsonian.

KEY TERMS

population
All the members of one species living in the same area at the same time, such as all the bluegill in one pond this summer.

census
A complete count of every individual in a population. It is possible for a few large, visible animals but usually too hard for most species.

sample
A part of a population or area that is counted carefully so it can be used to estimate the whole.

quadrat
A square frame or marked square, often 1 m on a side, placed on the ground so that the plants or slow animals inside it can be counted.

mark-recapture
A method for estimating the size of a population of moving animals: catch and mark some, release them, catch a second group, and use the share of marked animals to estimate the total.

population density

The number of individuals per unit of area, such as 12 deer per square kilometer or 10 dandelions per square meter.

CORE IDEAS

The story. In the 1800s many American families kept a Christmas custom called the “side hunt.” Men chose sides on Christmas Day, went into the fields and woods, and the team that brought back the most birds and animals won. Frank M. Chapman, a bird scientist at the American Museum of Natural History in New York and the editor of a bird magazine called *Bird-Lore*, proposed something new. Instead of shooting the birds, why not count them? On Christmas Day, 1900, twenty-seven observers held 25 counts in places from Toronto, Canada, to Pacific Grove, California, and recorded about 90 kinds of birds. The Christmas Bird Count has been held every winter since. Today tens of thousands of volunteers count in more than 2,000 circles, each 24 km across, making it one of the longest-running wildlife surveys in the world.

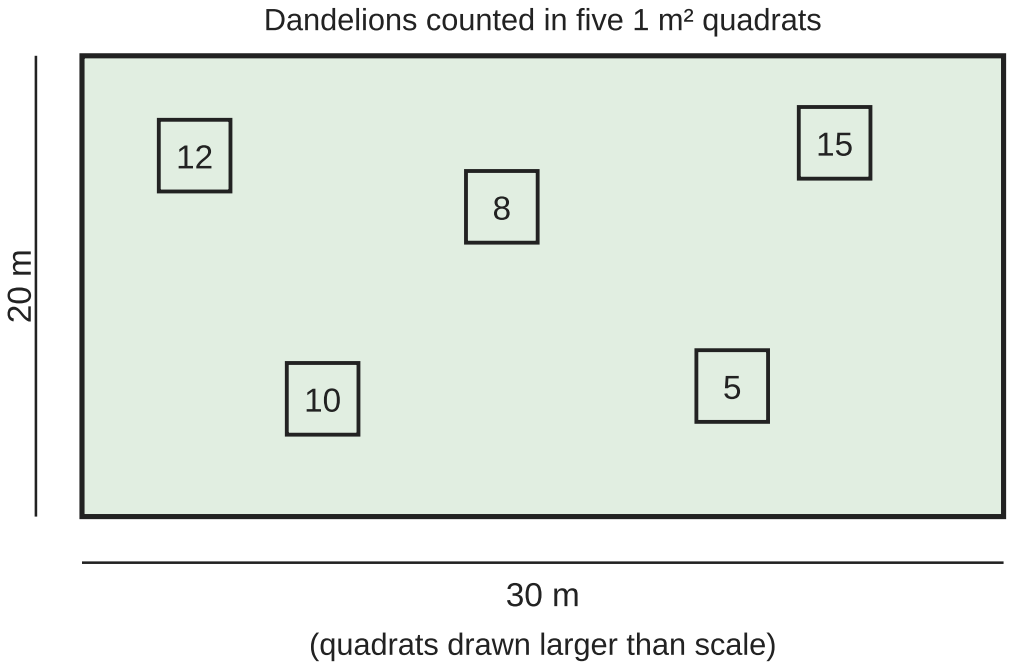
How they figured it out. Why count every year? Because one enormous number can fool you. In the autumn of 1813, John James Audubon rode along the Ohio River in Kentucky while flocks of passenger pigeons darkened the sky, and the birds kept passing for three days. He estimated one flock at more than a billion birds by multiplying the width of the column of birds, its speed, the time it took to pass, and how many birds he judged were packed into each square yard. Passenger pigeons seemed far too many ever to disappear. But nobody counted them carefully year after year, so few people noticed the decline until it was too late. The last passenger pigeon, a bird named Martha, died at the Cincinnati Zoo on September 1, 1914. The lesson for stewards is plain: a single big count tells you *how many*; only repeated counts made the same way tell you *which way the population is going*.

The big idea. A **population** is all the members of one species in one area at one time. Counting every one, a **census**, works for a few large, easy-to-see animals, such as cranes on a winter marsh. For most species, biologists count a **sample** and estimate. For plants and slow animals they use **quadrats**: square frames, often 1 m on a side, tossed at random spots. The average count per quadrat, times the total area, estimates the population. For animals that move, they use **mark-recapture**. Catch and mark M animals (with a band, tag or dab of paint) and release them. Later catch C animals and count R that are marked. If R out of C in the second catch are marked, then M out of the whole population N should be marked too, so **N = M × C ÷ R**. Dividing a population by its area gives its **population density**, such as 10 dandelions per square meter.

How populations change. A population grows when individuals are added and shrinks when they are lost. Births and *immigration* (moving in) add; deaths and *emigration* (moving out) subtract. Change = births + immigration − deaths − emigration. Dividing the change by the starting size gives the growth rate. A herd of 200 deer with 60 fawns born and 20 deaths in a year grows by 40, a rate of 20 percent. No population can grow like that forever, because food, water, shelter, disease and predators eventually limit it. You will meet that limit, called carrying capacity, in Lesson 7.4.

In the world today. State and federal biologists count fish with nets and electric shockers, deer from airplanes and with trail cameras, and ducks across the breeding grounds of Canada and the northern United States in an aerial survey flown every spring since 1955. Ordinary people help too: the Christmas Bird Count, the Great Backyard Bird Count and the eBird website collect millions of sightings a year. Good scientists always report counts as estimates and always ask how the counting was done. If twice as many people counted for twice as many hours, finding twice as many birds does not mean the population doubled.

God's handiwork. The shepherd who counts his sheep every evening knows at once if one is missing. Scripture tells every keeper of animals, "Be thou diligent to know the state of thy flocks, and look well to thy herds" (Proverbs 27:23). Counting is one of the first and most humble duties of a steward. Before you can care for a population, you must know how it is doing.



Quadrat sampling. Five 1 m by 1 m quadrats placed at random in a 30 m by 20 m field. The squares are drawn larger than scale so their counts can be read.

PICTURE STUDY



Passenger Pigeon (Plate 62 of The Birds of America), John James Audubon; engraved by Robert Havell Jr., Published between 1827 and 1838 · Hand-colored engraving and aquatint · Copies of *The Birds of America* are held by many libraries and museums; the original watercolors are at the New-York Historical Society.

John James Audubon (1785–1851) set out to paint every bird in North America life-size. His great book, *The Birds of America*, was printed, mostly in London, from copper plates engraved by Robert Havell Jr. and colored by hand, 435 plates in all. Audubon shot, measured and posed real birds with wires so he could draw them exactly, and he wrote long descriptions of their habits.

In this plate he painted a pair of passenger pigeons, the bird he had watched pass in flocks of more than a billion along the Ohio River in 1813. Less than a century after he painted them, the species was gone. The picture reminds us why naturalists count as well as admire.

Look closely

- Compare the two birds. How are their colors different? Which do you think is the male, the brighter one or the duller one?
- Look at the tails and wings. What shape are they? What does that shape suggest about how fast these birds flew?
- Find the place where the birds' beaks meet. What might they be doing?
- Look at how much of the page Audubon used. Why do you think he wanted his birds drawn life-size?

Talk about it

1. Audubon saw more passenger pigeons than any of us will ever see of one bird. Why did his huge estimate not protect the species?

2. If you could send one message back to the people of 1813 about counting the pigeons, what would you tell them?
3. How is a painting like this a kind of scientific record?

> **Safety first.** If you do the outdoor quadrat survey, wear long pants and closed shoes, learn to recognize poison ivy before you kneel in the grass, and check yourself for ticks afterward. Count wild animals by looking, not handling.

EXPERIMENT: BEANS IN A BAG: HOW GOOD IS MARK-RECAPTURE?

Real biologists cannot check their mark-recapture estimates by counting every fish in a lake. You can, because your "lake" is a bag of beans that a parent has counted secretly. Your question: **Does catching a bigger second sample give a more accurate estimate of the population?**

You will need

- A paper bag or a large bowl with a towel over it
- 300 to 500 dried white beans (a parent counts them secretly and writes the number on a hidden slip of paper)
- About 60 dried beans of a different color (red kidney or black beans), the "tags"
- A small paper cup
- Calculator, lab notebook and graph paper

Steps

1. Write your question and your **prediction**: Will a second catch of 10, 20 or 40 beans give the estimate closest to the true number?
2. **Mark:** Without looking, scoop out 50 white beans. These are your first catch (M = 50). Set them aside and put 50 colored beans into the bag in their place. These are your marked animals, released back into the lake.
3. Shake the bag well so the marked beans mix with the others. This is like letting tagged fish swim back among the rest.
4. **Recapture:** Without looking, draw out 10 beans (C = 10). Count how many are colored (R). Record C and R, then put the beans back and shake again.
5. Repeat the recapture with C = 20, and then with C = 40. Do each sample size three times, returning and shaking the beans between draws.
6. Name your variables. **What we change:** the size of the second catch (C). **What we keep the same:** the number marked (50), the bag, how well we shake, drawing without looking. **What we measure:** the number of marked beans recaptured (R).
7. For each draw, calculate N = M × C ÷ R. (If R is 0, the formula fails; write "no estimate.") Average the three estimates for each sample size.
8. Ask your parent to reveal the true number. Calculate the percent error for each average: (estimate − true) ÷ true × 100, ignoring the minus sign.

9. Make a bar graph of percent error for C = 10, 20 and 40, and write a conclusion: Was your prediction right? Which sample size would you trust most, and why?

Tips

- Remember the 50 white beans you removed in step 2 are counted as part of the population, because 50 colored beans took their place. The bag still holds the true number of beans.
- Small samples often give R = 0, 1 or 2, and a difference of one bean then changes your estimate a lot. That is the point of the experiment.
- Real biologists must also assume that marks do not fall off, that marked animals mix freely, and that no animals are born, die, arrive or leave between the two catches.

Check your work

- I wrote a question, a prediction and my variables before I started.
- I calculated an estimate with N = M × C ÷ R for every draw and averaged them.
- I graphed my percent errors and explained which sample size gave the most reliable estimate.

NATURE NOTEBOOK

1. Make a 1 m by 1 m quadrat from string and four sticks. Toss it at three random spots in a lawn or field and count one kind of plant (dandelions, clover or plantain) in each. Sketch the quadrat and record the counts.
2. Sit at a window or in a yard for 15 minutes and count every bird you see by kind. Write the date, time, weather and number of minutes watched, the way a Christmas Bird Count volunteer would.
3. Draw a passenger pigeon from Audubon’s plate or a museum photo. Beside it write the dates 1813 and 1914 and one sentence about what happened between them.

> **From history.** Mark-recapture began with fish and ducks. In the 1890s the Danish fisheries biologist C. G. J. Petersen tagged plaice, a flatfish, and used the share of tagged fish in later catches to estimate how many fish lived in the waters he studied. In 1930 Frederick C. Lincoln of the U.S. Bureau of Biological Survey used the same reasoning with leg bands on wild ducks to estimate North America’s waterfowl. The formula is still called the Lincoln–Petersen estimate, and bird banding stations across the continent still band and recapture birds every year.

WORKED EXAMPLES

Example 1. Biologists catch 30 painted turtles in a pond, mark each shell with a small paint dot, and release them. Two weeks later they catch 25 turtles, and 5 of them have paint dots. Estimate the number of painted turtles in the pond.

1. Write the values: marked in first catch M = 30; second catch C = 25; marked in second catch R = 5.
2. Reason: 5 out of 25 in the second catch are marked, which is 1 in 5. So the 30 marked turtles should be about 1 in 5 of the whole population.
3. Use the formula: N = M × C ÷ R = 30 × 25 ÷ 5.
4. 30 × 25 = 750, and 750 ÷ 5 = 150.

Answer: About 150 painted turtles live in the pond.

Example 2. A student places five 1 m² quadrats at random in a field 30 m long and 20 m wide and counts dandelions: 12, 8, 15, 10 and 5. Estimate the dandelion population of the field and its density.

(Use the map or drawing "Five random quadrats in a 600 m² field." shown earlier in this lesson.)

1. Average per quadrat: (12 + 8 + 15 + 10 + 5) ÷ 5 = 50 ÷ 5 = 10 dandelions per square meter. That is the population density.
2. Area of the field: 30 m × 20 m = 600 m².
3. Population estimate: 10 per m² × 600 m² = 6,000 dandelions.

Answer: About 6,000 dandelions, at a density of about 10 per square meter.

Example 3. A deer herd numbers 200 in the spring. During the year 60 fawns are born, 20 deer die, 8 deer move in from a neighboring woods and 8 move out. What is the herd size a year later, and what was its growth rate?

1. Change = births + immigration − deaths − emigration = 60 + 8 − 20 − 8 = 40.
2. New size: 200 + 40 = 240 deer.
3. Growth rate = change ÷ starting size = 40 ÷ 200 = 0.20, which is 20 percent per year.

Answer: 240 deer, a growth rate of 20 percent for the year.

PRACTICE

1. EASY Which of these is a population? (a) all the animals in a forest (b) all the bluegill in Miller's Pond this summer (c) every fish in North America (d) the birds and squirrels at

a feeder

2. EASY Give two reasons biologists usually estimate a population from a sample instead of taking a census.
3. MEDIUM Biologists net and tag 40 trout in a lake. A month later they net 60 trout, and 8 have tags. Estimate the trout population.
4. MEDIUM Four 1 m^2 quadrats in a lawn hold 6, 9, 3 and 6 clover plants. The lawn is 15 m by 12 m. Estimate the number of clover plants in the lawn.
5. EASY An aerial survey counts 360 pronghorn on a 90 km^2 stretch of grassland. What is the population density?
6. MEDIUM Data reading. One Christmas Bird Count circle recorded these eastern bluebird numbers and the total party-hours (hours spent counting by all groups combined):
   2019: 42 birds, 20 party-hours
   2020: 55 birds, 25 party-hours
   2021: 61 birds, 30 party-hours
   2022: 48 birds, 20 party-hours
   2023: 70 birds, 35 party-hours
   (a) By what percent did the number of bluebirds counted rise from 2019 to 2023? (b) Calculate birds per party-hour for each year. In which year was it highest? (c) Do the data show that the bluebird population grew? Explain.
7. HARD Data reading. A rabbit population on a small island was counted each spring:
   Year 0: 50
   Year 1: 75
   Year 2: 112
   Year 3: 168
   (a) By what factor did the population multiply each year? (b) Predict the count in year 4. (c) Give two reasons this pattern cannot continue for many more years.
8. MEDIUM A population of 500 prairie dogs has 120 births, 70 deaths, 10 immigrants and 20 emigrants in one year. Find the change and the growth rate.
9. MEDIUM Experiment design. Using a bag of beans, design an experiment to test whether marking more beans in the first catch (M = 20, 50 or 100) gives a more accurate mark-recapture estimate. State the independent variable, the dependent variable, three things to keep the same and how you will judge accuracy.
10. CHALLENGE Mark-recapture assumes that marks stay on and that marked animals are just as likely to be caught as unmarked ones. Suppose half of the paint dots on the turtles wash off before the second catch. Will the estimate be too high or too low? Explain using the formula $N = M \times C \div R$.

COMMON MISTAKES

- Thinking a population means all the animals in a place. A population is one species; all the species in a place together make a community.
- Thinking a bigger count always means a bigger population. If more people counted, for longer, or in better weather, the count can rise while the population stays the same. Compare counts made with the same effort.

- Setting up mark-recapture as M × R ÷ C. Check by reasoning: if few marked animals are recaptured, the population must be large, so R belongs on the bottom.

Make it a game · Estimation Station. A parent fills a clear jar or bowl with something small (beans, pasta, buttons) and counts it secretly. Each player gets two minutes and may use any sampling method: count a layer and multiply, weigh a small handful and the whole jar, or do a quick mark-recapture with colored pieces. Each player writes an estimate and explains the method. Closest estimate scores 3 points; any player who explains a correct method scores 1 point. Play three rounds with different jars.

Scripture. “Be thou diligent to know the state of thy flocks, and look well to thy herds.” (Proverbs 27:23, KJV)

A good herdsman counts and checks his animals regularly. Population counts are the same duty, done for the wild creatures God has put in our care.

Practice answers

1. (b). A population is one species in one area at one time.
2. Any two: there are too many individuals to count; animals move, hide or are active at night; the area is too large; a full count would cost too much time and money; catching every animal could harm them.
3. N = M × C ÷ R = 40 × 60 ÷ 8 = 2,400 ÷ 8 = 300 trout.
4. Average: (6 + 9 + 3 + 6) ÷ 4 = 24 ÷ 4 = 6 per m^2. Area: 15 × 12 = 180 m^2. Estimate: 6 × 180 = 1,080 clover plants.
5. 360 ÷ 90 = 4 pronghorn per square kilometer.
6. (a) (70 − 42) ÷ 42 = 0.667, about a 67 percent rise. (b) 2019: 2.10; 2020: 2.20; 2021: 2.03; 2022: 2.40; 2023: 2.00. Highest in 2022. (c) No. Birds per party-hour stayed about the same (2.0 to 2.4), so the bigger counts mostly came from more counting effort, not clearly from more bluebirds.
7. (a) About 1.5 each year (75 ÷ 50 = 1.5; 112 ÷ 75 ≈ 1.5; 168 ÷ 112 = 1.5), a growth rate of 50 percent. (b) 168 × 1.5 = 252 rabbits. (c) Any two: food runs out, shelter or space runs out, disease spreads in crowded populations, predators increase, rabbits can’t leave an island. These limiting factors slow growth.
8. Change = 120 + 10 − 70 − 20 = +40. Growth rate = 40 ÷ 500 = 0.08, or 8 percent per year. The new population is 540.
9. Independent variable: the number marked (M = 20, 50, 100). Dependent variable: the population estimate (and its percent error). Keep the same: the true number of beans, the second-catch size (for example C = 30), how long the bag is shaken, drawing without looking, number of trials (at least three per M). Judge accuracy by comparing the average estimate to the true number with percent error = |estimate − true| ÷ true × 100.
10. Too high. Fewer turtles will show marks in the second catch, so R will be smaller than it should be. Dividing by a smaller R makes N larger. For example, if R should have been 10 but only 5 dots remain, the estimate doubles.

7.3 Conservation Success: The Bison and the Whooping Crane

OBJECTIVES

- Tell how William Hornaday, private ranchers and the American Bison Society saved the bison, and how refuges, counts and captive breeding brought the whooping crane back from 15 birds.
- Calculate growth ratios, doubling times and percentages from real recovery numbers.
- Explain why some populations recover faster than others, and what a population bottleneck means for heredity.

Warm-up. Start with 2 pennies. Double them: 4. Double again: 8. Keep doubling and count how many doublings it takes to pass 500. Now guess: if a population doubles every 16 years, how many years would it take to grow from 15 to about 500? Write your guess and check it in Worked Example 2.

Video. Coming soon. Saving the American bison (William Hornaday, the American Bison Society, Yellowstone and Wichita Mountains herds) and the whooping crane recovery (Aransas National Wildlife Refuge, Wood Buffalo National Park, costume-rearing of chicks); search the U.S. Fish and Wildlife Service, National Park Service, Smithsonian, Parks Canada, the International Crane Foundation and nature footage of bison and cranes.

KEY TERMS

conservation
The wise use and protection of living things and the places they live, so that they last for future generations.

wildlife refuge
Land or water set aside and managed mainly for the protection of wild animals and their habitat.

habitat
The place where a living thing finds the food, water, shelter and space it needs to live and raise young.

captive breeding
Raising animals under human care so that their young can be added to the wild population.

population bottleneck
A sharp drop in a population to very few individuals. Afterward, all the survivors' descendants carry only the gene variety those few survivors had.

CORE IDEAS

The story of the bison. Bison once numbered in the tens of millions on the plains of North America. In the 1870s and 1880s hide hunters, railroads and the plow brought them almost to an end. In 1886 William T. Hornaday, the chief taxidermist of the Smithsonian's National Museum in Washington, realized the museum had no good bison specimens and went to Montana to collect them while he still could. In 1889 he published *The Extermination of the American Bison* with a careful count: only 1,091 bison were left in all of North America, wild and captive together. Hornaday did not stop at writing. In 1905 he helped found the American Bison Society at the New York Zoological Park (the Bronx Zoo), with Theodore Roosevelt as honorary president. In 1907 the zoo sent 15 bison by train to the Wichita Mountains in Oklahoma, where they became the start of a herd that today numbers about 650.

The ranchers who helped. Many of the last bison were saved not by governments but by private families. In the Texas Panhandle, Mary Ann Goodnight urged her husband, the cattleman Charles Goodnight, to rescue orphaned calves, and they built a herd. In Montana, Michel Pablo and Charles Allard raised a herd that began with a few calves brought in by a Pend d'Oreille man named Samuel Walking Coyote; Canada later bought hundreds of Pablo's bison for its parks. In South Dakota, James "Scotty" Philip kept a herd along the Missouri River. In 1902, when Yellowstone National Park's wild herd had fallen to about two dozen animals, the park bought 21 bison from the Pablo-Allard and Goodnight herds to strengthen it. Today there are several thousand bison in Yellowstone and roughly 400,000 in North America, most of them on private ranches.

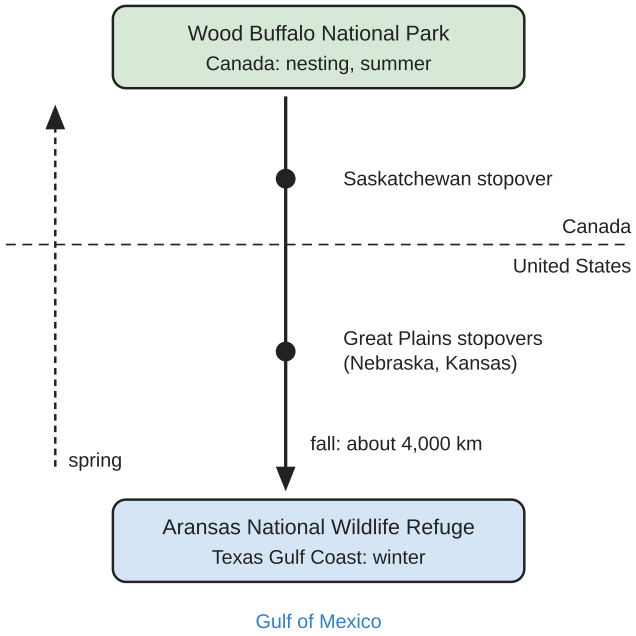
The story of the whooping crane. The whooping crane is the tallest bird in North America, about 1.5 m tall, with a wingspan of more than 2 m and a trumpeting call that carries for kilometers. Hunting and the draining of its marshes cut its numbers until, in the winter of 1941, only 15 birds remained in the flock that wintered at Aransas National Wildlife Refuge on the Texas coast (set aside in 1937). A tiny group in Louisiana soon died out. Robert Porter Allen of the National Audubon Society spent years studying the cranes, but no one knew where they nested until 1954, when a Canadian forester flying back from a fire spotted them in Wood Buffalo National Park, about 4,000 km north of Aransas.

How they figured it out. Recovery used several tools at once. Both countries protected the nesting grounds and the wintering grounds. Hunting cranes was forbidden, and hunters were taught to tell the white crane from snow geese. Biologists counted the flock every winter. They also noticed that a whooping crane pair usually lays two eggs but most often raises only one chick. Beginning in 1967, biologists collected one egg from some nests in Wood Buffalo and raised the chicks at the Patuxent Wildlife Research Center in Maryland, building a captive flock. Later, keepers wore white crane costumes and fed chicks with crane-head puppets so the young birds would not grow tame toward people. Today the wild Aransas–Wood Buffalo flock numbers more than 500 birds.

The big idea. A small population recovers when the causes of decline are removed and births outnumber deaths year after year. Growth then compounds like interest: 15 becomes

30, then 60, 120, 240, 480. Bison recovered faster than cranes because a bison cow can have a calf nearly every year from the age of two or three, while cranes do not breed until they are several years old and usually raise one chick. Both species passed through a **population bottleneck**. Every bison and whooping crane alive today descends from those few survivors, so each species carries less gene variety than it once did, the same heredity you studied with Mendel and DNA. Breeders and refuge managers keep careful family records so related animals are not paired.

God’s handiwork. Every fall the cranes fly from Canada to Texas, and every spring they return, guided along a route they learn from their parents. Long ago the prophet Jeremiah pointed to the migrating birds: “the turtle and the crane and the swallow observe the time of their coming” (Jeremiah 8:7). The people who saved the bison and the crane were stewards who noticed in time. Their work proves that dominion exercised with care can bring a creature back from the edge.



The migration of the Aransas–Wood Buffalo whooping crane flock (schematic, not to scale).

PICTURE STUDY



Buffalo Hunt under the Wolf-skin Mask, George Catlin, 1832–1833 · Oil on canvas · Smithsonian American Art Museum, Washington, D.C.

George Catlin (1796–1872) was a Pennsylvania lawyer turned painter who traveled up the Missouri River in 1832 to paint the tribes of the Great Plains and the animals they lived among. He painted quickly, often outdoors, and wrote long letters describing what he saw. Watching the great herds, Catlin wrote that the government ought to protect the plains, the bison and their people in a great “nation’s Park.” It is one of the earliest calls for a national park in America.

In this painting Catlin records a clever hunting method he saw. Bison were used to wolves following the herd and did not fear a single wolf, so hunters crept close under wolf skins until they were near enough for an arrow.

Look closely

- Find the two hunters. How did they disguise themselves? What are they carrying?
- Look at the bison closest to the hunters. Do they look alarmed or calm? Why?
- Count the bison you can see clearly. How does Catlin suggest that the herd goes on beyond the picture?
- Look at the land and sky. What tells you this is the open prairie?

Talk about it

1. What did the hunters have to understand about bison behavior to make this method work?
2. Catlin painted this scene about 55 years before Hornaday counted only 1,091 bison. What changed in between?

3. How is a careful painting like this useful to a scientist today?

> **Safety first.** If you visit a park with bison or cranes, watch from a distance. The National Park Service tells visitors to stay at least 25 yards (about 23 m) from bison and elk. A bull bison can weigh about 900 kg, nearly as much as a small car, and run faster than a person.

EXPERIMENT: ROLL FOR RECOVERY: MODELING A PROTECTED POPULATION

Why does protection make such a difference? In this dice model each token is one animal. Each "year" every animal has a chance to die and a chance to add a young one. You will compare an unprotected population with a protected one. Your question: **How does lowering the death rate change a small population over 8 years?**

You will need

- Several dice (5 or more makes it faster)
- About 60 small tokens (beans, buttons or paper squares)
- Lab notebook, pencil and graph paper
- A partner to roll or record

Steps

1. Write your question and a **prediction**: After 8 years, about how many animals will each population have?
2. **Unprotected population.** Start with 10 tokens. For each year, roll one die for every token. A roll of 1, 2 or 3 means that animal dies (remove it). A roll of 5 or 6 means it survives and adds one young (add a token). A roll of 4 means it simply survives.
3. Record the population at the end of each year for 8 years (or until it reaches 0).
4. **Protected population.** Start again with 10 tokens. Now only a roll of 1 means death (protection from hunting and habitat loss). A 5 or 6 still adds one young, and 2, 3 or 4 means the animal simply survives. Record 8 years.
5. Name your variables. **What we change:** the death rate (3 chances in 6 versus 1 chance in 6). **What we keep the same:** the starting number, the birth rule, the number of years. **What we measure:** the population each year.
6. Repeat both runs a second time if you can, and average the year-8 results.
7. Graph both populations on the same axes, years across the bottom and population up the side.
8. Calculate the expected yearly change for each: protected = 2/6 births − 1/6 deaths = +1/6 (about +17 percent); unprotected = 2/6 − 3/6 = −1/6 (about −17 percent). Compare these with your results.
9. Write a conclusion: Was your prediction right? Why might a real population of 15 cranes be in danger even when its average trend is upward?

Tips

- Roll for the animals present at the start of the year only. Young added this year wait until next year to roll.
- Dice are random, so two runs of the same rules can turn out quite differently. That chance is a real danger for very small populations: a few bad years can wipe them out.
- If the protected population grows past 60, you may stop rolling and just multiply by 1.17 per year to estimate.

Check your work

- I recorded the population for every year of both runs and graphed them.
- I named my independent, dependent and controlled variables.
- I compared my results with the expected change and explained the role of chance in small populations.

NATURE NOTEBOOK

1. Draw a whooping crane standing next to a meter stick that is 1.5 m tall. Label its height, red crown, black wingtips and long legs, and add its wingspan of more than 2 m with a line.
2. Draw a bison in side view. Label the shoulder hump, the shaggy front coat and the short horns. Beside it, write the numbers 1,091 (1889) and about 400,000 (today).
3. Make a timeline from 1886 to 1967 with at least six events from this lesson: Hornaday’s trip, his book, the American Bison Society, the Wichita herd, Yellowstone’s purchase, Aransas, the 15 cranes, the nesting grounds and the first eggs collected.

> **From history.** In March 1894 a Yellowstone scout caught a poacher named Ed Howell skinning bison he had killed in the park. At the time there was no federal law with a real penalty for killing animals in Yellowstone, so Howell could only be expelled. A writer for the magazine *Forest and Stream* was in the park and sent the story east, and the public outcry was so strong that Congress passed the Yellowstone Park Protection Act within weeks, in May 1894. It made poaching in the park a crime and helped protect the small wild herd that survived to 1902.

WORKED EXAMPLES

Example 1. In 1889 Hornaday counted 1,091 bison in North America: about 85 running wild in the United States, 200 in Yellowstone, 550 in Canada and 256 in captivity. Check that the parts add to 1,091. What percent were in captivity, and what fraction were in Canada?

1. Add the parts: 85 + 200 + 550 + 256 = 1,091. The count checks.
2. Captivity: 256 ÷ 1,091 = 0.235, which is about 23.5 percent.
3. Canada: 550 ÷ 1,091 = 0.504, a little more than one half.

Answer: The parts add to 1,091. About 23.5 percent were in captivity, and about half (50.4 percent) were in Canada. Herds kept by ranchers and zoos were a large share of the survivors.

Example 2. The Aransas whooping crane flock had 15 birds in 1941 and more than 500 about 80 years later. How many doublings take 15 to about 500? About how many years did each doubling take on average?

1. Double step by step: 15 → 30 → 60 → 120 → 240 → 480.
2. That is 5 doublings to reach about 480, close to 500.
3. Divide the time by the number of doublings: 80 years ÷ 5 = 16 years per doubling.
4. Check with the rule of 70 (doubling time ≈ 70 ÷ yearly growth percent): 70 ÷ 16 ≈ 4.4, so the flock grew about 4 to 5 percent a year on average.

Answer: About 5 doublings, roughly one every 16 years, an average growth of about 4 to 5 percent per year.

Example 3. In 1907 the Bronx Zoo shipped 15 bison (6 bulls and 9 cows) to the Wichita Mountains. Today the herd is kept at about 650. Write the bull-to-cow ratio in lowest terms, and find how many times larger the herd is now than in 1907.

1. Ratio of bulls to cows: 6 : 9. Divide both by 3: 2 : 3.
2. Growth factor: 650 ÷ 15 = 43.3.
3. Increase: 650 − 15 = 635 bison more than the founding herd.

Answer: Bulls to cows = 2 : 3. The herd is about 43 times its 1907 size, an increase of 635 animals. (Managers keep it near 650 by moving or selling extra bison so the range is not overgrazed.)

PRACTICE

1. EASY Give the low-point numbers for each species: (a) bison in all North America in Hornaday’s 1889 count; (b) whooping cranes in the Aransas flock in the winter of 1941.
2. EASY Where do the cranes of the main wild flock spend the summer, and where do they spend the winter?
3. MEDIUM Whooping cranes usually lay two eggs but most often raise only one chick. Explain how biologists used this fact to build a captive flock without lowering the number of chicks raised in the wild.
4. MEDIUM Suppose a crane family completes the 4,000 km fall migration in 50 days. What is its average distance per day? If it actually flies on only 20 of those days and rests at stopovers on the others, what is its average distance per flying day?
5. MEDIUM Data reading. A refuge kept these counts of a newly started bison herd (practice numbers):
   Year 0: 20
   Year 5: 32
   Year 10: 51
   Year 15: 82
   Year 20: 131
   (a) By what factor does the herd multiply every 5 years? (b) Predict the count in year 25. (c) Between which counts did the herd first pass double its starting size, and about how long does it take to double?
6. MEDIUM Data reading. A captive crane center recorded:
   Year 1: 40 eggs, 30 hatched, 18 chicks fledged (raised to flying age)
   Year 2: 50 eggs, 40 hatched, 30 fledged
   Year 3: 45 eggs, 36 hatched, 27 fledged
   (a) Find the hatching percent (hatched ÷ eggs) for each year. (b) Find the fledging percent (fledged ÷ hatched) for each year. (c) In which year was something likely wrong after hatching, and what might it have been?
7. HARD In 4–5 sentences, explain why private ranchers and zoos mattered so much in saving the bison. Use at least one number from the lesson.
8. EASY A whooping crane is about 1.5 m tall and has a wingspan of about 2.2 m. How many centimeters wider is the wingspan than the bird is tall? What is the ratio of wingspan to height, to one decimal place?
9. MEDIUM Experiment design. Keepers want to know whether crane chicks raised by costumed keepers survive better after release than chicks raised by keepers in ordinary clothes. Design a fair study. Name the independent variable, the dependent variable, three things to keep the same and one ethical concern.
10. CHALLENGE Explain what a population bottleneck is and why it matters for whooping cranes today, using what you learned about heredity in Units 1 and 2.

COMMON MISTAKES

- Thinking the bison was saved only by government action. Private ranchers, zoos and the American Bison Society kept the last herds alive, and governments later bought animals from them.
- Thinking a recovered number means a recovered species. A population that passed through a bottleneck has less gene variety than before, even when its numbers are large again.
- Thinking growth is the same every year in a small population. Chance events, a storm on the nesting ground or a disease, matter far more when there are only 15 animals than when there are 500.

Make it a game · Doubling Dash. Players race to answer doubling questions called out by a parent: “Start with 15 cranes. How many after 3 doublings?” (120) “A herd doubles every 8 years. How long from 50 to 400?” (24 years) “How many doublings from 1,091 to more than 100,000?” (7, since 1,091 × 128 is about 140,000). First correct answer scores 1 point; a player who also explains the steps scores a bonus point. First to 7 points wins.

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)

The “turtle” here is the turtledove. God built into the migrating birds a faithful sense of their appointed times. Jeremiah used them to call people to be just as faithful to God. Stewards who watch the cranes come and go each year are watching that same faithfulness.

Practice answers

1. (a) 1,091 bison. (b) 15 whooping cranes.
2. Summer (nesting): Wood Buffalo National Park in Canada. Winter: Aransas National Wildlife Refuge on the Texas Gulf Coast.
3. Since a pair usually raises only one chick, the second egg would often be lost anyway. Biologists collected one egg from nests that had two, left the other for the parents to raise, and hatched the collected eggs at Patuxent. The wild pairs still raised about as many chicks as before, and the extra eggs became a captive flock.
4. 4,000 ÷ 50 = 80 km per day overall. 4,000 ÷ 20 = 200 km per flying day.
5. (a) About 1.6 (32 ÷ 20 = 1.6; 51 ÷ 32 ≈ 1.6; 82 ÷ 51 ≈ 1.6; 131 ÷ 82 ≈ 1.6). (b) 131 × 1.6 ≈ 210 bison. (c) It passed 40 (double 20) between year 5 (32) and year 10 (51), so it doubles in about 7 to 8 years.
6. (a) Year 1: 75 percent; Year 2: 80 percent; Year 3: 80 percent. (b) Year 1: 60 percent; Year 2: 75 percent; Year 3: 75 percent. (c) Year 1, because a smaller share of hatched chicks survived to fly. Possible causes: disease, poor food, bad weather in outdoor pens, predators or inexperienced keepers.
7. A good answer includes: by 1889 only 1,091 bison were left, and about 256 of them were already in captivity, so herds kept by people were a large share of the survivors. Ranching families such as the Goodnights and Pablo and Allard raised calves when wild herds were

being destroyed. Their herds later supplied Yellowstone (21 bison in 1902) and Canada’s parks, and the Bronx Zoo’s herd started the Wichita Mountains herd with 15 animals. Without these private and zoo herds, there might have been too few bison to rebuild.

8. 220 cm − 150 cm = 70 cm wider. Ratio: 2.2 ÷ 1.5 ≈ 1.5, so the wingspan is about one and a half times the height.
9. Independent variable: costumed or uncostumed rearing. Dependent variable: the percent of released birds still alive (and wary of people) after one year, tracked with leg bands or radio transmitters. Keep the same: food, pen size, age at release, release site and season, and the number of chicks in each group (as many as possible). Ethical concern: chicks raised to be tame toward people may be put at greater risk, so the study should be small, closely watched and stopped if one group is clearly harmed.
10. A bottleneck is a sharp drop to very few individuals. All of today’s whooping cranes descend from the roughly 15 to 20 birds that survived in the 1940s, so they carry only the alleles (gene versions) those birds had. With less variety, harmful recessive alleles are more likely to be paired in a chick, and the species has fewer different traits to draw on if a new disease appears. Keepers use family records (pedigrees) to avoid pairing close relatives.

7.4 Hunting and Game Management

OBJECTIVES

- Tell how Aldo Leopold's *Game Management* (1933) and the Pittman–Robertson Act (1937) helped turn unregulated hunting into science-based management that brought back deer, turkeys and ducks.
- Define carrying capacity and limiting factors, and use a simple harvest model to find the largest harvest a herd can sustain year after year.
- Calculate population density, harvest targets and conservation funding, and explain hunting as a form of biblical dominion with care.

Warm-up. Put 10 crackers on a plate for a "herd" of 4 people. Each person needs 2 crackers to be "healthy." Is there enough food? Now add 2 more people to the herd without adding crackers. What happens? Write one sentence about what a wildlife manager could do if the herd keeps growing but the plate does not.

Video. Coming soon. Wildlife management and the Pittman–Robertson Act, white-tailed deer and wild turkey restoration, carrying capacity and deer exclosure studies, Aldo Leopold's life and work, the Federal Duck Stamp; search the U.S. Fish and Wildlife Service, state wildlife agencies (deer biologists at check stations), the Aldo Leopold Foundation, the National Wild Turkey Federation, Ducks Unlimited and hunter education channels.

KEY TERMS

game animal
A wild animal that may be legally hunted for food or sport under state or federal rules, such as deer, elk, wild turkey, ducks and rabbits.

carrying capacity
The largest population of a species that an area can support year after year without damaging the habitat, set by its food, water, shelter and space.

limiting factor
Anything that keeps a population from growing larger, such as scarce food, harsh winters, disease, predators or hunting.

hunting season
The dates set by law when a game animal may be hunted, chosen to avoid the times when the animals are mating, nesting or raising young.

bag limit
The number of a game animal one hunter may legally take in a day or a season.

sustained yield
A harvest that removes only the yearly surplus of a population, so the population can provide the same harvest again year after year.

CORE IDEAS

The story. On September 2, 1937, President Franklin D. Roosevelt signed the Federal Aid in Wildlife Restoration Act, usually called the Pittman–Robertson Act after its sponsors, Senator Key Pittman of Nevada and Representative A. Willis Robertson of Virginia. An existing tax on sporting guns and ammunition would now be sent to the states for one purpose: restoring wildlife. Hunters and sporting groups backed the plan, because they saw their own game disappearing. The states had to put up one dollar for every three federal dollars, and the money bought land, paid biologists and restored habitat. Since then the act has sent billions of dollars to state wildlife agencies, and the land and research it paid for help songbirds, wildflowers and hikers as well as hunters.

How they figured it out. Around 1900 the outlook was grim. Market hunters had shot game to sell in city markets with no seasons or limits. White-tailed deer had fallen to perhaps fewer than half a million in the whole United States, and wild turkeys, by some estimates, to about 30,000. A forester named Aldo Leopold, who had worked in the national forests of Arizona and New Mexico, became convinced that wildlife could be raised again like a crop if people understood what each species needed. In 1933 he published *Game Management*, the first textbook of the field, and became the first professor of game management at the University of Wisconsin. Leopold taught that the same tools that had harmed wildlife (the axe, the plow, the cow, fire and the gun) could be used to restore it, if they were guided by careful study.

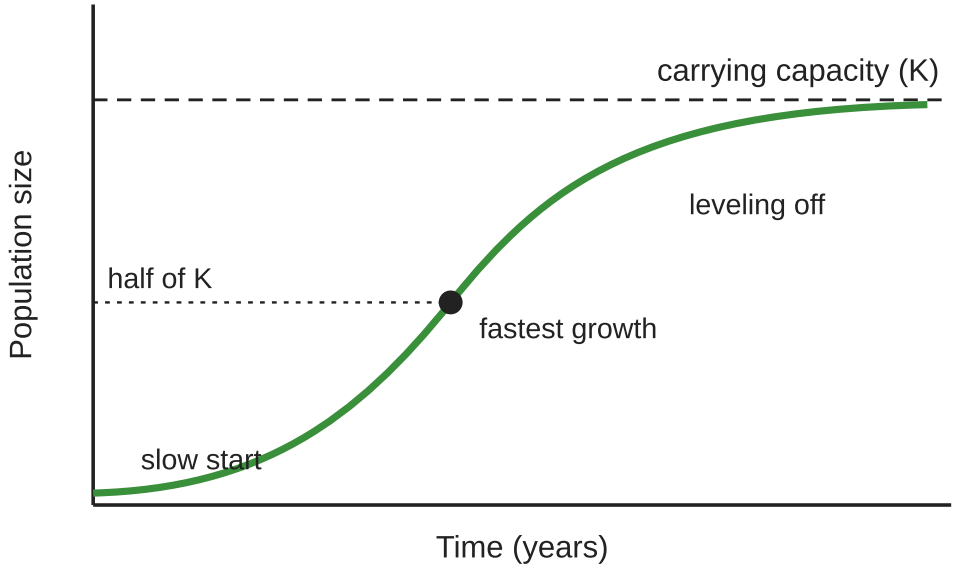
The big idea. Every habitat has a **carrying capacity**, the largest population it can support year after year. Below that level a population grows quickly. As it nears the limit, **limiting factors** such as food, winter shelter and disease slow it down, and the growth curve bends into an S shape (see the diagram). If a deer herd climbs above carrying capacity, the deer eat every reachable twig and seedling, leaving a bare “browse line” in the woods. Then many starve in a hard winter, and the damaged habitat can carry fewer deer than before. In much of the country wolves and mountain lions are gone, so regulated hunting is now the main tool for keeping deer healthy and in balance with their range. A herd near carrying capacity produces a yearly surplus of young. A **sustained yield** harvest takes about that surplus and no more, so the same harvest is possible again next year.

How managers do it. Biologists count herds from the air and with trail cameras, and at check stations they weigh harvested deer and age them by their teeth. With these numbers each state sets **hunting seasons** (deer in the fall after fawns are weaned, turkeys in the spring only for bearded males after most hens have mated) and **bag limits**. When a herd is too large, managers issue extra permits for does, because the number of does sets the number of fawns. The results have been remarkable. Today the United States has roughly 30 million white-tailed deer and about 6 million wild turkeys, and elk have been returned to states where they had vanished.

Hunting rightly. After the Flood God told Noah, “Every moving thing that liveth shall be meat for you” (Genesis 9:3), and Scripture speaks plainly of hunters such as Esau, who brought his father venison. But the Law also taught restraint: a person who found a bird’s

nest could take the eggs or young but had to let the mother go (Deuteronomy 22:6–7). Do not destroy the breeding stock. That is sustained yield in a single verse. Good hunters follow the same spirit today: they obey the law, take clean shots, use what they take and respect landowners. Since New York first required hunter education in 1949, every state has come to offer or require it, and hunting accidents have fallen sharply.

God's handiwork. God designed most creatures to produce more young than their habitat can hold. That surplus feeds hawks, foxes and people, and it lets a population bounce back after a bad year. Late in life Leopold wrote, in *A Sand County Almanac*, "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community." A Christian steward can add the reason behind that rule: the community belongs to its Maker, and we hunt, harvest and manage it as His tenants.



S-shaped (logistic) growth. A population grows fastest near half of carrying capacity and levels off as it approaches K.

PICTURE STUDY



Right and Left, Winslow Homer, 1909 · Oil on canvas · National Gallery of Art, Washington, D.C.

Winslow Homer (1836–1910) was one of America's greatest painters of the sea and the outdoors. He was a hunter and fisherman himself and painted from long experience at his home on the rocky coast of Prouts Neck, Maine. *Right and Left* was one of the last major paintings he made.

The title comes from hunting: a "right and left" is a double, when a hunter with a two-barreled shotgun brings down a bird with each barrel, one after the other. Homer puts us not beside the hunter but up among the ducks, at the very instant of the shot.

Look closely

- Find the hunter. How big is he compared with the ducks? Why do you think Homer made him so small?
- Look at the two ducks. Which one has been hit, and how can you tell?
- Look at the waves and the sky. What season and weather do you think it is?
- Look closely at the ducks' markings: white patches, dark heads and bright eyes. Could you identify this species in the field from Homer's painting?

Talk about it

1. Why might a painter who hunted choose to show the moment from the duck's point of view?
2. What do you think Homer wanted viewers to feel about wild ducks and the hunt?
3. How do duck seasons and bag limits make sure there will be goldeneyes over the waves next winter too?

> **Safety first.** This lesson is about hunting, but the project uses only pencil, calculator and beans. Never touch a firearm, bow or hunting knife without a trained adult present. Every state requires or offers a hunter education course before a young person may hunt; take it before you ever go afield, and always wear blaze orange where the law requires it.

EXPERIMENT: HARVEST AND THE HERD: A CARRYING-CAPACITY MODEL

Wildlife managers must decide each year how many deer hunters may take. Take too few and the herd outgrows its range; take too many and the herd shrinks. In this model you will find the answer with numbers. Your question: **What yearly harvest keeps a deer herd at carrying capacity with no animals starving and the largest possible harvest?**

You will need

- Calculator
- Lab notebook, ruler and graph paper
- Optional: a bag of 700 dried beans to act out the first year (each bean = 1 deer)

Steps

1. Write your question and a **prediction**: Which yearly harvest (0, 100, 200 or 250 deer) will give the most deer for hunters without starvation and without shrinking the herd?
2. Learn the model rules. The habitat's carrying capacity is **500 deer**. Each spring, fawns add 40 percent to the herd (multiply by 1.4 and round to the nearest whole deer). Each fall, hunters take the harvest. Each winter, any deer above 500 starve.
3. Name your variables. **What we change:** the yearly harvest. **What we keep the same:** the starting herd (500), the fawn rate (40 percent), the carrying capacity (500) and the number of years (5). **What we measure:** the herd each year, the number harvested and the number that starve.
4. Make a table for harvest = 0 with columns Year, Spring herd, After harvest, Starved, Winter herd. Start: spring herd = 500 × 1.4 = 700. Fill in 5 years.
5. Repeat the table for harvests of 100, 200 and 250 deer per year. If the herd after harvest is ever smaller than the harvest, the herd has collapsed: write 0 and stop.
6. Total the deer harvested and the deer starved over 5 years for each harvest level.
7. Graph the winter herd size against year for all four harvest levels on one set of axes.
8. If you have beans, act out year 1 for harvest = 200: count out 500, add 200 "fawns," remove 200 "harvested" and see how many remain for winter.
9. Write a conclusion: Which harvest gave the most deer to hunters while keeping the herd steady? What happened when the harvest was too small? Too large? How does this show sustained yield?

Tips

- In this simple model the herd starts at carrying capacity. Real herds are often below or above it, and real managers count every year and adjust.

- Starvation in the harvest = 0 table is not a mistake. That is what happens in real woods when a herd outgrows its winter food.
- The extra deer that starve each winter are a lost harvest: they could have fed families instead.

Check your work

- I completed a five-year table for each of the four harvest levels.
- I totaled harvested and starved deer and graphed the herd for every harvest level.
- I identified the sustained-yield harvest and explained what happens above and below it.

NATURE NOTEBOOK

1. Draw the S-shaped growth curve. Label carrying capacity (K), the slow start, the fastest growth and the leveling off. Mark with an arrow where a manager would like to keep a deer herd.
2. Look up your state's hunting regulations (online or in a printed guide) for one game animal. Record its season dates and bag limit, and write one sentence about why the season falls when it does.
3. Find a patch of woods and look for a browse line: a height below which twigs and seedlings are eaten away. Sketch it, estimate its height in centimeters, and note any deer tracks or droppings.

> **From history.** In 1934 Congress created the Federal Duck Stamp, which every waterfowl hunter aged 16 and older must buy each year. The first stamp, drawn by the Pulitzer Prize–winning cartoonist Jay N. "Ding" Darling, showed two mallards landing on a marsh and cost one dollar. Ninety-eight cents of every dollar from duck stamp sales goes to buy or lease wetlands for the National Wildlife Refuge System, and those marshes shelter not only ducks but herons, frogs, turtles and songbirds. Many birdwatchers and stamp collectors buy the stamp too, just to help.

WORKED EXAMPLES

Example 1. Under the Pittman–Robertson Act, an 11 percent federal tax is paid on rifles, shotguns and ammunition. (a) How much tax goes to wildlife from a $600 rifle and a $30 box of ammunition? (b) A state plans an $80,000 wetland project. The federal share is 75 percent and the state's share is 25 percent. How much does each pay?

1. Rifle: $600 × 0.11 = $66.00.
2. Ammunition: $30 × 0.11 = $3.30.
3. Total tax: $66.00 + $3.30 = $69.30.
4. Federal share: $80,000 × 0.75 = $60,000.
5. State share: $80,000 × 0.25 = $20,000. Check: $60,000 + $20,000 = $80,000.

Answer: (a) $69.30 goes toward wildlife restoration. (b) Federal $60,000 and state $20,000, three federal dollars for every state dollar.

Example 2. Biologists estimate 1,800 deer in a 120 km² county. Their goal, based on browse surveys, is 8 deer per square kilometer. What is the present density, what herd size is the goal, and how many deer must be removed to reach it?

1. Present density: 1,800 deer ÷ 120 km² = 15 deer per km².
2. Goal herd: 8 deer per km² × 120 km² = 960 deer.
3. Reduction needed: 1,800 − 960 = 840 deer.
4. Because each spring adds fawns, managers spread this over several seasons and issue extra doe permits.

Answer: Density 15 deer per km²; goal 960 deer; about 840 deer must be removed (over several seasons, plus that year's fawn crop).

Example 3. A herd sits at its carrying capacity of 500 deer. Each spring the fawn crop adds 40 percent. Compare a yearly harvest of 0 deer with a harvest of 200 deer. How many deer starve each winter in each case?

(Use the map or drawing "A herd at carrying capacity produces a yearly surplus that a sustained-yield har" shown earlier in this lesson.)

1. Spring herd: 500 × 1.4 = 700 deer.
2. Harvest 0: 700 deer go into winter. Only 500 can be fed, so 700 − 500 = 200 starve. Next spring starts again at 500.
3. Harvest 200: 700 − 200 = 500 deer go into winter. None starve. Next spring starts at 500.
4. Either way the herd returns to 500, but with harvest 0 the 200 surplus deer die of hunger, while with harvest 200 they feed families and the range is not overgrazed.

Answer: Harvest 0: 200 deer starve each winter. Harvest 200: none starve, and 200 deer are harvested every year. 200 is the sustained yield.

PRACTICE

1. EASY Define carrying capacity in your own words and name three things that set it for a deer herd.
2. EASY Which of these is NOT a limiting factor for a wild turkey population? (a) a cold, wet spring that kills poults (b) foxes and raccoons eating eggs (c) the color of the turkey's feathers (d) a hunting season
3. EASY A box of shotgun shells costs $45. How much Pittman–Robertson tax (11 percent) goes to wildlife restoration?
4. MEDIUM A 200 km² hunting district holds about 2,400 deer. Managers want 9 deer per square kilometer. Find the present density and how many deer must be removed to reach the goal.
5. MEDIUM A check station records 300 bucks and 450 does taken in one season. Write the ratio of bucks to does in lowest terms, and find what percent of the harvest was does.
6. MEDIUM Data reading. Biologists in one forest measured deer density and the percent of young oak seedlings with browsed tips:
   2016: 10 deer per km², 35 percent browsed
   2018: 14 deer per km², 55 percent browsed
   2020: 18 deer per km², 80 percent browsed
   2022: 12 deer per km², 50 percent browsed
   2024: 9 deer per km², 30 percent browsed
   (a) Describe the relationship between deer density and browsing. (b) What most likely happened between 2020 and 2022? (c) Predict the percent browsed at 8 deer per km².
7. HARD Data reading. Use the model from this lesson's project (carrying capacity 500; spring fawns add 40 percent; fall harvest; deer above 500 starve in winter; the herd starts at 500). (a) With a harvest of 150, how many deer starve each winter? (b) With a

harvest of 250, the winter herd goes 450, then 380, then 282. Find the next winter's herd. (c) Which harvest gives the largest yield that can be repeated every year?

8. MEDIUM Explain how the rule in Deuteronomy 22:6–7 is like a modern spring turkey season that allows hunters to take only bearded turkeys (mostly males).
9. MEDIUM Experiment design. A forester suspects that deer are keeping young trees from growing in a woodlot. Design an exclosure experiment to test this. Include the independent variable, the dependent variable, controls and how long it should run.
10. CHALLENGE Some people think protecting deer from all hunting is always best for deer. In 4–5 sentences, explain why a herd with no hunting and no large predators may end up worse off. Use the terms carrying capacity and limiting factor.

COMMON MISTAKES

- Thinking hunting is the reason game animals were once scarce. Unregulated market hunting and habitat loss nearly wiped out deer and turkeys; regulated hunting, with seasons, limits and hunter-funded restoration, helped bring them back.
- Thinking a population left completely alone always stays healthy. Without predators or hunting, deer can overshoot carrying capacity, wreck their habitat and starve.
- Thinking carrying capacity is a fixed number. It changes with drought, deep snow, acorn crops, forest age and farming, so managers must count and adjust every year.

Make it a game · Food, Water, Shelter. Best with 6 or more players outdoors. Split into "deer" and "habitat." Each round, deer turn their backs and choose a need by making a sign (hands on stomach = food, hands at mouth = water, hands over head = shelter), and habitat players secretly choose one too. On "Go!" both sides turn and deer run to find a habitat player making the same sign. A deer that finds a match brings that habitat player back as a new deer (a fawn); a deer that finds none becomes habitat. Record the number of deer each round for 10 rounds, then graph it. In round 6, the parent may call "drought" and remove two habitat players to see what happens.

Scripture. "If a bird's nest chance to be before thee in the way in any tree, or on the ground, whether they be young ones, or eggs, and the dam sitting upon the young, or upon the eggs, thou shalt not take the dam with the young: But thou shalt in any wise let the dam go, and take the young to thee; that it may be well with thee, and that thou mayest prolong thy days." (Deuteronomy 22:6–7, KJV)

The "dam" is the mother bird. God allowed His people to take food from the wild, but not to destroy the source of next year's young. That is the heart of game management: take the surplus, protect the breeding stock.

Practice answers

1. Carrying capacity is the largest population an area can support year after year without being damaged. For deer it is set by things such as winter food (twigs, acorns), water, shelter from cold and snow, and space.

2. (c). Feather color does not limit the population size; the others reduce survival or numbers.
3. $45 × 0.11 = $4.95.
4. Present density: 2,400 ÷ 200 = 12 deer per km². Goal: 9 × 200 = 1,800 deer. Remove 2,400 − 1,800 = 600 deer (plus that year's fawns).
5. 300 : 450 = 2 : 3. Does: 450 ÷ 750 = 0.60, or 60 percent.
6. (a) As deer density rises, the percent of browsed seedlings rises (a positive relationship), about 5 percentage points for each added deer per km². (b) The herd was reduced, likely by extra doe permits or a longer season, and browsing fell with it. (c) About 25 percent (following the pattern from 10 → 35 and 9 → 30).
7. (a) 700 − 150 = 550 going into winter; 550 − 500 = 50 starve. (b) 282 × 1.4 = 394.8 ≈ 395 in spring; 395 − 250 = 145 deer. The herd is collapsing. (c) 200 deer, exactly the yearly surplus; it leaves 500 deer each winter with none starving.
8. Both protect the breeding mothers. The law let a person take the eggs or young but required letting the mother bird go, so she could nest again. A spring season for bearded birds lets hunters harvest males while the hens, which lay the eggs and raise the poults, survive to keep the population going. Both are sustained-yield rules.
9. Build several fenced plots (for example, four 5 m by 5 m plots with fences 2.4 m tall that deer cannot jump) and mark the same number of unfenced plots of the same size nearby with similar soil, light and slope. Independent variable: fenced (no deer) or unfenced (deer can feed). Dependent variable: the number and height of tree seedlings in each plot. Controls: same forest type, plot size, sunlight, soil and starting seedling counts. Measure every year for at least 3 to 5 years and compare averages.
10. A good answer includes: without hunting or predators, the herd keeps growing until it passes carrying capacity. The deer then overbrowse their range, destroying seedlings and shrubs, so the habitat can carry even fewer deer. Starvation, disease and harsh winters become the limiting factors instead of a planned harvest, and many deer die slowly. Car collisions and crop damage rise too. A sustained-yield harvest keeps the herd near a healthy level, so both the deer and their habitat stay in good condition.

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. Genesis 2:15 says God put the man in the garden “to dress it and to keep it.” Which statement best fits this verse? (a) People should never change the land. (b) People may use the land any way they like. (c) People should work the land so it is fruitful and also guard it from harm. (d) Only farmers are stewards.
2. (5 pts) Diagram item. Draw an energy pyramid with four levels for this food chain: algae → water fleas → small fish → kingfisher. The algae store 30,000 kJ. Label each level with the organism and its energy using the 10 percent rule.
3. (5 pts) Classify each as a producer, consumer or decomposer: seagrass, brown pelican, mold on a fallen log, mangrove tree, mullet. Then explain in one sentence why decomposers are necessary.
4. (4 pts) Multiple choice. Which method is best for estimating the number of largemouth bass in a lake? (a) a census of every fish (b) quadrats on the lake bottom (c) mark-recapture (d) counting fish seen from the dock for one minute
5. (6 pts) Biologists band 50 ducks on a marsh. A week later they catch 40 ducks, and 10 have bands. Estimate the duck population and state one assumption the estimate depends on.
6. (6 pts) Data reading. Four 1 m² quadrats in a meadow held 7, 11, 9 and 13 milkweed plants. The meadow is 25 m by 40 m. (a) What is the average density? (b) Estimate the milkweed population. (c) Why is it better to use four quadrats than one?
7. (4 pts) Multiple choice. In the winter of 1941, the last 15 birds of the main whooping crane flock wintered at (a) Pelican Island, Florida (b) Yellowstone National Park (c) Aransas National Wildlife Refuge, Texas (d) Wood Buffalo National Park, Canada
8. (6 pts) In 1907, 15 bison were shipped from the Bronx Zoo to the Wichita Mountains of Oklahoma. Today that herd is kept near 650. (a) About how many times larger is the herd now? (b) Name two people or groups from the lesson who helped save the bison, and what each did.
9. (6 pts) The whooping crane flock grew from 15 birds to more than 500. (a) How many doublings is that, approximately? (b) Explain why biologists could collect one egg from many nests without reducing the number of chicks the wild cranes raised.
10. (6 pts) Under the Pittman–Robertson Act, an 11 percent tax is paid on a $500 shotgun. (a) How much goes to wildlife restoration? (b) A state starts a $120,000 habitat project with a 75 percent federal share. How much does the state pay?
11. (8 pts) A deer herd lives in a valley with a carrying capacity of 600 deer. Each spring fawns add 50 percent to the herd. Deer above 600 starve each winter. (a) If the herd starts the year at 600 and no deer are hunted, how many starve? (b) What yearly harvest is the sustained yield? (c) Explain, using the words carrying capacity and limiting factor, why a planned harvest is better for this herd than no harvest.

UNIT PROJECT: MY POPULATION STUDY

Choose one species near your home that you can count safely and repeatedly: a plant such as dandelions, clover or milkweed, or a common bird at a feeder. Over at least two weeks, count it at least four times using a method from this unit (quadrats for plants; timed counts for birds, recording minutes watched and weather). Record your data in a table, calculate density or birds per hour, and make a graph.

Then write a one-page steward's report: describe the habitat (biotic and abiotic parts), place your species in a food chain, explain what limits its population, and recommend one realistic way your family could "dress and keep" this habitat better. Include at least one labeled sketch and one KJV verse from the unit.

- **Method**: Uses a correct sampling method (random quadrats or equal-effort timed counts), repeats it at least four times and records dates, conditions and effort.
- **Data and math**: Data table is complete and neat; density or rate is calculated correctly with units; the graph has a title, labeled axes and correct scale.
- **Ecology**: The report correctly names biotic and abiotic parts, a food chain with producer, consumer and decomposer, and at least one limiting factor.
- **Stewardship**: The recommendation is practical and connected to the data, and the report explains how it reflects dominion with care (Genesis 1:28; 2:15).

Answer key

1. (c). To dress is to work and tend; to keep is to guard. Dominion includes both use and care.
2. A pyramid, widest at the bottom: algae 30,000 kJ; water fleas 3,000 kJ; small fish 300 kJ; kingfisher 30 kJ (at the narrow top). Full credit requires correct order, correct values and a shape that narrows upward.
3. Producers: seagrass, mangrove tree. Consumers: brown pelican, mullet. Decomposer: mold. Decomposers break down dead material and return nutrients to the soil and water so producers can use them again.
4. (c). Fish move and cannot be seen all at once, so biologists catch, mark, release and recapture them.
5. $N = M \times C \div R = 50 \times 40 \div 10 = 200$ ducks. Assumptions (any one): bands are not lost; banded ducks mix freely and are as likely to be caught as others; no ducks arrive, leave, hatch or die between the catches.
6. (a) $(7 + 11 + 9 + 13) \div 4 = 40 \div 4 = 10$ plants per m^2. (b) Area $25 \times 40 = 1{,}000\ m^2$; $10 \times 1{,}000 = 10{,}000$ plants. (c) Plants are not spread evenly, so several random samples average out patches that are unusually thick or thin and give a more reliable estimate.
7. (c) Aransas National Wildlife Refuge, Texas. (Wood Buffalo is where they nest in summer.)
8. (a) $650 \div 15 \approx 43$ times larger. (b) Any two: William Hornaday counted the last bison (1,091 in 1889), warned the nation and helped found the American Bison Society; the American Bison Society and the Bronx Zoo started new herds such as Wichita; Charles and Mary Ann Goodnight rescued calves and built a herd in Texas; Michel Pablo and Charles Allard kept a large Montana herd that supplied Canada's parks; Yellowstone bought 21 bison in 1902 to rebuild its herd.

9. (a) 15 → 30 → 60 → 120 → 240 → 480: about 5 doublings. (b) Whooping cranes usually lay two eggs but most often raise only one chick, so the second egg was usually lost anyway. Taking it let biologists hatch and raise a captive flock while the parents still raised their one chick.
10. (a) $500 × 0.11 = $55. (b) State share is 25 percent: $120,000 × 0.25 = $30,000 (federal $90,000).
11. (a) 600 × 1.5 = 900 in spring; 900 − 600 = 300 starve. (b) 300 deer per year, which brings the herd back to exactly 600 with none starving. (c) Without a harvest, the herd overshoots carrying capacity every year, starvation becomes the limiting factor, and the hungry deer overbrowse the valley so it can carry fewer deer later. A planned harvest takes the surplus, keeps the herd at a healthy size and protects the habitat.

UNIT 8

Careers in Life Science

Life science is not only something to study; it is something people do for a living, every day, to serve their neighbors. In this unit you will meet people who turned careful observation into a life's work. Florence Nightingale counted the dead at Scutari and proved with a graph that clean hospitals save lives. John James Audubon tied silver thread to young phoebes' legs in 1804 and began a science that game wardens and wildlife biologists still use. Norman Borlaug crossed wheat by hand in the dust of Mexico until his new varieties could stand up to rust and wind. Maria Sibylla Merian sailed to Suriname at 52 to watch caterpillars become moths on their own food plants.

Along the way you will look at the training, daily work and character each career asks for: doctors, nurses and veterinarians; wildlife biologists and game wardens; plant breeders, agronomists, soil scientists and extension agents. You will measure pulse rates, figure doses by body mass, estimate populations by mark-recapture, calculate crop yields and use Punnett squares the way breeders do. The unit, and the course, ends with your own field study: a real question, real quadrats or a transect, real data and an honest report.

Every one of these careers is a way of obeying the first commands God gave: to have dominion and to "dress" and "keep" the garden (Genesis 1:28; 2:15). The best scientists in this unit worked with skill, patience and truthfulness because they believed the people, animals and fields they served were worth caring for.

BEFORE YOU BEGIN

- Can calculate a percent, an average and a simple rate (amount per unit of time or area)
- Can complete a one-gene Punnett square and give the expected ratio (Unit 1)
- Can identify the independent, dependent and controlled variables in an experiment
- Has practiced counting a population and reading bar and line graphs (Unit 7)

MASTERY CHECKLIST

- I can tell how Florence Nightingale used records and graphs to improve hospital care, and describe the work and training of doctors, nurses and veterinarians.
- I can measure a pulse, calculate beats per minute and figure a dose by body mass.
- I can explain how wildlife biologists and game wardens work together, and estimate a population with mark-recapture.
- I can tell how Norman Borlaug bred better wheat, calculate crop yield per hectare and use a Punnett square to predict offspring.
- I can plan and carry out a field study with quadrats or a transect and write a report with question, prediction, methods, data, analysis and conclusion.

OPTIONAL BOOKS AND RESOURCES

- **USGS Bird Banding Laboratory** (https://www.usgs.gov/labs/bird-banding-laboratory): Free. Learn how bird banding works and how to report a band you find (Lesson 8.2). Reporting a found band tells you where and when the bird was banded.
- **All About Birds, from the Cornell Lab of Ornithology** (https://www.allaboutbirds.org/): Free. A reliable bird identification guide with photos, range maps and songs, useful for the two-feeder experiment and for field studies.
- ***The Natural History of Selborne* by Gilbert White (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/search/?query=natural+history+of+selborne): Free. A classic field naturalist's notebook from 1789. Read a few of White's letters on swallows, swifts or earthworms before planning your own field study (Lesson 8.4).

8.1 Veterinarians, Nurses and Doctors ★

OBJECTIVES

- Tell how Florence Nightingale used careful records and graphs at Scutari to show that most soldiers' deaths came from preventable disease.
- Explain how doctors, nurses and veterinarians use anatomy, physiology and microbiology, and describe the training path for each career.
- Measure and calculate pulse rate, percent death rate and a dose by body mass, and read a graph of heart rates in different mammals.

Warm-up. Find your pulse on the thumb side of your wrist with two fingers (not your thumb, which has a pulse of its own). Count the beats for 15 seconds while a parent watches a clock. Multiply by 4. Now find the pulse of a willing family dog or cat inside its back thigh where the leg meets the body, or ask a parent to try. Is the animal's heart faster or slower than yours? Write both numbers down.

Video. Coming soon. Florence Nightingale at Scutari and her rose diagram, plus a day in the life of a veterinarian, a registered nurse and a family doctor; search history channels, Royal Statistical Society or museum explainers, university veterinary schools and hospital career videos.

KEY TERMS

vital signs
The basic measurements of how a body is working: body temperature, pulse, breathing rate and blood pressure.

physiology
The study of how the parts of a living body work and work together, such as how the heart pumps blood.

diagnosis
Identifying an illness or injury from its signs, symptoms and test results; it works much like testing a hypothesis.

registered nurse
A licensed health worker who cares for patients day and night, gives medicines, watches for changes and teaches patients and families.

veterinarian
A doctor who prevents, diagnoses and treats disease and injury in animals, from pets to cattle, horses and zoo animals.

sanitation
Keeping places clean and safe from disease, especially through clean water, working drains and the removal of waste.

CORE IDEAS

The story. In early November 1854 a ship carried Florence Nightingale and 38 nurses to the Barrack Hospital at Scutari, across the Bosporus from Constantinople (today's Istanbul). Britain was fighting the Crimean War, and sick and wounded soldiers were shipped across the Black Sea to this enormous stone building. The nurses found men lying in crowded wards with too few blankets, too little clean food, broken drains under the floors and rats in the corridors. Nightingale was 34 years old. She set her nurses to scrubbing floors, washing linen, cooking proper meals and writing things down. At night she walked the long wards with a lamp, checking on the men, and she became known around the world as "the Lady with the Lamp."

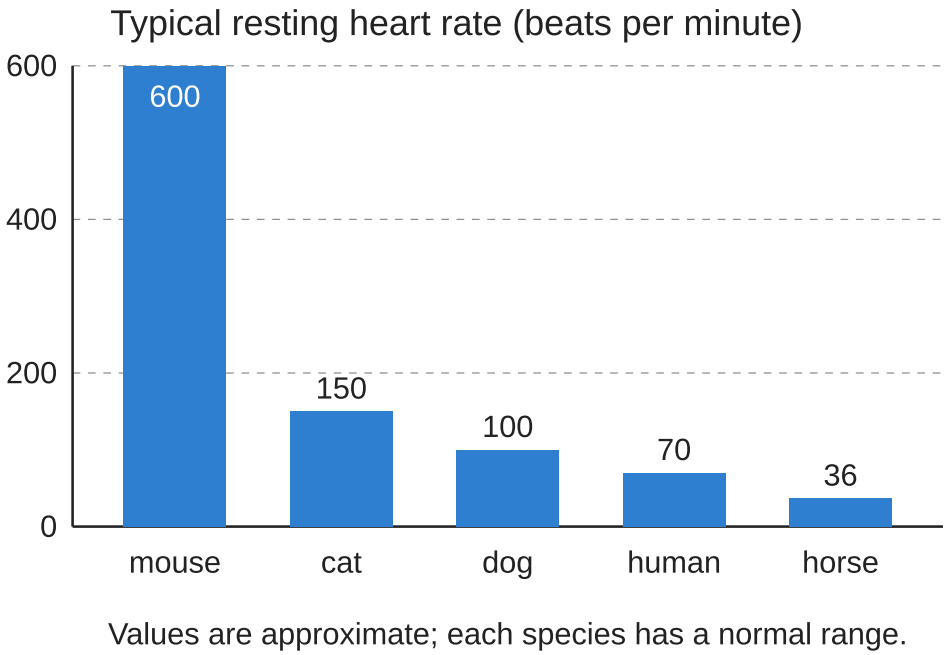
How they figured it out. Nightingale did more than comfort the soldiers. She counted. Month by month, deaths and their causes were recorded, and the numbers told a shocking story: far more soldiers died of diseases such as cholera, typhus and dysentery than from wounds received in battle. In the winter of 1854–1855 the hospital's death rate was terribly high. In March 1855 a Sanitary Commission sent from London flushed the sewers, cleared away filth and improved the flow of fresh air, and over the following months the death rate fell steeply. After the war Nightingale worked with the statistician William Farr, and in 1858 she published her famous "rose" diagrams, in which the size of each colored wedge showed the deaths in one month. Anyone could see at a glance that most of the deaths could have been prevented. She was elected the first woman member of the Royal Statistical Society, and her graphs helped change how hospitals and army camps were built and kept.

The big idea. Medicine is life science put to work. Doctors, nurses and veterinarians all use **anatomy** (the structure of the body), **physiology** (how it works), microbiology (germs and how they spread), chemistry (how medicines act) and genetics (inherited conditions, like the ones you traced on pedigrees in Unit 1). They begin the way every scientist begins: by observing and measuring. The **vital signs** are temperature, pulse, breathing rate and blood pressure. A healthy adult's resting pulse is usually 60 to 100 beats per minute, and normal body temperature is about 37 °C. A **diagnosis** works like a hypothesis: the doctor gathers signs, suggests a likely cause, and orders tests that could prove the idea wrong. The doctor usually diagnoses and prescribes. The nurse is with the patient hour after hour, giving medicines, checking vital signs and noticing the first sign that something is changing. A veterinarian does both jobs for many different species, and the species matter. A dog's normal temperature is about 38.5 °C, a horse's resting heart beats only about 28 to 44 times a minute, chocolate can poison a dog, and some pain medicines that are safe for people are deadly to cats. A vet must think in ratios, comparing each patient to the normal values for its own kind and size.

In the world today. In the United States a physician usually spends 4 years in college, 4 years in medical school and then 3 to 7 years in residency, training in hospitals under experienced doctors. A registered nurse earns a 2-year or 4-year nursing degree and passes a national licensing exam; nurse practitioners and nurse anesthetists study further. A veterinarian usually finishes college and then a 4-year Doctor of Veterinary Medicine program; places in vet school are few, so good grades in biology and chemistry matter.

Around these three careers stand many others: veterinary technicians, paramedics, pharmacists, physical therapists, laboratory scientists and the country large-animal vets who keep cattle, sheep and horses healthy and so protect the food on your table. Every one of them needs careful arithmetic, because doses are figured by body mass and a misplaced decimal point can harm a patient. Every one of them also needs character: honesty in records, patience, steady hands and kindness to the frightened.

God's handiwork. The psalmist wrote, "I will praise thee; for I am fearfully and wonderfully made" (Psalm 139:14). The body was made to heal: skin closes over a cut, broken bone knits, white blood cells hunt down invaders. A good physician does not create healing; he or she cleans, protects, supports and removes what blocks the healing God built into the body. Because people are made in the image of God (Genesis 1:27), caring for the sick has always been close to the heart of Christian life. Luke, who wrote a Gospel and the book of Acts, is called "the beloved physician" (Colossians 4:14). Animals are cared for too: "A righteous man regardeth the life of his beast" (Proverbs 12:10). Nightingale herself believed God had called her to nursing, and she answered that call with a lamp, a scrub brush and a notebook full of numbers.



Typical resting heart rates of five mammals (approximate). Smaller mammals generally have faster hearts.

PICTURE STUDY

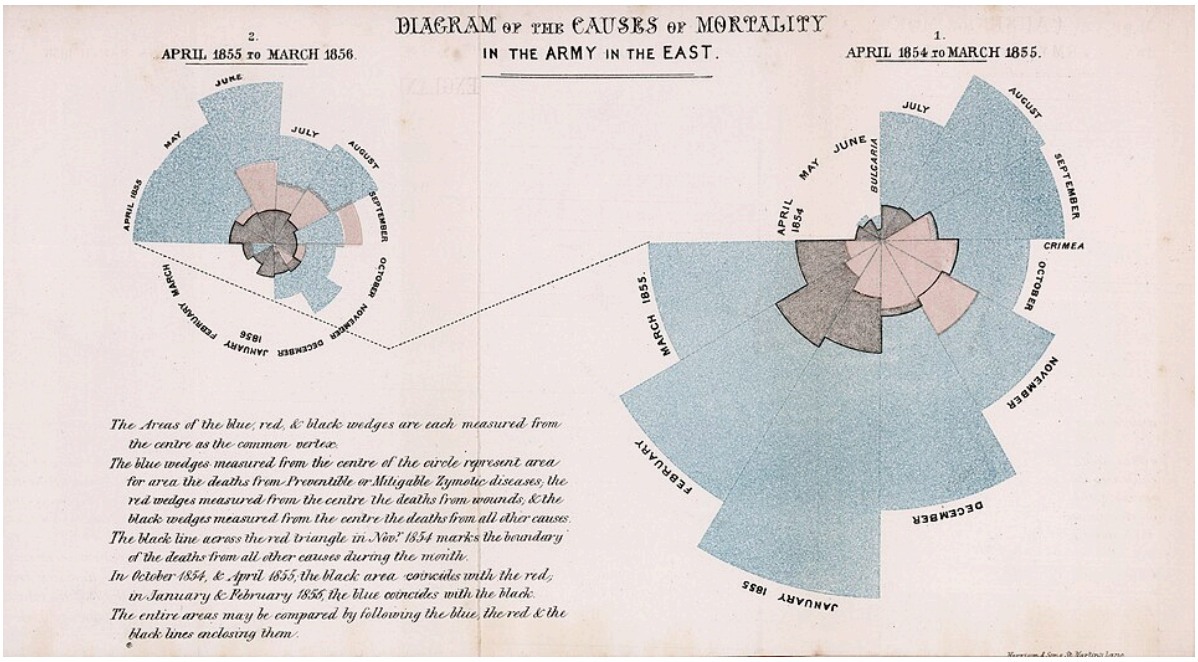


Diagram of the Causes of Mortality in the Army in the East, Florence Nightingale, 1858 · Printed color diagram (polar area or “rose” diagram) · Published in Nightingale’s reports on the health of the British Army; copies in many libraries

This is not a painting but a picture made of numbers. Florence Nightingale designed it after she came home from the Crimean War, so that members of Parliament and army officers who would never read a long table could see the truth at once. Each wedge stands for one month. The bigger the wedge, the more soldiers died that month.

The right-hand rose covers April 1854 to March 1855, and the left-hand rose covers April 1855 to March 1856. The blue wedges are deaths from diseases that could have been prevented or lessened, the red wedges are deaths from wounds, and the dark wedges are deaths from all other causes.

Look closely

- Find the largest wedges. In which rose are they, and what color are they?
- Compare the blue areas with the red areas. Which cause killed more soldiers?
- Look at the left-hand rose, after the Sanitary Commission’s cleanup in March 1855. How have the wedges changed?
- Read the small printed notes under the diagram. Nightingale explained how to read her own graph.

Talk about it

1. Why might a picture of the numbers persuade people better than a table of the same numbers?

2. What does this diagram teach about the importance of keeping careful records in medicine?
3. If you were a nurse or doctor today, what would you want to count, and why?

> **Safety first.** Only do the exercise in this project if you are healthy and a parent agrees. Stop at once if you feel dizzy, short of breath or have chest pain. Take an animal's pulse only on a calm, friendly pet with the owner holding it, and never on a strange or injured animal.

EXPERIMENT: THE PULSE RECOVERY EXPERIMENT

Nurses check the pulse because it tells how hard the heart is working. In this experiment you will measure how fast your pulse rises with exercise and how long it takes to come back down. A fit heart usually recovers faster. You will work exactly like a nurse on a ward: measure, record, compare.

You will need

- A clock or phone timer that shows seconds
- Lab notebook, pencil and ruler
- A partner (parent or sibling) to keep time
- Graph paper

Steps

1. Write your question: How long does my pulse take to return to its resting rate after one minute of jumping jacks?
2. Write a prediction with a number, such as "It will take about 3 minutes."
3. List what you keep the same: the same exercise, for the same time, at the same time of day, counted the same way (15 seconds × 4).
4. Sit quietly for 5 minutes. Measure your resting pulse three times and take the average.
5. Do jumping jacks for exactly 1 minute. Sit down and take your pulse at once (time 0), then every minute for 6 minutes.
6. Record a table: Time after exercise (min), Beats in 15 s, Beats per minute.
7. On another day, repeat the whole test to see whether your results are repeatable.
8. Draw a line graph with time on the horizontal axis and beats per minute on the vertical axis. Draw a dashed line across the graph at your resting average.
9. Write a conclusion: How many minutes did recovery take? Was your prediction close? Name one thing that could have made your count inaccurate.

Tips

- Use two fingers, not your thumb. Press gently; pressing hard can make the pulse hard to feel.
- Counting for 15 seconds and multiplying by 4 is quick but can be off by up to 4 beats. Counting for 30 seconds and multiplying by 2 is more accurate.

- If someone in the family is willing, compare two people. Remember that one comparison is not enough to prove a rule.

Check your work

- I measured my resting pulse three times and found the average.
- I recorded a full table and made a labeled line graph.
- I named the variable I changed, the variables I kept the same and what I measured.

NATURE NOTEBOOK

1. Copy one of Nightingale's roses in simple form: draw a circle, divide it into 12 wedges for 12 months, and shade the winter wedges larger. Label the colors.
2. Draw a simple outline of a dog and of a person side by side. Label where you would take each one's pulse and write the normal resting range beside each.
3. Make a three-column chart: Doctor, Nurse, Veterinarian. Under each, list training, one daily task and one school subject that matters most.

> **From history.** The world's first veterinary school was founded at Lyon, France, in 1761 by Claude Bourgelat, at a time when cattle plague was killing herds across Europe. Nearly a hundred years later, in 1860, Florence Nightingale opened the Nightingale Training School for nurses at St Thomas' Hospital in London, paid for by a fund the public had raised in her honor. Her short book *Notes on Nursing* (1859) urged fresh air, light, cleanliness, quiet and careful observation of the patient, and it was read in homes as well as hospitals.

WORKED EXAMPLES

Example 1. A nurse counts 18 pulse beats in 15 seconds on a resting adult patient. What is the pulse in beats per minute, and is it in the normal resting range of 60 to 100?

1. There are 60 seconds in a minute, and 60 ÷ 15 = 4, so a 15-second count must be multiplied by 4.
2. 18 beats × 4 = 72 beats per minute.
3. 72 is between 60 and 100.

Answer: 72 beats per minute, which is in the normal resting range.

Example 2. Practice label (not a real medicine): “Give 5 mg per kg of body mass.” A veterinarian weighs a dog at 24 kg. The tablets contain 40 mg each. How many milligrams does the dog need, and how many tablets is that?

1. Dose = rate × body mass = 5 mg/kg × 24 kg = 120 mg.
2. Number of tablets = 120 mg ÷ 40 mg per tablet = 3 tablets.
3. Check the units: kg cancels, leaving mg; mg ÷ mg per tablet leaves tablets.

Answer: 120 mg, which is 3 tablets. (Real doses are always set by a veterinarian for the particular animal.)

Example 3. An imaginary army hospital treats 1,200 patients in January and 60 of them die. In June, after the drains are cleaned, it treats 1,000 patients and 20 die. Find the death rate as a percent for each month and how many times lower the June rate is.

1. January: 60 ÷ 1,200 = 0.05 = 5%.
2. June: 20 ÷ 1,000 = 0.02 = 2%.
3. Compare: 5% ÷ 2% = 2.5.
4. We must use rates, not raw numbers, because the number of patients changed from month to month.

Answer: January 5%, June 2%; the June death rate is 2.5 times lower.

PRACTICE

1. EASY Name the four vital signs.
2. EASY At Scutari, what killed more soldiers: battle wounds or disease? What kind of changes made the death rate fall?
3. EASY Give one difference between the usual work of a doctor and a registered nurse.
4. MEDIUM A child’s pulse is 23 beats in 15 seconds. What is the pulse in beats per minute?
5. MEDIUM Practice label: “2 mg per kg.” A cat has a mass of 4.5 kg. How many milligrams is the dose?
6. MEDIUM Data reading. Use the heart-rate graph. (a) About how many times faster does a mouse’s heart beat than a human’s? (b) Which statement is best supported by the graph? A. Larger mammals have faster hearts. B. Smaller mammals generally have faster resting heart rates. C. All mammals have the same heart rate. D. Dogs have the slowest heart rate.
   (Use the map or drawing “Typical resting heart rates (beats per minute).” shown earlier in this lesson.)
7. MEDIUM Data reading. A nurse records a patient’s temperature after a fever medicine is given at 8:00. 8:00, 38.9 °C; 12:00, 38.4 °C; 16:00, 37.6 °C; 20:00, 37.1 °C. (a) By how

many degrees did the temperature fall from 8:00 to 20:00? (b) What was the average fall per hour? (c) Between which two readings did it fall fastest?

8. HARD In one month a hospital ward had 400 patients and 34 died. The next month it had 250 patients and 10 died. A visitor says, “Deaths fell from 34 to 10, so the ward improved by 24.” Calculate both death rates and explain why rates are the fair way to compare.
9. HARD Experiment design. A student wants to know whether a 10-minute daily walk lowers resting pulse over four weeks. Describe a fair experiment: the independent variable, the dependent variable, two controlled variables, and why more than one person should be tested.
10. CHALLENGE Explain in 3 or 4 sentences why a veterinarian must think in ratios and compare each patient to its own species, using at least two facts from the lesson.

COMMON MISTAKES

- Thinking a fever is the disease itself. A fever is the body’s response to infection or illness; it is a sign that helps with diagnosis.
- Thinking antibiotics cure every infection. Antibiotics work against bacteria, not viruses such as the common cold (see Lesson 3.3).
- Thinking animals have the same normal vital signs as people. Each species, and even each size of animal, has its own normal ranges.

Make it a game · Normal or Not?. A parent reads a patient card aloud, such as “Adult human, resting pulse 120,” “Dog, temperature 38.5 °C,” “Horse, resting pulse 36” or “Adult human, temperature 39.4 °C.” You have ten seconds to call “Normal!” or “Check it!” and give a reason. Score a point for each correct call and a bonus point if you can say what you would measure next. Then switch roles and make up cards for your parent.

Scripture. “But a certain Samaritan, as he journeyed, came where he was: and when he saw him, he had compassion on him, And went to him, and bound up his wounds, pouring in oil and wine, and set him on his own beast, and brought him to an inn, and took care of him.” (Luke 10:33–34, KJV)

The Good Samaritan did what nurses and doctors still do: he saw, he stopped, he treated the wounds, and he arranged care that lasted beyond the first hour. Skill in medicine begins with compassion that is willing to stop.

Practice answers

1. Body temperature, pulse (heart rate), breathing rate and blood pressure.
2. Disease (such as cholera, typhus and dysentery) killed far more. Sanitation made the difference: flushing the sewers, clearing filth, fresh air, clean linen and better food.
3. Example: the doctor usually makes the diagnosis and prescribes treatment, while the nurse gives continuous care, gives medicines, checks vital signs and watches for changes hour by hour.

4. 23 × 4 = 92 beats per minute.
5. 2 mg/kg × 4.5 kg = 9 mg.
6. (a) 600 ÷ 70 ≈ 8.6, so about 8 to 9 times faster. (b) B.
7. (a) 38.9 − 37.1 = 1.8 °C. (b) 1.8 °C ÷ 12 hours = 0.15 °C per hour. (c) Between 12:00 and 16:00 (a fall of 0.8 °C in 4 hours).
8. First month: 34 ÷ 400 = 8.5%. Second month: 10 ÷ 250 = 4%. The death rate fell by more than half. Raw numbers are not fair because the number of patients changed; a rate compares deaths to the number of patients, as Nightingale did.
9. Independent variable: whether the person takes the daily walk (one group walks, a similar group does not). Dependent variable: resting pulse in beats per minute, measured the same way each week. Controlled variables: time of day of measuring, sitting 5 minutes before counting, same counting method, similar ages and health. More people should be tested because one person’s pulse can change for many reasons (sleep, illness, excitement), so several people make the result more trustworthy.
10. Animals of different kinds and sizes have different normal values: a horse’s resting heart beats about 28 to 44 times a minute while a mouse’s beats hundreds of times, and a dog’s normal temperature (about 38.5 °C) is higher than a person’s (about 37 °C). Doses are figured per kilogram, so a 4 kg cat and a 40 kg dog need very different amounts. Some substances are safe for one species and poisonous to another, such as chocolate for dogs or certain pain medicines for cats. So a vet cannot use one set of numbers for every patient.

8.2 Wildlife Biologists and Game Wardens

OBJECTIVES

- Tell how John James Audubon’s threads on phoebes’ legs (1804) grew into modern bird banding and radio tracking, and explain what wildlife biologists learn from marked animals.
- Describe the work, training and character needed by wildlife biologists and game wardens, and how the two careers work together.
- Calculate migration speed, band reporting rate and a mark-recapture population estimate, and read a grouped bar graph of field counts.

Warm-up. Look out a window for 5 minutes and tally every bird you see. Now ask yourself: Was that the same robin twice, or two robins? How could you ever know? Write down one way you could tell individual birds apart without harming them.

Video. Coming soon. Bird banding at a banding station, radio collars and GPS tracking of elk or bears, and a day with a state game warden or conservation officer; search USGS Bird Banding Laboratory, U.S. Fish and Wildlife Service, state wildlife agency channels, Cornell Lab of Ornithology and nature footage.

KEY TERMS

wildlife biologist
A scientist who studies wild animals and their habitats: counting, marking and tracking them to learn how many there are, where they go and what they need.

game warden
A law officer, also called a conservation officer, who enforces hunting, fishing and wildlife laws, helps the public and protects wild animals and the people who enjoy them.

bird banding
Placing a light numbered band on a bird’s leg so that if the bird is caught or found again, people learn where it went and how long it lived.

telemetry
Tracking an animal from a distance with a radio or GPS collar or tag that sends signals about its location.

habitat
The place where an animal lives and finds its food, water, shelter and space to raise young.

bag limit
The greatest number of a game animal one hunter or angler may legally take in a day or a season.

CORE IDEAS

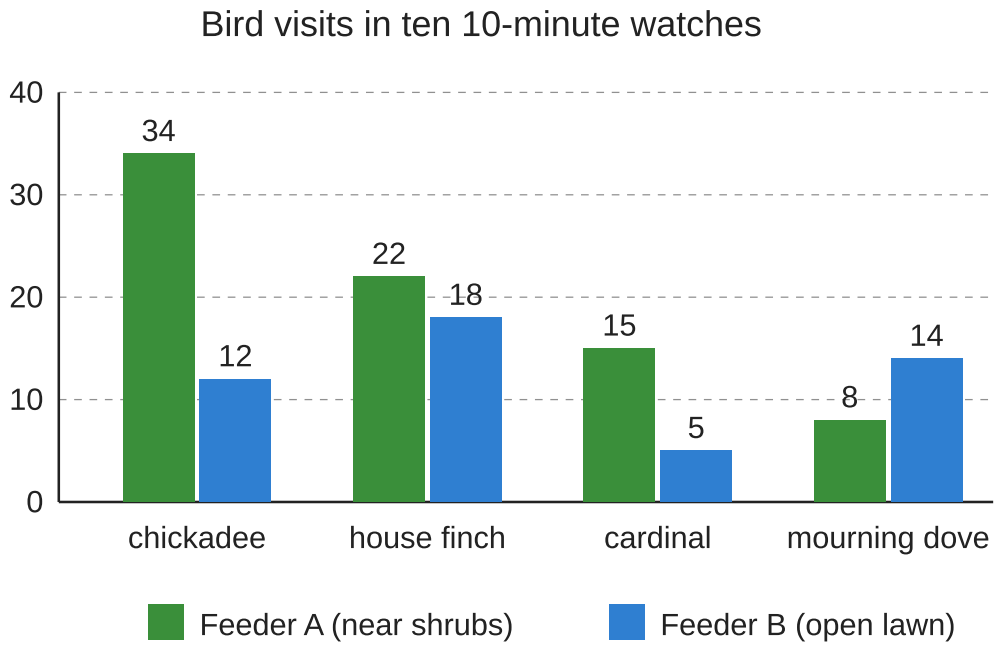
The story. In the spring of 1804 a young Frenchman named John James Audubon was living at Mill Grove, his father's farm near Philadelphia. In a cave above the creek a pair of Eastern Phoebes had built their mossy nest, and Audubon sat with them so often that the birds let him handle the nestlings. He wondered: would these same birds come back next year? So he tied a light silver thread loosely around one leg of each young bird. Audubon later wrote that the next spring he found phoebes nesting nearby that still wore his threads. It is the first known bird banding in America, done by the man who would go on to paint *The Birds of America*.

How they figured it out. Audubon's question was a good one, and better tools followed. In 1899 a Danish schoolteacher, Hans Christian Mortensen, put numbered metal rings on young starlings, so that any ring found later could be traced back to him. In 1920 the United States government began a national Bird Banding Laboratory, now run by the U.S. Geological Survey, which keeps the records for the millions of birds banded across North America. If you ever find a banded bird, you can report the number and learn where it came from. In the early 1960s the brothers Frank and John Craighead fitted grizzly bears in Yellowstone with some of the first radio collars, so they could follow a bear through forest and snow by its signal. Today biologists use GPS collars and tags small enough for songbirds, and the data arrive on a computer screen.

The big idea. A **wildlife biologist** asks the questions a hunter, farmer or landowner needs answered: How many deer live in this county? Are the young surviving? Where do the ducks spend the winter? What does this **habitat** lack? To answer, biologists count animals from airplanes and on foot, mark and recapture them, band birds, collar elk, check the stomachs and teeth of animals taken by hunters, and measure plants, water and cover. Their data help the state set hunting seasons and **bag limits** so that each year's harvest leaves a healthy population. A **game warden** makes sure those rules are kept. Wardens check licenses and limits, catch poachers, teach hunter safety classes, rescue lost hikers and stranded animals, and investigate hunting accidents. The two careers depend on each other: the biologist learns what the land can sustain, and the warden protects it. Some wardens gave their lives for that work. In 1905 Guy Bradley, a game warden hired to guard the egret and heron nesting colonies of south Florida from plume hunters, was shot and killed while trying to stop a poacher. His death moved many Americans to support stronger laws to protect birds.

In the world today. Most wildlife biologists earn a college degree in wildlife biology, ecology or a related science, and many earn a master's degree. They need to identify animals and plants, handle animals safely, use statistics and maps, write clear reports and still enjoy a cold dawn in a duck blind. Game wardens usually complete a law-enforcement academy as well as training in wildlife, boating, first aid and firearms; many have degrees in wildlife or criminal justice. Wardens must be physically fit, calm under pressure, fair and good with people, because most of the hunters and anglers they meet are honest neighbors who want the same healthy woods and waters. Both careers often begin with summer jobs: counting fish at a dam, banding ducks or clearing trails.

God’s handiwork. God asked Job, “Doth the hawk fly by thy wisdom, and stretch her wings toward the south?” (Job 39:26). Migration is still one of the wonders of creation. A ruby-throated hummingbird that weighs about 3 grams can cross the Gulf of Mexico without stopping, and a phoebe can return to the same bridge or barn where it nested the year before. Wildlife biologists do not invent this order; they discover it, band by band and count by count. And because God gave people dominion over the fowls and the beasts (Genesis 1:28) and charged them to keep what they were given (Genesis 2:15), the warden who protects a nesting colony and the biologist who counts it are both doing a work of faithful care.



A student’s count of bird visits in ten 10-minute watches at two feeders: A near shrubs, B in the open.

PICTURE STUDY



Carolina Parakeet (Plate 26 of The Birds of America), John James Audubon; engraved by Robert Havell Jr., Painted about 1825; published in *The Birds of America*, 1827–1838 · Hand-colored engraving and aquatint, made from Audubon's watercolor · Copies in many libraries and museums; Audubon's original watercolor is at the New-York Historical Society

The Carolina parakeet was the only parrot native to the eastern United States. Flocks once flashed green and gold through river forests from Florida to the Ohio Valley. Audubon painted them feeding on cocklebur, a weed whose spiny seeds they loved. In his own lifetime he noticed that the flocks were growing smaller.

No wildlife biologists were counting them, and no wardens were guarding them. The last known Carolina parakeet died at the Cincinnati Zoo in 1918. Its story is one reason Americans began to train people to study wild birds and to enforce laws that protect them.

Look closely

- Count the parakeets. How many do you see, and how are they arranged?
- Compare the heads. Can you find a bird whose head is green instead of yellow? Audubon showed a young bird beside the adults.
- Look at the cocklebur plant. What parts of the plant are the birds eating?
- Notice how Audubon shows birds from many angles: from the side, from below, turning. Why would a naturalist do that?

Talk about it

1. What kinds of records could a wildlife biologist have kept on these birds if the profession had existed in 1825?
2. How does a painting like this serve as a scientific record?

3. What does the loss of this bird teach about the value of counting and caring for wildlife early, before numbers fall?

> **Safety first.** Never touch or pick up wild birds, nests, eggs or wild mammals. Banding wild birds requires a federal permit and training. Watch from a distance, wash your hands after cleaning a feeder, and stay away from any animal that acts sick, unafraid or aggressive.

EXPERIMENT: THE TWO-FEEDER EXPERIMENT

Wildlife biologists often ask how habitat affects where animals go. Small birds must eat while watching for hawks and cats, so many prefer food close to cover. You will test this with two feeders and careful counts, the same way a biologist would design a field study.

You will need

- Two identical bird feeders (or two identical shallow trays)
- The same kind of seed for both, such as black oil sunflower seed
- A measuring cup
- Binoculars (helpful) and a bird guide or bird-identification app
- Lab notebook, pencil and a watch or timer

Steps

1. Question: Do more birds visit a feeder near shrubs or trees than one in the open?
2. Prediction: write which feeder will get more visits and why.
3. Place Feeder A about 2 m from shrubs or a tree, and Feeder B at least 10 m from any cover. Keep the height and seed the same.
4. Fill each with the same amount of seed (for example, 2 cups). Let the birds find the feeders for 3 to 5 days before you start counting.
5. Count from a window or quiet spot for 10 minutes at a time. A visit is one bird landing on a feeder. Tally visits by species for each feeder.
6. Do at least ten 10-minute watches at different times of day over a week or two.
7. Halfway through, swap the two feeders' positions so that any difference in the feeders themselves is cancelled out.
8. Total the visits for each feeder and each species. Make a grouped bar graph like the one in this lesson.
9. Write a conclusion and name two things that could have affected your counts (weather, a cat nearby, counting the same bird twice).

Tips

- Keep the feeders clean and stop if you see sick birds; clean them with hot soapy water and let them dry.
- Record the date, start time, weather and temperature on every count sheet. Real biologists never leave these out.

- If your result surprises you, that is still a result. Report what you saw, not what you hoped to see.

Check your work

- I named my independent variable (distance from cover) and my dependent variable (number of visits).
- I kept the seed, feeder type, height and watch length the same.
- I made a grouped bar graph and wrote a conclusion with at least two possible sources of error.

NATURE NOTEBOOK

1. Draw a bird’s leg with a numbered band on it. Beside it, write what a person who finds the band should do and what the record could teach.
2. Sketch a map of your yard or a nearby park. Mark cover (shrubs, trees), food and water. Circle the best spot for wildlife to hide.
3. Write a short “field journal” entry as if you were a game warden checking hunters at dawn on opening day: date, weather, what you checked and what you saw.

> **From history.** Guy Bradley grew up in south Florida and knew the Everglades well. In 1902 he was hired as one of the first wardens paid through the Audubon societies to guard nesting egrets and herons, whose long breeding plumes were sold for women’s hats. On July 8, 1905, he went out by boat to stop a man shooting birds at a rookery near Flamingo and was shot and killed. His death, and those of other wardens, helped win support for stronger bird-protection laws, including the Migratory Bird Treaty Act of 1918. Today the egrets nest again in the Everglades, and an award for wildlife law officers bears his name.

WORKED EXAMPLES

Example 1. A banded songbird is caught at a banding station and recaught 15 days later at another station 1,200 km to the south. What was its average migration speed in kilometers per day?

1. Speed = distance ÷ time.
2. 1,200 km ÷ 15 days = 80 km per day.
3. This is an average; the bird may have flown several hundred kilometers on some nights and rested on others.

Answer: 80 km per day (average).

Example 2. Biologists band 400 mallard ducks in late summer. During the next hunting season, hunters report 36 of those band numbers. What percent of the banded ducks were reported?

1. Reporting rate = reported bands ÷ banded birds.
2. 36 ÷ 400 = 0.09.
3. 0.09 × 100 = 9%.

Answer: 9% of the banded ducks were reported.

Example 3. A biologist catches 50 box turtles in a woodlot, marks each one harmlessly and releases them. Two weeks later she catches 40 turtles, and 10 of them are marked. Estimate the turtle population using the mark-recapture (Lincoln-Petersen) method.

1. The idea: the fraction marked in the second catch should match the fraction marked in the whole population.
2. 10 marked out of 40 caught = 1/4 of the second catch is marked.
3. So the 50 marked turtles are about 1/4 of the whole population: N = 50 × 4 = 200.
4. Formula form: N = (marked first × total second catch) ÷ marked in second catch = (50 × 40) ÷ 10 = 200.

Answer: About 200 turtles.

PRACTICE

1. EASY What did Audubon tie to the legs of the young phoebes in 1804, and what question was he trying to answer?
2. EASY Name two jobs a game warden does and two jobs a wildlife biologist does.
3. EASY What is telemetry, and what advantage does it have over a leg band?
4. MEDIUM A GPS-collared elk moves 84 km from its summer range to its winter range in 6 days. What is its average speed in km per day?
5. MEDIUM Biologists mark 60 trout in a stream. A week later they catch 45 trout, and 9 are marked. Estimate the trout population.
6. MEDIUM Data reading. Use the two-feeder graph. (a) How many total visits did Feeder A receive? Feeder B? (b) Which species visited Feeder B more than Feeder A? (c) Which statement is best supported? A. All birds avoid open feeders. B. Most species in this study visited the feeder near cover more often. C. Mourning doves are the most common bird. D. Feeder B had better seed.
   (Use the map or drawing “Bird visits at Feeder A (near shrubs) and Feeder B (open lawn).” shown earlier in this lesson.)
7. MEDIUM Data reading. A banding station reports where its banded Canada geese were found: 0–100 km away, 42 bands; 101–500 km, 25 bands; 501–1,000 km, 18 bands;

more than 1,000 km, 15 bands. (a) How many bands were reported in all? (b) What percent were found more than 500 km away? (c) A student concludes, “Most of these geese never migrate.” Is that supported? Explain.

8. HARD In the turtle example, the biologist accidentally marks turtles with paint that washes off in the rain. Would her population estimate be too high or too low? Explain.
9. HARD Experiment design. A biologist wants to know whether planting shrub rows along field edges increases the number of quail. Describe a fair study, naming the independent variable, the dependent variable, two controlled variables and why she should study several fields, not one.
10. CHALLENGE In 3 or 4 sentences, explain how wildlife biologists and game wardens depend on each other, and connect their work to Genesis 2:15.

COMMON MISTAKES

- Thinking wildlife work means keeping people away from animals. Much of it is managing hunting, fishing and land use so that people can keep enjoying healthy wildlife year after year.
- Thinking a single count tells the whole story. Animal numbers change with season, weather and time of day, so biologists repeat counts and use methods like mark-recapture.
- Thinking game wardens are only “ticket writers.” They are trained law officers who also teach, rescue, investigate and help landowners and sportsmen.

Make it a game · Biologist or Warden?. A parent reads a job task aloud: “Fits a GPS collar on an elk,” “Checks a fishing license,” “Counts ducks from an airplane,” “Teaches a hunter safety class,” “Tests the water in a trout stream,” “Rescues a deer from ice.” Shout “Biologist!” or “Warden!” (or “Both!”) and give a reason. One point per correct answer, a bonus point if you can name the tool used for the job.

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)

The prophet noticed migration long before anyone banded a bird: the stork, the turtledove, the crane and the swallow come and go on time. Wildlife biologists measure that faithful timing. Jeremiah turns it into a question for us: if birds keep the order God set, how much more should we?

Practice answers

1. Light silver thread. He wanted to know whether the same birds would return to the same place the next year.
2. Game warden (any two): checks licenses and bag limits, catches poachers, teaches hunter safety, rescues people or animals, investigates hunting accidents. Wildlife biologist (any two): counts animals, bands or collars them, studies habitat, checks animals taken by hunters, recommends seasons and limits.

3. Telemetry is tracking an animal from a distance with a radio or GPS collar or tag. A band tells you only where the animal was banded and where it was found again; telemetry shows where the animal goes in between, day after day.
4. 84 km ÷ 6 days = 14 km per day.
5. N = (60 × 45) ÷ 9 = 2,700 ÷ 9 = 300 trout.
6. (a) A: 34 + 22 + 15 + 8 = 79. B: 12 + 18 + 5 + 14 = 49. (b) Mourning dove (14 at B vs 8 at A). (c) B.
7. (a) 42 + 25 + 18 + 15 = 100. (b) 18 + 15 = 33, so 33%. (c) Not fully. Many bands come from nearby partly because more people hunt or live near the station, and a goose found nearby in one season may have migrated in another. The table shows where bands were reported, not the whole life of each goose.
8. Too high. Some marked turtles would look unmarked, so she would count fewer marked turtles in the second catch. Dividing by a smaller number gives a larger N.
9. Independent variable: whether a field has shrub rows planted. Dependent variable: number of quail counted (for example, calling males counted at dawn). Controlled variables: same counting method and time of day, same season, similar field size and crops, similar hunting pressure. Several fields with and without shrubs are needed because one field could differ by chance (soil, predators, neighbors), and repeating the comparison makes the result reliable.
10. Biologists count and study animals and habitat to learn how many animals the land can support and how many can be safely harvested, which guides seasons and bag limits. Wardens enforce those rules so that the harvest stays within what the biologists found sustainable and poachers do not take more. Without the biologist the rules would be guesses; without the warden the rules would be ignored. Together they “dress” and “keep” the land God gave, as Adam was told in Genesis 2:15.

8.3 Agricultural Science: Norman Borlaug and the Wheat Fields of Mexico

OBJECTIVES

- Tell how Norman Borlaug, beginning in Mexico in 1944, bred wheat that resisted stem rust and stood up under heavy grain, and explain how he used Mendel’s rules and shuttle breeding.
- Name at least five careers in agricultural science and explain how each uses biology, chemistry or genetics.
- Calculate crop yield per hectare and percent increase, predict offspring with a Punnett square, and read a fertilizer data table.

Warm-up. Hold a slice of bread, a spoon of rice and an apple. For each one, trace it back: who grew it, from what seed, on what kind of land? Now guess how many different scientists might have helped that food reach your table. Write your guess down and check it at the end of the lesson.

Video. Coming soon. Norman Borlaug and the wheat breeding program in Mexico, how plant breeders cross wheat by hand, and careers in agronomy, soil science and animal science; search USDA, land-grant university extension channels, CIMMYT, FFA and 4-H career videos, and documentary footage of wheat harvest.

KEY TERMS

agronomy
The science of growing field crops and managing soil, water and nutrients so that farms produce well year after year.

crop yield
The amount of crop harvested from a given area of land, often given in kilograms or metric tons per hectare.

plant breeding
Crossing chosen parent plants and selecting the best offspring, generation after generation, to develop better varieties.

disease resistance
An inherited ability of a plant or animal to keep from being badly harmed by a particular disease.

lodging
When grain stalks bend or fall over, often because the heads are heavy or wind and rain push them down; fallen grain is hard to harvest and may rot.

extension agent

A scientist from a state university who brings research to local farmers, gardeners and 4-H clubs and answers their questions.

CORE IDEAS

The story. In 1944 a young plant scientist from Iowa named Norman Borlaug arrived in Mexico to help its farmers grow more wheat. He had grown up on a small farm near Cresco, Iowa, wrestled in college, and earned a doctorate in plant pathology, the study of plant diseases. What he found in Mexico discouraged him. A fungus called **stem rust** covered the wheat stems with rusty red pustules, robbed the plants of water and food, and left the heads shriveled. Fields that should have fed families produced only a little grain. Borlaug worked in the dust and heat of the Yaqui Valley in the state of Sonora, often sleeping in rough buildings and plowing with borrowed equipment, and set out to breed a better wheat.

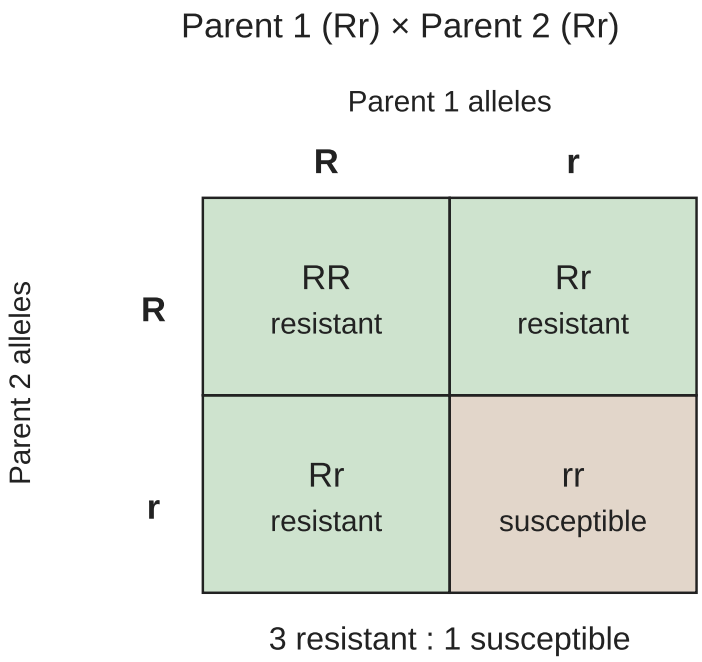
How they figured it out. Borlaug used the rules Gregor Mendel had discovered with peas. He crossed wheat plants by hand, one flower at a time, removing the pollen-bearing parts of one plant and dusting it with pollen from another. Then he grew the offspring, infected them with rust on purpose and kept only the plants that stayed healthy. His team made thousands of crosses each year. Breeding usually takes one generation per year, but Borlaug had an idea: grow one crop in the low, warm Yaqui Valley in winter and the next in the cool highlands near Mexico City in summer. This **shuttle breeding** gave two generations a year and cut the time in half. It also selected plants that grew well in many places. Then a new problem came. When farmers fed the improved wheat with fertilizer, the heavy heads made the tall stems fall over, which farmers call **lodging**. Borlaug crossed his wheats with short-stemmed varieties that had come from Japan by way of a breeder in Washington State. The new semi-dwarf wheats had strong, short stems that held up heavy heads of grain. Within about twenty years Mexico was growing several times as much wheat as before, and in the 1960s the new wheats were sent to India and Pakistan, where harvests rose sharply. In 1970 Borlaug received the Nobel Peace Prize.

The big idea. Agricultural science is life science on the scale of a whole nation’s dinner table. Plant breeders use genetics: if resistance to a disease is dominant, a breeder can use a **Punnett square** to predict how many seedlings in a cross will resist it. Agronomists and soil scientists study how roots take up water, nitrogen, phosphorus and potassium, and how many kilograms of each a crop needs for good **yield** without waste. Entomologists study insects, both pests and helpers such as bees and lady beetles. Animal scientists study the nutrition, health and breeding of cattle, hogs, sheep and poultry. Food scientists keep food safe and nourishing on its way from farm to table. Notice that all this work is variation *within kinds*. Borlaug’s short, rust-resistant wheat is still wheat, bred from the variety God built into wheat at the beginning, as Mendel’s peas remained peas.

In the world today. In 1862 Abraham Lincoln signed the Morrill Act, which gave land to each state to found a college teaching agriculture and the mechanic arts. These land-grant universities still train most American agricultural scientists. In 1914 Congress created the Cooperative Extension Service, which places **extension agents** in nearly every county to carry research to farmers and families; 4-H clubs grew up alongside it, and FFA, founded in

1928, trains young people in agriculture through school programs. Careers include agronomist, plant breeder, soil scientist, entomologist, animal scientist, veterinarian, agricultural engineer, food scientist and farm manager. A farmer today is often a scientist too, testing soil, reading weather data, keeping breeding records and measuring yields field by field. Students who like biology, chemistry, math and being outdoors fit well.

God's handiwork. On the third day God said, "Let the earth bring forth grass, the herb yielding seed, and the fruit tree yielding fruit after his kind, whose seed is in itself" (Genesis 1:11). Every seed carries its own instructions, which you studied in the DNA unit, and those instructions hold so much built-in variety that breeders can draw out short stems, rust resistance or larger grains without making a new kind of plant. After the Flood God promised that "seedtime and harvest" would not cease (Genesis 8:22). Agricultural scientists work inside that promise. Borlaug liked to say that you cannot build peace on empty stomachs, and his life showed how patient, careful science can serve one's neighbor, even neighbors on the other side of the world.



Crossing two wheat plants that each carry one resistance allele (R) and one susceptible allele (r), if resistance is dominant.

PICTURE STUDY



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

Pieter Bruegel the Elder painted this harvest scene in 1565 as one of a series showing the seasons of the year for the house of a wealthy merchant in Antwerp. It shows Flemish farm families bringing in the wheat by hand, as farmers had done for thousands of years.

Look closely at the wheat. It stands nearly as tall as the men. That was normal for the old varieties. Four hundred years later, plant breeders like Norman Borlaug would develop much shorter wheats that do not fall over under heavy grain.

Look closely

- Find the men cutting wheat. What tool are they using, and how high does the wheat reach on their bodies?
- Find the workers eating under the tree. What foods can you see? Where did that food come from?
- Look for sheaves of wheat that have been tied and stood up. Why would farmers stand them up in the field?
- Look into the distance. What else can you see of the farm, the village and the land?

Talk about it

1. How would a field of tall wheat like this be hurt by a heavy rain and wind just before harvest?
2. How many people does it take to harvest this field by hand? How has agricultural science changed that?
3. What do you think Bruegel admired about these farm families?

> **Safety first.** Fertilizer is a chemical. Have a parent mix it, wear gloves if the label says so, keep it away from food and younger children, and wash your hands after handling soil and fertilizer.

EXPERIMENT: THE SEEDLING EXPERIMENT: DOES FERTILIZER CHANGE GROWTH?

Agronomists test how much plant food a crop needs. You will run a small, fair test with fast-growing seeds, measuring growth to the millimeter like a real crop scientist.

You will need

- 12 small pots or cut-down paper cups with drainage holes
- Potting soil (the same bag for all pots)
- Bean, pea, radish or wheat seeds (wheat berries from a grocery store often sprout)
- Liquid houseplant fertilizer
- Measuring spoons, a 1-liter jug and a metric ruler
- Masking tape and marker for labels, lab notebook

Steps

1. Question: How does the amount of fertilizer affect seedling height after 14 days?
2. Prediction: write which group you think will grow tallest, and whether more fertilizer is always better.
3. Make three groups of four pots: Group 0 gets plain water; Group 1 gets fertilizer mixed at the label strength; Group 2 gets fertilizer at double the label strength. Group 0 is your control.
4. Fill every pot with the same amount of soil. Plant 2 seeds per pot at the same depth (about 2 cm). Later, keep the taller seedling in each pot.
5. Keep everything else the same: same window, same water amount on the same days, same temperature.
6. Every 2 days, measure each seedling from the soil to the tip of the tallest leaf in millimeters. Record in a table.
7. On day 14, find the average height for each group.
8. Make a bar graph of average height for the three groups and a line graph of height over time.
9. Write a conclusion. Did the double-strength group grow best? What would an agronomist advise a farmer about using the right amount, not the most?

Tips

- Four pots per group are better than one, because one seedling can be weak by chance.
- Too much fertilizer can burn roots. If your double-strength plants struggle, that is a real result worth reporting.
- Label each pot clearly before planting. A mixed-up label ruins a whole experiment.

Check your work

- I had a control group and changed only one variable.
- I measured in millimeters and recorded every measurement with the date.
- I calculated averages and made two graphs.

NATURE NOTEBOOK

1. Draw a wheat plant from roots to head. Label the roots, stem, leaves, head and kernels. Beside it, draw a tall old variety and a semi-dwarf variety to scale.
2. Draw a map of Mexico and mark the two places used for shuttle breeding: the Yaqui Valley in Sonora and the highlands near Mexico City. Write which season each crop was grown.
3. List five foods you ate today. For each one, name one agricultural scientist (breeder, soil scientist, entomologist, animal scientist, food scientist) who helped bring it to you.

> **From history.** George Washington Carver, who taught at Tuskegee Institute in Alabama from 1896, was an agricultural scientist of an earlier generation. Cotton had worn out much of the Southern soil, so he urged farmers to rotate their cotton with peanuts and cowpeas, legumes that help restore nitrogen to the soil, and to grow sweet potatoes as well, and he traveled the countryside with a wagon fitted out as a “movable school” to teach poor farm families. Like Borlaug, Carver believed that science was a way of serving neighbors, and he spoke often of his faith in God as the Creator whose works he studied.

WORKED EXAMPLES

Example 1. A farmer harvests 7,500 kg of wheat from a 2.5-hectare field. Before planting an improved variety, the same field produced 3,000 kg. Find the yield per hectare before and after, and the percent increase.

1. Before: 3,000 kg ÷ 2.5 ha = 1,200 kg/ha.
2. After: 7,500 kg ÷ 2.5 ha = 3,000 kg/ha.
3. Increase = 3,000 − 1,200 = 1,800 kg/ha.
4. Percent increase = 1,800 ÷ 1,200 × 100 = 150%.

Answer: 1,200 kg/ha before, 3,000 kg/ha after; a 150% increase (2.5 times as much).

Example 2. Suppose resistance to a strain of stem rust is controlled by one gene, and the resistant allele (R) is dominant over the susceptible allele (r). A breeder crosses two plants that are both Rr and grows 400 seedlings. How many should be resistant?

(Use the map or drawing "Rr × Rr gives a 3 : 1 ratio of resistant to susceptible plants." shown earlier in this lesson.)

1. Make a Punnett square: each parent can pass R or r.
2. The four boxes are RR, Rr, Rr and rr.
3. RR and Rr plants are resistant (3 of 4 boxes); rr is susceptible (1 of 4).
4. Expected resistant = 3/4 × 400 = 300 seedlings; susceptible = 100.

Answer: About 300 resistant and 100 susceptible (a 3 : 1 ratio).

Example 3. A breeder needs 10 generations of crosses and selection to develop a new wheat. How many years does this take with one crop per year, and with shuttle breeding (two crops per year)?

1. One generation per year: 10 generations ÷ 1 per year = 10 years.
2. Two generations per year: 10 ÷ 2 = 5 years.
3. Shuttle breeding saves 10 − 5 = 5 years.

Answer: 10 years with one crop a year; 5 years with shuttle breeding, saving 5 years.

PRACTICE

1. EASY What disease attacked Mexico's wheat when Borlaug arrived in 1944, and what kind of living thing causes it?
2. EASY What is lodging, and how did semi-dwarf wheat solve it?
3. EASY Match each career to its work: (a) entomologist, (b) soil scientist, (c) animal scientist, (d) extension agent. 1. studies nutrition and breeding of livestock; 2. brings university research to local farmers; 3. studies insect pests and helpers; 4. studies nutrients, water and texture of soil.
4. MEDIUM A 4-hectare field yields 18,000 kg of corn. What is the yield in kg/ha and in metric tons per hectare? (1 metric ton = 1,000 kg.)
5. MEDIUM A breeder crosses a resistant plant that is RR with a susceptible plant that is rr. What fraction of the offspring will be resistant? What is their genotype?
6. MEDIUM Data reading. An agronomist tests nitrogen fertilizer on wheat plots. Nitrogen (kg/ha): 0, 50, 100, 150, 200. Yield (metric tons/ha): 3.0, 4.2, 5.1, 5.5, 5.6. (a) How much did yield increase from 0 to 50 kg/ha of nitrogen? (b) From 150 to 200? (c) Which statement is best supported? A. Yield doubles with every 50 kg of nitrogen. B. Each added 50 kg of nitrogen raised yield by less than the 50 kg before it. C. Nitrogen lowers yield. D. The best amount is 0 kg/ha.

7. MEDIUM Data reading. A student measured average seedling heights (mm) on day 14: water only, 62 mm; label-strength fertilizer, 85 mm; double-strength fertilizer, 58 mm. (a) Which group grew tallest? (b) By what percent was the label-strength group taller than the control? (c) What does the double-strength result suggest?
8. HARD Explain how shuttle breeding gave Borlaug two advantages, not just one.
9. HARD Experiment design. A farmer wants to know whether a new wheat variety yields more than her old one. Design a fair field trial: what she changes, what she keeps the same (at least three things), what she measures, and why she should plant several small plots of each variety in different parts of the field rather than one big plot of each.
10. CHALLENGE A friend says, “Borlaug’s wheat proves that breeders can turn one kind of plant into a new kind.” Write a short, respectful reply using what you know about variation within kinds.

COMMON MISTAKES

- Thinking plants get their food from the soil. Plants make their own food (sugar) by photosynthesis from carbon dioxide and water; from the soil they take water and mineral nutrients such as nitrogen.
- Thinking more fertilizer always means more crop. Yields level off, and too much can harm plants and waste money.
- Thinking a Punnett square tells exactly what will happen. It gives expected ratios; real counts vary by chance, especially with few offspring.

> **Make it a game · Farm to Table Chain.** One player names a food, such as “pizza.” The next player names one ingredient (wheat flour), the next names the plant or animal (wheat), and the next names an agricultural scientist who helps (plant breeder, soil scientist, entomologist, animal scientist or food scientist) and says what that person does. Anyone who gets stuck starts a new food. Score a point for each correct link.

> **Scripture.** “While the earth remaineth, seedtime and harvest, and cold and heat, and summer and winter, and day and night shall not cease.” (Genesis 8:22, KJV)

God promised Noah that the seasons would keep their order. Every farmer and agricultural scientist relies on that promise each time a seed goes into the ground, and studies its patterns to feed more people.

Practice answers

1. Stem rust, caused by a fungus.
2. Lodging is when grain stalks fall over, often under heavy heads of grain. Semi-dwarf wheat has short, strong stems that hold up heavy heads without falling.
3. (a) 3, (b) 4, (c) 1, (d) 2.
4. 18,000 ÷ 4 = 4,500 kg/ha = 4.5 metric tons per hectare.

5. All of them (100%) will be resistant. Every offspring gets R from one parent and r from the other, so all are Rr.
6. (a) 4.2 − 3.0 = 1.2 t/ha. (b) 5.6 − 5.5 = 0.1 t/ha. (c) B. Adding more fertilizer gives smaller and smaller gains (diminishing returns), so a farmer would likely stop around 100 to 150 kg/ha.
7. (a) Label-strength fertilizer. (b) (85 − 62) ÷ 62 × 100 ≈ 37%. (c) Too much fertilizer can harm growth (for example by burning roots), so more is not always better.
8. First, it gave two generations a year instead of one, cutting breeding time in half. Second, because the plants were grown in two very different places (low, warm Yaqui Valley and cool highlands), the selected wheats grew well under many day lengths and climates, so they could be planted widely, even in other countries.
9. Change: the variety (new vs old). Keep the same: planting date, seeding rate, fertilizer, soil preparation, watering, harvest date and method. Measure: yield in kg/ha for each plot. Several plots spread across the field are needed because soil, moisture and slope vary from place to place; if each variety had only one plot, a difference might come from better soil, not a better variety.
10. Borlaug drew out variety that was already present in wheat: short stems, rust resistance and larger heads came from crossing different wheats and selecting the best. The result was still wheat that can cross with other wheat. This is variation within a kind, like dog breeds or finch beaks, which we can observe directly; it does not show wheat becoming a different kind of plant.

8.4 Capstone: A Field Study Report

OBJECTIVES

- Tell how Maria Sibylla Merian carried out a field study in Suriname (1699–1701) and why her careful observations made her book a scientific record.
- Plan and carry out a field study using quadrats or a transect, with a testable question, controlled variables and repeated samples.
- Calculate mean, population density and frequency from field data, and write a report with question, methods, data, analysis and conclusion.

Warm-up. Lay a shoelace or string in a circle on the lawn or in a flowerbed, about the size of a dinner plate. For 5 minutes, list every living thing you can find inside it: plants, insects, spiders, worms, even moss. How many different kinds did you find? Would a circle 3 meters away give the same list? Predict, then check.

Video. Coming soon. How to use a quadrat and a line transect in a field study, how to keep a field notebook, and Maria Sibylla Merian's Surinam insect drawings; search university field biology channels, Smithsonian, natural history museum channels, Cornell Lab of Ornithology and Science Max style experiment videos.

KEY TERMS

field study
A scientific investigation carried out outdoors where living things actually live, rather than in a laboratory.

quadrat
A square frame of known size (for example 50 cm × 50 cm or 1 m × 1 m) placed on the ground to count or measure the living things inside it.

transect
A straight line, often a measuring tape, laid across a habitat; samples are taken at regular distances along it to show how life changes from place to place.

population density
The number of individuals of one kind per unit of area, such as 12 dandelions per square meter.

frequency
The percent of sample quadrats in which a species is found at least once.

sample size
The number of measurements or samples taken; larger samples give more reliable averages.

CORE IDEAS

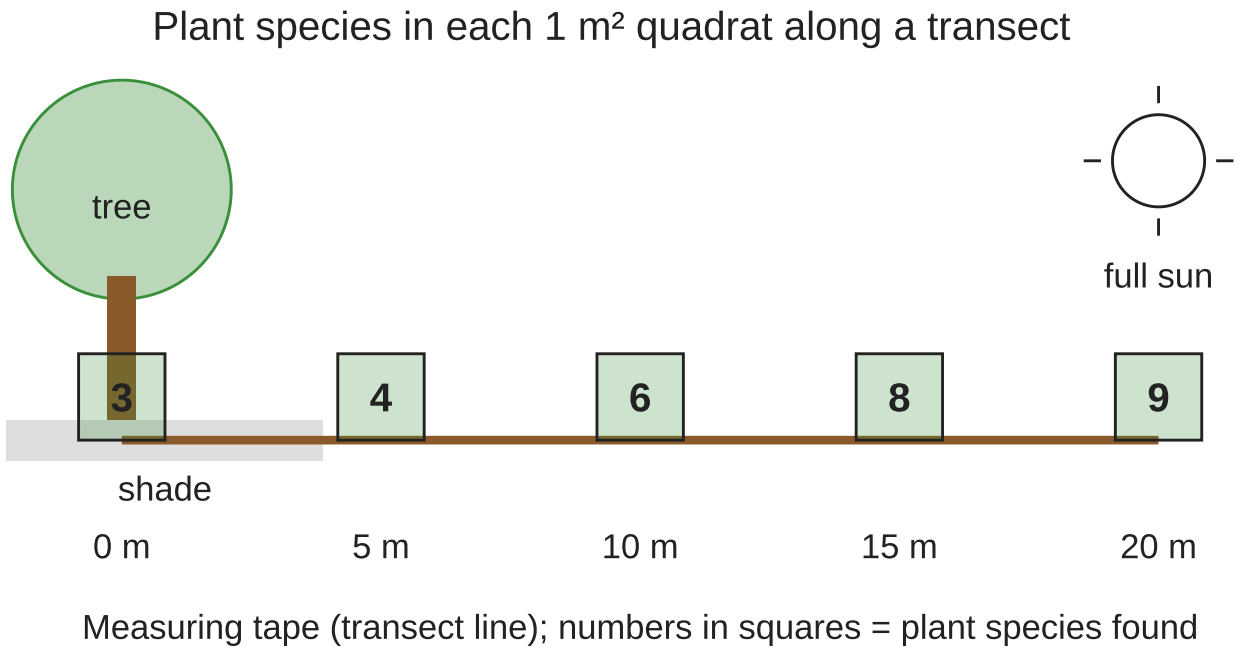
The story. In June 1699 Maria Sibylla Merian, a 52-year-old artist and naturalist from Frankfurt who lived in Amsterdam, sailed for Suriname on the northern coast of South America with her daughter Dorothea. No one had paid for the journey; she had sold many of her own paintings to fund it. She had spent years in Europe raising caterpillars in boxes and watching them become butterflies and moths, and she wanted to see the insects of the tropics live in their own home. For nearly two years she walked the plantations and forest edges, sometimes with local guides cutting a way through the brush, collecting caterpillars, feeding them their own food plants and drawing each stage. Illness forced her home in 1701, but she brought her notes, drawings and specimens with her.

How they figured it out. Many naturalists of Merian's day pinned dead insects in drawers and drew them alone. Merian did something more scientific: she recorded the whole life cycle in the place where it happened. On a single plate she would show the plant a caterpillar ate, the eggs, the caterpillar, the pupa and the adult, with notes on dates and behavior. In 1705 she published *Metamorphosis insectorum Surinamensium*, with 60 large engraved plates. Her book helped show that insects come from eggs laid by adults of their own kind, not from rotting matter, and that each kind of caterpillar depends on particular food plants. That is the heart of a field study: go where living things live, ask a clear question, observe patiently, record exactly and report honestly.

The big idea. A modern field study report has the same parts every scientist uses. **Question**: something you can answer by measuring, such as "Are there more plant species in the sunny part of the yard than under the oak tree?" **Prediction**: your best guess with a reason. **Site and methods**: where, when, and exactly how you sampled, so someone else could repeat it. Biologists cannot count every blade of grass, so they sample. A **quadrat** is a square of known area placed at random or at set spots; you count what is inside. A **transect** is a measuring tape stretched across a habitat, with a quadrat placed every few meters to show how life changes from shade to sun or from wet ground to dry. **Data**: tables with units, dates and weather. **Analysis**: averages, **population density** (number per square meter), **frequency** (percent of quadrats where a species appears) and a graph. **Conclusion**: answer the question, compare with the prediction, and name sources of error and what you would do next. A larger **sample size** makes the answer more trustworthy, and a fair study changes only one thing between the places compared.

Try it and see. Your capstone is a real field study of your own. Choose a small patch of land you can visit several times: a lawn, a pasture, a woodlot edge, a pond bank or a garden. Pick one question that compares two places or follows a transect. Make a quadrat from four 50 cm sticks or a wire coat hanger bent into a square, or tape a 1 m square of string with stakes. Take at least ten samples in each place, record soil moisture or temperature if you can, and photograph or sketch each quadrat. Then write your report in the six parts above, with at least one table and one graph. This is how wildlife biologists count deer browse, agronomists count weeds and ecologists survey a prairie, and it uses the counting, ratios and graphs you practiced in every lesson of this unit.

God’s handiwork. “The works of the LORD are great, sought out of all them that have pleasure therein” (Psalm 111:2). Merian, a Christian woman who saw the insects she painted as the work of God, sought out His works with delight, and so can you. A single square meter of lawn may hold a dozen kinds of plants, hundreds of tiny animals and a world of soil life, each made after its kind and each doing its part. When you measure carefully and report honestly, even when the results surprise you, you are practicing the truthfulness that every career in this unit depends on, from the nurse’s chart to the biologist’s count.



A student’s transect from the shade of a tree into full sun, with the number of plant species found in each 1 m² quadrat.

PICTURE STUDY



Pineapple with Cockroaches (Merian's study for Plate 1 of Metamorphosis insectorum Surinamensium), Maria Sibylla Merian, About 1701–1705 · Watercolor and bodycolor on vellum · British Museum, London

Merian opened her great book on the insects of Suriname with the pineapple, a fruit Europeans prized and rarely saw fresh. This is her own painting on vellum, made from her Suriname notes and sketches, from which the first engraved plate of the book (1705) was made. Around the fruit she showed cockroaches, insects that troubled the colonists' homes and storerooms, at more than one stage of life.

The picture is beautiful, but it is also data. Merian painted the insects carefully and placed them on the plants where she found them, so that a reader could learn what lived where and what it ate.

Look closely

- Look at the pineapple's crown, scales and leaves. How carefully did Merian draw their shapes and patterns?
- Find the insects. Are they all the same size? What might the different sizes show?
- Notice what is left out: there is no landscape or background. Why might a scientist leave the background empty?
- Choose one small detail and describe it as exactly as you can in words, the way you would in a field notebook.

Talk about it

1. How is a scientific illustration like Merian's different from a decorative painting of fruit?
2. What did Merian have to do in the field before she could make this picture?

3. If you made one plate for your own field study, what plant and animals would you put on it?

> **Safety first.** Do your field study with a parent's permission and with an adult nearby. Learn to recognize poison ivy (and poison oak or sumac in your area) before you kneel in the grass. Wear long pants and check for ticks afterward. Never sample near deep or fast water, and do not touch wild mushrooms, wild animals or animal droppings. Wash your hands when you finish.

EXPERIMENT: MY FIELD STUDY

Now you are the scientist. You will choose a question about living things near your home, sample them with quadrats or a transect, and write a full field study report. This project becomes the unit portfolio.

You will need

- A quadrat: four sticks 50 cm long tied in a square, or a 1 m × 1 m square of string and four tent stakes
- A measuring tape (at least 10 m) for a transect
- Lab notebook, pencil, clipboard and a metric ruler
- A plant or insect field guide or a reliable identification app
- A thermometer (optional) and a phone or camera for photos
- Garden gloves

Steps

1. Choose your site and walk it once just to look. Sketch a map with north marked.
2. Write one testable question. Examples: Are there more plant species in sun than in shade? Are dandelions denser near the path than in the middle of the lawn? Are there more earthworms under leaf litter than under bare soil?
3. Write your prediction and the reason for it.
4. Plan your methods: which two places you will compare (or where your transect will run), how many quadrats (at least 10 per place), how you will choose quadrat spots fairly (for example, toss a beanbag over your shoulder or use every 2 m on a tape), and what you will count.
5. List what you will keep the same: quadrat size, time of day, how you count, who counts.
6. Collect data on at least two different days. Record the date, time, weather and temperature each time.
7. Make a data table, then calculate the mean count per quadrat, the density per square meter and the frequency of the main species.
8. Make at least one graph (bar graph to compare places, or line graph along a transect).
9. Write your report with six headings: Question, Prediction, Site and Methods, Data, Analysis, Conclusion. In the conclusion, name two sources of error and one new question your study raised.

10. Present your report to your family as a scientist would at a meeting: 5 minutes, with your graph.

Tips

- Pick one question and do it well. A small, careful study is better than a big, careless one.
- If you cannot identify a plant, call it “Species A” and sketch it. Scientists do this too, and identify it later.
- Do not move your quadrat to a “better” spot. Choosing spots by a rule keeps you from fooling yourself.

Check your work

- My question can be answered by counting or measuring.
- I took at least 10 samples in each place on at least two days.
- My report has all six parts, a table, a graph and calculations with units.
- I named sources of error and reported my results honestly.

NATURE NOTEBOOK

1. Make a Merian-style plate: draw one plant from your study site with one animal that lives on it, showing at least two life stages if you can find them. Add the date, place and size.
2. Draw a bird’s-eye map of your study site with your quadrats or transect marked to scale (for example, 1 cm = 1 m).
3. Write a field-notebook entry for one sampling day: date, time, weather, temperature, what you counted and one thing that surprised you.

> **From history.** Gilbert White, the curate of the English village of Selborne, kept careful notes on the birds, plants, insects and weather of his parish for decades. His letters to two fellow naturalists were published in 1789 as *The Natural History of Selborne*, one of the most often reprinted books in the English language. White noticed that swifts, swallows and martins arrived on nearly the same dates each spring, and he wrote that earthworms, small as they seem, do great work in loosening and enriching the soil. His book shows that a patient observer can do real science within walking distance of home.

WORKED EXAMPLES

Example 1. A student places ten 50 cm × 50 cm quadrats on a lawn and counts dandelions: 2, 4, 3, 0, 5, 3, 2, 4, 3, 4. The lawn measures 15 m × 10 m. Find the mean per quadrat, the density per square meter and the estimated number of dandelions on the whole lawn.

1. Total = 2 + 4 + 3 + 0 + 5 + 3 + 2 + 4 + 3 + 4 = 30 dandelions.
2. Mean per quadrat = 30 ÷ 10 = 3 dandelions.
3. Area of one quadrat = 0.5 m × 0.5 m = 0.25 m². Density = 3 ÷ 0.25 m² = 12 dandelions per m².
4. Lawn area = 15 m × 10 m = 150 m². Estimate = 12 per m² × 150 m² = 1,800 dandelions.

Answer: Mean 3 per quadrat; density 12 per m²; about 1,800 dandelions on the lawn.

Example 2. Use the transect diagram. The number of plant species in the quadrats at 0, 5, 10, 15 and 20 m is 3, 4, 6, 8 and 9. Find the mean number of species, the range, and the average change in species per meter from 0 m to 20 m.

(Use the map or drawing “Plant species counted along a 20 m transect.” shown earlier in this lesson.)

1. Mean = (3 + 4 + 6 + 8 + 9) ÷ 5 = 30 ÷ 5 = 6 species.
2. Range = highest − lowest = 9 − 3 = 6 species.
3. Change from 0 m to 20 m = 9 − 3 = 6 species over 20 m.
4. Average change = 6 species ÷ 20 m = 0.3 species per meter.

Answer: Mean 6 species; range 6; about 0.3 more species per meter moving from shade into sun.

Example 3. In 20 quadrats in a pasture, white clover appears in 14, plantain in 9 and thistle in 3. Find the frequency of each species as a percent.

1. Frequency = quadrats with the species ÷ total quadrats × 100.
2. Clover: 14 ÷ 20 × 100 = 70%.
3. Plantain: 9 ÷ 20 × 100 = 45%.
4. Thistle: 3 ÷ 20 × 100 = 15%.

Answer: Clover 70%, plantain 45%, thistle 15%.

PRACTICE

1. EASY Where did Maria Sibylla Merian do her field study, and what did she raise and draw there?
2. EASY List the six parts of a field study report in order.
3. EASY What is the difference between a quadrat and a transect?
4. MEDIUM A 1 m² quadrat is placed 8 times in a meadow. The clover plants counted are 5, 7, 6, 4, 8, 6, 5, 7. Find the mean density per m².
5. MEDIUM Using 25 cm × 25 cm quadrats, a student finds an average of 2 ant hills per quadrat. What is the density per square meter? (Hint: how many 25 cm squares fit in 1 m²?)
6. MEDIUM Data reading. Use the transect diagram. (a) How many plant species were found at 10 m? (b) Between which two neighboring quadrats did the number of species increase the most? (c) Which statement is best supported? A. Shade has no plants. B. In this transect, the number of plant species increased from shade toward sun. C. Sunlight causes more species everywhere. D. The tree is dying.
   (Use the map or drawing "Plant species counted along a 20 m transect." shown earlier in this lesson.)
7. MEDIUM Data reading. A student counted earthworms in ten 50 cm × 50 cm quadrats, digging 10 cm deep, in two places. Under leaf litter: mean 8 worms, soil temperature 14 °C, soil moist. Bare soil: mean 2 worms, soil temperature 19 °C, soil dry. (a) How many times more worms were found under leaf litter? (b) Name two variables that differed between the places. (c) Can the student conclude that leaf litter alone caused the difference? Explain.
8. HARD A student places all 10 of her quadrats where she sees the most flowers. Explain what is wrong with this method and how to fix it.
9. HARD Experiment design. Write a complete plan for a field study on the question "Do more insects visit flowers in the morning or the afternoon?" Name the independent variable, the dependent variable, three controlled variables and your sample size.
10. CHALLENGE In 4 or 5 sentences, explain how the skills of a field study report are used in at least three careers from this unit.

COMMON MISTAKES

- Thinking one sample is enough. One quadrat may land on an unusual spot by chance; many samples give a reliable average.
- Changing several things between the places compared and then naming just one as the cause. Note every difference and be careful in the conclusion.
- Leaving the dates, times, weather and units out of the data. Without them, no one, including you, can repeat or check the study.

> **Make it a game · Quadrat Race.** Each player tosses a homemade quadrat onto the lawn (no aiming). Set a timer for 3 minutes. Count every different kind of plant or small animal inside your square; sketch any you cannot name and call it Species A, B and so on. The player with the most kinds earns 2 points, but anyone who can name a correct key term

(quadrat, transect, density, frequency, sample size) for the round earns a bonus point. Play five rounds and then average everyone's counts together as a real field team would.

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

Science is a way of seeking out God's works with delight. Merian in Suriname, White in Selborne and you in your own backyard are all doing what this verse describes.

Practice answers

1. In Suriname, on the northern coast of South America (1699–1701). She raised caterpillars and other insects on their food plants and drew every stage of their life cycles.
2. Question, Prediction, Site and Methods, Data, Analysis, Conclusion.
3. A quadrat is a square of known area used to count what is inside it. A transect is a straight line across a habitat along which samples (often quadrats) are taken at regular distances to show change from place to place.
4. Total = 48. Mean = 48 ÷ 8 = 6 clover plants per m^2.
5. One quadrat is 0.25 m × 0.25 m = 0.0625 m^2, so 16 quadrats fit in 1 m^2. Density = 2 × 16 = 32 ant hills per m^2 (or 2 ÷ 0.0625 = 32).
6. (a) 6. (b) Between 5 m and 10 m (from 4 to 6) and between 10 m and 15 m (from 6 to 8); both increase by 2. (c) B. Statement C goes beyond the data, since one transect in one yard cannot prove a rule for everywhere.
7. (a) 8 ÷ 2 = 4 times more. (b) Leaf cover, soil temperature and soil moisture (any two). (c) No. Moisture and temperature also differed, so any of them (or all together) could explain the difference. A fair test would change only one variable, for example by adding leaf litter to some bare plots and comparing them later with plots left bare.
8. It is biased: she chose spots that would give high counts, so her average will be too high and will not represent the whole area. She should choose spots by a fair rule, such as random tosses, a random-number grid or every 2 m along a tape, decided before looking.
9. Independent variable: time of day (morning, for example 9:00 to 10:00, vs afternoon, 14:00 to 15:00). Dependent variable: number of insect visits to flowers in a set time. Controlled variables: the same flower patch or same number of flowers, the same length of each watch (for example 10 minutes), the same observer and counting rule, similar weather (no rain, similar wind). Sample size: at least 5 watches at each time on different days, so one unusual day does not decide the answer.
10. A nurse records vital signs carefully with times and units, just as a field scientist records data, and a doctor tests a diagnosis like a hypothesis. A wildlife biologist samples a population with counts and mark-recapture because no one can count every animal, then calculates densities and reports them so seasons and bag limits can be set. An agronomist runs field trials with several plots of each variety, keeps other variables the same and calculates yield per hectare. In every career, honest records, fair sampling, clear graphs and careful conclusions decide whether people and animals are helped.

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. Which of these is NOT one of the four vital signs? A. pulse B. blood pressure C. body mass D. breathing rate
2. (6 pts) A nurse counts 26 beats in 15 seconds on a resting adult. (a) What is the pulse in beats per minute? (b) Is it in the normal adult resting range of 60 to 100? (c) Practice label: “3 mg per kg.” What dose would a 30 kg dog receive?
3. (4 pts) Multiple choice. Florence Nightingale’s records from Scutari showed that most soldiers in the hospital died from A. battle wounds B. diseases that better sanitation could prevent C. old age D. cold weather alone
4. (6 pts) Biologists capture and mark 80 rabbits, then release them. A week later they capture 60 rabbits, and 12 are marked. Estimate the population and show your work.
5. (4 pts) Multiple choice. Which task is most likely done by a game warden rather than a wildlife biologist? A. fitting a GPS collar on an elk B. checking a hunter’s license and bag limit C. counting ducks from an airplane D. measuring plant cover in a habitat
6. (5 pts) What can scientists learn from bird banding? Give two things, and tell what you should do if you find a banded bird.
7. (6 pts) Rust resistance (R) is dominant to susceptibility (r). A breeder crosses an Rr plant with an rr plant. (a) Draw the Punnett square. (b) What percent of the offspring are expected to be resistant? (c) Out of 200 seedlings, about how many?
8. (4 pts) Multiple choice. Why did Borlaug cross his wheats with short-stemmed varieties? A. Short wheat needs no water. B. Short, strong stems do not fall over (lodge) under heavy heads of grain. C. Short wheat is a new kind of plant. D. Short wheat cannot get stem rust.
9. (6 pts) A 3-hectare field produced 5,400 kg of wheat with the old variety and 12,600 kg with a new variety. Find the yield per hectare for each and the percent increase.
10. (8 pts) Diagram item. Draw and label a diagram of a 12 m transect running from a pond edge (wet) to a dry hilltop, with four 1 m² quadrats placed at 0, 4, 8 and 12 m. Label the transect line, each quadrat, the distances and the wet and dry ends. Rushes are wetland plants. If the quadrats at 0, 4, 8 and 12 m contain 10, 7, 5 and 2 rush plants, which end of the transect (0 m or 12 m) should be the pond edge? What is the mean number of rush plants per quadrat?
11. (7 pts) A student asks, “Are there more dandelions near the sidewalk than in the middle of the lawn?” (a) Name the independent and dependent variables. (b) Name two things to keep the same. (c) Explain why she should take at least 10 quadrats in each place and choose them by a fair rule. (d) Using 50 cm × 50 cm quadrats, she finds a mean of 5 dandelions near the sidewalk. What is the density per m²?

UNIT PROJECT: MY FIELD STUDY REPORT

Carry out the field study from Lesson 8.4 and present it as a finished scientific report. Include a map of your site, your field notebook pages with dates and weather, a clean data table, calculations of mean, density and frequency, at least one graph and a Merian-style illustration of one plant and animal from your site. Write the report under six headings: Question, Prediction, Site and Methods, Data, Analysis, Conclusion.

Add a one-page career reflection: choose one career from this unit (doctor, nurse, veterinarian, wildlife biologist, game warden or agricultural scientist), tell what training it needs, and explain which skills from your field study that career would use. If possible, interview someone in that career with three prepared questions and include their answers.

- **Scientific question and methods**: The question can be answered by measuring; the methods name the variables, quadrat size, sample size (at least 10 per place) and a fair way of choosing sample spots, clear enough for someone else to repeat.
- **Data and analysis**: Data are complete, dated and in units; mean, density and frequency are calculated correctly; the graph is labeled with title, axes and units.
- **Conclusion and honesty**: The conclusion answers the question, compares the result with the prediction, names at least two sources of error and suggests a next question, reporting the results truthfully even if they surprised the student.
- **Illustration and career reflection**: The illustration is careful and labeled with date, place and size; the career reflection describes real training and connects field-study skills to the chosen career.

Answer key

1. C. Body mass is important (for example, for doses) but is not a vital sign. The four vital signs are temperature, pulse, breathing rate and blood pressure.
2. (a) 26 × 4 = 104 beats per minute. (b) No, it is slightly above 100, so the nurse would recheck it and report it. (c) 3 mg/kg × 30 kg = 90 mg.
3. B.
4. N = (80 × 60) ÷ 12 = 4,800 ÷ 12 = 400 rabbits.
5. B.
6. Any two: where birds migrate, how far and how fast they travel, whether they return to the same nesting place, how long they live, what fraction survive or are harvested. If you find a band, record the number, date and place and report it to the Bird Banding Laboratory.
7. (a) Boxes: Rr, Rr, rr, rr. (b) 50%. (c) About 100 seedlings.
8. B.
9. Old: 5,400 ÷ 3 = 1,800 kg/ha. New: 12,600 ÷ 3 = 4,200 kg/ha. Increase = 2,400 kg/ha; 2,400 ÷ 1,800 × 100 ≈ 133%.
10. Diagram: a straight line labeled “transect” with distance marks at 0, 4, 8 and 12 m, a square at each mark labeled “1 m² quadrat,” the 0 m end labeled “pond edge (wet)” and the 12 m end labeled “hilltop (dry).” The 0 m end should be the pond edge, because rushes are wetland plants and the most (10) grow there, falling to 2 on the dry hilltop. Mean = (2 + 5 + 7 + 10) ÷ 4 = 24 ÷ 4 = 6 rush plants per quadrat (6 per m²).

11. (a) Independent: location (near the sidewalk or middle of the lawn). Dependent: number of dandelions per quadrat. (b) Any two: same quadrat size, same day and time, same counting rule, same counter. (c) Many quadrats give a reliable average because one quadrat could be unusual by chance; a fair rule prevents her from choosing spots that favor her prediction. (d) $5 \div 0.25\ \text{m}^2 = 20$ dandelions per m^2.

Bonus: Nature Lab

This optional bonus unit takes the year's science outdoors. All year you have studied heredity, design and origins from books, diagrams and Punnett squares. Now you will do what Gilbert White, Charles Darwin, Charles Willson Peale and Lewis and Clark did: go out, look carefully, measure, count and bring home evidence. "The works of the LORD are great, sought out of all them that have pleasure therein" (Psalm 111:2).

You will keep a field journal on a measured walk, survey a yard with quadrats and estimate whole populations, visit a zoo, farm or museum with a real question and a data sheet, and build a labeled herbarium with a dichotomous key. Each lesson is lighter than a regular lesson and is best done from spring to fall, but each one practices the skills of a real biologist: observation kept apart from inference, random sampling, ratios and percentages, controlled experiments and honest records.

BEFORE YOU BEGIN

- Can complete a one-trait Punnett square and turn it into a ratio (Unit 1)
- Can calculate a mean, a percent and an area in square meters
- Knows the difference between independent and dependent variables
- Can draw a simple bar graph with labeled axes

MASTERY CHECKLIST

- I can keep a field journal page with a full header, a measured sketch with a scale bar, and observations kept apart from inferences.
- I can calibrate my pace and measure a route in meters.
- I can use random quadrats to find population density and species richness and estimate a whole-yard population.
- I can collect behavior or trait data on a visit and compare farm offspring to a Punnett-square prediction.
- I can read a museum sign and separate what is observed from what is interpreted.
- I can press, label and key out plant specimens, collecting legally and with care.

OPTIONAL BOOKS AND RESOURCES

- **iNaturalist** (https://www.inaturalist.org/): Free. Photograph a plant or animal and get help identifying it from a worldwide community of naturalists. A good tool for a photo herbarium and backyard survey (Lessons 9.2 and 9.4). Students should use it through a parent's account.
- **Merlin Bird ID, from the Cornell Lab of Ornithology** (https://merlin.allaboutbirds.org/): Free app. Identifies birds from a photo, a description, or their songs, much as Gilbert White told the three "willow-wrens" apart by ear (Lesson 9.1).

- ***The Natural History of Selborne* by Gilbert White (free at Project Gutenberg)** (https://www.gutenberg.org/ebooks/search/?query=natural+history+of+selborne): Free. Read a few of White's letters about swallows, earthworms or his tortoise as a model of patient observation.

9.1 Nature Journal Walk

OBJECTIVES

- Keep a field journal page the way naturalists such as Gilbert White did: date, place, weather, a measured sketch and careful notes.
- Tell an observation from an inference and record both honestly, keeping them apart.
- Calibrate your pace and use it to measure and map a walking route in meters.

Warm-up. Set any small natural object on the table: a leaf, a pinecone, a shell or a feather from a hen. Set a timer for two minutes and write down everything you can observe with your senses, with no guesses. Then write one sentence that begins “I think…” about where it came from or what happened to it. The first list is observations. The last sentence is an inference.

Video. Coming soon. nature journaling for teens, field sketching with a scale bar, and Gilbert White of Selborne; search naturalist and nature-journal channels, the Cornell Lab of Ornithology, Smithsonian, and quiet nature footage of English countryside birds.

KEY TERMS

observation
Something you notice directly with your senses or measure with a tool, such as “the leaf is 6 cm long” or “the bird sang 5 times in a minute.”

inference
A reasonable explanation or conclusion drawn from observations, such as “a rabbit probably chewed this stem.” It can be wrong, so label it.

phenology
The study of the timing of yearly events in living things: first flowers, leaf-out, the arrival of migrating birds, the first frog calls.

scale bar
A short line on a drawing or map that shows how long a real distance is, so anyone can measure the real size from the picture.

calibrated pace
The measured length of your own step, found by counting your paces over a known distance. It lets you measure ground without a tape.

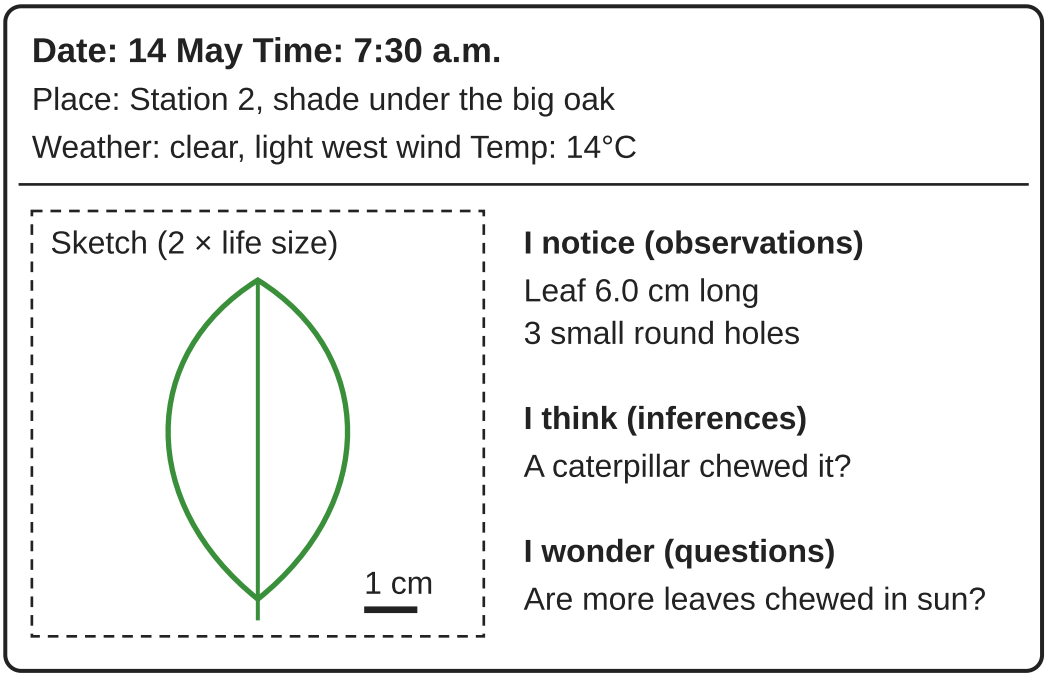
CORE IDEAS

The story. In 1768 Gilbert White, the curate of the little village of Selborne in Hampshire, England, began filling in a new kind of notebook. His friend Daines Barrington had designed *The Naturalist’s Journal*, with printed columns for the date, the weather, the thermometer and barometer readings, the wind, and the plants and birds seen that day. White kept his

journal almost every day until his death in 1793, a record of about twenty-five years in one parish. Because he listened so carefully, he noticed that the small greenish “willow-wrens” that every country person lumped together were really three different birds, told apart by their songs. Today we call them the chiffchaff, the willow warbler and the wood warbler. His letters about Selborne became *The Natural History of Selborne* (1789), one of the most-read nature books in the English language.

The big idea. A field journal is not a diary of feelings or a book of pretty pictures. It is **data**. Every page starts with a header (date, time, place, weather and temperature) because a note without those facts cannot be compared to anything. Then come **observations**: what you see, hear and measure, with numbers and units. A sketch with a **scale bar** lets anyone recover the real size later. **Inferences** belong in the journal too, but labeled, because they are guesses that might be wrong. When you return to the same place again and again, the journal becomes a record of change through the seasons, the science called **phenology**. One page is a snapshot. Fifty pages are a pattern. That is how White, with no laboratory, made discoveries that still stand.

Try it and see. On today’s walk you will measure the route with your own **calibrated pace**, stop at three stations, and fill one journal page per station using the layout in the figure. You will practice the habit that turned a country curate into a great naturalist: looking long enough to notice what everyone else walks past. **God’s handiwork.** Job told his friends, “But ask now the beasts, and they shall teach thee” (Job 12:7). A journal is how a scientist asks, and how he or she remembers the answer.



A field journal page: header first, a measured sketch with a scale bar, and notes that keep observations and inferences apart.

PICTURE STUDY



Young Hare, Albrecht Dürer, 1502 · Watercolor and gouache on paper · Albertina, Vienna, Austria

Albrecht Dürer of Nuremberg was the greatest German artist of his day, and he was also a patient observer of nature. In 1502 he painted this hare so carefully that you can follow the direction of the fur as it changes over the shoulders, the back and the haunches. He signed it with his monogram, “AD,” and the date.

Dürer’s hare is not a scientific diagram, but it was made the way a naturalist works: by looking long and recording exactly what is there, not what one expects. That is the habit of a good field journal.

Look closely

- Look closely at the eye. Can you find the reflection of a window in it? What does that tell you about where Dürer was working?
- Follow the fur with your finger. Where does it change direction, and where is it short or long?
- Count the whiskers you can see on one side of the face.
- Find Dürer’s monogram and the date. Where did he put them?

Talk about it

1. Which details in this painting are observations that a scientist could check on a real hare?
2. Why would an artist or a naturalist spend hours on one small animal instead of quickly drawing many?
3. What would you need to add to this picture to make it a field journal page?

> **Safety first.** Walk with an adult or tell one exactly where you are going and when you will return. Wear closed shoes and long pants in tall grass, and check for ticks afterward. Learn to recognize poison ivy (“leaves of three, let it be”) and stinging nettle. Do not touch or chase wild animals, and leave nests alone. Never look directly at the sun, even to check the weather.

EXPERIMENT: THREE STATIONS, ONE WALK

You will walk a short route, measure it with your calibrated pace, and stop at three different spots for exactly five minutes each. The question: **Does the number of different kinds of living things you notice change between a sunny open spot, a shady spot and an edge (where a lawn meets a hedge, a woods or a fence line)?**

You will need

- A bound notebook or sketchbook and a pencil (pencil does not run in rain)
- A 30 cm ruler and a tape measure or a 10 m length of string marked with tape
- An outdoor thermometer
- A timer or watch
- A hand lens (optional)
- Colored pencils for later (optional)

Steps

1. Calibrate your pace: measure 20 m on a sidewalk or driveway, walk it naturally three times, and count your paces each time. Divide 20 m by your average number of paces to find meters per pace.
2. Write your prediction: which station will have the most different kinds of living things, and why?
3. Choose a route with three stations: open and sunny, shady, and an edge. Count paces between stations and convert them to meters.
4. At each station, write the header: date, time, station name, weather, and the air temperature read from your thermometer after it has sat in the shade for two minutes.
5. Set the timer for five minutes. Tally every different kind of plant and animal you notice (you do not need names; “small black ant” or “clover with three leaflets” is fine). Keep the five minutes exact at every station.
6. Sketch one thing from each station with a scale bar, and write one observation, one inference (labeled) and one question beside it.
7. At home, make a table: station, temperature, number of kinds. Draw a bar graph of the number of kinds at each station.
8. Write two or three sentences: Was your prediction right? What else besides sun and shade might explain the difference?

Tips

- **What we change:** the station. **What we keep the same:** five minutes, the same observer, the same morning or afternoon. **What we measure:** the number of different kinds, plus temperature.
- Sit still for the first minute. Animals that hid when you arrived often come back out.
- Write the inference in a different place on the page, or start it with “I think,” so you never mistake it for an observation later.

Check your work

- Every page has a full header with date, time, place, weather and temperature.
- My sketches have scale bars, and my observations and inferences are kept apart.
- I measured my route in meters using my calibrated pace and graphed my station counts.

NATURE NOTEBOOK

1. Draw a map of your walk from above with a north arrow, the three stations marked, and the distance between them in meters.
2. Choose one leaf and draw it twice life size. Add a scale bar that shows 1 cm of the real leaf.
3. Start a phenology list at the back of your journal: “first dandelion,” “first robin heard,” “first frost.” Add dates through the year.

> **From history.** Charles Darwin read *The Natural History of Selborne* as a boy. In his autobiography he remembered that White’s book gave him great pleasure in watching the habits of birds, and that he even wondered why every gentleman did not become a bird-watcher. Gilbert White never traveled far from his village, yet his patient notes from one parish have been reprinted in hundreds of editions.

WORKED EXAMPLES

Example 1. A student walks a measured 20 m line three times and takes 27, 29 and 28 paces. Later she walks from the back door to the creek in 350 paces. How far is it to the creek in meters?

1. Average paces over 20 m: (27 + 29 + 28) ÷ 3 = 84 ÷ 3 = 28 paces.
2. Length of one pace: 20 m ÷ 28 paces ≈ 0.71 m per pace.
3. Distance to the creek: 350 paces × 0.71 m per pace ≈ 250 m. (Working with exact fractions: 350 × 20 ÷ 28 = 250 m.)

Answer: About 250 m. Her pace is about 0.71 m.

PRACTICE

1. EASY Label each note O (observation) or I (inference): (a) The oak leaf is 11 cm long. (b) A deer ate the tops off these tulips. (c) The air temperature in the shade is 18°C. (d) The robin is looking for worms.
2. MEDIUM Your brother takes 25 paces over a measured 15 m. He then paces the edge of a field and counts 400 paces. How long is the field edge?
3. MEDIUM A student watched the same flower bed for 5 minutes at five times on one sunny day and recorded:
   8:00, 12°C, 2 bees
   10:00, 17°C, 9 bees
   12:00, 22°C, 15 bees
   14:00, 24°C, 14 bees
   16:00, 20°C, 8 bees
   (a) At what time were the most bees seen? (b) Describe the relationship between temperature and bee count between 8:00 and 12:00. (c) Does the 14:00 reading fit that pattern perfectly? (d) Can we conclude from one day that temperature *causes* bee visits?
4. HARD You draw a beetle 3 times life size. The beetle on your page is 4.5 cm long. (a) How long is the real beetle in millimeters? (b) How long should a scale bar that stands for 5 mm of real beetle be on your page?
5. CHALLENGE Design an experiment for your journal to answer: Do more insects visit yellow flowers or white flowers in our yard? Name the independent variable, the dependent variable, three things to keep the same, and how many observations you would make.

COMMON MISTAKES

- Thinking a nature journal is mainly art. The drawing matters, but without the date, place, weather and measurements, the page cannot be used as data.
- Writing an inference as if it were an observation (“the hawk was hunting”) so that later you cannot tell what you actually saw.
- Calling one day’s notes a pattern. A trend needs repeated observations at the same place over time, as Gilbert White made for twenty-five years.

Make it a game · Observation or Inference?. One player reads a sentence from his or her journal or makes one up about something in the yard. The others call “Observation!” or “Inference!” A correct call scores a point. A bonus point goes to anyone who can turn an inference into an observation that would test it (“A rabbit ate it” becomes “There are rabbit droppings 30 cm away”). Play to ten points.

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)

Creation is a book that teaches anyone willing to watch and listen. A field journal is a way of asking good questions and writing down what the creatures “tell” us.

Practice answers

1. (a) O. (b) I: we did not see a deer eat them, though hoof prints might support it. (c) O. (d) I: we observe the robin hopping and tilting its head; “looking for worms” is an explanation.
2. 15 m ÷ 25 = 0.6 m per pace. 400 × 0.6 m = 240 m.
3. (a) 12:00, with 15 bees. (b) As temperature rose, bee counts rose. (c) Not perfectly: 14:00 was warmest (24°C) but had 14 bees, one fewer than at 12:00. (d) No. One day is not enough, and other things changed with time of day, such as sunlight and how much nectar the flowers had. The data show a relationship, not proof of cause.
4. (a) 4.5 cm ÷ 3 = 1.5 cm = 15 mm. (b) 5 mm × 3 = 15 mm, or 1.5 cm.
5. Sample answer: Independent variable: flower color (yellow or white). Dependent variable: number of insect visits in 5 minutes. Keep the same: the length of each watch, time of day and weather, distance of the observer from the flowers, and roughly the same number of open blooms in each patch (and similar sun exposure). Repeat many times, for example ten 5-minute watches of each color on several different days, alternating which color is watched first, then compare averages.

9.2 Backyard Survey

OBJECTIVES

- Survey a yard or field with quadrats and a transect, placing them by random sampling instead of by eye.
- Calculate population density (individuals per square meter) and species richness from quadrat counts, and estimate a whole-yard population.
- Retell Charles Darwin's weed-plot count and explain what it showed about how many young plants survive.

Warm-up. Spill a handful of dried beans or rice across a sheet of newspaper. Without counting them all, how could you estimate the total? Cut a 5 cm × 5 cm square hole in an index card, drop it on the paper three times without looking, count the grains inside the hole each time, and make an estimate. Then count them all and compare.

Video. Coming soon. quadrat and transect sampling for students, backyard BioBlitz, and Darwin at Down House; search USGS, National Park Service, Smithsonian, ecology field-method channels, and backyard nature footage of lawn insects and wildflowers.

KEY TERMS

quadrat
A square frame of known area, such as 0.5 m × 0.5 m (0.25 m²), laid on the ground so that the living things inside it can be counted.

population density
The number of individuals of one species per unit of area, for example 19 dandelions per square meter.

species richness
The number of different species (kinds) found in a place, no matter how many individuals of each.

random sampling
Choosing where to sample by chance (dice, random numbers) so that the counter's own choices do not bias the results.

transect
A straight line laid across a habitat, along which observations or quadrats are taken at regular distances to see how life changes from one place to another.

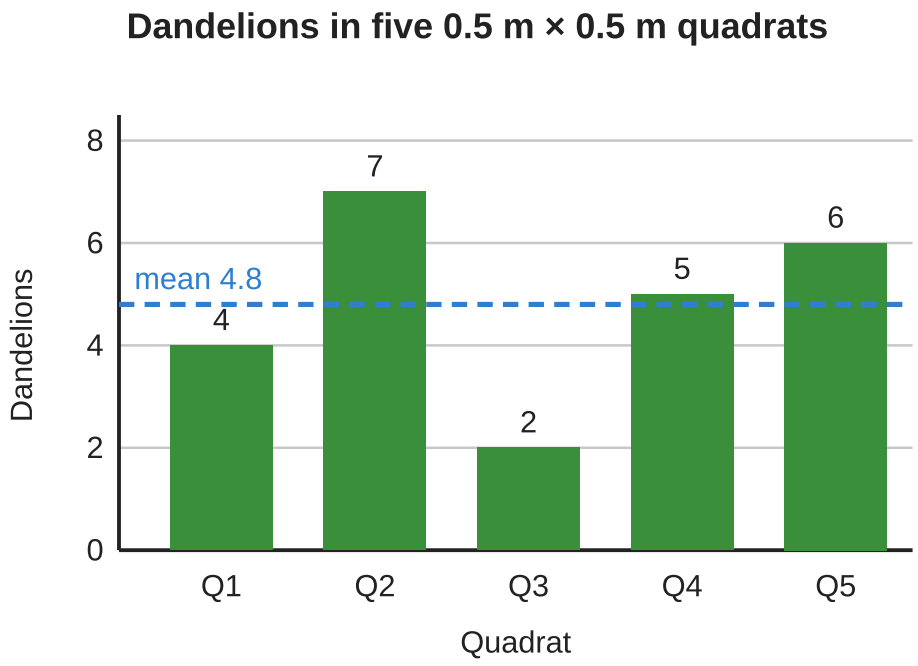
CORE IDEAS

The story. In the 1850s, while he was writing *On the Origin of Species* at Down House in Kent, England, Charles Darwin ran a survey in his own garden. He dug and cleared a little patch of ground three feet long and two feet wide (about 90 cm by 60 cm), so that no older

plants would crowd the new ones. As the seedlings of native weeds came up, he marked every one. Out of 357 seedlings, he reported, no fewer than 295 were destroyed, chiefly by slugs and insects. In another test, he let a small plot of mown lawn (three feet by four) grow freely; of the 20 species growing in it, 9 died out as the more vigorous plants overgrew the weaker ones. Darwin used numbers like these to show how many more living things are born than survive. Every scientist, whatever he or she concludes about origins, can check and repeat counts like these, because they are observations.

How they figured it out. Counting every plant in a whole yard is impossible, so ecologists count small samples and multiply. A **quadrat** is a square of known area dropped in several places chosen by **random sampling**. From the counts you can find **population density** (individuals per square meter) and **species richness** (how many different kinds). Multiply the density by the area of the whole yard and you have an estimate of the total population. A **transect**, a string stretched from sunny lawn into shade, shows how the plants and animals change from one habitat to another. More quadrats give a better estimate, the same way more coin flips give a ratio closer to one-half, as Mendel knew when he counted thousands of peas.

God’s handiwork. A single square meter of an ordinary lawn may hold clover, plantain, dandelions, several grasses, ants, spiders, beetles and earthworms, each reproducing after its kind. Jesus told His listeners to “consider the lilies of the field, how they grow.” A backyard survey is a careful way of considering: measuring abundance, noticing what thrives in sun and shade, and learning to manage your own ground wisely, as Adam was set in the garden “to dress it and to keep it.”



Dandelions counted in five randomly placed 0.5 m × 0.5 m quadrats. The dashed line marks the mean, 4.8 per quadrat.

PICTURE STUDY



The Large Piece of Turf, Albrecht Dürer, 1503 · Watercolor and gouache on paper · Albertina, Vienna, Austria

A year after his famous hare, Albrecht Dürer painted something most people step on without a glance: a patch of ordinary meadow. He seems to have dug up a clump of turf and painted it from very low, as if he were lying on the ground beside it.

Botanists have recognized many of the plants, including dandelion, greater plantain and several meadow grasses. In a sense, Dürer made a quadrat survey five hundred years ago, recording one small square of earth so exactly that we can still count what grew in it.

Look closely

- Find the dandelions. How many flower heads or seed heads can you count?
- Find the broad, ribbed leaves of plantain near the bottom. How are they different from the grass blades?
- Notice the roots and soil at the base. Why might Dürer have painted from so low a viewpoint?
- Try to count how many different kinds of plants you can tell apart.

Talk about it

1. If this patch of turf were a quadrat, what would its species richness be by your count?
2. Why do you think Dürer chose such a humble subject?
3. Which plants in this painting might grow in your own yard today?

> **Safety first.** Check the area with an adult first. Avoid lawns that were recently sprayed with weed killer or fertilizer. Wear gloves when parting plants, watch for bees on clover

> and dandelions, learn to recognize poison ivy, and check for ticks afterward. Push stakes into the ground carefully and pull them all up when you finish. Wash your hands when you come in.

EXPERIMENT: SUN VERSUS SHADE QUADRAT SURVEY

You will build a quadrat and survey two parts of a yard, field or park. The question: **Is species richness higher in a sunny area or a shady area of the same yard?** You will also estimate the number of one common plant, such as dandelions or clover, in the whole yard.

You will need

- Four sticks or tent stakes and 2.2 m of string, or four garden canes cut to 0.5 m and taped at the corners into a square
- Meter stick or tape measure
- A die or a phone random-number tool
- Notebook, pencil and a clipboard
- Hand lens and garden gloves
- A long string or rope for a transect (optional)

Steps

1. Write your prediction: will the sunny or the shady area have more different kinds of plants and small animals? Give a reason.
2. Build a 0.5 m × 0.5 m quadrat. Its area is 0.25 m^2, so four quadrats equal 1 m^2.
3. Measure the length and width of the sunny area and the shady area, and calculate each area in square meters.
4. Place five quadrats in each area at random: pace off a number of steps from a corner chosen by rolling a die for each direction. Do not choose the “interesting” spots.
5. In each quadrat, count the individuals of your chosen common plant, and list every different kind of plant and animal you find (a sketch or description is fine if you do not know the name).
6. Record a table: area, quadrat number, count of chosen plant, number of kinds.
7. Calculate the average number of kinds per quadrat in each area, the density of your chosen plant (per m^2), and an estimate of how many of that plant grow in the whole yard.
8. Draw a bar graph comparing the two areas and write three sentences: Was your prediction right? What might explain the difference? How could you make your estimate more trustworthy?

Tips

- **What we change:** sun or shade. **What we keep the same:** quadrat size, number of quadrats, the person counting, the day and the method of choosing spots. **What we measure:** number of kinds and number of the chosen plant.

- Decide your rules before you start. For example: “a plant counts if its stem comes out of the ground inside the frame.”
- If you have a long string, try a transect: lay it from sun into shade and place a quadrat every 2 m along it.

Check your work

- I placed my quadrats by chance, not by choosing spots I liked.
- I calculated density in individuals per square meter and estimated a whole-yard total.
- I compared species richness in sun and shade with a graph and an honest conclusion.

NATURE NOTEBOOK

1. Draw your best quadrat from directly above, life size or at half size, and show every plant in it with a key.
2. Sketch the most common animal you found (an ant, spider, beetle or worm) with a scale bar, and note where in the quadrat it was.
3. Draw a simple map of your yard showing the sunny and shady areas, their measured sizes, and where each quadrat fell.

> **From history.** The quadrat method was introduced in 1898 by two young botanists at the University of Nebraska, Roscoe Pound and Frederic Clements, who counted plants in square plots to describe the prairie. Clements went on to become one of America’s best-known plant ecologists. Pound took a different road: he became a famous legal scholar and served for twenty years as dean of Harvard Law School.

WORKED EXAMPLES

Example 1. A student drops five 0.5 m × 0.5 m quadrats at random on a lawn and counts dandelions: 4, 7, 2, 5 and 6 (see the graph). The lawn measures 10 m by 12 m. Estimate the dandelion density and the total number of dandelions on the lawn.

(Use the map or drawing “Five quadrat counts and their mean.” shown earlier in this lesson.)

1. Area of one quadrat: 0.5 m × 0.5 m = 0.25 m². Area sampled: 5 × 0.25 m² = 1.25 m².
2. Total counted: 4 + 7 + 2 + 5 + 6 = 24 dandelions. Mean per quadrat: 24 ÷ 5 = 4.8.
3. Density: 24 ÷ 1.25 m² = 19.2 dandelions per m² (the same as 4.8 ÷ 0.25).
4. Lawn area: 10 m × 12 m = 120 m².
5. Estimated total: 19.2 per m² × 120 m² = 2,304, so about 2,300 dandelions.

Answer: About 19 dandelions per square meter, and about 2,300 on the whole lawn.

PRACTICE

1. EASY In Darwin's weed plot, 295 of 357 seedlings were destroyed. How many survived, and what percent were destroyed?
2. MEDIUM A student counts white clover plants in four 1 m² quadrats: 12, 8, 15 and 9. The field is 50 m × 20 m. Estimate the density and the total number of clover plants.
3. MEDIUM Two students surveyed the same yard with five 0.25 m² quadrats in each area. Number of different kinds found:
   Sunny lawn: 6, 7, 5, 8, 6
   Shade under a maple: 3, 4, 2, 4, 3
   (a) Find the mean number of kinds per quadrat in each area. (b) Which area had greater species richness? (c) Give one possible explanation besides sunlight. (d) Why is it better to compare means than to compare one quadrat from each area?
4. HARD A student wants to count ants, so she places all her quadrats right next to ant hills because "that's where the ants are." Then she multiplies her density by the area of the yard. Explain what is wrong and how to fix it.
5. CHALLENGE Design an experiment to test whether pill bugs (roly-polies) are found more under boards in damp shade than under boards in a dry, sunny spot. Include your independent and dependent variables, controls, and how long you would run it.

COMMON MISTAKES

- Counting one quadrat and treating it as the whole yard. Living things are patchy, so several random samples are needed.
- Mixing up the number of individuals with the number of species. Fifty dandelions in a quadrat is high density but a species richness of only one.
- Forgetting the units of area. A count of 5 per quadrat means nothing until you know the quadrat is 0.25 m², which makes it 20 per m².

> **Make it a game · Quadrat Toss.** Each player tosses a hula hoop or a string loop over the shoulder onto the lawn without looking. Set a timer for three minutes and list every different kind of living thing inside your loop. Highest species richness wins the round, but any player who can correctly name three of his or her kinds earns a bonus point. Play three rounds and add up the scores.

> **Scripture.** "And why take ye thought for raiment? Consider the lilies of the field, how they grow; they toil not, neither do they spin: And yet I say unto you, That even Solomon in all his glory was not arrayed like one of these." (Matthew 6:28–29, KJV)

Jesus pointed His listeners to the ordinary wildflowers at their feet. A careful survey is one way to "consider" them: to count, compare and wonder at how richly God clothes even a small patch of ground.

Practice answers

1. 357 − 295 = 62 survived. 295 ÷ 357 ≈ 0.826, so about 83% were destroyed (about 17% survived).
2. Total 44 in 4 m², so 11 per m². Field area 1,000 m². Estimate 11 × 1,000 = 11,000 clover plants.
3. (a) Sunny: 32 ÷ 5 = 6.4. Shade: 16 ÷ 5 = 3.2. (b) The sunny lawn, about twice as rich. (c) Possible answers: the maple’s roots take water and nutrients; fallen leaves smother small plants; the soil is drier or more compacted under the tree. (d) Single quadrats vary a lot by chance (sunny ones ranged from 5 to 8); the mean of several is a more reliable picture of the whole area.
4. Her samples are biased: she chose spots with far more ants than an average spot, so her density is too high and her whole-yard estimate will be much too large. She should place quadrats at random (using dice or random numbers) so that every part of the yard has the same chance of being sampled, and take enough quadrats to average out chance differences.
5. Sample answer: Lay identical boards (same size and wood), for example three in damp shade and three in a dry, sunny place. Independent variable: location (damp shade or dry sun). Dependent variable: number of pill bugs under each board. Keep the same: board size and type, the time of day of each check, how the board is lifted, and how long the boards have been down. Check each morning for 7 to 10 days, count quickly, set each board back gently, and compare the average count per board in each location. Measuring soil moisture or temperature under each board would add useful data.

9.3 Zoo, Farm or Museum Visit

OBJECTIVES

- Plan a visit to a zoo, farm or natural history museum around one scientific question, and collect data there instead of just looking.
- Record animal behavior with an ethogram and scan sampling, or record inherited traits on a farm and compare them to Punnett-square predictions.
- Read a museum sign carefully, separating what is observed (bones, measurements) from what is interpreted (ages, stories).

Warm-up. Watch a pet, a backyard bird or a squirrel through a window for three minutes. Every 30 seconds, write one word for what it is doing at that instant: resting, eating, walking, grooming, watching or something else. Count your tallies. You have just done scan sampling, the method zoo scientists use.

Video. Coming soon. Charles Willson Peale and the mastodon, zoo animal behavior studies, and cattle coat-color genetics; search the Smithsonian, natural history museum channels, zoo education channels, university agricultural extension channels, and farm and wildlife footage.

KEY TERMS

ethogram
A list of the behaviors an animal performs, each with a clear definition (for example, “resting: lying down with eyes closed or half closed”), used so that every observer records behavior the same way.

scan sampling
Recording what an animal (or each animal in a group) is doing at fixed moments, such as every 60 seconds, so that the tallies show how its time is divided.

breed
A group of domestic animals within one kind, bred by people for particular inherited traits, such as Angus or Hereford cattle.

cast
A copy of a bone, fossil or specimen made by pouring material such as plaster or resin into a mold. Many museum skeletons are partly or entirely casts.

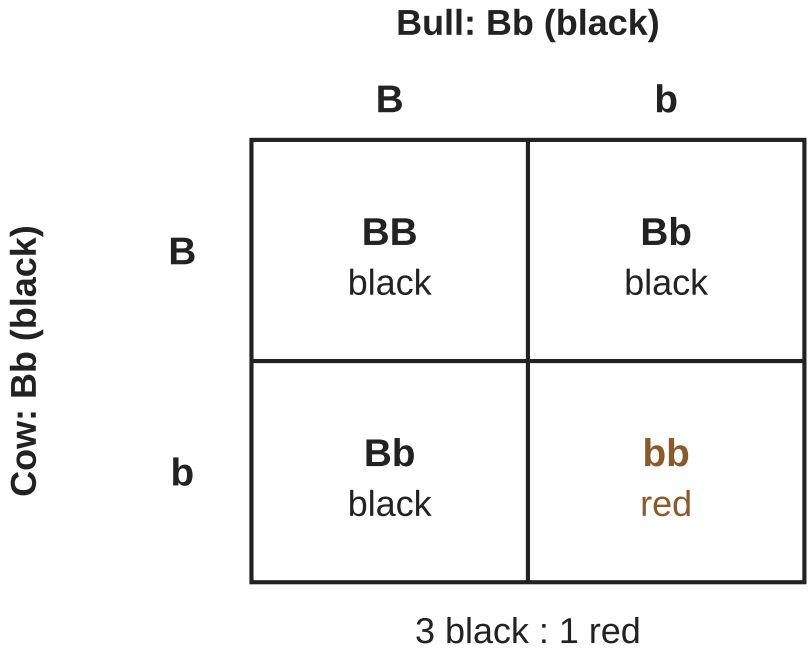
interpretation
An explanation of what observations mean. A museum sign usually mixes observations (size, where found) with interpretations (age, how the animal lived).

CORE IDEAS

The story. In the summer of 1801, the painter and naturalist Charles Willson Peale heard that huge bones had been found in a marshy pit on John Masten's farm near Newburgh, New York. The pit kept filling with water, so Peale had a giant wooden wheel built. Men walked inside it like a treadmill, turning a chain of buckets that lifted the water out while workers dug. Peale took the bones home to Philadelphia, filled in the missing pieces with carved copies, and by the end of 1801 his museum was showing the first mounted skeleton of the great beast Americans then called the "mammoth." Scientists soon showed it was a different animal, now called the American mastodon. Peale's museum also arranged birds in Linnaean order in cases painted with their natural surroundings, so that ordinary visitors could learn classification just by walking through.

How to visit like a scientist. A trip becomes science when you bring a question and a data sheet. At a **zoo**, choose one animal, write a short **ethogram**, and use **scan sampling**: every 60 seconds for 20 minutes, mark what the animal is doing. At a **farm**, study heredity. In cattle, black coat (B) is dominant over red (b), and polled, or hornless (P), is dominant over horned (p). Count the calves of each color and compare your counts to a Punnett square. Different **breeds**, from tiny Dexters to huge Holsteins, show how much variety God built into one kind. At a **museum**, measure and sketch, and read every sign twice: once for the observations (what bone, how long, where found, real or **cast**) and once for the **interpretations** (ages, behavior, ancestry).

God's handiwork. "Be thou diligent to know the state of thy flocks, and look well to thy herds." Good farmers, keepers and curators are careful observers, and their work is a picture of the dominion and care God gave people in Genesis 1:28. When you stand under a mastodon skeleton or watch a newborn calf stand on wobbly legs, you are looking at the same handiwork Peale wanted every visitor to see.



Two black Bb parents: expected offspring 1 BB : 2 Bb : 1 bb, or 3 black : 1 red.

⏳ Thinking About Time

What the sign says. What the sign says: a museum sign beside a mastodon skeleton will often say that American mastodons lived during the Ice Age, or Pleistocene, and died out about 10,000 to 11,000 years ago. In the dinosaur hall, the textbook number you will read is that the last dinosaurs died out about 66 million years ago.

What we observe. What we observe: real bones and teeth, often dug from bogs, gravel and lake beds like Peale's pit at Newburgh; their size, shape and wear; the layers they were found in; and laboratory measurements such as the amount of carbon-14 left in bone. The ages on the sign are interpretations of those measurements, based on assumptions about the past.

How Christians read it. How Christians read it: many Christians, reading Genesis as history, hold that mastodons descended from the elephant kind preserved on the Ark, spread over the earth after the Flood, and lived during an Ice Age that followed the Flood and lasted centuries, not tens of thousands of years. Some Christians hold other views about the timing. All sides agree on the bones themselves.

Try it. At the museum, copy one sign word for word and underline observations in one color and interpretations in another.

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 heavy curtain, as if inviting you in. Behind him stretches the Long Room of his museum in the Pennsylvania State House, the building we now call Independence Hall, with rows of bird cases and portraits above them.

In the lower right are bones of the mastodon he dug up in 1801. At the lower left lies a wild turkey he is about to prepare, with his tools beside it. Peale wanted the museum to be a school for everyone, not a collection for the few.

Look closely

- Find the mastodon bones. Which ones can you recognize?
- Look at the bird cases along the wall. How are they arranged?
- Find the wild turkey and the tools at the lower left. What job are they waiting for?
- Look at the visitors in the gallery. What are they doing?

Talk about it

1. Why do you think Peale painted himself lifting a curtain rather than simply standing in his museum?
2. How did arranging birds in cases by classification help visitors learn?
3. What would you want a visitor to notice first if you built a museum of your own?

> **Safety first.** At a zoo, stay behind every barrier and never feed animals unless staff invite you. On a farm, ask before entering a pen, never stand directly behind a horse or cow,

> stay away from bulls and from mothers with young, and watch for electric fences. Wash your hands with soap and water after touching any animal, fence or pen, even if your hands look clean, because animals can carry germs such as harmful *E. coli*. In a museum, touch only the specimens marked for handling.

EXPERIMENT: MY FIELD TRIP DATA SHEET

Choose one of three studies, write your question before you go, and come home with real data. **Zoo:** How does one animal divide its time? **Farm:** Do the coat colors of calves, kids, lambs or chicks match a Punnett-square prediction? **Museum:** How much of what a sign says is observation, and how much is interpretation?

You will need

- Clipboard, pencil and a printed or hand-ruled data sheet
- Watch or phone timer
- Tape measure (for a museum or farm, if allowed)
- Small notebook for sketches
- Camera (ask before photographing on a farm)

Steps

1. Before the trip, write your question and your prediction. For a farm, ask the farmer ahead of time what colors the parents are.
2. Make your data sheet. Zoo: an ethogram of 4 to 6 behaviors with definitions, and 20 rows for 20 one-minute scans. Farm: a table of animal, color, horned or polled, and the parents if known. Museum: a table with columns for sign, observation, interpretation.
3. At the site, sit or stand quietly in one spot. Zoo: record the behavior at the beep of the timer every 60 seconds for 20 minutes. Farm: record every young animal you can see clearly, or ask the farmer for the herd record. Museum: study at least five signs.
4. Make one measured sketch of the animal or specimen, with a scale bar or a note of its real size.
5. Ask a keeper, farmer or docent one good question and write down the answer.
6. At home, turn your tallies into percentages or ratios and draw a bar graph or a Punnett square.
7. Write a short conclusion: Did the data match your prediction? What would you change if you went again?

Tips

- **What we change:** depends on your study (time of day at a zoo, parents' genotypes on a farm). **What we keep the same:** the observer, the interval, the definitions. **What we measure:** behavior counts, offspring counts, or sign statements.
- Small numbers wander from the expected ratio. Twelve calves can easily be 10 black and 2 red instead of 9 and 3.

- If a farm animal is black, you cannot tell from looking whether it is BB or Bb. Only its offspring or a DNA test can show that.

Check your work

- I went with a written question and came home with a full data sheet.
- I turned my data into a graph or a Punnett-square comparison.
- I can explain the difference between what I observed and what a sign interpreted.

NATURE NOTEBOOK

1. Draw one animal or skeleton from the side with its real height noted, and draw yourself beside it at the same scale.
2. Copy one museum sign and use two colors to mark observations and interpretations.
3. Draw a farm family tree (a small pedigree) for one cow, ewe or doe and her offspring, showing coat color.

> **From history.** Charles Willson Peale filled his family as well as his museum with art and science: he named several of his children after great painters and naturalists, including Raphaelle, Rembrandt, Rubens, Titian and Charles Linnaeus Peale. Rembrandt Peale became a well-known portrait painter, and Titian Ramsay Peale became a naturalist and artist who later sailed on a United States expedition to collect specimens.

WORKED EXAMPLES

Example 1. A farmer's herd has two black cattle that are both known to carry red (Bb). Over several years they produce 20 calves. Use a Punnett square to predict the genotype ratio and how many calves should be black and how many red.

(Use the map or drawing "Bb × Bb gives 3 black : 1 red." shown earlier in this lesson.)

1. Each parent can pass on B or b. Put B and b across the top and down the side.
2. Fill the four boxes: BB, Bb, Bb, bb.
3. Genotype ratio: 1 BB : 2 Bb : 1 bb. Since B (black) is dominant, BB and Bb calves are black and only bb calves are red: 3 black : 1 red.
4. Out of 20 calves: black = 20 × 3/4 = 15; red = 20 × 1/4 = 5.

Answer: 1 BB : 2 Bb : 1 bb, so we expect about 15 black calves and 5 red calves. Real counts may differ somewhat by chance.

PRACTICE

1. EASY Sort these museum-sign statements into observation (O) or interpretation (I): (a) This tusk is 2.1 m long. (b) This animal lived in herds. (c) These bones were found in a marsh in New York. (d) This animal died out 11,000 years ago.

2. MEDIUM A student scan-sampled a zoo giraffe once a minute for 20 minutes:
   Eating: 9
   Walking: 5
   Standing alert: 4
   Grooming: 2
   (a) What percent of the scans was the giraffe eating? (b) About how many minutes of a 60-minute hour would you expect it to spend walking, if this sample is typical? (c) Name one thing that could make this sample untypical.
3. MEDIUM In cattle, polled (P) is dominant over horned (p). A polled bull that is Pp is bred to horned cows (pp). What fraction of the calves should be polled? Out of 12 calves, how many?
4. HARD A museum mastodon skeleton is labeled with a shoulder height of 2.8 m. You are 1.6 m tall. (a) How many times taller at the shoulder is the mastodon? (b) In your sketch, you draw yourself 4 cm tall. How tall should the mastodon be drawn to the same scale?
5. CHALLENGE Design a study to answer: Do the goats at a petting farm spend more time eating in the morning than in the afternoon? Name your method, variables, controls and how you would make the result trustworthy.

COMMON MISTAKES

- Assuming every skeleton in a museum is made of real bone. Many mounts are casts, or real bone completed with casts; good signs tell you which.
- Thinking a dominant trait must be the most common one. Dominant means it shows when one copy is present, not that it is frequent in the herd.
- Expecting small samples to match a ratio exactly. Five red calves in twenty is the expectation; four or six is still a normal result.

> **Make it a game · Sign Detective.** A parent reads a sentence from a real museum sign, a zoo placard or a farm brochure. Players hold up one finger for observation or two for interpretation, then explain. A correct call is worth one point, and a good explanation of how the statement could be checked is worth a second point. The first to ten wins.

> **Scripture.** “Be thou diligent to know the state of thy flocks, and look well to thy herds.” (Proverbs 27:23, KJV)

A good farmer knows each animal, its health and its parentage. Careful watching and record keeping, the heart of today’s data sheet, is old wisdom.

Practice answers

1. (a) O. (b) I. (c) O. (d) I: the age comes from interpreting measurements with assumptions about the past.
2. (a) 9 ÷ 20 = 45%. (b) 5 ÷ 20 = 25%, and 25% of 60 minutes = 15 minutes. (c) Possible answers: feeding time had just begun; it was the hottest part of the day; crowds or keepers

were nearby; 20 minutes is a short sample.

3. Punnett square: Pp, Pp, pp, pp. One-half should be polled (Pp) and one-half horned (pp). Out of 12 calves, about 6 polled and 6 horned.
4. (a) 2.8 ÷ 1.6 = 1.75 times. (b) 4 cm × 1.75 = 7 cm.
5. Sample answer: Use scan sampling with an ethogram (eating, resting, walking, other). Independent variable: time of day (morning or afternoon). Dependent variable: percent of scans spent eating. Keep the same: the same goats, the same 1-minute interval, the same 30-minute watch length, the same observer and definitions, and days with similar weather. Note when the farm feeds the goats, since feeding times could explain the result. Repeat on several days (for example, 4 mornings and 4 afternoons) and compare the averages.

9.4 Specimen Collection

OBJECTIVES

- Collect, press, dry and mount plant specimens with complete data labels, following the rules of ethical and legal collecting.
- Use and write a simple dichotomous key to identify specimens by their traits.
- Explain why labeled voucher specimens, from Lewis and Clark's plants to a home herbarium, let other people check a scientist's work.

Warm-up. Take five different leaves from house plants, the yard or a bag of salad greens. Without looking anything up, sort them into two groups by one trait you can see (edges smooth or toothed, one blade or many leaflets). Then split each group again by a second trait. You have just built the start of a dichotomous key.

Video. Coming soon. how to press and mount plant specimens, herbarium tours, and the Lewis and Clark plant collection; search natural history museum and university herbarium channels, the Smithsonian, botanical garden channels, and nature footage of wildflowers and trees.

KEY TERMS

specimen
A real organism, or part of one, collected and preserved for study, such as a pressed leaf, a shell or a pinned insect.

herbarium
A collection of pressed, dried plant specimens mounted on sheets of heavy paper, labeled, and stored in order for study. The word also names the building or room that holds them.

voucher specimen
A specimen kept as proof of what was found in a study, so that others can check the identification later.

data label
The label with a specimen giving at least the name (if known), date, exact place, habitat and collector. Without it, a specimen loses most of its scientific value.

dichotomous key
A tool for identifying living things by making a series of choices between two statements (for example, leaves opposite or leaves alternate) until the name is reached.

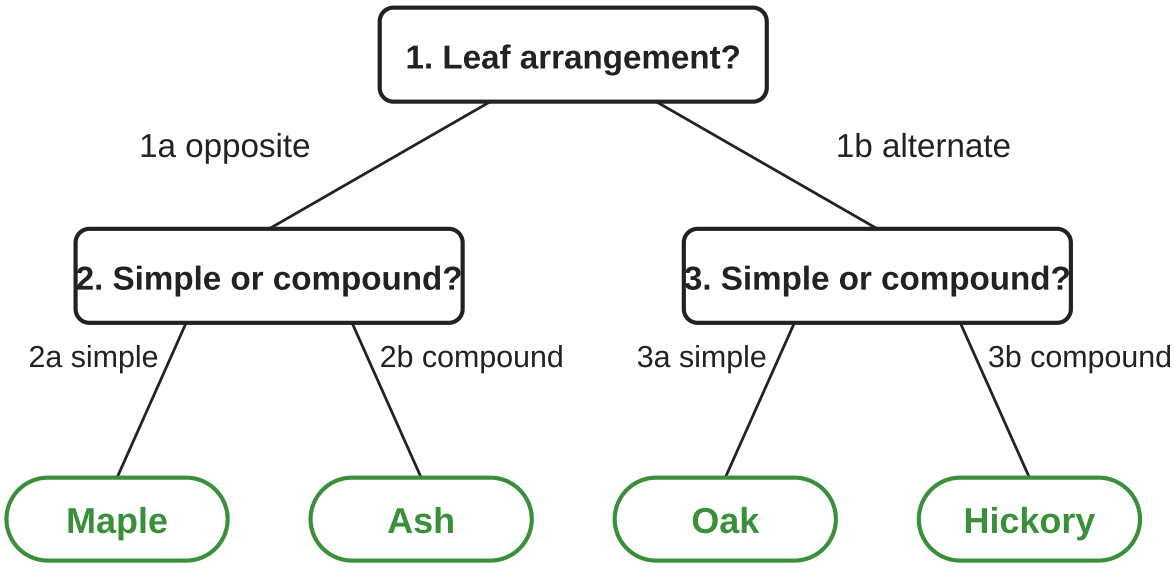
CORE IDEAS

The story. When President Thomas Jefferson sent Meriwether Lewis and William Clark west in 1804, his instructions asked them to note the plants and animals of every country they passed through. Lewis, who had studied botany in Philadelphia before the trip, pressed

plants between sheets of paper and wrote on each one when and where he found it. Not all of them made it home: a cache of specimens buried along the way was spoiled by water. But a large set reached Philadelphia, and the botanist Frederick Pursh described many of them in his book on North American plants in 1814. Pursh named two new plant groups for the captains: *Lewisia*, which includes the bitterroot, Montana's state flower, and *Clarkia*. More than two hundred of the expedition's pressed plants still survive, most of them at the Academy of Natural Sciences in Philadelphia. Botanists today can open the folders and check Pursh's work for themselves.

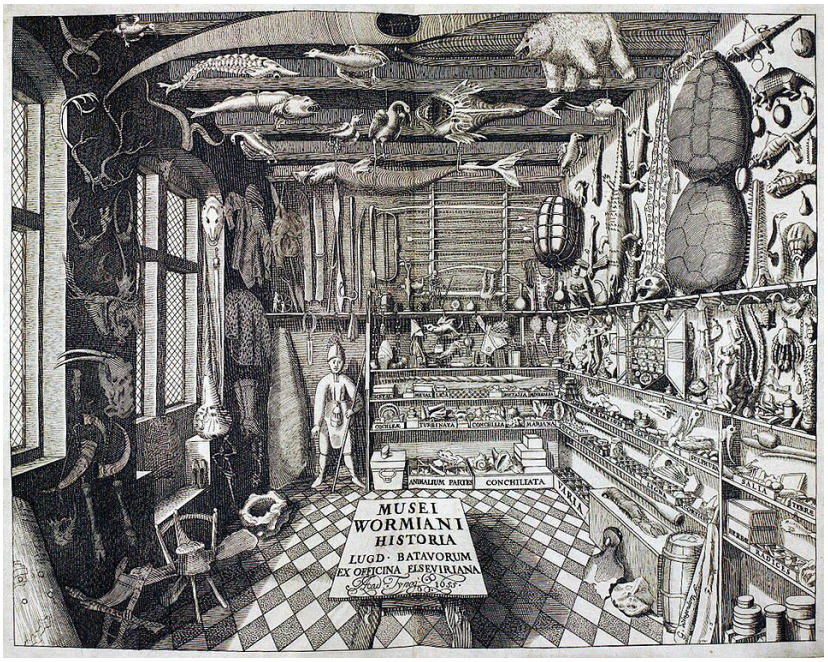
How it is done. A **specimen** is evidence you can hold. To make a plant specimen, collect a piece with leaves (and flowers or seeds if possible), arrange it flat between newspaper, press it between cardboard under weight, and change the paper as it absorbs moisture. The plant is dry when its mass stops changing. Then mount it on heavy paper with a **data label**: name, date, exact place, habitat and collector. A labeled **voucher specimen** lets anyone check an identification later. This matters, as the Danish naturalist Ole Worm showed in the 1600s when he demonstrated that the "unicorn horns" sold in Europe were really narwhal tusks: a specimen in hand settles questions that stories cannot. To sort a collection, scientists use a **dichotomous key**, a chain of two-way choices based on traits you can see, the same Linnaean habit of grouping by visible likeness you met earlier in this course.

God's handiwork, and our care. Solomon "spake of trees, from the cedar tree that is in Lebanon even unto the hyssop that springeth out of the wall," and of beasts, birds, creeping things and fishes. A home collection follows in his steps, with rules that show good stewardship. Collect only common plants, only where you have permission, and take only a small part. Never collect protected or rare species. In the United States, the feathers, nests and eggs of most wild native birds may not legally be kept, so photograph them instead. A photograph with full data is a fine "virtual specimen," and many naturalists now collect that way.



A simple dichotomous key for four common trees. Each step offers two choices based on a trait you can see.

PICTURE STUDY



Frontispiece of the Museum Wormianum, Engraver for Ole Worm's catalogue, 1655 · Engraving · Printed in Leiden, the Netherlands; copies of the book are held in rare-book libraries in many countries.

Ole Worm was a Danish physician and professor in Copenhagen who gathered one of the most famous "cabinets of curiosities" of his time: shells, minerals, fossils, plants, stuffed animals, tools and objects from faraway lands. A year after his death in 1654, a catalogue of the collection was published with this engraving as its opening picture.

Worm's cabinet was more than a show of oddities. He used his specimens to test claims, and he wrote careful descriptions of them. Natural history museums, herbaria and home specimen boxes all descend from rooms like this one.

Look closely

- Find the animals hanging from the ceiling. How many can you count?
- Look at the boxes on the shelves. Some carry labels. Why would a collector label boxes instead of single objects?
- Find horns and antlers on the walls. How are they arranged?
- Look for shells, stones and other small objects. Can you tell any of them apart?

Talk about it

1. What is the difference between a room of curiosities and a scientific collection?
2. If Worm's labels were lost, what would his specimens still be able to teach? What would be lost?
3. How would you arrange your own collection so that a visitor could learn from it?

> **Safety first.** Collect only with an adult's permission and the landowner's permission. Learn to recognize poison ivy, poison oak and poison sumac before you go, and never collect them. Watch for thorns and stinging nettle, and wear gloves. Use pruning shears or scissors carefully, cutting away from your body. Never taste any plant, berry or mushroom, and do not collect wild mushrooms. Wash your hands after collecting.

EXPERIMENT: A TEN-SPECIMEN HERBARIUM (AND A DRYING TEST)

You will collect, press, mount and label ten plant specimens and build a key for them. Along the way you will run a small experiment. The question: **Does changing the newspaper every day make plant specimens dry faster than leaving the same paper in place?**

You will need

- Newspaper and corrugated cardboard cut to the same size (about 30 cm × 45 cm)
- Heavy books, bricks or a plant press with straps
- Pruning shears or scissors, gloves and a bag or folder for carrying specimens
- Kitchen scale that reads to 0.1 g
- Ten sheets of heavy cardstock
- White glue or narrow strips of paper tape
- Labels, a fine pen and a hand lens

Steps

1. Write your prediction for the drying test.
2. Collect ten common plants, each from a different species if possible: a leafy stem from each, with flowers or seeds if present. Write the date, exact place and habitat in your

notebook as you collect each one.
3. Choose two plants of the same kind (two similar sprigs of clover or two maple leaves) for the experiment. Weigh each and record its starting mass.
4. Arrange every specimen flat inside a folded sheet of newspaper, with at least one leaf turned to show its underside. Stack the folders with cardboard between them and put weight on top.
5. Experiment: for one test plant, replace its newspaper with dry newspaper every day. Leave the other test plant in the same newspaper. Keep both under the same weight in the same room.
6. Weigh both test plants every two days and record the mass. A plant is dry when its mass stops changing.
7. When all specimens are dry (often one to two weeks), mount each on cardstock with glue or paper strips and attach a data label in the lower right corner.
8. Write a dichotomous key that separates your ten specimens, and test it on a family member.
9. Graph the mass of the two test plants over time and write your conclusion.

Tips

- **What we change:** whether the paper is changed daily. **What we keep the same:** the kind and size of plant, the weight on top, the room. **What we measure:** mass every two days and the day each plant is fully dry.
- Plants that dry slowly can turn brown or grow mold, which is why herbarium workers change the paper often.
- If collecting is not allowed where you are, make a photo herbarium: photograph each plant beside a ruler and add the same data label.

Check your work

- Every specimen has a complete data label: name or description, date, exact place, habitat and collector.
- I collected only common plants, with permission, and took only small parts.
- My drying-test graph and conclusion use real measured masses.

NATURE NOTEBOOK

1. Draw one specimen sheet as it will look when finished, with the plant placed and the data label in the corner.
2. Draw one leaf from each of your specimens at half size and label its arrangement (opposite or alternate) and whether it is simple or compound.
3. Draw the narwhal and its long tusk, and write one sentence about how Ole Worm used real specimens to correct a false story.

> **From history.** After Carl Linnaeus died in 1778, his great collection of pressed plants, insects, shells and books was offered for sale. In 1784 a young English naturalist, James

Edward Smith, bought it and shipped it to London. A few years later he founded the Linnean Society of London, which still cares for Linnaeus's herbarium today, so that botanists can compare their plants with the very specimens Linnaeus used when he named them.

WORKED EXAMPLES

Example 1. A student weighs a fresh maple sprig while pressing it: Day 0, 8.0 g; Day 2, 5.1 g; Day 4, 3.2 g; Day 6, 2.2 g; Day 8, 2.0 g; Day 10, 2.0 g. (a) On which day was it fully dry? (b) What percent of the fresh mass was water? (c) What was the average rate of mass loss in the first 4 days?

1. (a) The mass stopped changing between Day 8 and Day 10 (2.0 g both times), so it was dry by Day 8.
2. (b) Water lost: 8.0 g − 2.0 g = 6.0 g. Percent water: 6.0 ÷ 8.0 = 0.75 = 75%.
3. (c) Mass lost in the first 4 days: 8.0 g − 3.2 g = 4.8 g. Rate: 4.8 g ÷ 4 days = 1.2 g per day.

Answer: (a) Day 8. (b) 75% water. (c) 1.2 g per day in the first 4 days; the drying then slowed down.

PRACTICE

1. EASY List five pieces of information that belong on a specimen's data label, and explain why the exact place matters.
2. EASY Use the key in the figure. A twig has leaves in pairs across from each other, and each leaf is made of several leaflets on one stalk. What tree is it? What tree has alternate, simple leaves?
   (Use the map or drawing "Use this key." shown earlier in this lesson.)
3. MEDIUM A student pressed two similar 10.0 g plant samples. Sample A had its newspaper changed daily; sample B did not. Masses in grams:
   Day 0: A 10.0, B 10.0
   Day 2: A 6.0, B 7.5
   Day 4: A 3.5, B 5.5
   Day 6: A 2.6, B 4.0
   Day 8: A 2.5, B 3.0
   Day 10: A 2.5, B 2.6
   (a) Which sample dried faster? (b) By which day was A fully dry, and how do you know? (c) What percent of A's fresh mass was water? (d) Is B certainly dry on Day 10? Explain.
4. HARD Explain why a museum keeps a labeled voucher specimen instead of just writing down the name of the plant that was found. Use Ole Worm or the Lewis and Clark collection as an example.
5. CHALLENGE Design an experiment to test whether pressed flowers keep more of their color when dried in a dark closet than on a sunny windowsill. Give the variables, controls

and what you will measure.

COMMON MISTAKES

- Thinking the specimen is what matters and the label is extra. A specimen with no place or date is nearly useless to science.
- Assuming any feather, nest or egg found outdoors may be kept. In the United States, those of most wild native birds are protected by law.
- Using traits in a key that change with the season or the age of the plant, such as flower color, when a steady trait such as leaf arrangement would work better.

Make it a game · Mystery Specimen Key. One player secretly chooses a specimen from the herbarium. The others may only ask yes-or-no questions about traits you can see ("Are the leaves opposite?" "Is the edge toothed?"), just like steps in a key. Write each question down. The player who names the specimen in the fewest questions wins the round, and the winning set of questions becomes a new dichotomous key.

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)

God gave Solomon wisdom that reached from the tallest tree to the smallest wall plant. Collecting, naming and describing the creatures of a place is an old and honorable part of wisdom.

Practice answers

1. Name (or description if unknown), date collected, exact place (for example, town, road or GPS coordinates), habitat (such as damp shade at a woods edge) and collector's name. The place lets other scientists know where the plant grows and go back to find it again, and it shows changes over time.
2. Opposite and compound: ash. Alternate and simple: oak (in this key).
3. (a) A, the one with daily paper changes: it lost mass faster at every step. (b) Day 8, because its mass did not change from Day 8 to Day 10 (2.5 g). (c) 7.5 g ÷ 10.0 g = 75%. (d) Not certainly: B's mass was still falling (3.0 g to 2.6 g), so it should be weighed again until two readings in a row are the same.
4. A name can be a mistake, but a specimen can be checked. If someone later doubts an identification or the species is renamed, scientists can look at the actual plant. Ole Worm used real narwhal tusks to show that "unicorn horns" came from a whale, and botanists today can still open Lewis and Clark's pressed plants and confirm what Pursh described.
5. Sample answer: Press several flowers of the same kind and color, picked the same day, split into two equal groups. Independent variable: light (dark closet or sunny windowsill). Dependent variable: color after drying, judged by comparing each flower to a paint-chip color card or by photographing them in the same light. Keep the same: kind of flower, press and weight, paper, number of days and room temperature (if possible). Use at least five flowers in each group and have someone who does not know which group is which judge the colors.

Unit 9 review

This six-problem review is worth 60 points. Show your work for calculations, draw neatly for the diagram item, and use complete sentences for explanations.

1. (10 pts) (a) Multiple choice: Which journal entry is an inference? A. The leaf is 7 cm long. B. The air is 16°C in the shade. C. A squirrel buried acorns here. D. Three crows called from the oak. (b) A student takes 30 paces over a measured 24 m. How long is a path she walks in 250 paces?
2. (10 pts) A student places six 0.5 m × 0.5 m quadrats at random on a 15 m × 8 m lawn and counts plantain plants: 3, 5, 2, 6, 4, 4. (a) Find the density per square meter. (b) Estimate the total number of plantain plants on the lawn. (c) Why should the quadrats be placed at random?
3. (10 pts) Data reading. Species richness in five quadrats: Open meadow: 9, 7, 8, 10, 6. Under pine trees: 2, 3, 1, 3, 1. (a) Find each mean. (b) About how many times richer is the meadow? (c) Multiple choice: Which is the best conclusion? A. Pine trees kill all plants. B. In this survey, the meadow quadrats had higher species richness than the quadrats under pines. C. Sunlight is the only cause of the difference. D. Five quadrats prove the result for every forest.
4. (10 pts) Diagram item. In cattle, black (B) is dominant over red (b). Draw and fill in a Punnett square for a Bb bull and a bb cow. Label each box black or red, give the expected ratio, and predict how many of 16 calves will be red.
5. (10 pts) A museum sign reads: “This American mastodon was found in a bog in New York. Its shoulder height was about 2.7 m. It lived during the Ice Age and died out about 11,000 years ago.” (a) List two observations and two interpretations in the sign. (b) Name two things you could record with scan sampling at a zoo, and what an ethogram is.
6. (10 pts) (a) A fresh leaf weighs 6.0 g. After pressing, its mass is 1.5 g on Day 7 and 1.5 g on Day 9. What percent of the fresh leaf was water, and how do you know it is dry? (b) Name four things a data label must include. (c) Experiment design: you want to know whether thick cardboard between specimens makes them dry faster than no cardboard. Name the independent variable, the dependent variable and two controls.

Unit project: my nature lab field book

Gather the work of this unit into one field book that a real naturalist would be proud of: your journal walk pages with a route map in meters, your quadrat survey table and bar graph, your zoo, farm or museum data sheet with its graph or Punnett square, and at least ten mounted herbarium specimens with full data labels and your own dichotomous key. Finish with a one-page written report titled “What I Observed and What I Inferred,” explaining one discovery from each lesson and how you kept your observations separate from your interpretations.

- **Records**: Every page and specimen has a complete header or label: date, time or season, exact place, weather or habitat and collector.

- **Measurement and math**: Distances, densities, percents and ratios are calculated correctly with units, and graphs are labeled and accurate.
- **Scientific thinking**: Questions, predictions, variables and controls are stated; observations are kept apart from inferences; conclusions do not claim more than the data show.
- **Care and stewardship**: Sketches are neat and measured, specimens are well pressed and mounted, and all collecting was done legally, with permission and with care for the land.

Answer key

1. (a) C. No one saw the squirrel bury acorns; it is an explanation of what was seen. (b) 24 m ÷ 30 = 0.8 m per pace; 250 × 0.8 m = 200 m.
2. (a) Total 24 in 6 × 0.25 m^2 = 1.5 m^2, so 24 ÷ 1.5 = 16 per m^2. (b) Lawn area 120 m^2; 16 × 120 = 1,920, about 1,900 plants. (c) Random placement keeps the counter from choosing spots that are unusually thick or thin, so the sample fairly represents the whole lawn.
3. (a) Meadow 40 ÷ 5 = 8.0; pines 10 ÷ 5 = 2.0. (b) About 4 times. (c) B. It states what the data show without claiming more than one survey can prove.
4. Top: B, b. Side: b, b. Boxes: Bb (black), bb (red), Bb (black), bb (red). Ratio 1 black : 1 red (1 Bb : 1 bb). Expected red calves: 16 × 1/2 = 8.
5. (a) Observations: found in a bog in New York; shoulder height about 2.7 m (a measurement of the bones). Interpretations: that it lived during “the Ice Age” as the museum dates it; that it died out about 11,000 years ago (an age calculated with assumptions about the past). Many Christians read these bones as belonging to an Ice Age after the Flood. (b) For example: how often the animal is eating and how often it is resting, recorded at fixed intervals such as every minute. An ethogram is a list of an animal’s behaviors with clear definitions so they are recorded the same way each time.
6. (a) Water: 6.0 − 1.5 = 4.5 g; 4.5 ÷ 6.0 = 75%. It is dry because its mass did not change between Day 7 and Day 9. (b) Any four of: name or description, date, exact place, habitat, collector. (c) Independent: cardboard or no cardboard. Dependent: mass over time, or number of days until mass stops changing. Controls (any two): same kind and size of plant, same weight on top, same newspaper, same room, same weighing schedule.