High School Biology

First edition | **9 units + optional The Human Body (Optional Bonus Unit)** | **40 lessons**

One credit with lab | **A video for every lesson** | **Worksheets A and B with keys**

Where this leads

Fields of study: Biology, Medicine, Nursing, Veterinary science, Agriculture and animal science, Forestry and wildlife management, Biotechnology, Public health.

Jobs and careers (trades, licenses and degree paths):

- DEGREE Physician, dentist or physician assistant
- DEGREE Registered nurse
- DEGREE Veterinarian
- DEGREE Wildlife biologist or game warden
- DEGREE Agronomist or plant breeder
- 2-YR / CERT Veterinary technician
- 2-YR / CERT Medical laboratory technician
- 2-YR / CERT EMT or paramedic
- TRADE Farmer, rancher or beekeeper
- TRADE Arborist or landscaper
- FIELD Park ranger or naturalist

Key topics and where they're used:

- **Cells and the microscope**: medical labs, pathology, food safety
- **Genetics and DNA**: plant and animal breeding, medicine, forensics
- **Microbes**: nursing, sanitation, food and brewing
- **Ecology and stewardship**: farming, ranching, forestry, wildlife management

Paths are examples, not promises. Most careers need further training, an apprenticeship, a license or a degree.

FIRST EDITION

Course guide

This is a full-year, college-preparatory biology course with lab for students in grades 9–10. It covers the whole introductory core: the study of life and the microscope, the chemistry of life, cells, photosynthesis and respiration, heredity, DNA and the genetic code, variation and origins, the diversity of living things, and ecology and stewardship, with an optional bonus unit on the human body. Every lesson has key terms, the story of its discovery, worked examples, a practice set with answers, a lab,

two printable worksheets (A and B) with separate answer keys, and a history note. Each unit ends with a 100-point test, Unit 8 ends with a lab practical, and there is a midterm after Unit 5 and a final after Unit 9, all with printable keys for the parent.

Biology was discovered by people who looked closely and counted carefully, and the course is built around them: Redi covering his jars, Leeuwenhoek writing to the Royal Society about the animalcules in his teeth, Mendel counting 28,000 pea plants, Franklin's X-ray photograph, Fleming noticing a moldy dish. The labs use a microscope (or a phone clip-on lens), onions, eggs, potatoes, yeast, strawberries, agar plates, a flower and a dissection, real or virtual. Many of these scientists, Ray, Linnaeus, Mendel and Pasteur among them, were men of faith who studied living things as the works of God, and the course says so where it is true.

Unit 7, on variation, adaptation and origins, follows the same approach as the site's Life Science and High School Geology courses: observations first, claims about the unobserved past labeled as interpretations, and every view (young-earth creation, old-earth creation, intelligent design and Darwinian theory) stated fairly in terms its own holders would accept before it is weighed. A parent should read Unit 7 before the student begins it.

> Videos were chosen lesson by lesson from trusted teaching channels: the Amoeba Sisters (short, clear animated lessons), Bozeman Science, Khan Academy, MooMooMath and Science, Cognito, the Cornell Lab of Ornithology and Carolina Biological's Carolina Science, with a few history and origins videos from Discovery Science and the Institute for Creation Research in Unit 7 and elsewhere. Each video was matched to its lesson by topic, channel and length and confirmed to play embedded; as with any video, a parent preview is wise, especially in Units 6–8. Most run under 10 minutes; a few longer ones have a note saying how to watch them.

Start with Lesson 1.1 →

Who it is for

Written for students in grades 9–10. Algebra I, before or at the same time, helps with probability, Punnett ratios and population graphs. Chemistry is not required: Unit 2 teaches the chemistry biology needs, so Biology can come first and Chemistry follow in grades 10–11. Students work fairly independently, reading each lesson and

checking their own practice, with a parent present for the dissection, agar plates and anything involving heat or chemicals.

How to use this course

1. **The weekly rhythm.** Each lesson takes four sessions of 20–50 minutes: (1) warm-up, video and core ideas; (2) worked examples and the first practice questions; (3) the lab and lab notebook; (4) the rest of the practice set and Worksheet A, checked and corrected. Worksheet B is a second set for review or a retake. Each unit ends with a test day, and the midterm and final each have a review day. At five sessions a week the nine core units fill about 32 weeks; the optional Human Body unit adds about four.
2. **Story, then biology, then use.** Read the core ideas in order. The story and "how they figured it out" explain why the idea exists; then comes the biology, then where it is used today.
3. **Practice and worksheets.** Questions are marked easy, medium and hard. Mark your work against the answers the same day and correct every miss. The printable worksheets have separate keys for the parent.
4. **The lab notebook.** Use a bound notebook for the whole year. For every lab write the date, question, hypothesis with a reason, procedure, observations and sketches with the magnification, a data table, a graph where it fits, and a conclusion with sources of error.
5. **Tests and exams.** Each unit test is worth 100 points and mixes short answers, a few calculations, a lab-data question and a short essay. The Unit 7 essay is graded first on whether each view of origins is stated accurately and fairly (a rubric is in the key). The Unit 8 lab practical asks the student to identify slides and specimens and label a dissection.
6. **Reproduction and the human body.** Lessons 5.4 (meiosis, XX and XY) and 6.4 (biotechnology and bioethics) touch on human reproduction and the beginning of life. They are written plainly and modestly from the conviction that every human being is made in the image of God; parents may wish to read them first.
7. **Safety.** Read the safety note before every lab. Agar plates are sealed with tape and never reopened, then destroyed with bleach by an adult. Never eat wild mushrooms or plants. Wear gloves and goggles for dissection, and wash hands after handling soil, pond water or raw meat.

Scope and sequence

UNIT 1 · WEEKS 1–4

The Study of Life

What life is, Redi, Spallanzani and Pasteur overturning spontaneous generation, Hooke and Leeuwenhoek at the microscope, and naming living things from John Ray to Linnaeus.

1.1 What Is Life? Seven Marks of Living Things (“O LORD, how manifold are thy works!”)

1.2 Life from Life: Redi (1668), Spallanzani (1768) and Pasteur’s Swan-Neck Flasks (1859–1862)

1.3 The Microscope: Hooke’s Micrographia (1665), Leeuwenhoek’s Animalcules and the Wet Mount

1.4 Naming the Living World: John Ray (1691) and Linnaeus’s Systema Naturae (1735)

UNIT 2 · WEEKS 4–7

The Chemistry of Life

The chemistry biology needs: water and pH, carbohydrates and lipids from Wöhler’s urea, proteins and enzymes, and Miescher’s nucleic acids.

2.1 Atoms, Water and pH for Biologists

2.2 Carbohydrates and Lipids: Wöhler’s Urea (1828) and Organic Chemistry

2.3 Proteins and Enzymes: Fischer’s Lock and Key and Sumner’s Urease Crystal (1926)

2.4 Nucleic Acids: Miescher’s “Nuclein” (1869)

UNIT 3 · WEEKS 7–11

Cells

Cell theory from Schleiden, Schwann and Virchow, the organelles as a workshop, membranes, diffusion and osmosis, and Flemming’s mitosis.

3.1 Cell Theory: Schleiden (1838), Schwann (1839) and Virchow’s “Every Cell from a Cell” (1855)

3.2 Organelles: The Cell as a Workshop

3.3 Membranes, Diffusion and Osmosis

3.4 Cell Division: Flemming Sees Mitosis (1882)

UNIT 4 · WEEKS 11–14

Energy in Living Things

Van Helmont’s willow to Ingenhousz’s sunlight, photosynthesis and the Calvin cycle, cellular respiration and Krebs, and Pasteur’s fermentation.

4.1 Van Helmont’s Willow, Priestley’s Mint and Ingenhousz’s Sunlight (1648–1779)

4.2 Photosynthesis: Light Reactions and the Calvin Cycle

4.3 Cellular Respiration: Krebs and the Citric Acid Cycle (1937)

4.4 Fermentation: Pasteur, Yeast and Tired Muscles

UNIT 5 · WEEKS 14–18

Heredity

Mendel's peas and the rediscovery of 1900, probability and Punnett squares, blood types and Morgan's fly, and meiosis, chromosomes and pedigrees.

5.1 The Friar and His Peas: Mendel (1865–1866) and the Rediscovery of 1900

5.2 Probability, Punnett Squares and Dihybrid Crosses

5.3 Beyond Mendel: Incomplete Dominance, Blood Types and Morgan's White-Eyed Fly (1910)

5.4 Meiosis, Chromosomes and Pedigrees (Male and Female, XX and XY)

UNIT 6 · WEEKS 18–21

DNA and the Genetic Code

Griffith, Avery and Hershey–Chase, the double helix of Franklin, Watson and Crick, the genetic code, and mutations, biotechnology and bioethics.

6.1 Finding the Genetic Material: Griffith (1928), Avery (1944), Hershey and Chase (1952)

6.2 The Double Helix: Chargaff, Franklin (Photo 51, 1952), Watson and Crick (1953)

6.3 Replication, Transcription and Translation: Nirenberg Cracks the Code (1961)

6.4 Mutations, Biotechnology and Bioethics: Mullis's PCR (1983) and the Image of God

UNIT 7 · WEEKS 21–25

Variation, Adaptation and Origins

What Darwin observed, variation and adaptation within kinds, the case for common descent and the open questions, and the views of origins fairly compared.

7.1 Darwin's Voyage (1831–1836) and What He Observed

7.2 Variation Within Kinds: Finch Beaks, Peppered Moths, Antibiotic Resistance and Blyth's Conserving Selection (1835)

7.3 Common Descent: The Claim, the Evidence Offered and the Open Questions

7.4 Origins Fairly Told: Creation, Intelligent Design and Darwinian Theory Compared

UNIT 8 · WEEKS 25–28

The Diversity of Life

Bacteria and viruses with Jenner, Koch and Pasteur, protists and fungi with Fleming's penicillin, plants with Grew and Hales, and animals with Cuvier and the dissection lab.

8.1 Bacteria and Viruses: Jenner (1796), Koch's Postulates (1884) and Pasteur's Rabies Vaccine (1885)

8.2 Protists and Fungi: Fleming's Penicillin (1928)

8.3 Plants: Grew, Malpighi and Hales's Vegetable Staticks (1727)

8.4 Animals: Cuvier's Comparative Anatomy and the Dissection Lab

UNIT 9 · WEEKS 28–31

Ecology and Stewardship

Food webs and Elton's pyramid, the water, carbon and nitrogen cycles, population growth and Gause's experiments, and dominion and wildlife stewardship.

9.1 Ecosystems, Food Webs and Elton's Pyramid (1927)

9.2 Cycles of Matter: Water ("All the Rivers Run into the Sea"), Carbon and Nitrogen

9.3 Populations: Growth, Carrying Capacity and Gause's Experiments (1934)

9.4 Dominion and Care: Game Management, the Bison and the Duck Stamp (1934)

UNIT 10 · WEEKS 32–35

The Human Body (Optional Bonus Unit)

Optional: Vesalius and the skeleton, Harvey and the circulation, Beaumont and digestion, and nerves, the senses and Damadian's MRI.

10.1 Vesalius and the Skeleton: De Humani Corporis Fabrica (1543)

10.2 Harvey and the Circulation of the Blood (1628): "The Life of the Flesh Is in the Blood"

10.3 Beaumont and Digestion (1822–1833)

10.4 Nerves, Senses and Damadian's MRI (1970s)

Weekly pacing calendar

WEEK	PLAN
1	• Day 1: Lesson 1.1 What Is Life? Seven Marks of Living Things ("O LORD, how manifold are thy works!"): warm-up, video and core ideas • Day 2: Lesson 1.1: worked examples and first practice problems • Day 3: Lesson 1.1: lab and lab notebook • Day 4: Lesson 1.1: practice set, Worksheet A and corrections • Day 5: Lesson 1.2 Life from Life: Redi (1668), Spallanzani (1768) and Pasteur's Swan-Neck Flasks (1859–1862): warm-up, video and core ideas *Five sessions a week of about 45 minutes. Families on a four-day week can combine the practice day of one lesson with the first day of the next.*
2	• Day 1: Lesson 1.2: worked examples and first practice problems • Day 2: Lesson 1.2: lab and lab notebook • Day 3: Lesson 1.2: practice set, Worksheet A and corrections • Day 4: Lesson 1.3 The Microscope: Hooke's Micrographia (1665), Leeuwenhoek's Animalcules and the Wet Mount: warm-up, video and core ideas • Day 5: Lesson 1.3: worked examples and first practice problems
3	• Day 1: Lesson 1.3: lab and lab notebook • Day 2: Lesson 1.3: practice set, Worksheet A and corrections

WEEK	PLAN
	• Day 3: Lesson 1.4 Naming the Living World: John Ray (1691) and Linnaeus's Systema Naturae (1735): warm-up, video and core ideas • Day 4: Lesson 1.4: worked examples and first practice problems • Day 5: Lesson 1.4: lab and lab notebook
4	• Day 1: Lesson 1.4: practice set, Worksheet A and corrections • Day 2: Unit 1 test (Worksheet B sets make a good review the day before) • Day 3: Lesson 2.1 Atoms, Water and pH for Biologists: warm-up, video and core ideas • Day 4: Lesson 2.1: worked examples and first practice problems • Day 5: Lesson 2.1: lab and lab notebook
5	• Day 1: Lesson 2.1: practice set, Worksheet A and corrections • Day 2: Lesson 2.2 Carbohydrates and Lipids: Wöhler's Urea (1828) and Organic Chemistry: warm-up, video and core ideas • Day 3: Lesson 2.2: worked examples and first practice problems • Day 4: Lesson 2.2: lab and lab notebook • Day 5: Lesson 2.2: practice set, Worksheet A and corrections
6	• Day 1: Lesson 2.3 Proteins and Enzymes: Fischer's Lock and Key and Sumner's Urease Crystal (1926): warm-up, video and core ideas • Day 2: Lesson 2.3: worked examples and first practice problems • Day 3: Lesson 2.3: lab and lab notebook • Day 4: Lesson 2.3: practice set, Worksheet A and corrections • Day 5: Lesson 2.4 Nucleic Acids: Miescher's "Nuclein" (1869): warm-up, video and core ideas
7	• Day 1: Lesson 2.4: worked examples and first practice problems • Day 2: Lesson 2.4: lab and lab notebook • Day 3: Lesson 2.4: practice set, Worksheet A and corrections • Day 4: Unit 2 test (Worksheet B sets make a good review the day before) • Day 5: Lesson 3.1 Cell Theory: Schleiden (1838), Schwann (1839) and Virchow's "Every Cell from a Cell" (1855): warm-up, video and core ideas

WEEK	PLAN
8	• Day 1: Lesson 3.1: worked examples and first practice problems • Day 2: Lesson 3.1: lab and lab notebook • Day 3: Lesson 3.1: practice set, Worksheet A and corrections • Day 4: Lesson 3.2 Organelles: The Cell as a Workshop: warm-up, video and core ideas • Day 5: Lesson 3.2: worked examples and first practice problems
9	• Day 1: Lesson 3.2: lab and lab notebook • Day 2: Lesson 3.2: practice set, Worksheet A and corrections • Day 3: Lesson 3.3 Membranes, Diffusion and Osmosis: warm-up, video and core ideas • Day 4: Lesson 3.3: worked examples and first practice problems • Day 5: Lesson 3.3: lab and lab notebook
10	• Day 1: Lesson 3.3: practice set, Worksheet A and corrections • Day 2: Lesson 3.4 Cell Division: Flemming Sees Mitosis (1882): warm-up, video and core ideas • Day 3: Lesson 3.4: worked examples and first practice problems • Day 4: Lesson 3.4: lab and lab notebook • Day 5: Lesson 3.4: practice set, Worksheet A and corrections
11	• Day 1: Unit 3 test (Worksheet B sets make a good review the day before) • Day 2: Lesson 4.1 Van Helmont's Willow, Priestley's Mint and Ingenhousz's Sunlight (1648–1779): warm-up, video and core ideas • Day 3: Lesson 4.1: worked examples and first practice problems • Day 4: Lesson 4.1: lab and lab notebook • Day 5: Lesson 4.1: practice set, Worksheet A and corrections
12	• Day 1: Lesson 4.2 Photosynthesis: Light Reactions and the Calvin Cycle: warm-up, video and core ideas • Day 2: Lesson 4.2: worked examples and first practice problems • Day 3: Lesson 4.2: lab and lab notebook • Day 4: Lesson 4.2: practice set, Worksheet A and corrections • Day 5: Lesson 4.3 Cellular Respiration: Krebs and the Citric Acid Cycle (1937): warm-up, video and core ideas
13	• Day 1: Lesson 4.3: worked examples and first practice problems • Day 2: Lesson 4.3: lab and lab notebook • Day 3: Lesson 4.3: practice set, Worksheet A and corrections

WEEK	PLAN
	• Day 4: Lesson 4.4 Fermentation: Pasteur, Yeast and Tired Muscles: warm-up, video and core ideas • Day 5: Lesson 4.4: worked examples and first practice problems
14	• Day 1: Lesson 4.4: lab and lab notebook • Day 2: Lesson 4.4: practice set, Worksheet A and corrections • Day 3: Unit 4 test (Worksheet B sets make a good review the day before) • Day 4: Lesson 5.1 The Friar and His Peas: Mendel (1865–1866) and the Rediscovery of 1900: warm-up, video and core ideas • Day 5: Lesson 5.1: worked examples and first practice problems
15	• Day 1: Lesson 5.1: lab and lab notebook • Day 2: Lesson 5.1: practice set, Worksheet A and corrections • Day 3: Lesson 5.2 Probability, Punnett Squares and Dihybrid Crosses: warm-up, video and core ideas • Day 4: Lesson 5.2: worked examples and first practice problems • Day 5: Lesson 5.2: lab and lab notebook
16	• Day 1: Lesson 5.2: practice set, Worksheet A and corrections • Day 2: Lesson 5.3 Beyond Mendel: Incomplete Dominance, Blood Types and Morgan's White-Eyed Fly (1910): warm-up, video and core ideas • Day 3: Lesson 5.3: worked examples and first practice problems • Day 4: Lesson 5.3: lab and lab notebook • Day 5: Lesson 5.3: practice set, Worksheet A and corrections
17	• Day 1: Lesson 5.4 Meiosis, Chromosomes and Pedigrees (Male and Female, XX and XY): warm-up, video and core ideas • Day 2: Lesson 5.4: worked examples and first practice problems • Day 3: Lesson 5.4: lab and lab notebook • Day 4: Lesson 5.4: practice set, Worksheet A and corrections • Day 5: Unit 5 test (Worksheet B sets make a good review the day before)

WEEK	PLAN
18	• Day 1: Midterm review: formula sheet and missed problems • Day 2: Midterm exam • Day 3: Lesson 6.1 Finding the Genetic Material: Griffith (1928), Avery (1944), Hershey and Chase (1952): warm-up, video and core ideas • Day 4: Lesson 6.1: worked examples and first practice problems • Day 5: Lesson 6.1: lab and lab notebook
19	• Day 1: Lesson 6.1: practice set, Worksheet A and corrections • Day 2: Lesson 6.2 The Double Helix: Chargaff, Franklin (Photo 51, 1952), Watson and Crick (1953): warm-up, video and core ideas • Day 3: Lesson 6.2: worked examples and first practice problems • Day 4: Lesson 6.2: lab and lab notebook • Day 5: Lesson 6.2: practice set, Worksheet A and corrections
20	• Day 1: Lesson 6.3 Replication, Transcription and Translation: Nirenberg Cracks the Code (1961): warm-up, video and core ideas • Day 2: Lesson 6.3: worked examples and first practice problems • Day 3: Lesson 6.3: lab and lab notebook • Day 4: Lesson 6.3: practice set, Worksheet A and corrections • Day 5: Lesson 6.4 Mutations, Biotechnology and Bioethics: Mullis's PCR (1983) and the Image of God: warm-up, video and core ideas
21	• Day 1: Lesson 6.4: worked examples and first practice problems • Day 2: Lesson 6.4: lab and lab notebook • Day 3: Lesson 6.4: practice set, Worksheet A and corrections • Day 4: Unit 6 test (Worksheet B sets make a good review the day before) • Day 5: Lesson 7.1 Darwin's Voyage (1831–1836) and What He Observed: warm-up, video and core ideas
22	• Day 1: Lesson 7.1: worked examples and first practice problems • Day 2: Lesson 7.1: lab and lab notebook • Day 3: Lesson 7.1: practice set, Worksheet A and corrections • Day 4: Lesson 7.2 Variation Within Kinds: Finch Beaks, Peppered Moths, Antibiotic Resistance and Blyth's Conserving Selection (1835): warm-up, video and core ideas • Day 5: Lesson 7.2: worked examples and first practice problems
23	• Day 1: Lesson 7.2: lab and lab notebook

WEEK	PLAN
	• Day 2: Lesson 7.2: practice set, Worksheet A and corrections • Day 3: Lesson 7.3 Common Descent: The Claim, the Evidence Offered and the Open Questions: warm-up, video and core ideas • Day 4: Lesson 7.3: worked examples and first practice problems • Day 5: Lesson 7.3: lab and lab notebook
24	• Day 1: Lesson 7.3: practice set, Worksheet A and corrections • Day 2: Lesson 7.4 Origins Fairly Told: Creation, Intelligent Design and Darwinian Theory Compared: warm-up, video and core ideas • Day 3: Lesson 7.4: worked examples and first practice problems • Day 4: Lesson 7.4: lab and lab notebook • Day 5: Lesson 7.4: practice set, Worksheet A and corrections
25	• Day 1: Unit 7 test (Worksheet B sets make a good review the day before) • Day 2: Lesson 8.1 Bacteria and Viruses: Jenner (1796), Koch's Postulates (1884) and Pasteur's Rabies Vaccine (1885): warm-up, video and core ideas • Day 3: Lesson 8.1: worked examples and first practice problems • Day 4: Lesson 8.1: lab and lab notebook • Day 5: Lesson 8.1: practice set, Worksheet A and corrections
26	• Day 1: Lesson 8.2 Protists and Fungi: Fleming's Penicillin (1928): warm-up, video and core ideas • Day 2: Lesson 8.2: worked examples and first practice problems • Day 3: Lesson 8.2: lab and lab notebook • Day 4: Lesson 8.2: practice set, Worksheet A and corrections • Day 5: Lesson 8.3 Plants: Grew, Malpighi and Hales's Vegetable Staticks (1727): warm-up, video and core ideas
27	• Day 1: Lesson 8.3: worked examples and first practice problems • Day 2: Lesson 8.3: lab and lab notebook • Day 3: Lesson 8.3: practice set, Worksheet A and corrections • Day 4: Lesson 8.4 Animals: Cuvier's Comparative Anatomy and the Dissection Lab: warm-up, video and core ideas • Day 5: Lesson 8.4: worked examples and first practice problems
28	• Day 1: Lesson 8.4: lab and lab notebook • Day 2: Lesson 8.4: practice set, Worksheet A and corrections • Day 3: Unit 8 test (Worksheet B sets make a good review the day before)

WEEK	PLAN
	• Day 4: Lesson 9.1 Ecosystems, Food Webs and Elton's Pyramid (1927): warm-up, video and core ideas • Day 5: Lesson 9.1: worked examples and first practice problems
29	• Day 1: Lesson 9.1: lab and lab notebook • Day 2: Lesson 9.1: practice set, Worksheet A and corrections • Day 3: Lesson 9.2 Cycles of Matter: Water ("All the Rivers Run into the Sea"), Carbon and Nitrogen: warm-up, video and core ideas • Day 4: Lesson 9.2: worked examples and first practice problems • Day 5: Lesson 9.2: lab and lab notebook
30	• Day 1: Lesson 9.2: practice set, Worksheet A and corrections • Day 2: Lesson 9.3 Populations: Growth, Carrying Capacity and Gause's Experiments (1934): warm-up, video and core ideas • Day 3: Lesson 9.3: worked examples and first practice problems • Day 4: Lesson 9.3: lab and lab notebook • Day 5: Lesson 9.3: practice set, Worksheet A and corrections
31	• Day 1: Lesson 9.4 Dominion and Care: Game Management, the Bison and the Duck Stamp (1934): warm-up, video and core ideas • Day 2: Lesson 9.4: worked examples and first practice problems • Day 3: Lesson 9.4: lab and lab notebook • Day 4: Lesson 9.4: practice set, Worksheet A and corrections • Day 5: Unit 9 test (Worksheet B sets make a good review the day before)
32	• Day 1: Final review • Day 2: Final exam • Day 3: Lesson 10.1 Vesalius and the Skeleton: De Humani Corporis Fabrica (1543): warm-up, video and core ideas • Day 4: Lesson 10.1: worked examples and first practice problems • Day 5: Lesson 10.1: lab and lab notebook

WEEK	PLAN
33	• Day 1: Lesson 10.1: practice set, Worksheet A and corrections • Day 2: Lesson 10.2 Harvey and the Circulation of the Blood (1628): “The Life of the Flesh Is in the Blood”: warm-up, video and core ideas • Day 3: Lesson 10.2: worked examples and first practice problems • Day 4: Lesson 10.2: lab and lab notebook • Day 5: Lesson 10.2: practice set, Worksheet A and corrections
34	• Day 1: Lesson 10.3 Beaumont and Digestion (1822–1833): warm-up, video and core ideas • Day 2: Lesson 10.3: worked examples and first practice problems • Day 3: Lesson 10.3: lab and lab notebook • Day 4: Lesson 10.3: practice set, Worksheet A and corrections • Day 5: Lesson 10.4 Nerves, Senses and Damadian’s MRI (1970s): warm-up, video and core ideas
35	• Day 1: Lesson 10.4: worked examples and first practice problems • Day 2: Lesson 10.4: lab and lab notebook • Day 3: Lesson 10.4: practice set, Worksheet A and corrections • Day 4: Unit 10 test (Worksheet B sets make a good review the day before)

Materials

Microscope

Budget path: a phone clip-on microscope, about $20. Full path: a compound microscope (40–1000×, LED, mechanical stage), about $150–250, which will also serve a younger sibling for years.

Slides and stains

Blank slides, cover slips and a prepared-slide set (onion root tip, blood, bacteria, protists), about $15–40; iodine tincture and optional methylene blue, about $8–15.

Dissection

A dissection kit with an earthworm and a perch or frog, about $40–70, or a free virtual dissection.

Agar plates and test strips

Ten pre-poured nutrient agar plates (about $15); PTC taste strips and pond nitrate and pH strips (about $15).

Safety

Splash goggles and nitrile gloves (about $20, shared with Chemistry).

Kitchen and garden supplies

Onions, potatoes, eggs, corn syrup, vinegar, yeast, sugar, strawberries, dish soap, rubbing alcohol, baking soda, a syringe, crackers, pineapple, gelatin, a chicken wing, a hula hoop, bread and store mushrooms; about $25.

Bound lab notebook, pencil, ruler, colored pencils

For every lab, sketch and corrected practice set.

Budget

The core lab total is about $150 on the budget path and about $350–400 with a compound microscope and real dissection specimens.

Grading

Grades come from the practice sets, the labs and the Unit 8 lab practical, the lab notebook, the unit tests, the midterm and the final. A lab earns full credit for honest observations carefully recorded and explained, even when the result is not what was expected.

PART	%
Practice sets and worksheets (completed and corrected)	**15**
Labs and lab practical	**25**
Lab notebook (sketches, data, honesty)	**10**
Unit tests	**30**
Midterm exam	**10**
Final exam	**10**

Scale: A 90–100, B 80–89, C 70–79, D 60–69, F below 60.

- Practice is graded for completion and correction: a question done, checked and correctly reworked earns full credit.

- The Unit 7 essay is graded first on fairness, using the rubric in the key, not on which view the student holds.
- Unit 10 is optional and is not on the midterm or final. If it is taken, count its test with the other unit tests.
- For a high-school transcript this course is one full credit of laboratory biology.

A NOTE TO PARENTS

You do not need to know biology to supervise this course well. Your jobs are to keep the rhythm, check the practice against the answers, ask the student to explain one idea aloud each week, look over the lab notebook, set up the Unit 8 lab practical, and be present for the dissection and the agar plates.

Unit 7 deals with origins. It teaches what is observed (variation, adaptation and selection within kinds) as fact, labels claims about the unobserved past as interpretations, and asks the student to state each view fairly before weighing it, by the rule of Proverbs 18:17. It draws on creation-friendly sources such as the Institute for Creation Research and Discovery Science as well as mainstream biology. Please read the unit first so you can discuss it together.

Human beings are taught as made in God's image, male and female (Genesis 1:27), with sex taught as XX and XY biology. Bioethics in Lesson 6.4 begins from the worth of every human life at every stage. Ecology is taught as stewardship: careful measurement in the service of the dominion God gave, with conservation told through its successes.

Series verse: "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)

UNIT 1

The Study of Life

What makes a living thing alive, and where do living things come from? This first unit lays the groundwork for the whole course: the marks of life, the experiments of Redi, Spallanzani and Pasteur that overturned the old belief in spontaneous generation, the microscope that opened the world of cells to Hooke and Leeuwenhoek, and the system of names that John Ray and Carl Linnaeus gave to the living world.

Students learn to use a microscope and make a wet mount, skills they will use all year. If you do not yet own a microscope, Lesson 1.3 gives a budget path.

PREREQUISITES

- None. A curious mind and a notebook.

MASTERY CHECKLIST

- ☐ I can list and explain the characteristics shared by living things.
- ☐ I can describe how Redi, Spallanzani and Pasteur disproved spontaneous generation, and why controls matter.
- ☐ I can use a compound microscope, calculate magnification and make a wet mount.
- ☐ I can explain binomial nomenclature and use a dichotomous key.

LESSONS IN THIS UNIT

1.1 What Is Life? Seven Marks of Living Things (“O LORD, how manifold are thy works!”)

4 sessions of 45 minutes

1.2 Life from Life: Redi (1668), Spallanzani (1768) and Pasteur’s Swan-Neck Flasks (1859–1862)

4 sessions of 45 minutes

1.3 The Microscope: Hooke's Micrographia (1665), Leeuwenhoek's Animalcules and the Wet Mount

4 sessions of 45 minutes

1.4 Naming the Living World: John Ray (1691) and Linnaeus's Systema Naturae (1735)

4 sessions of 45 minutes

Unit 1 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **9 pts** **Lesson 1.1**
   What stimulus did the yeast respond to?

2. **9 pts** **Lesson 1.1**
   What does biology mean?

3. **9 pts** **Lesson 1.2**
   Spallanzani was a priest; Pasteur was a devout believer. Did their faith hinder their science? Explain.

4. **8 pts** **Lesson 1.2**
   What is the dependent variable in an experiment?

5. **8 pts** **Lesson 1.3**
   Name two parts of a compound microscope.

6. **8 pts** **Lesson 1.3**
   Why do you lower a cover slip at an angle?

7. **8 pts** **Lesson 1.3**

   At 40× total (4× objective) the field of view is 5.0 mm across. At 100× (10× objective), what is the field diameter? If 6 cells fit across it end to end, how long is one cell in micrometers?

8. **8 pts** **Lesson 1.4**

   Which level is broader: kingdom or phylum?

9. **8 pts** **Lesson 1.4**

   Write a good first couplet for a key separating a pine needle, an oak leaf and a maple leaf.

LAB AND DATA

10. **10 pts**

    Pasteur boiled broth in two flasks. One had a straight neck open to the air; the other had a long S-shaped “swan neck” that let air in but trapped dust. After weeks, only the straight-necked flask was cloudy with microbes. (a) What was the independent variable? (b) Why was the swan neck important? (c) What happened when he tipped the swan-neck flask so broth touched the dust in the bend?

SHORT ESSAY

11. **15 pts**

    “O LORD, how manifold are thy works!” (Psalm 104:24). Choose one scientist from this unit and explain how careful observation or experiment changed what people believed about living things. Include what was believed before and the evidence that changed it.

ANSWER KEY

1. Sugar (food) and warmth.
2. The study of life.
3. No; both did careful experiments that overturned a popular belief, and both saw nature as orderly creation worth studying.
4. The factor measured to see the effect.
5. Eyepiece, objective, stage, diaphragm, focus knobs, light.
6. To push out air so bubbles do not hide the specimen.
7. 2.0 mm; about 333 µm per cell
   Field shrinks in proportion: 5.0 × 4/10 = 2.0 mm · 2.0 mm ÷ 6 = 0.333 mm = 333 µm
8. Kingdom.
9. 1a. Leaf needle-like → pine; 1b. Leaf broad and flat → go to 2.
10. (a) Whether dust (carrying microbes) could reach the broth. (b) It let in air, answering the objection that boiling or sealing destroyed a "vital force" in air, while keeping out microbes. (c) The broth soon became cloudy, showing that microbes came from the dust, not from the broth itself.
11. Look for: accurate history (Redi's covered jars 1668, Spallanzani's sealed flasks 1768, Pasteur's swan-neck flasks 1859–1862, Hooke's Micrographia 1665, Leeuwenhoek's animalcules 1670s, Ray's species concept 1686, Linnaeus 1735); the old belief clearly stated; the experiment and its control described; what changed; a connection to the wonder of creation is welcome but not required.

Printable answer key (PDF, for the parent)

1.1 What Is Life? Seven Marks of Living Things ("O LORD, how manifold are thy works!")

OBJECTIVES

- List and explain the characteristics of living things.
- Distinguish living, once-living and nonliving things.
- Describe the levels of organization from cell to biosphere.

> **Warm-up.** Make three columns: living, once living, never living. Sort ten things from around the house and yard: a dog, a wooden spoon, a rock, a mushroom, a candle flame, a seed, a leaf on the ground, a crystal, a cotton shirt, yourself. Which were hard to decide?

WATCH

GCSE Biology - Characteristics of Living Things (Organisms)

Cognito · 6:23

https://www.youtube.com/watch?v=aGDFNZApXXI

> **WHEN TO WATCH**
> After the warm-up.

BACKUP VIDEO

Characteristics of Living Things-What makes something alive?

MooMooMath and Science · 3:14

https://www.youtube.com/watch?v=30qOijVBS7o

As a review after the core ideas.

KEY TERMS

organism

An individual living thing.

cell

The smallest unit that can carry out all the processes of life.

metabolism

All the chemical reactions by which an organism builds up and breaks down materials and uses energy.

homeostasis

Keeping a stable internal environment, such as body temperature.

stimulus

A change in the environment that causes an organism to respond.

biology

The study of living things.

CORE IDEAS

The story. People have always known the difference between a sleeping cat and a stone, but saying exactly what life is turns out to be hard. Aristotle sorted the world into nonliving things, plants (which grow and reproduce), animals (which also sense and move) and people (who also reason). Modern biologists use a checklist instead. Psalm 104 is a hymn to the variety of life God sustains: grass for cattle, trees for birds, the sea "wherein are things creeping innumerable."

How they figured it out. Biologists noticed that every living thing shares certain marks, and a thing that has only one or two (fire grows and uses oxygen; crystals grow) is not alive. The common list: (1) made of one or more cells; (2) uses energy (metabolism); (3) grows and develops; (4) responds to stimuli; (5) reproduces; (6) maintains homeostasis; (7) has inherited instructions in DNA. Viruses are the famous puzzle: they have genetic material and reproduce, but only inside a living cell (Unit 8).

The biology. Life is organized in levels: molecules form cells; cells form tissues; tissues form organs; organs form organ systems; systems form an organism. Organisms of one kind in one place are a population; populations together form a community; a community with its nonliving surroundings is an ecosystem; all ecosystems together are the biosphere. Each level has properties the level below does not.

Where it is used. Doctors check homeostasis (temperature, blood sugar, blood pressure) to judge health. Farmers manage growth and reproduction; ecologists study populations and ecosystems. NASA used a checklist like this one when it designed experiments to look for life on Mars.

LAB

Is It Alive? Yeast and the Seven Marks

You will test baker's yeast for several marks of life.

You will need

- A packet of dry yeast, sugar, warm water, three small bottles, three balloons
- A magnifier or microscope if available

Steps

1. Bottle 1: yeast + warm water. Bottle 2: yeast + warm water + 1 tsp sugar. Bottle 3: sugar + warm water, no yeast.
2. Stretch a balloon over each and wait 30 minutes. Record balloon size and smell.
3. Look at a drop from bottle 2 under magnification if you can: are there tiny round cells, some budding?
4. Fill in a checklist of the seven marks with evidence for each.

Check your work

- ☐ Which bottle produced gas? What was the control?
- ☐ Which marks of life did yeast show?

LAB NOTEBOOK

1. Data and observations for all three bottles.
2. A seven-mark checklist for yeast with evidence.

> **From history.** Carl Linnaeus divided nature into three kingdoms: animal, vegetable and mineral. Biology as a word was coined about 1800 by several writers, including Jean-Baptiste Lamarck and Gottfried Treviranus.

WORKED EXAMPLES

Example 1. Is a flame alive? Use the characteristics.

▼ **Show solution**

1. A flame uses energy and fuel, grows and can “reproduce” by spreading.
2. But it has no cells, no DNA, no homeostasis and no true response.
3. Having a few marks is not enough.

Answer: No: it lacks cells, DNA and homeostasis

Example 2. Put these in order from smallest to largest: organ, population, cell, ecosystem, tissue, organism.

▼ **Show solution**

1. Cell → tissue → organ → organism → population → ecosystem

Answer: Cell, tissue, organ, organism, population, ecosystem

PRACTICE

1. Easy List four characteristics of living things.

   ▼ **Show answer**

   Any four: cells, metabolism, growth and development, response to stimuli, reproduction, homeostasis, DNA.

2. Easy What is homeostasis? Give an example.

   ▼ **Show answer**

   Keeping a stable internal environment; sweating to cool down.

3. Medium Why is fire not alive though it grows and uses oxygen?

   ▼ **Show answer**

   It has no cells, DNA or homeostasis.

COMMON MISTAKES

- Calling something alive because it moves or grows.
- Forgetting that once-living things (wood, cotton) are no longer alive.
- Mixing up population (one kind) and community (many kinds).

Make it a game · Twenty Questions: Alive?. One person thinks of a thing; others ask only yes/no questions using the seven marks (“Is it made of cells?”). Name it in twenty questions.

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

Biology is the study of the manifold works of God, made in wisdom and filling the earth.

1.2 Life from Life: Redi (1668), Spallanzani (1768) and Pasteur's Swan-Neck Flasks (1859–1862)

OBJECTIVES

- Describe the theory of spontaneous generation and why people believed it.
- Explain the experiments of Redi, Spallanzani and Pasteur, including their controls.
- Identify independent, dependent and controlled variables in an experiment.

> **Warm-up.** Leave a slice of bread in a bag for a week (start it last week if you can). Where did the mold come from? Write down three possible explanations.

WATCH

Louis Pasteur | That's a Fact

Institute for Creation Research · 1:54

https://www.youtube.com/watch?v=THnWCXIvcpo

> **WHEN TO WATCH**
> After the story of Pasteur.

BACKUP VIDEO

Louis Pasteur: A Man of Science and Faith

Discovery Science · 34:13

https://www.youtube.com/watch?v=WAAdCqkUEkI

Optional longer biography (34 minutes) for a free afternoon.

KEY TERMS

spontaneous generation

The old idea that living things arise from nonliving matter, such as maggots from meat.

biogenesis

The principle that living things come only from other living things.

hypothesis

A testable explanation for an observation.

control group

The group in an experiment that does not receive the tested change, for comparison.

independent variable

The factor the experimenter deliberately changes.

dependent variable

The factor that is measured to see the effect.

CORE IDEAS

The story. For two thousand years people believed that frogs came from mud, maggots from rotting meat and mice from grain and dirty rags. In 1668 the Italian physician Francesco Redi put meat into jars: some open, some covered with gauze, some sealed. Flies laid eggs on the open meat and on the gauze; maggots appeared only where flies could reach. In 1768 Lazzaro Spallanzani, a priest and naturalist, boiled broth and sealed the flasks by melting the glass; they stayed clear. Critics said boiling and sealing had destroyed a "vital force" in the air.

How they figured it out. In 1859–1862 Louis Pasteur answered the critics. He boiled broth in flasks whose necks he had heated and drawn into a long S-shape. Air could flow freely in, but dust and microbes settled in the bend. The broth stayed clear for months; some of his flasks are still clear today at the Pasteur Institute. When he broke the neck or tipped the broth into the bend, microbes grew within days. The French Academy of Sciences awarded him its prize in 1862. Pasteur, a believer, is reported to have said that the more he studied nature, the more he stood amazed at the work of the Creator.

The biology. The principle of *biogenesis*, "life comes from life," is one of biology's foundations. These experiments also model the scientific method: an observation, a hypothesis, an experiment with one independent variable, a control group, measured results, a conclusion and others repeating the work. Good experiments change only one variable and keep everything else the same (controlled variables).

Where it is used. Pasteur's work led directly to pasteurization of milk and wine, to sterilizing surgical instruments (Joseph Lister, 1867), to canning, and to the germ theory of disease (Unit 8). Hospitals, kitchens and food factories all rely on the fact that microbes come from other microbes.

Safety first. Do not open cloudy jars indoors or smell them closely. Dispose of jars sealed, in the trash. Wash hands after handling bread.

LAB

Redi's Jars and Pasteur's Broth

You will repeat a version of the classic experiments safely with broth and bread.

You will need

- Four clean jars, bouillon cube broth, cheesecloth or a coffee filter, plastic wrap, rubber bands, a pot (adult)
- Two slices of bread, two zip-top bags

Steps

1. With an adult, boil broth for 10 minutes and pour it into four jars.
2. Jar 1: leave open. Jar 2: cover with cheesecloth. Jar 3: seal with plastic wrap while hot. Jar 4: open, but add a pinch of garden soil.
3. Bread: one slice in a bag after rubbing on the floor; one untouched in a bag. Seal both.
4. Observe daily for a week: cloudiness, smell (do not open sealed jars), mold.

Check your work

- ☐ Which jars became cloudy first?
- ☐ What did the soil jar show?
- ☐ Why must all jars hold the same broth at the same temperature?

LAB NOTEBOOK

1. A daily data table for jars and bread.
2. A conclusion naming the independent, dependent and controlled variables.

From history. Pasteur suffered a stroke in 1868 that partly paralyzed him, yet afterward he developed vaccines for chicken cholera, anthrax and rabies. His swan-neck flasks, sealed in the 1860s, remain sterile at the Pasteur Institute in Paris.

WORKED EXAMPLES

Example 1. In Redi's experiment, name the independent variable, the dependent variable and one controlled variable.

▼ **Show solution**

1. Independent: whether flies could reach the meat (open, gauze, sealed).
2. Dependent: whether maggots appeared on the meat.
3. Controlled: the type of meat, the jars, the temperature, the time.

Answer: Access by flies; maggots appearing; same meat and jars

Example 2. Why was Spallanzani's experiment not enough to convince everyone?

▼ **Show solution**

1. He sealed the flasks, so no fresh air could enter.
2. Critics claimed air contained a vital force needed for life to arise.
3. Pasteur's open swan neck let air in and still kept microbes out.

Answer: Sealing kept out air, leaving room for the vital-force objection

PRACTICE

1. Easy What is spontaneous generation?

   ▼ **Show answer**

   The old idea that living things arise from nonliving matter.

2. Easy What is biogenesis?

   ▼ **Show answer**

   The principle that life comes only from life.

3. Medium What did Redi's gauze-covered jar show?

   ▼ **Show answer**

   Flies laid eggs on the gauze but no maggots appeared on the meat, so maggots come from fly eggs.

COMMON MISTAKES

- Thinking one experiment settled the question forever; it took two centuries of better experiments.
- Changing more than one variable at a time.
- Forgetting the control group.

Make it a game · Spot the Control. The parent describes a simple experiment (does music help plants grow?). The student names the independent variable, the dependent variable, the control and two controlled variables.

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)

God made each plant to yield seed after his kind. Life comes from life, as Redi and Pasteur found by experiment.

1.3 The Microscope: Hooke's Micrographia (1665), Leeuwenhoek's Animalcules and the Wet Mount

OBJECTIVES

- Name the parts of a compound light microscope and use it correctly.
- Calculate total magnification and estimate the size of cells.
- Prepare a wet mount and draw what you see.

> **Warm-up.** Look at a newspaper letter "e" with your eye, then with a magnifying glass. How does it look different? Sketch both.

WATCH

Microscopes and How to Use a Light Microscope

Amoeba Sisters · 9:16

https://www.youtube.com/watch?v=tVcEEw6qbBQ

> **WHEN TO WATCH**
> Before the lab.

BACKUP VIDEO

How to Make a Wet Mount of Human Cheek Cells

Carolina Science · 1:30

https://www.youtube.com/watch?v=3aQYc6DeWsY

Just before making your cheek-cell slide.

KEY TERMS

compound microscope

A microscope with two sets of lenses, an eyepiece and an objective.

magnification

How many times larger an image appears than the object.

resolution

The ability to show two close points as separate.

field of view

The circle of light seen through the microscope.

wet mount

A slide with a specimen in a drop of water under a cover slip.

stain

A dye that colors parts of a cell to make them visible.

CORE IDEAS

The story. In 1665 Robert Hooke, curator of experiments at the Royal Society, published *Micrographia*, a book of astonishing drawings made with his compound microscope: a flea, a louse, the eye of a fly. Looking at a thin slice of cork, he saw tiny boxes and called them cells, like monks' rooms. In Delft, the cloth merchant Antonie van Leeuwenhoek ground tiny single lenses that magnified up to about 270 times. From 1673 he sent letters to the Royal Society describing "animalcules" swimming in pond water, bacteria scraped from his teeth, and red blood cells.

How they figured it out. A lens bends light so an object appears larger. A compound microscope uses an objective lens near the specimen and an eyepiece near the eye; their magnifications multiply. Magnification is useless without resolution, the sharpness to see small details separately. Light microscopes resolve down to about 0.2 micrometers. Electron microscopes, invented in the 1930s, resolve much smaller.

The biology. Total magnification = eyepiece × objective (10× × 40× = 400×). Parts: eyepiece, objectives on a revolving nosepiece, stage with clips, diaphragm controlling light, coarse and fine focus knobs, light source. Rules: carry with two hands; start on low power; use coarse focus only on low power; switch to high power and use only fine focus. As magnification increases, the field of view shrinks in proportion. Cells are measured in micrometers (μm): 1 mm = 1000 μm. A human cheek cell is about 60 μm across.

Where it is used. Doctors diagnose infections and cancers from slides; farmers check soil and water; forensic scientists compare hairs and fibers. The microscope opened the whole world of cells, which is the subject of Unit 3.

> **Safety first.** Iodine stains skin and clothes. Use a fresh toothpick and do not share. Wash hands after handling pond water. Never point a mirror microscope at the sun.

LAB

Cheek Cells, Onion Skin and Pond Water

You will make three wet mounts and draw what you see at two magnifications.

You will need

- A compound microscope (40×–400×), slides, cover slips, a dropper
- Iodine (Lugol's or drugstore tincture) or methylene blue stain, a flat toothpick, an onion, a sample of pond or puddle water
- Budget path: a $15 clip-on phone microscope or a borrowed microscope; or use microscope photographs from a library book

Steps

1. Onion: peel a thin, transparent layer from inside an onion scale. Lay it flat in a drop of water, add a drop of iodine at the edge, and lower a cover slip at an angle.
2. Cheek: gently scrape the inside of your cheek with the flat toothpick, smear on a slide, add stain and a cover slip.
3. Pond water: one drop from the bottom sediment, no stain.
4. For each, focus on low power, center, switch to high power, use fine focus, and draw a circle-framed sketch with magnification labeled.

Check your work

☐ Which cells had a regular, boxy shape? Why?

☐ What moved in the pond water?

LAB NOTEBOOK

1. Three labeled sketches with magnifications.
2. Size estimates for one onion and one cheek cell.

KEY FORMULAS

$$\text{total magnification} = \text{eyepiece} \times \text{objective}$$

$$1\ \text{mm} = 1000\ \mu\text{m}$$

> **From history.** Leeuwenhoek never revealed how he made his best lenses. Of the more than 500 he made, only about ten survive. He lived to 90 and kept sending letters to the Royal Society until his death in 1723.

WORKED EXAMPLES

Example 1. A 10× eyepiece is used with a 40× objective. The field of view at 40× was 4.5 mm. Find the total magnification and the field of view now.

▼ **Show solution**

1. Total: 10 × 40 = 400×.
2. Field shrinks by the ratio of magnifications: 4.5 × 40/400 = 0.45 mm.

Answer: 400×; 0.45 mm (450 µm)

Example 2. At 400× with a 450 µm field, about 8 cells fit across. How big is each cell?

▼ **Show solution**

1. 450 ÷ 8

Answer: About 56 µm

PRACTICE

1. Easy What did Hooke see in cork and what did he call it?

   ▼ **Show answer**

   Tiny boxes; he called them cells.

2. Easy A microscope has a 10× eyepiece and a 4× objective. What is the total magnification?

   ▼ **Show answer**

   40×

3. Medium What did Leeuwenhoek call the tiny living things he saw?

   ▼ **Show answer**

   Animalcules.

4. Hard At 40× total (4× objective) the field of view is 4.0 mm across. At 100× (10× objective), what is the field diameter? If 10 cells fit across it end to end, how long is one cell in micrometers?

   ▼ **Show answer**

   1.6 mm; about 160 µm per cell

5. Hard At 40× total (4× objective) the field of view is 5.0 mm across. At 400× (40× objective), what is the field diameter? If 4 cells fit across it end to end, how long is one cell in micrometers?

   ▼ **Show answer**

   0.50 mm; about 125 µm per cell

COMMON MISTAKES

- Using the coarse knob on high power and cracking the slide.
- Making the specimen too thick to see through.
- Forgetting that a microscope image is upside down and reversed.

> **Make it a game · Microscope Parts Relay.** The parent points to a part of the microscope (or a diagram); the student names it and its job in five seconds.

> **Scripture.** “The works of the LORD are great, sought out of all them that have pleasure therein.” (Psalm 111:2, KJV)
>
> The works of the LORD are great, sought out of all them that have pleasure therein. The microscope opened a world of His works too small to see.

1.4 Naming the Living World: John Ray (1691) and Linnaeus's Systema Naturae (1735)

OBJECTIVES

- Explain binomial nomenclature and write scientific names correctly.
- List the levels of classification from domain to species.
- Use and build a dichotomous key.

> **Warm-up.** A robin in England and a robin in America are different birds. A "buzzard" in Britain is a hawk; in America it is a vulture. Why might scientists need one name for each kind of animal?

WATCH

Taxonomy and scientific names

Khan Academy · 6:28

https://www.youtube.com/watch?v=kZPGOPh-xyk

> **WHEN TO WATCH**
> After the history.

BACKUP VIDEO

Dichotomous Keys: Identification Achievement Unlocked

Amoeba Sisters · 6:38

https://www.youtube.com/watch?v=wpKulkADzBk

Before building your own key.

KEY TERMS

taxonomy

The science of naming and classifying organisms.

binomial nomenclature

The two-part scientific name: genus and species, such as *Homo sapiens*.

genus

A group of closely related species; the first part of a scientific name.

species

A group of organisms that can interbreed and produce fertile offspring.

dichotomous key

A tool that identifies organisms through a series of paired choices.

domain

The broadest level of classification: Bacteria, Archaea or Eukarya.

CORE IDEAS

The story. Before 1700 a plant might have a Latin name a dozen words long. The English naturalist John Ray, a Puritan clergyman, spent his life cataloging plants and animals. In *The Wisdom of God Manifested in the Works of the Creation* (1691) he argued that the design of living things shows the Creator's wisdom, and he gave the first biological definition of a species: plants that breed true from seed. In 1735 the Swedish botanist Carl Linnaeus published *Systema Naturae*, sorting living things into nested groups, and in 1753 he gave every plant a short two-part name.

How they figured it out. Linnaeus grouped organisms by shared physical features: flowers by the number of stamens and pistils, animals by teeth, toes and body plan. A saying attributed to him sums up his view: God created, Linnaeus arranged. Later biologists added DNA comparisons and the level of domain (Carl Woese, 1977). Classification is revised as new evidence comes in.

The biology. The levels: domain, kingdom, phylum, class, order, family, genus, species ("Dear King Philip Came Over For Good Soup"). A scientific name has a capitalized genus and a lowercase species, in italics (or underlined by hand): *Canis lupus*, the gray wolf. A dichotomous key gives two choices at each step ("leaves needle-like" or "leaves broad") and leads to a name.

Where it is used. Scientific names let a doctor in Brazil and one in Japan know they are discussing the same bacterium; let farmers identify weeds and pests; let game wardens enforce hunting laws; and let botanists find medicinal plants. Field guides are built on keys.

LAB

Build a Leaf Key

You will collect leaves and build a dichotomous key that someone else can use.

You will need

- Eight to ten leaves from different trees or shrubs (or pictures), paper, a field guide or a plant ID app to check

Steps

1. Lay out the leaves. Choose a feature that splits them into two groups (simple vs compound, smooth vs toothed edge, needle vs broad).
2. Keep splitting each group in two until each leaf stands alone.
3. Write the key as numbered pairs of choices.
4. Have a family member use your key to identify two leaves without help.

Check your work

- ☐ Did your tester reach the right names?
- ☐ Which choices were confusing? How would you fix them?

LAB NOTEBOOK

1. Your dichotomous key.
2. Pressed leaves or sketches with their common and scientific names.

> **From history.** Linnaeus gave his rival botanists' names to ugly weeds and his friends' names to beautiful flowers. He named over 12,000 species and sent students around the world to collect; several died on the voyages.

WORKED EXAMPLES

Example 1. Write the scientific name of the domestic cat correctly. Its genus is Felis and its species name catus.

▼ **Show solution**

1. Capitalize the genus, lowercase the species, italicize both.

Answer: *Felis catus*

Example 2. Which are more closely related: two animals in the same family or two in the same order?

▼ **Show solution**

1. Family is a smaller, more specific group inside an order.

Answer: Same family

PRACTICE

1. Easy What are the two parts of a scientific name?

   ▼ **Show answer**

   Genus and species.

2. Easy List the eight levels of classification in order.

   ▼ **Show answer**

   Domain, kingdom, phylum, class, order, family, genus, species.

3. Medium Why do scientists use Latin scientific names instead of common names?

   ▼ **Show answer**

   Common names vary by place and language; one scientific name is used worldwide.

COMMON MISTAKES

- Capitalizing the species name or not italicizing.
- Making key choices that are not true opposites (“big” vs “green”).
- Thinking classification never changes.

Make it a game · King Philip Says. The parent calls a level (“order!”); the student says the next level down and the one above. Then reverse the mnemonic.

Scripture. “And out of the ground the LORD God formed every beast of the field, and every fowl of the air; and brought them unto Adam to see what he would call them: and whatsoever Adam called every living creature, that was the name thereof.” (Genesis 2:19, KJV)

Adam named the animals God brought to him. Taxonomy continues that first work of naming.

UNIT 1

The Study of Life

What makes a living thing alive, and where do living things come from? This first unit lays the groundwork for the whole course: the marks of life, the experiments of Redi, Spallanzani and Pasteur that overturned the old belief in spontaneous generation, the microscope that opened the world of cells to Hooke and Leeuwenhoek, and the system of names that John Ray and Carl Linnaeus gave to the living world.

Students learn to use a microscope and make a wet mount, skills they will use all year. If you do not yet own a microscope, Lesson 1.3 gives a budget path.

PREREQUISITES

- None. A curious mind and a notebook.

MASTERY CHECKLIST

- ☐ I can list and explain the characteristics shared by living things.
- ☐ I can describe how Redi, Spallanzani and Pasteur disproved spontaneous generation, and why controls matter.
- ☐ I can use a compound microscope, calculate magnification and make a wet mount.
- ☐ I can explain binomial nomenclature and use a dichotomous key.

LESSONS IN THIS UNIT

1.1 What Is Life? Seven Marks of Living Things (“O LORD, how manifold are thy works!”)

4 sessions of 45 minutes

1.2 Life from Life: Redi (1668), Spallanzani (1768) and Pasteur’s Swan-Neck Flasks (1859–1862)

4 sessions of 45 minutes

1.3 The Microscope: Hooke's Micrographia (1665), Leeuwenhoek's Animalcules and the Wet Mount

4 sessions of 45 minutes

1.4 Naming the Living World: John Ray (1691) and Linnaeus's Systema Naturae (1735)

4 sessions of 45 minutes

Unit 1 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **9 pts** **Lesson 1.1**
   What stimulus did the yeast respond to?

2. **9 pts** **Lesson 1.1**
   What does biology mean?

3. **9 pts** **Lesson 1.2**
   Spallanzani was a priest; Pasteur was a devout believer. Did their faith hinder their science? Explain.

4. **8 pts** **Lesson 1.2**
   What is the dependent variable in an experiment?

5. **8 pts** **Lesson 1.3**
   Name two parts of a compound microscope.

6. **8 pts** **Lesson 1.3**
   Why do you lower a cover slip at an angle?

7. **8 pts** **Lesson 1.3**

   At 40× total (4× objective) the field of view is 5.0 mm across. At 100× (10× objective), what is the field diameter? If 6 cells fit across it end to end, how long is one cell in micrometers?

8. **8 pts** **Lesson 1.4**

   Which level is broader: kingdom or phylum?

9. **8 pts** **Lesson 1.4**

   Write a good first couplet for a key separating a pine needle, an oak leaf and a maple leaf.

LAB AND DATA

10. **10 pts**

    Pasteur boiled broth in two flasks. One had a straight neck open to the air; the other had a long S-shaped “swan neck” that let air in but trapped dust. After weeks, only the straight-necked flask was cloudy with microbes. (a) What was the independent variable? (b) Why was the swan neck important? (c) What happened when he tipped the swan-neck flask so broth touched the dust in the bend?

SHORT ESSAY

11. **15 pts**

    “O LORD, how manifold are thy works!” (Psalm 104:24). Choose one scientist from this unit and explain how careful observation or experiment changed what people believed about living things. Include what was believed before and the evidence that changed it.

ANSWER KEY

1. Sugar (food) and warmth.
2. The study of life.
3. No; both did careful experiments that overturned a popular belief, and both saw nature as orderly creation worth studying.
4. The factor measured to see the effect.
5. Eyepiece, objective, stage, diaphragm, focus knobs, light.
6. To push out air so bubbles do not hide the specimen.
7. 2.0 mm; about 333 µm per cell
   Field shrinks in proportion: 5.0 × 4/10 = 2.0 mm · 2.0 mm ÷ 6 = 0.333 mm = 333 µm
8. Kingdom.
9. 1a. Leaf needle-like → pine; 1b. Leaf broad and flat → go to 2.
10. (a) Whether dust (carrying microbes) could reach the broth. (b) It let in air, answering the objection that boiling or sealing destroyed a "vital force" in air, while keeping out microbes. (c) The broth soon became cloudy, showing that microbes came from the dust, not from the broth itself.
11. Look for: accurate history (Redi's covered jars 1668, Spallanzani's sealed flasks 1768, Pasteur's swan-neck flasks 1859–1862, Hooke's Micrographia 1665, Leeuwenhoek's animalcules 1670s, Ray's species concept 1686, Linnaeus 1735); the old belief clearly stated; the experiment and its control described; what changed; a connection to the wonder of creation is welcome but not required.

Printable answer key (PDF, for the parent)

UNIT 2

The Chemistry of Life

Living things are made of the same atoms as rocks and air, put together with astonishing precision. This unit teaches the chemistry a biologist needs: atoms, bonds, water and pH, and the four great families of biological molecules: carbohydrates, lipids, proteins and nucleic acids. Students meet Wöhler, who made an organic compound from inorganic salts in 1828; Emil Fischer's lock-and-key enzymes; James Sumner, who crystallized an enzyme with one arm; and Friedrich Miescher, who found DNA in pus from bandages.

No chemistry course is required first; this unit teaches what is needed. Students who have taken Chemistry will find Lessons 2.1 and 2.2 a quick review.

PREREQUISITES

- Unit 1

MASTERY CHECKLIST

- ☐ I can describe atoms, ions, covalent bonds and hydrogen bonds, and explain water's properties that matter for life.
- ☐ I can explain pH and buffers in living things.
- ☐ I can identify carbohydrates, lipids, proteins and nucleic acids by their building blocks and jobs, and test foods for them.
- ☐ I can explain how enzymes work and what affects their activity.

LESSONS IN THIS UNIT

2.1 Atoms, Water and pH for Biologists — 4 sessions of 45 minutes

2.2 Carbohydrates and Lipids: Wöhler's Urea (1828) and Organic Chemistry

4 sessions of 45 minutes

2.3 Proteins and Enzymes: Fischer's Lock and Key and Sumner's Urease Crystal (1926)

4 sessions of 45 minutes

Unit 2 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 2.1**
   What is a hydrogen bond?

2. **10 pts** **Lesson 2.1**
   Why does a coastal city have milder temperatures than an inland one?

3. **10 pts** **Lesson 2.2**
   Name a steroid and its job.

4. **9 pts** **Lesson 2.2**
   What is a polymer?

5. **9 pts** **Lesson 2.3**
   Why is a fever above 41 °C dangerous?

6. **9 pts** **Lesson 2.3**
   What is the active site?

7. **9 pts** **Lesson 2.4**
   Why did it take until the 1940s to accept DNA as the genetic material?

8. **9 pts** **Lesson 2.4**
   What sugar is in DNA?

LAB AND DATA

9. **10 pts**

A student tests four foods. Iodine turns blue-black with food A; Benedict's solution turns orange when heated with food B; food C leaves a translucent spot on brown paper; biuret reagent turns violet with food D. Name the molecule each test detects.

SHORT ESSAY

10. **15 pts**

An enzyme is sometimes compared to a lock and its substrate to a key. Explain how enzymes speed reactions, why each enzyme acts on only certain molecules, and why a high fever or a change in pH can stop an enzyme from working.

ANSWER KEY

1. A weak attraction between a slightly positive H and a slightly negative atom like O.
2. The ocean's high specific heat absorbs heat in summer and releases it in winter.
3. Cholesterol (membranes) or a hormone such as testosterone or estrogen.
4. A large molecule made of many repeating monomers.
5. High temperatures begin to denature proteins, including enzymes.
6. The pocket on an enzyme where the substrate binds.
7. It seemed too simple (four bases) compared with proteins; Avery's 1944 experiment was needed.
8. Deoxyribose.
9. A: starch (iodine). B: simple sugars such as glucose (Benedict's). C: lipids (grease spot). D: protein (biuret).
10. Look for: enzymes are proteins (catalysts) that lower activation energy; the active site has a specific shape matching the substrate (Fischer's lock and key, later refined to induced fit); enzymes are not used up; heat and pH change break hydrogen bonds and other forces holding the protein's shape (denaturation), changing the active site so the substrate no longer fits.

Printable answer key (PDF, for the parent)

2.1 Atoms, Water and pH for Biologists

OBJECTIVES

- Describe atoms, elements, ions and covalent and hydrogen bonds.
- Explain the properties of water that make life possible.
- Explain pH and the role of buffers in the body.

> **Warm-up.** Fill a glass with water to the very brim, then keep adding drops. How high above the rim can the water dome before it spills? Why doesn't it spill sooner?

WATCH

Properties of Water

Amoeba Sisters · 6:51

https://www.youtube.com/watch?v=3jwAGWky98c

> **WHEN TO WATCH**
> After the core ideas on water.

BACKUP VIDEO

Water: A Polar Molecule

Bozeman Science · 8:37

https://www.youtube.com/watch?v=iOOvX0jmhJ4

For a review of polarity.

KEY TERMS

element
A pure substance made of only one kind of atom.

compound
A substance made of two or more elements chemically combined.

covalent bond
A bond formed when atoms share electrons.

hydrogen bond
A weak attraction between a slightly positive hydrogen and a slightly negative atom such as oxygen.

pH

A scale from 0 to 14 measuring how acidic or basic a solution is; 7 is neutral.

buffer

A substance that resists changes in pH.

CORE IDEAS

The story. Your body is about 65% oxygen, 18% carbon, 10% hydrogen and 3% nitrogen by mass, with calcium, phosphorus and traces of many others. Four elements, C, H, O and N, make up about 96% of living matter. In 1913 the Harvard physiologist Lawrence Henderson wrote *The Fitness of the Environment*, arguing that water and carbon have a remarkable set of properties that seem uniquely suited for life.

How they figured it out. Atoms combine by sharing electrons (covalent bonds) or by transferring them to form ions. In water, oxygen pulls the shared electrons harder than hydrogen does, so the molecule is polar: slightly negative at the oxygen, slightly positive at the hydrogens. Neighboring water molecules attract by hydrogen bonds. These weak bonds explain nearly every special property of water.

The biology. Water's properties: *cohesion* (water sticks to itself, giving surface tension) and *adhesion* (to other surfaces), which together lift water up plant stems; *high specific heat*, which steadies body and ocean temperatures; *ice floats*, so lakes freeze from the top and fish survive; and water *dissolves* many substances, so it carries nutrients in blood and sap. pH measures hydrogen ion concentration: each unit is a factor of 10. Blood stays at pH 7.35–7.45 thanks to buffers such as bicarbonate; stomach acid is about pH 2.

Where it is used. Sweating cools us because evaporating water carries off heat. Doctors watch blood pH closely in diabetic and kidney patients. Gardeners test soil pH. Water striders walk on water because of surface tension.

> **Safety first.** Rubbing alcohol is flammable: no flames. Do not touch hot lamps.

LAB

Water’s Strange Properties

You will measure surface tension, capillary action and specific heat with kitchen materials.

You will need

- A penny, a dropper, water, rubbing alcohol
- Celery stalk, food coloring, a glass
- Two identical pans, one with sand and one with water, a lamp, a thermometer
- pH strips or red cabbage indicator, lemon juice, milk, baking soda solution

Steps

1. Count drops of water and of alcohol that fit on a penny.
2. Stand a fresh-cut celery stalk in colored water overnight and look at the cut end the next day.
3. Set the sand and water pans under the same lamp for 20 minutes, measuring temperature every 5 minutes.
4. Test the pH of four household liquids.

Check your work

- ☐ Which liquid held more drops? Why?
- ☐ Which pan warmed faster? Why does this matter for coastal climates?

LAB NOTEBOOK

1. Data tables for all four tests.
2. One sentence linking each result to hydrogen bonding.

> **From history.** Henderson, though not a Christian apologist, concluded that the fitness of water and carbon for life could not be accidental. His argument is still discussed in debates about design.

WORKED EXAMPLES

Example 1. How many times more acidic is stomach acid (pH 2) than pure water (pH 7)?

▼ **Show solution**

1. Each unit is a factor of 10.
2. $7 - 2 = 5$ units: 10^5.

Answer: 100,000 times

Example 2. Explain why sweating cools you, using water's properties.

▼ **Show solution**

1. Evaporating water must break hydrogen bonds.
2. That energy comes from your skin as heat.

Answer: Evaporation carries away heat

PRACTICE

1. Easy Which four elements make up about 96% of living matter?

   ▼ **Show answer**

   Carbon, hydrogen, oxygen and nitrogen.

2. Easy What is the pH of pure water?

   ▼ **Show answer**

   7

3. Medium Why is water called polar?

   ▼ **Show answer**

   Oxygen pulls electrons harder, so the oxygen end is slightly negative and the hydrogen ends slightly positive.

COMMON MISTAKES

- Thinking pH 4 is only a little more acidic than pH 5 (it is 10 times).
- Calling the bonds inside a water molecule hydrogen bonds; those are covalent.
- Forgetting that ice is less dense than liquid water.

Make it a game · Water Superpowers. The parent describes a scene (a pond in winter, a tall redwood, a hot runner, a water strider). The student names the property of water at work.

Scripture. “Ho, every one that thirsteth, come ye to the waters, and he that hath no money; come ye, buy, and eat; yea, come, buy wine and milk without money and without price.” (Isaiah 55:1, KJV)

Water is the first thing life needs. Isaiah uses it for the free gift God offers to all who thirst.

2.2 Carbohydrates and Lipids: Wöhler's Urea (1828) and Organic Chemistry

OBJECTIVES

- Explain why carbon is the backbone of biological molecules.
- Describe monomers, polymers and dehydration synthesis and hydrolysis.
- Identify carbohydrates and lipids by structure and function.

> **Warm-up.** Chew a plain saltine cracker for two full minutes without swallowing. Does the taste change? What might be happening?

WATCH

Biomolecules (Updated 2023)

Amoeba Sisters · 7:49

https://www.youtube.com/watch?v=1Dx7LDwINLU

> **WHEN TO WATCH**
> After Wöhler's story.

BACKUP VIDEO

Carbohydrates

Bozeman Science · 8:49

https://www.youtube.com/watch?v=_zm_DyD6FJ0

With the carbohydrate section.

KEY TERMS

organic compound

A compound built on a carbon framework, usually with hydrogen.

monomer

A small molecule that can join with others to form a polymer.

polymer

A large molecule made of many repeating monomers.

carbohydrate

A sugar or starch made of C, H and O, used for energy and structure.

lipid

A fat, oil, wax or steroid; insoluble in water; stores energy and forms membranes.

dehydration synthesis

Joining monomers by removing a water molecule; hydrolysis is the reverse.

CORE IDEAS

The story. Early chemists believed that the compounds of living things could be made only by a "vital force" inside living organisms. In 1828 Friedrich Wöhler, a student of Berzelius, heated ammonium cyanate, an inorganic salt, and obtained urea, a compound found in urine. He wrote to Berzelius: "I can make urea without needing kidneys." Vitalism did not die at once, but organic chemistry, the chemistry of carbon compounds, was born.

How they figured it out. Carbon has four valence electrons and forms four strong covalent bonds, making chains, branches and rings of almost endless variety. Living things build large molecules (polymers) from small units (monomers) by dehydration synthesis, removing a water molecule at each link. Digestion does the reverse, hydrolysis, adding water to break links.

The biology. *Carbohydrates* (C, H, O in about a 1:2:1 ratio): monosaccharides such as glucose and fructose; disaccharides such as sucrose (table sugar) and lactose; polysaccharides such as starch (plant energy storage), glycogen (animal storage in liver and muscle) and cellulose (plant cell walls, the most abundant organic compound on earth). *Lipids*: fats and oils (glycerol plus three fatty acids; saturated fats are solid, unsaturated oils liquid), phospholipids (the double layer of cell membranes), steroids such as cholesterol and some hormones, and waxes. Fats store about twice the energy per gram of carbohydrates.

Where it is used. Bread, pasta and potatoes provide starch; cotton and paper are cellulose; animals that eat grass rely on microbes to digest cellulose. Bears store fat for winter. Cell membranes in every cell are phospholipid bilayers (Unit 3).

> **Safety first.** Goggles on. Iodine stains and is poisonous if swallowed. Benedict's solution contains copper sulfate: avoid skin and eyes. Adult handles hot water.

LAB

Testing Foods for Starch, Sugar and Fat

You will run classic food tests on kitchen foods.

You will need

- Iodine tincture, Benedict's solution (science supplier, about $8) or glucose test strips, brown paper bag
- Foods: potato, bread, apple juice, honey, butter, peanut, egg white, milk, water
- Small cups, droppers, a pan of hot water (adult)

Steps

1. Starch: add 2 drops of iodine to a sample of each food; blue-black means starch.
2. Sugar: mix a little food with water and Benedict's solution in a heat-safe cup set in very hot water for 5 minutes; green, orange or red means simple sugar.
3. Fat: rub each food on brown paper, let dry 10 minutes, and hold to the light; a translucent spot means fat.
4. Use water as a negative control in every test.

Check your work

- ☐ Which foods contained starch? Sugar? Fat?
- ☐ Why is water used as a control?

LAB NOTEBOOK

1. A results grid of foods × tests.
2. A conclusion matching foods to molecule types.

> **From history.** Wöhler and his friend Justus von Liebig discovered that two compounds can have the same formula but different structures (isomers), a key idea for understanding sugars such as glucose and fructose.

WORKED EXAMPLES

Example 1. Two glucose molecules ($C_6H_{12}O_6$) join by dehydration synthesis. What is the formula of the product?

▼ **Show solution**

1. Add: $C_{12}H_{24}O_{12}$
2. Remove one water: $C_{12}H_{22}O_{11}$ (maltose)

Answer: $C_{12}H_{22}O_{11}$

Example 2. Why did the saltine taste sweeter after two minutes?

▼ **Show solution**

1. Saliva contains the enzyme amylase.
2. It hydrolyzes starch into maltose, a sugar.

Answer: Starch was broken into sugar

PRACTICE

1. Easy What element is the backbone of organic compounds?

   ▼ **Show answer**

   Carbon.

2. Easy Name the monomer of starch.

   ▼ **Show answer**

   Glucose.

3. Medium What did Wöhler's synthesis of urea show?

   ▼ **Show answer**

   Organic compounds can be made from inorganic materials, without a vital force.

COMMON MISTAKES

- Calling all lipids fats; membranes and cholesterol are lipids too.
- Thinking cellulose is digestible by humans.
- Confusing dehydration synthesis (building) and hydrolysis (breaking).

Make it a game · Macro Match. The parent names a food or substance (cotton, olive oil, honey, steak fat, potato, cholesterol, a candle). The student names the molecule family and its monomer or parts.

Scripture. “He causeth the grass to grow for the cattle, and herb for the service of man: that he may bring forth food out of the earth; And wine that maketh glad the heart of man, and oil to make his face to shine, and bread which strengtheneth man’s heart.” (Psalm 104:14–15, KJV)

God causes grass and herbs to grow so that man may bring forth bread, oil and wine: carbohydrates and lipids from the field.

2.3 Proteins and Enzymes: Fischer's Lock and Key and Sumner's Urease Crystal (1926)

OBJECTIVES

- Describe amino acids, peptide bonds and the levels of protein structure.
- List jobs that proteins do in living things.
- Explain how enzymes work and what affects them.

> **Warm-up.** Crack an egg into a pan (adult) and watch the clear white turn solid white as it cooks. Can you un-cook it? What might heat be doing to the egg's molecules?

WATCH

Enzymes (Updated)

Amoeba Sisters · 5:47

https://www.youtube.com/watch?v=qgVFkRn8f10

> **WHEN TO WATCH**
> After the story.

BACKUP VIDEO

Protein Structure and Folding

Amoeba Sisters · 7:46

https://www.youtube.com/watch?v=hok2hyED9go

With protein structure.

KEY TERMS

amino acid

One of 20 small molecules that link to form proteins.

peptide bond

The covalent bond linking two amino acids.

protein

A large molecule of one or more folded chains of amino acids.

enzyme

A protein that speeds a chemical reaction without being used up.

active site

The pocket on an enzyme where the substrate binds.

denature

To change a protein's shape so it no longer works.

CORE IDEAS

The story. In 1894 Emil Fischer, who also worked out the structures of sugars, proposed that an enzyme fits its substrate like a lock fits a key. But what were enzymes made of? Many scientists doubted they were proteins at all. James Sumner at Cornell, who had lost his left arm in a hunting accident as a boy, worked for nine years to purify the enzyme urease from jack beans. In 1926 he obtained crystals and showed they were pure protein. He shared the 1946 Nobel Prize.

How they figured it out. Proteins are chains of amino acids joined by peptide bonds. Twenty amino acids, like letters of an alphabet, can spell an enormous variety of proteins. The sequence (primary structure) determines how the chain folds into coils and sheets (secondary), then a precise three-dimensional shape (tertiary), and sometimes several chains together (quaternary). Shape determines job.

The biology. Proteins do nearly everything: enzymes speed reactions; hemoglobin carries oxygen; antibodies fight infection; collagen and keratin build skin, hair and tendons; actin and myosin contract muscles; insulin signals cells. An enzyme lowers the activation energy of a reaction. Its substrate fits the active site, the reaction happens, and the enzyme is released unchanged. Daniel Koshland refined Fischer's idea in 1958: the active site flexes slightly to grip the substrate (induced fit). Heat, the wrong pH or certain chemicals denature an enzyme by disrupting the bonds that hold its shape.

Where it is used. Meat tenderizers contain papain, an enzyme from papaya; laundry detergents contain enzymes that digest stains; cheese is made with the enzyme rennet; people who lack the enzyme lactase cannot digest milk sugar. A fever above about 41 °C is dangerous partly because it begins to denature proteins.

> **Safety first.** Goggles on. Adult handles boiling water. 3% peroxide only; rinse skin if splashed.

LAB

Catalase: An Enzyme at Work

You will measure how temperature and pH affect the enzyme catalase in raw potato or liver.

You will need

- Raw potato (or chicken liver), 3% hydrogen peroxide, small cups or test tubes, a ruler
- Ice water, room water, hot water, boiling water (adult), vinegar, baking soda solution

Steps

1. Cut equal small cubes of potato. Drop one in 10 mL of peroxide and measure the height of the foam after 1 minute.
2. Soak cubes for 5 minutes in ice water, room water, hot water and boiling water before testing each the same way.
3. Soak cubes in vinegar and in baking soda solution and test.
4. Graph foam height versus temperature.

Check your work

- ☐ At what temperature was catalase most active?
- ☐ What did boiling do? Why?
- ☐ How did pH affect the enzyme?

LAB NOTEBOOK

1. Foam heights for all conditions and the temperature graph.
2. An explanation using denaturation.

> **From history.** Sumner was told he could never do chemistry with one arm. He learned to do everything left-handed with his remaining right arm, and played tennis and skied as well.

WORKED EXAMPLES

Example 1. A chain of 100 amino acids is made from 20 kinds. How many different sequences are possible?

▼ **Show solution**

1. 20 choices at each of 100 positions: 20^{100}.
2. That is about 10^{130}.

Answer: About 10^{130}, far more than the atoms in the visible universe

Example 2. Why does cooked egg white not turn clear again when cooled?

▼ **Show solution**

1. Heat denatured the proteins, unfolding them.
2. They tangled together in new bonds; the original folding is lost.

Answer: Denaturation is usually irreversible

PRACTICE

1. Easy What are the building blocks of proteins?

   ▼ **Show answer**

   Amino acids.

2. Easy What is an enzyme?

   ▼ **Show answer**

   A protein that speeds a reaction without being used up.

3. Medium What did Fischer's lock-and-key model propose?

   ▼ **Show answer**

   The substrate fits the enzyme's active site as a key fits a lock.

COMMON MISTAKES

- Thinking enzymes are used up in reactions.
- Saying enzymes "die" at high temperature; they are molecules, and they denature.
- Forgetting that each enzyme has its own best temperature and pH.

Make it a game · Protein Jobs. The parent names a protein (hemoglobin, insulin, keratin, amylase, antibody, collagen, myosin). The student gives its job in one sentence.

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)

Proteins folded in exact shapes do the work of every cell: part of how we are fearfully and wonderfully made.

2.4 Nucleic Acids: Miescher's "Nuclein" (1869)

OBJECTIVES

- Describe the structure of a nucleotide.
- Compare DNA and RNA.
- Explain the role of nucleic acids and of ATP.

> **Warm-up.** A recipe card, a blueprint and a computer program all store instructions. What would a cell need to store instructions, and what would those instructions be for?

WATCH

Nucleic Acids

Bozeman Science · 8:00

https://www.youtube.com/watch?v=NNASRkIU5Fw

> **WHEN TO WATCH**
> After the story.

BACKUP VIDEO

Introduction to nucleic acids and nucleotides

Khan Academy · 5:55

https://www.youtube.com/watch?v=hI4v7v8AdfI

With the DNA vs RNA comparison.

KEY TERMS

nucleic acid
A polymer of nucleotides that stores and transmits genetic information: DNA or RNA.

nucleotide
The monomer of a nucleic acid: a sugar, a phosphate and a nitrogen base.

DNA
Deoxyribonucleic acid, the double-stranded molecule of heredity.

RNA
Ribonucleic acid, a single-stranded nucleic acid that helps make proteins.

nitrogen base

Adenine, guanine, cytosine, thymine or uracil.

ATP

Adenosine triphosphate, the cell's energy currency, built from a nucleotide.

CORE IDEAS

The story. In 1869 the young Swiss doctor Friedrich Miescher, working in a castle-laboratory in Tübingen, wanted to study the chemistry of white blood cells. He got them from pus on used bandages from a nearby hospital. From the cell nuclei he extracted a new substance, rich in phosphorus and unlike any protein, and called it "nuclein." Later he found large amounts in salmon sperm. He suspected it might be involved in heredity but could not prove it. Seventy-five years passed before Avery showed that it was (Unit 6).

How they figured it out. Over the next decades Albrecht Kossel identified the five nitrogen bases (Nobel Prize 1910), and Phoebus Levene found that nucleic acids are chains of nucleotides, each made of a sugar, a phosphate and a base. DNA's sugar is deoxyribose; RNA's is ribose.

The biology. DNA is double-stranded, with bases A, T, G and C; it stays in the nucleus and stores the instructions for making proteins. RNA is usually single-stranded, uses U (uracil) instead of T, and carries and translates those instructions (Unit 6). The order of bases is the message, much as the order of letters makes words. ATP, a nucleotide with three phosphates, carries energy: breaking off the last phosphate releases energy that powers cell work (Unit 4).

Where it is used. DNA testing identifies people in criminal cases and family history, diagnoses inherited diseases and identifies food fraud. Every living cell runs on ATP; a human recycles roughly his own body weight of ATP each day.

> **Safety first.** Isopropyl alcohol is flammable and poisonous: no flames, do not drink. Work in a ventilated room.

LAB

Extracting DNA from Strawberries

You will extract visible strands of DNA from strawberries with kitchen materials.

You will need

- Three strawberries (or a banana), a zip-top bag
- Dish soap, salt, water, a coffee filter, a clear glass
- Ice-cold 91% isopropyl alcohol (kept in the freezer), a wooden skewer

Steps

1. Mix 1 tsp dish soap, 1/4 tsp salt and 1/2 cup water: the extraction buffer.
2. Mash the strawberries in the bag with 2 tbsp buffer for 2 minutes.
3. Filter the mash through the coffee filter into the glass.
4. Slowly pour an equal volume of ice-cold alcohol down the side of the glass. Wait 2 minutes. Wind the white, stringy DNA onto the skewer.

Check your work

- ☐ What did the soap do? The salt?
- ☐ Why does DNA appear only in the alcohol layer?

LAB NOTEBOOK

1. Observations with a sketch of the DNA strands.
2. The job of each ingredient.

> **From history.** Miescher died of tuberculosis at 51 in 1895. His uncle Wilhelm His wrote that Miescher's work would one day be valued; it is now considered the discovery of DNA.

WORKED EXAMPLES

Example 1. List three differences between DNA and RNA.

▼ **Show solution**

1. Sugar: deoxyribose vs ribose.
2. Bases: T in DNA, U in RNA.
3. Strands: DNA double, RNA usually single.

Answer: Sugar, base (T vs U), number of strands

Example 2. What are the three parts of a nucleotide?

▼ **Show solution**

1. A five-carbon sugar, a phosphate group and a nitrogen base.

Answer: Sugar, phosphate, base

PRACTICE

1. Easy What are the monomers of nucleic acids?

   ▼ **Show answer**

   Nucleotides.

2. Easy Name the four bases of DNA.

   ▼ **Show answer**

   Adenine, thymine, guanine, cytosine.

3. Medium What did Miescher discover in 1869, and from what?

   ▼ **Show answer**

   Nuclein (DNA), from white blood cells in pus on bandages.

COMMON MISTAKES

- Thinking the visible strands are a single DNA molecule (they are millions of molecules tangled together).
- Mixing up uracil and thymine.
- Forgetting that ATP is related to nucleotides.

Make it a game · Pair the Bases. The parent calls out a DNA base; the student calls its partner. Then switch to RNA (A pairs with U).

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)

Thine eyes did see my substance, yet being unperfect; and in thy book all my members were written. DNA is a written record within every cell.

UNIT 2

The Chemistry of Life

Living things are made of the same atoms as rocks and air, put together with astonishing precision. This unit teaches the chemistry a biologist needs: atoms, bonds, water and pH, and the four great families of biological molecules: carbohydrates, lipids, proteins and nucleic acids. Students meet Wöhler, who made an organic compound from inorganic salts in 1828; Emil Fischer's lock-and-key enzymes; James Sumner, who crystallized an enzyme with one arm; and Friedrich Miescher, who found DNA in pus from bandages.

No chemistry course is required first; this unit teaches what is needed. Students who have taken Chemistry will find Lessons 2.1 and 2.2 a quick review.

PREREQUISITES

- Unit 1

MASTERY CHECKLIST

- ☐ I can describe atoms, ions, covalent bonds and hydrogen bonds, and explain water's properties that matter for life.
- ☐ I can explain pH and buffers in living things.
- ☐ I can identify carbohydrates, lipids, proteins and nucleic acids by their building blocks and jobs, and test foods for them.
- ☐ I can explain how enzymes work and what affects their activity.

LESSONS IN THIS UNIT

2.1 Atoms, Water and pH for Biologists — 4 sessions of 45 minutes

2.2 Carbohydrates and Lipids: Wöhler's Urea (1828) and Organic Chemistry

4 sessions of 45 minutes

2.3 Proteins and Enzymes: Fischer's Lock and Key and Sumner's Urease Crystal (1926)

4 sessions of 45 minutes

Unit 2 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 2.1**
   What is a hydrogen bond?

2. **10 pts** **Lesson 2.1**
   Why does a coastal city have milder temperatures than an inland one?

3. **10 pts** **Lesson 2.2**
   Name a steroid and its job.

4. **9 pts** **Lesson 2.2**
   What is a polymer?

5. **9 pts** **Lesson 2.3**
   Why is a fever above 41 °C dangerous?

6. **9 pts** **Lesson 2.3**
   What is the active site?

7. **9 pts** **Lesson 2.4**
   Why did it take until the 1940s to accept DNA as the genetic material?

8. **9 pts** **Lesson 2.4**
   What sugar is in DNA?

LAB AND DATA

9. **10 pts**

A student tests four foods. Iodine turns blue-black with food A; Benedict's solution turns orange when heated with food B; food C leaves a translucent spot on brown paper; biuret reagent turns violet with food D. Name the molecule each test detects.

SHORT ESSAY

10. **15 pts**

An enzyme is sometimes compared to a lock and its substrate to a key. Explain how enzymes speed reactions, why each enzyme acts on only certain molecules, and why a high fever or a change in pH can stop an enzyme from working.

ANSWER KEY

1. A weak attraction between a slightly positive H and a slightly negative atom like O.
2. The ocean's high specific heat absorbs heat in summer and releases it in winter.
3. Cholesterol (membranes) or a hormone such as testosterone or estrogen.
4. A large molecule made of many repeating monomers.
5. High temperatures begin to denature proteins, including enzymes.
6. The pocket on an enzyme where the substrate binds.
7. It seemed too simple (four bases) compared with proteins; Avery's 1944 experiment was needed.
8. Deoxyribose.
9. A: starch (iodine). B: simple sugars such as glucose (Benedict's). C: lipids (grease spot). D: protein (biuret).
10. Look for: enzymes are proteins (catalysts) that lower activation energy; the active site has a specific shape matching the substrate (Fischer's lock and key, later refined to induced fit); enzymes are not used up; heat and pH change break hydrogen bonds and other forces holding the protein's shape (denaturation), changing the active site so the substrate no longer fits.

Printable answer key (PDF, for the parent)

UNIT 3

Cells

Every living thing is made of cells, and every cell comes from a cell. This unit follows the cell theory from Schleiden, Schwann and Virchow, tours the organelles of plant, animal and bacterial cells, explains how membranes control what enters and leaves by diffusion, osmosis and active transport, and watches cells divide as Walther Flemming first saw them in 1882.

The microscope is used in every lesson. The potato osmosis lab gives the first real data set of the year.

PREREQUISITES

- Unit 1 (microscope)
- Unit 2 (biological molecules)

MASTERY CHECKLIST

- ☐ I can state the cell theory and the scientists who built it.
- ☐ I can name the organelles of plant and animal cells and their jobs, and compare prokaryotes and eukaryotes.
- ☐ I can explain diffusion, osmosis and active transport and predict the effect of hypertonic and hypotonic solutions.
- ☐ I can describe the cell cycle and the stages of mitosis.

LESSONS IN THIS UNIT

3.1	**Cell Theory: Schleiden (1838), Schwann (1839) and Virchow's "Every Cell from a Cell" (1855)**	4 sessions of 45 minutes
3.2	**Organelles: The Cell as a Workshop**	4 sessions of 45 minutes
3.3	**Membranes, Diffusion and Osmosis**	4 sessions of 45 minutes
3.4	**Cell Division: Flemming Sees Mitosis (1882)**	4 sessions of 45 minutes

Unit 3 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **9 pts** **Lesson 3.1**

   How big are most cells?

2. **9 pts** **Lesson 3.1**

   What does the nucleus contain?

3. **9 pts** **Lesson 3.2**

   Do plant cells have mitochondria?

4. **8 pts** **Lesson 3.2**

   Why did the electron microscope revolutionize cell biology?

5. **8 pts** **Lesson 3.3**

   What did Nollet’s pig-bladder experiment show?

6. **8 pts** **Lesson 3.3**

   What are aquaporins?

7. **8 pts** **Lesson 3.3**

   A potato core weighed 2.83 g before soaking and 2.42 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

8. **8 pts** **Lesson 3.4**

   Most cells in the onion root were in interphase. What does that tell you?

9. **8 pts** **Lesson 3.4**

   What does mitosis do for a growing child?

LAB AND DATA

10. **10 pts**

Potato cores are soaked for 24 hours in sugar solutions. Percent change in mass: 0 M +12%, 0.2 M +4%, 0.4 M −3%, 0.6 M −9%. (a) In which solutions did water enter the cells? (b) Estimate the concentration at which the potato would neither gain nor lose mass. (c) What does that number tell you?

SHORT ESSAY

11. **15 pts**

Virchow wrote “Omnis cellula e cellula”: every cell from a cell. Explain the three parts of the cell theory, how Schleiden, Schwann and Virchow each contributed, and why the cell theory is a foundation for medicine.

ANSWER KEY

1. About 1–100 µm.
2. The cell’s DNA.
3. Yes.
4. Its far higher resolution revealed organelles invisible with light.
5. Water moves across a membrane toward the more concentrated side (osmosis).
6. Protein channels that let water cross membranes quickly.
7. -14.5%; hypertonic (water moved out)
   $(2.42 - 2.83)/2.83 \times 100 = -14.5\%$
8. Interphase takes most of the cell cycle.
9. Makes new cells for growth.
10. (a) 0 M and 0.2 M (hypotonic). (b) About 0.3 M, where the graph crosses zero (between +4% and −3%). (c) The concentration of dissolved substances inside the potato cells is about equivalent to 0.3 M sugar.
11. Look for: all living things are made of cells; the cell is the basic unit of life; all cells come from pre-existing cells; Schleiden (plants, 1838), Schwann (animals, 1839), Virchow (1855, cells from cells, overturning the idea that cells crystallize from fluid); medicine: disease as disordered cells (Virchow’s cellular pathology), cancer as uncontrolled division, infections caught from other cells.

Printable answer key (PDF, for the parent)

3.1 Cell Theory: Schleiden (1838), Schwann (1839) and Virchow's "Every Cell from a Cell" (1855)

OBJECTIVES

- State the three parts of the cell theory.
- Explain how each scientist contributed.
- Compare cell sizes and explain why cells are small.

> **Warm-up.** A sugar cube is 1 cm on a side. Find its surface area and volume. Now cut it into eight 0.5 cm cubes. What is the total surface area now? Why might a cell want lots of surface for its size?

WATCH

Cell theory

Khan Academy · 8:02

https://www.youtube.com/watch?v=zk3vlhz1b6k

> **WHEN TO WATCH**
> After the story.

BACKUP VIDEO

Cell Theory vs Modern Cell Theory

MooMooMath and Science · 3:17

https://www.youtube.com/watch?v=ABRXm5lpnag

As a short review.

KEY TERMS

cell theory
All living things are made of cells; the cell is the basic unit of life; all cells come from pre-existing cells.

unicellular
Made of a single cell.

multicellular

Made of many cells.

surface area to volume ratio

The amount of surface compared with the amount of inside; it falls as a cell grows.

pathology

The study of disease.

nucleus

The organelle that holds a eukaryotic cell's DNA.

CORE IDEAS

The story. Hooke named cells in 1665, but for 170 years no one realized that all living things are made of them. In 1831 the Scottish botanist Robert Brown noticed a dark spot in every orchid cell and called it the nucleus. In 1838 Matthias Schleiden, a German lawyer turned botanist, concluded that all plants are made of cells. Over dinner he told the physiologist Theodor Schwann about the nuclei he saw; Schwann realized he had seen the same in animal tissues, and in 1839 he declared that animals too are made of cells.

How they figured it out. Schleiden and Schwann thought new cells formed by crystallizing out of fluid, like salt from brine. Robert Remak watched frog embryo cells divide, and in 1855 the Berlin physician Rudolf Virchow, building on Remak's work, declared "Omnis cellula e cellula": every cell arises from a cell. Virchow founded cellular pathology: disease is a disorder of cells.

The biology. Most cells are 1–100 μm across. They stay small because materials must pass through the membrane: as a cell grows, its volume (which needs supplies) grows faster than its surface (which brings them in). Doubling a cube's side multiplies surface by 4 but volume by 8. Large organisms are made of many small cells, not a few giant ones.

Where it is used. Biopsies diagnose cancer by examining cells. Blood counts measure cells. Virchow's principle explains why infections spread from cell to cell and why tissues heal by cell division.

LAB

Agar Cubes and Cell Size

You will model diffusion into cells of different sizes.

You will need

- Unflavored gelatin made with a little baking soda and phenolphthalein or red cabbage juice (or a block of firm gelatin with cabbage juice)
- Vinegar, a knife, a ruler, cups

Steps

1. Cut gelatin cubes 1 cm, 2 cm and 3 cm on a side.
2. Soak them in vinegar for 10 minutes.
3. Remove, blot, cut in half and measure how far the color change reached.
4. Calculate the percent of each cube's volume that changed color.

Check your work

- ☐ Which cube was most completely reached by the vinegar?
- ☐ What does this suggest about cell size?

LAB NOTEBOOK

1. Data: cube size, SA, V, ratio, depth of color change, percent changed.
2. A conclusion about why cells are small.

> **From history.** Virchow was also a public-health reformer who designed Berlin's sewer system. He opposed Darwin's theory in his later years, warning that it was being taught as settled before the evidence was in.

WORKED EXAMPLES

Example 1. A cube cell has side 1 µm; another has side 3 µm. Find each surface-area-to-volume ratio.

▼ **Show solution**

1. 1 µm: SA = 6, V = 1, ratio 6:1.
2. 3 µm: SA = 54, V = 27, ratio 2:1.

Answer: 6:1 and 2:1; the small cell has three times more surface per volume

PRACTICE

1. Easy State the three parts of the cell theory.

   ▼ **Show answer**

   All living things are made of cells; the cell is the basic unit of life; all cells come from pre-existing cells.

2. Easy Who concluded that all plants are made of cells?

   ▼ **Show answer**

   Schleiden (1838).

3. Medium What did Virchow mean by “Omnis cellula e cellula”?

   ▼ **Show answer**

   Every cell comes from a pre-existing cell.

COMMON MISTAKES

- Thinking Hooke discovered the cell theory; he only saw and named cells.
- Thinking larger organisms have larger cells (an elephant’s cells are about the size of a mouse’s).
- Forgetting the third part of the theory: cells come from cells.

> **Make it a game · Who Said It?.** The parent reads a clue (“I saw nuclei in orchids,” “every cell from a cell,” “animals too are cells”). The student names Brown, Virchow, Schwann, Schleiden or Hooke.

> **Scripture.** “Thou hast clothed me with skin and flesh, and hast fenced me with bones and sinews.” (Job 10:11, KJV)
>
> Job describes God clothing him with skin and flesh and fencing him with bones and sinews: a body built of countless cells.

3.2 Organelles: The Cell as a Workshop

OBJECTIVES

- Name the organelles of eukaryotic cells and their jobs.
- Compare plant and animal cells.
- Compare prokaryotic and eukaryotic cells.

> **Warm-up.** Think of a factory that makes bicycles. List the departments it needs (headquarters, power plant, assembly line, shipping, security gate, warehouse). Keep the list; you will match it to the cell.

WATCH

Cell Organelles and Structures Review

Amoeba Sisters · 8:16

https://www.youtube.com/watch?v=6mgkoqcm6Sg

> **WHEN TO WATCH**
> After the warm-up.

BACKUP VIDEO

Prokaryotic vs. Eukaryotic Cells (Updated)

Amoeba Sisters · 5:28

https://www.youtube.com/watch?v=Pxujitlv8wc

With the prokaryote comparison.

KEY TERMS

organelle
A specialized structure in a cell with a particular job.

cell membrane
The thin, flexible boundary of a cell that controls what enters and leaves.

mitochondrion
The organelle that releases energy from food by cellular respiration.

chloroplast
The organelle in plant cells where photosynthesis occurs.

ribosome

A small structure that builds proteins.

prokaryote

A cell with no nucleus or membrane-bound organelles, such as a bacterium.

CORE IDEAS

The story. Through a light microscope a cell looks mostly empty. The electron microscope, invented by Ernst Ruska and Max Knoll in 1931, changed that. In the 1940s–1950s George Palade, Albert Claude and Christian de Duve used it, along with spinning cells apart in a centrifuge, to map the cell's inner machinery: ribosomes, endoplasmic reticulum, Golgi apparatus, lysosomes. They shared the 1974 Nobel Prize.

How they figured it out. By grinding cells and spinning them at different speeds, Claude and de Duve separated parts by size and weight and tested what each part did. Palade traced radioactive amino acids as they moved from ribosomes through the endoplasmic reticulum and Golgi to leave the cell, revealing the cell's assembly line.

The biology. *Nucleus*: headquarters, holds DNA. *Ribosomes*: build proteins. *Rough ER* (studded with ribosomes): assembly line for proteins; *smooth ER*: makes lipids. *Golgi apparatus*: packages and ships. *Lysosomes*: digest waste (animal cells). *Mitochondria*: power plants. *Cell membrane*: security gate. *Cytoskeleton*: framework and tracks. Plant cells add a rigid *cell wall* of cellulose, *chloroplasts* for photosynthesis and a large *central vacuole* for water storage. Prokaryotes (bacteria and archaea) have no nucleus; their DNA floats in the cytoplasm; they have ribosomes, a membrane and usually a wall, and they are about one-tenth the size of eukaryotic cells.

Where it is used. Many antibiotics work by attacking bacterial ribosomes or walls that differ from ours. Some inherited diseases are failures of lysosomes or mitochondria. The tiny protein machines of the cell, such as ATP synthase, have inspired engineers and are often cited as examples of design.

LAB

Plant and Animal Cells Compared

You will observe elodea or onion and cheek cells and build a cell model.

You will need

- Microscope, slides, cover slips, iodine
- Elodea (aquarium store) or onion; cheek cells
- Model: a zip-top bag (membrane), a box (wall), gelatin or clear corn syrup, and household items for organelles

Steps

1. Observe an elodea leaf at 400×: look for green chloroplasts moving in a stream (cytoplasmic streaming) and the cell wall.
2. Observe stained cheek cells again: nucleus, membrane, no wall.
3. Draw both cells side by side and label what you see.
4. Build a 3-D plant or animal cell model with a labeled key.

Check your work

- ☐ What did plant cells have that cheek cells lacked?
- ☐ Why do chloroplasts move?

LAB NOTEBOOK

1. Side-by-side labeled drawings.
2. A photo of the model with its key.

> **From history.** De Duve discovered the lysosome in 1955 almost by accident: an enzyme's activity went up when his cell extracts sat in the refrigerator for five days, suggesting it had been sealed in a membrane sac that slowly broke open.

WORKED EXAMPLES

Example 1. A cell has a cell wall, ribosomes and DNA but no nucleus or mitochondria. What kind of cell is it?

▼ **Show solution**

1. No nucleus means prokaryote.
2. Wall and ribosomes fit a bacterium.

Answer: A prokaryote (bacterium)

Example 2. Trace a protein made for export from the cell.

▼ **Show solution**

1. Made on ribosomes of the rough ER.
2. Moves through the ER to the Golgi.
3. Packaged in a vesicle and released at the membrane.

Answer: Ribosome → rough ER → Golgi → vesicle → membrane

PRACTICE

1. Easy What organelle holds the cell's DNA?

   ▼ **Show answer**

   The nucleus.

2. Easy Where are proteins made?

   ▼ **Show answer**

   On ribosomes.

3. Medium Name three structures found in plant cells but not animal cells.

   ▼ **Show answer**

   Cell wall, chloroplasts, large central vacuole.

COMMON MISTAKES

- Thinking plant cells lack mitochondria; they have both mitochondria and chloroplasts.
- Thinking prokaryotes have no DNA; they have DNA but no nucleus.

- Confusing the cell wall with the cell membrane.

> **Make it a game · Factory Match.** Use the warm-up list of factory departments. The parent names one; the student names the matching organelle and why.

> **Scripture.** “The LORD by wisdom hath founded the earth; by understanding hath he established the heavens.” (Proverbs 3:19, KJV)
>
> The LORD by wisdom hath founded the earth. The same wisdom shows in the cell’s orderly workshop.

3.3 Membranes, Diffusion and Osmosis

OBJECTIVES

- Describe the structure of the cell membrane.
- Explain diffusion, osmosis, facilitated diffusion and active transport.
- Predict the effect of hypotonic, isotonic and hypertonic solutions on cells.

> **Warm-up.** Put a raw egg in a cup of vinegar (soak for 2 days in advance so the shell dissolves). Weigh it, then soak it in corn syrup overnight. What happens to its size? (Start this now; finish in the lab.)

WATCH

Cell Transport

Amoeba Sisters · 7:50

https://www.youtube.com/watch?v=Ptmlvtei8hw

> **WHEN TO WATCH**
> After the membrane structure.

BACKUP VIDEO

Osmosis and Water Potential (Updated)

Amoeba Sisters · 9:50

https://www.youtube.com/watch?v=L-osEc07vMs

With osmosis.

KEY TERMS

phospholipid bilayer
The double layer of phospholipids forming the cell membrane, with water-loving heads outside and water-fearing tails inside.

diffusion
Movement of particles from higher to lower concentration.

osmosis
Diffusion of water across a selectively permeable membrane.

hypertonic
Having a higher solute concentration than the cell; water leaves the cell.

hypotonic

Having a lower solute concentration than the cell; water enters the cell.

active transport

Movement of substances against a concentration gradient using energy (ATP).

CORE IDEAS

The story. In 1748 the French priest-physicist Jean-Antoine Nollet tied a pig's bladder over a jar of wine and set it in water. Water flowed in until the bladder bulged and burst: the first recorded osmosis experiment. In 1972 S. Jonathan Singer and Garth Nicolson described the membrane as a *fluid mosaic*: a sea of phospholipids with proteins floating in it like icebergs. In 1992 Peter Agre discovered aquaporins, protein channels that let water pass quickly (Nobel Prize 2003).

How they figured it out. Phospholipids have a water-loving (hydrophilic) head and two water-fearing (hydrophobic) tails. In water they arrange themselves tails in, heads out, forming a two-layer sheet. Small nonpolar molecules (oxygen, carbon dioxide) slip through; ions and sugars need protein channels or pumps. The membrane is selectively permeable.

The biology. *Passive transport* needs no energy: diffusion, osmosis and facilitated diffusion through channels, always from high to low concentration. *Active transport* uses ATP to pump substances uphill; the sodium-potassium pump uses about a quarter of your resting energy. In a *hypotonic* solution water enters cells: animal cells swell and may burst; plant cells become firm (turgid) against their walls. In a *hypertonic* solution water leaves: animal cells shrivel; plant cells wilt. In an *isotonic* solution there is no net change. Large particles enter by endocytosis and leave by exocytosis.

Where it is used. IV fluids must be isotonic with blood (0.9% saline). Salting meat and sugaring fruit preserve them by drawing water out of microbes. Wilted lettuce crisps in cold water. Drinking seawater dehydrates you because it is hypertonic to body fluids.

LAB

Potato Osmosis

You will find the concentration of solutes in potato cells by soaking cores in sugar solutions.

You will need

- A potato, an apple corer or straw, a knife, a 0.01 g scale, paper towels
- Sugar, water, five labeled cups: 0, 0.2, 0.4, 0.6 and 0.8 M sugar (0.2 M ≈ 68 g sugar per liter)
- The egg from the warm-up

Steps

1. Cut 10 cores the same length (about 3 cm). Blot and weigh in pairs.
2. Put two cores in each solution for 24 hours.
3. Blot gently and reweigh. Calculate percent change for each.
4. Graph percent change versus concentration; find where the line crosses zero.
5. Weigh the egg after vinegar, after corn syrup and after a day in water.

Check your work

- ☐ At what concentration did cores neither gain nor lose mass?
- ☐ What happened to the egg in corn syrup? In water?

LAB NOTEBOOK

1. Data table and graph with the zero-crossing marked.
2. Egg masses and an explanation.

KEY FORMULAS

$$\%\ \text{change in mass} = \frac{\text{final} - \text{initial}}{\text{initial}} \times 100$$

From history. Agre found aquaporins while studying Rh blood-group proteins. He tested the new protein by putting it into frog eggs; in plain water they swelled and burst within minutes, while normal eggs did not.

WORKED EXAMPLES

Example 1. A red blood cell is placed in distilled water. Predict and explain.

▼ **Show solution**

1. Distilled water has fewer solutes than the cell: hypotonic.
2. Water moves in by osmosis.
3. Animal cells have no wall, so the cell swells and bursts.

Answer: It swells and bursts

Example 2. A potato core goes from 4.00 g to 3.60 g in salt water. Find the percent change and classify the solution.

▼ **Show solution**

1. $(3.60 - 4.00)/4.00 \times 100 = -10\%$
2. Mass lost: water left the cells.

Answer: −10%; hypertonic

PRACTICE

1. Easy What is osmosis?

   ▼ **Show answer**

   The diffusion of water across a selectively permeable membrane.

2. Easy What is the membrane mostly made of?

   ▼ **Show answer**

   A phospholipid bilayer with proteins.

3. Medium A potato core weighed 2.79 g before soaking and 1.98 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

   ▼ **Show answer**

   -29.0%; hypertonic (water moved out)

4. **Medium** A potato core weighed 3.05 g before soaking and 3.37 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

   ▼ **Show answer**

   +10.5%; hypotonic (water moved in)

5. **Medium** A potato core weighed 2.01 g before soaking and 2.78 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

   ▼ **Show answer**

   +38.3%; hypotonic (water moved in)

COMMON MISTAKES

- Saying salt or sugar moves in osmosis; osmosis is water movement.
- Mixing up hypertonic and hypotonic (hyper = more solute outside).
- Thinking diffusion stops at equilibrium; particles still move, but with no net change.

Make it a game · Swell or Shrink?. The parent names a cell and a solution (red cell in seawater, lettuce in tap water, slug with salt). The student says swell, shrink or no change and names the solution type.

Scripture. “As cold waters to a thirsty soul, so is good news from a far country.” (Proverbs 25:25, KJV)

As cold waters to a thirsty soul: water moving into thirsty cells is osmosis.

3.4 Cell Division: Flemming Sees Mitosis (1882)

OBJECTIVES

- Describe the cell cycle: interphase, mitosis and cytokinesis.
- Identify the stages of mitosis.
- Explain how the cell cycle is controlled and what happens in cancer.

> **Warm-up.** A cut on your finger heals in a week. Where do the new skin cells come from? Do they have the same DNA as the old ones?

WATCH

Mitosis (UPDATED 2026)

Amoeba Sisters · 8:42

https://www.youtube.com/watch?v=ShEzlXZPpPM

> **WHEN TO WATCH**
> After the stages.

BACKUP VIDEO

The Cell Cycle (and cancer) [Updated]

Amoeba Sisters · 9:20

https://www.youtube.com/watch?v=QVCjdNxJreE

With the cancer discussion.

KEY TERMS

cell cycle
The repeating series of growth, DNA copying and division in a cell's life.

interphase
The part of the cell cycle when the cell grows and copies its DNA.

mitosis
Division of the nucleus into two identical nuclei.

cytokinesis
Division of the cytoplasm into two daughter cells.

chromosome

A threadlike structure of DNA and protein that carries genes.

cancer

A disease in which cells divide uncontrollably.

CORE IDEAS

The story. In the 1870s the German anatomist Walther Flemming used new aniline dyes to stain the cells of salamander larvae, whose chromosomes are unusually large. He saw threadlike structures in the nucleus that he called *chromatin* (from the Greek for color), and watched them split and move apart. In 1882 he published *Cell Substance, Nucleus and Cell Division* with drawings so accurate they are still reproduced today, and he named the process *mitosis*, from the Greek for thread.

How they figured it out. Flemming could not watch one living cell go through every stage, so he arranged thousands of stained, fixed cells in a logical sequence. Later, time-lapse filming confirmed his order. He did not know what the threads did; their role in heredity was recognized after Mendel's work was rediscovered in 1900 (Unit 5).

The biology. Interphase (most of a cell's life): G1 growth, S (DNA synthesis: each chromosome is copied into two sister chromatids), G2 preparation. Mitosis: *prophase* (chromosomes condense, spindle forms), *metaphase* (chromosomes line up in the middle), *anaphase* (sister chromatids pulled apart), *telophase* (nuclei re-form). Cytokinesis then splits the cell: animal cells pinch in; plant cells build a cell plate. The two daughter cells are genetically identical. Checkpoints control the cycle; when they fail through mutations, cells divide without limit and form tumors: cancer.

Where it is used. Mitosis grows a baby from one cell to trillions, heals wounds and replaces worn-out cells (your stomach lining every few days). Many cancer drugs attack dividing cells, which is why they cause hair loss. Plant cuttings grow into new plants by mitosis.

LAB

Onion Root Tip Mitosis

You will find and count cells in each stage of mitosis in a prepared onion root tip slide (or photo).

You will need

- A prepared onion root tip slide (about $5 from a supplier) and microscope, or a set of root-tip micrographs
- Pipe cleaners or yarn in two colors for a chromosome model

Steps

1. Find the zone just behind the root cap where cells are dividing.
2. At 400×, count 100 cells and classify each as interphase, prophase, metaphase, anaphase or telophase.
3. Calculate the percent in each stage and estimate the time in each (24-hour cycle).
4. Model mitosis with pipe-cleaner chromosomes for two chromosome pairs.

Check your work

- ☐ Which stage had the most cells? What does that mean?
- ☐ Which stage of mitosis is shortest?

LAB NOTEBOOK

1. Count table, percents and estimated times.
2. Sketches of each stage you found.

> **From history.** Flemming worked at the University of Kiel and taught for free in workers' evening classes. He died in 1905, before the importance of chromosomes for heredity was fully understood.

WORKED EXAMPLES

Example 1. A human body cell has 46 chromosomes. How many does each daughter cell have after mitosis?

▼ **Show solution**

1. Mitosis makes identical copies.

Answer: 46

Example 2. In a root tip, 20 of 200 cells are in mitosis and the cell cycle takes 24 hours. About how long does mitosis last?

▼ **Show solution**

1. Fraction in mitosis = 20/200 = 0.10.
2. 0.10 × 24 h = 2.4 h

Answer: About 2.4 hours

PRACTICE

1. Easy List the four stages of mitosis in order.

   ▼ **Show answer**

   Prophase, metaphase, anaphase, telophase.

2. Easy What happens during the S phase of interphase?

   ▼ **Show answer**

   The DNA is copied.

3. Medium What happens in metaphase?

   ▼ **Show answer**

   Chromosomes line up across the middle of the cell.

COMMON MISTAKES

- Calling interphase a resting stage; the cell is busy growing and copying DNA.
- Thinking daughter cells have half the chromosomes (that is meiosis, Unit 5).
- Mixing up the order of the stages (PMAT).

Make it a game · PMAT Charades. Family members are chromosomes in the hallway. The parent calls a stage; the "chromosomes" move into position (line up, pull apart). The student narrates.

Scripture. "For thou hast possessed my reins: thou hast covered me in my mother's womb." (Psalm 139:13, KJV)

Thou hast covered me in my mother's womb. Every person grows from one cell by countless divisions.

UNIT 3

Cells

Every living thing is made of cells, and every cell comes from a cell. This unit follows the cell theory from Schleiden, Schwann and Virchow, tours the organelles of plant, animal and bacterial cells, explains how membranes control what enters and leaves by diffusion, osmosis and active transport, and watches cells divide as Walther Flemming first saw them in 1882.

The microscope is used in every lesson. The potato osmosis lab gives the first real data set of the year.

PREREQUISITES

- Unit 1 (microscope)
- Unit 2 (biological molecules)

MASTERY CHECKLIST

- ☐ I can state the cell theory and the scientists who built it.
- ☐ I can name the organelles of plant and animal cells and their jobs, and compare prokaryotes and eukaryotes.
- ☐ I can explain diffusion, osmosis and active transport and predict the effect of hypertonic and hypotonic solutions.
- ☐ I can describe the cell cycle and the stages of mitosis.

LESSONS IN THIS UNIT

3.1	**Cell Theory: Schleiden (1838), Schwann (1839) and Virchow's "Every Cell from a Cell" (1855)**	4 sessions of 45 minutes
3.2	**Organelles: The Cell as a Workshop**	4 sessions of 45 minutes
3.3	**Membranes, Diffusion and Osmosis**	4 sessions of 45 minutes
3.4	**Cell Division: Flemming Sees Mitosis (1882)**	4 sessions of 45 minutes

Unit 3 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **9 pts** **Lesson 3.1**

   How big are most cells?

2. **9 pts** **Lesson 3.1**

   What does the nucleus contain?

3. **9 pts** **Lesson 3.2**

   Do plant cells have mitochondria?

4. **8 pts** **Lesson 3.2**

   Why did the electron microscope revolutionize cell biology?

5. **8 pts** **Lesson 3.3**

   What did Nollet’s pig-bladder experiment show?

6. **8 pts** **Lesson 3.3**

   What are aquaporins?

7. **8 pts** **Lesson 3.3**

   A potato core weighed 2.83 g before soaking and 2.42 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

8. **8 pts** **Lesson 3.4**

   Most cells in the onion root were in interphase. What does that tell you?

9. **8 pts** **Lesson 3.4**

   What does mitosis do for a growing child?

LAB AND DATA

10. **10 pts**

Potato cores are soaked for 24 hours in sugar solutions. Percent change in mass: 0 M +12%, 0.2 M +4%, 0.4 M −3%, 0.6 M −9%. (a) In which solutions did water enter the cells? (b) Estimate the concentration at which the potato would neither gain nor lose mass. (c) What does that number tell you?

SHORT ESSAY

11. **15 pts**

Virchow wrote “Omnis cellula e cellula”: every cell from a cell. Explain the three parts of the cell theory, how Schleiden, Schwann and Virchow each contributed, and why the cell theory is a foundation for medicine.

ANSWER KEY

1. About 1–100 µm.
2. The cell’s DNA.
3. Yes.
4. Its far higher resolution revealed organelles invisible with light.
5. Water moves across a membrane toward the more concentrated side (osmosis).
6. Protein channels that let water cross membranes quickly.
7. -14.5%; hypertonic (water moved out)
   $(2.42 - 2.83)/2.83 \times 100 = -14.5\%$
8. Interphase takes most of the cell cycle.
9. Makes new cells for growth.
10. (a) 0 M and 0.2 M (hypotonic). (b) About 0.3 M, where the graph crosses zero (between +4% and −3%). (c) The concentration of dissolved substances inside the potato cells is about equivalent to 0.3 M sugar.
11. Look for: all living things are made of cells; the cell is the basic unit of life; all cells come from pre-existing cells; Schleiden (plants, 1838), Schwann (animals, 1839), Virchow (1855, cells from cells, overturning the idea that cells crystallize from fluid); medicine: disease as disordered cells (Virchow’s cellular pathology), cancer as uncontrolled division, infections caught from other cells.

Printable answer key (PDF, for the parent)

UNIT 4

Energy in Living Things

Every living thing needs energy, and almost all of it starts as sunlight. This unit follows the experiments that discovered photosynthesis, from van Helmont's willow tree to Priestley's mint and Ingenhousz's sunlit leaves, then studies the light reactions and the Calvin cycle, cellular respiration and Hans Krebs's citric acid cycle, and fermentation from Pasteur's yeast to the burn in a sprinter's legs.

The two central equations are learned by heart: photosynthesis and respiration are mirror images.

PREREQUISITES

- Unit 2 (carbohydrates, enzymes, ATP)
- Unit 3 (chloroplasts and mitochondria)

MASTERY CHECKLIST

- ☐ I can describe the experiments of van Helmont, Priestley and Ingenhousz and what each showed.
- ☐ I can write the overall equation of photosynthesis and describe the light reactions and the Calvin cycle.
- ☐ I can write the equation of cellular respiration, describe its three stages and explain the role of ATP.
- ☐ I can compare aerobic respiration with alcoholic and lactic acid fermentation.

LESSONS IN THIS UNIT

4.1 Van Helmont's Willow, Priestley's Mint and Ingenhousz's Sunlight (1648–1779)

4 sessions of 45 minutes

4.2 Photosynthesis: Light Reactions and the Calvin Cycle — 4 sessions of 45 minutes

4.3 Cellular Respiration: Krebs and the Citric Acid Cycle (1937)

4 sessions of 45 minutes

Unit 4 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 4.1**
   Where in the cell does photosynthesis happen?

2. **10 pts** **Lesson 4.1**
   Most of a tree's dry mass comes from where?

3. **10 pts** **Lesson 4.2**
   Why is the Calvin cycle called a cycle?

4. **9 pts** **Lesson 4.2**
   What gas is released by the light reactions?

5. **9 pts** **Lesson 4.3**
   Why do cells release glucose's energy in many small steps?

6. **9 pts** **Lesson 4.3**
   What gas do you breathe out that is made by respiration?

7. **9 pts** **Lesson 4.4**
   Why do you keep breathing hard after a sprint?

8. **9 pts** **Lesson 4.4**
   What kind of organism is yeast?

LAB AND DATA

9. **10 pts**

Elodea sprigs are placed in water with a little baking soda at different distances from a lamp, and bubbles are counted for 5 minutes: 10 cm, 62 bubbles; 20 cm, 35; 40 cm, 12; dark, 0. (a) What gas is in the bubbles? (b) What is the independent variable? (c) Why add baking soda? (d) What do the results show?

SHORT ESSAY

10. **15 pts**

Photosynthesis and cellular respiration are sometimes called mirror images. Write both equations, explain where each happens and what each does with energy, and describe how the two processes link plants and animals.

ANSWER KEY

1. In chloroplasts.
2. Carbon dioxide from the air.
3. The five-carbon starting molecule is regenerated each turn.
4. Oxygen.
5. So the energy can be captured in ATP instead of lost as heat.
6. Carbon dioxide.
7. To repay the oxygen debt by processing lactate and restoring ATP.
8. A single-celled fungus.
9. (a) Oxygen. (b) Light intensity (distance from the lamp). (c) It supplies dissolved CO_2 for photosynthesis. (d) The rate of photosynthesis increases with light intensity; with no light, no photosynthesis.
10. Look for: $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$ in chloroplasts, storing light energy in sugar; $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{ATP}$ in mitochondria (cytoplasm for glycolysis), releasing energy as ATP; plants do both; the products of one are the reactants of the other; animals depend on plants for food and oxygen; plants use the CO_2 animals release.

Printable answer key (PDF, for the parent)

4.1 Van Helmont's Willow, Priestley's Mint and Ingenhousz's Sunlight (1648–1779)

OBJECTIVES

- Describe the classic experiments that discovered photosynthesis.
- Identify what each experiment showed and what it missed.
- State the overall equation for photosynthesis.

> **Warm-up.** A huge oak grows from a small acorn. Where does all that wood come from? Write your best guess before reading.

WATCH

Photosynthesis (UPDATED)

Amoeba Sisters · 7:59

https://www.youtube.com/watch?v=CMiPYHNNg28

> **WHEN TO WATCH**
> After the warm-up.

BACKUP VIDEO

Exploring Photosynthesis

Carolina Science · 4:00

https://www.youtube.com/watch?v=0AUHgBJ-ul8

After the three experiments.

KEY TERMS

photosynthesis

The process by which plants use light energy to make sugar from carbon dioxide and water, releasing oxygen.

autotroph

An organism that makes its own food, such as a plant.

heterotroph

An organism that gets food by eating other organisms.

chlorophyll

The green pigment that absorbs light for photosynthesis.

stomata

Tiny pores in leaves that let gases in and out.

glucose

A simple sugar, $C_6H_{12}O_6$, made in photosynthesis.

CORE IDEAS

The story. Jan Baptist van Helmont, a Flemish physician, planted a 5-pound willow in 200 pounds of dried soil and watered it for five years. The tree gained 164 pounds; the soil lost only 2 ounces. He concluded (published 1648) that the tree was made from water. In 1771 Joseph Priestley, an English minister and chemist, put a candle in a sealed jar; it went out. A mouse in a sealed jar died. But a sprig of mint in a sealed jar "restored" the air so that a candle could burn and a mouse could live. In 1779 the Dutch physician Jan Ingenhousz showed that plants restore air only in sunlight, and only their green parts do it.

How they figured it out. Each experiment answered part of the question. Van Helmont was right that the mass did not come from soil, but missed the air. Priestley found that plants make the air breathable (oxygen, though he did not call it that). Ingenhousz added light and green tissue. Jean Senebier showed that plants take in "fixed air" (carbon dioxide), and Nicolas-Théodore de Saussure (1804) showed that plants gain mass from carbon dioxide and water together.

The biology. $6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$. Most of a tree's dry mass comes from carbon dioxide in the air. Leaves take in CO_2 through stomata, water arrives from the roots, chlorophyll in chloroplasts absorbs red and blue light (reflecting green), and oxygen leaves through the stomata. Plants are autotrophs; animals are heterotrophs that depend on them.

Where it is used. Greenhouse growers add carbon dioxide and light to raise yields. Nearly all food chains begin with photosynthesis. The oxygen we breathe is replenished by plants and algae.

LAB

Floating Leaf Disks

You will watch leaf disks rise as photosynthesis fills them with oxygen.

You will need

- Fresh spinach leaves, a hole punch or straw, a 10 mL syringe (no needle)
- Water, baking soda, a drop of dish soap, two clear cups, a bright lamp, a timer

Steps

1. Make 0.2% baking soda water (1/8 tsp in 300 mL) with one drop of soap.
2. Punch 20 disks. Put 10 in the syringe with solution, cap with a finger and pull the plunger to draw air out of the leaves until they sink.
3. Put 10 sunk disks in a cup under the lamp and 10 in a cup in a dark cupboard.
4. Count floating disks every minute for 20 minutes.

Check your work

- ☐ How long until half the lit disks floated?
- ☐ What happened in the dark?
- ☐ What made them float?

LAB NOTEBOOK

1. Data table and a graph of floating disks over time.
2. An explanation linking floating to oxygen production.

> **From history.** Priestley was a dissenting minister whose house and laboratory were burned by a mob in 1791 for his political and religious views. He emigrated to Pennsylvania in 1794.

WORKED EXAMPLES

Example 1. Van Helmont's willow gained 164 lb; the soil lost 2 oz. What fraction of the gain could have come from soil?

▼ **Show solution**

1. 2 oz = 0.125 lb.
2. 0.125/164 = 0.00076.

Answer: Less than 0.1%: the soil supplied almost none of the mass

PRACTICE

1. Easy Write the overall equation for photosynthesis.

   ▼ **Show answer**

   $$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$$

2. Easy What did van Helmont conclude from his willow?

   ▼ **Show answer**

   The tree's mass came from water, not soil.

3. Medium What did Priestley's mint and mouse experiment show?

   ▼ **Show answer**

   Plants restore air so animals can breathe and candles can burn.

COMMON MISTAKES

- Thinking plants get their mass from the soil.
- Thinking plants do not respire; they do, day and night.
- Saying plants make oxygen from carbon dioxide; the oxygen comes from water (shown with isotopes in 1941).

> **Make it a game · Who Found What?.** The parent names a clue (willow, mint and mouse, sunlight, fixed air). The student names the scientist and the discovery.

> **Scripture.** “And God said, Behold, I have given you every herb bearing seed, which is upon the face of all the earth, and every tree, in the which is the fruit of a tree yielding seed; to you it shall be for meat. And to every beast of the earth, and to every fowl of the air, and to every thing that creepeth upon the earth, wherein there is life, I have given every green herb for meat: and it was so.” (Genesis 1:29–30, KJV)
>
> God gave every green herb for meat. Photosynthesis is the source of that food for every creature.

4.2 Photosynthesis: Light Reactions and the Calvin Cycle

OBJECTIVES

- Describe the structure of a chloroplast.
- Explain what happens in the light reactions and the Calvin cycle.
- Describe factors that affect the rate of photosynthesis.

> **Warm-up.** A solar panel turns light into electricity, and a battery stores it. In a plant, what might play the role of the panel and of the battery?

WATCH

Conceptual overview of light dependent reactions

Khan Academy · 9:04

https://www.youtube.com/watch?v=vEsAtC9d_MQ

> **WHEN TO WATCH**
> After the chloroplast structure.

BACKUP VIDEO

Photosynthesis: Calvin Cycle

Khan Academy · 13:28

https://www.youtube.com/watch?v=slm6D2VEXYs

For the Calvin cycle (13 minutes).

KEY TERMS

thylakoid
A flattened sac in the chloroplast where the light reactions happen.

stroma
The fluid around the thylakoids where the Calvin cycle happens.

light reactions
Reactions that capture light energy to make ATP and NADPH and split water, releasing oxygen.

Calvin cycle
Reactions that use ATP and NADPH to build sugar from carbon dioxide.

NADPH

An energy-carrying molecule that brings high-energy electrons to the Calvin cycle.

limiting factor

The condition in shortest supply that limits a process's rate.

CORE IDEAS

The story. In 1937 Robert Hill showed that isolated chloroplasts in light release oxygen even without carbon dioxide, so oxygen release and sugar-building are separate steps. In the late 1940s Melvin Calvin, Andrew Benson and James Bassham at Berkeley fed algae radioactive carbon-14 dioxide, stopped the reaction after a few seconds by plunging the algae into boiling alcohol, and traced which molecules carried the label. They mapped the cycle of reactions that builds sugar; Calvin won the 1961 Nobel Prize.

How they figured it out. Photosynthesis happens in two linked stages. In the thylakoid membranes, chlorophyll absorbs light; the energy splits water (releasing oxygen) and makes ATP and NADPH. In the stroma, the Calvin cycle uses that ATP and NADPH to attach carbon dioxide to a five-carbon sugar with the enzyme rubisco, probably the most abundant protein on earth, eventually producing glucose.

The biology. Light reactions: light + water → oxygen + ATP + NADPH. Calvin cycle: CO_2 + ATP + NADPH → sugar (the spent carriers return to the thylakoids). The rate of photosynthesis depends on light intensity, carbon dioxide concentration and temperature; whichever is in shortest supply is the limiting factor. Too much heat denatures the enzymes.

Where it is used. Farmers and greenhouse growers manage limiting factors. Corn and sugarcane use a variation (C_4 photosynthesis) that works better in heat. Scientists study artificial photosynthesis to make fuels from sunlight.

> **Safety first.** Alcohol is flammable: no flames. Keep water away from the lamp.

LAB

Chromatography of Leaf Pigments and Elodea Bubbles

You will separate leaf pigments and measure photosynthesis rate versus light.

You will need

- Spinach, coffee filter strips, rubbing alcohol, a coin, a tall glass
- Elodea, baking soda water, a lamp, a ruler, a test tube or clear cup

Steps

1. Roll a coin over a spinach leaf on a filter strip to make a green line 2 cm from the bottom. Stand the strip in 1 cm of alcohol and cover. Wait 30 minutes and label the bands.
2. Place an elodea sprig cut-end up in baking soda water. Count bubbles per minute at 10, 20 and 40 cm from the lamp.
3. Graph bubbles per minute versus distance.

Check your work

- ☐ How many pigment bands did you see?
- ☐ How did light intensity affect the bubble rate?

LAB NOTEBOOK

1. The taped chromatogram with bands labeled.
2. Elodea data and graph.

> **From history.** Calvin's team used a "lollipop" flask of algae lit from both sides, with a valve to drain samples into boiling alcohol within seconds.

WORKED EXAMPLES

Example 1. A plant in a greenhouse is in bright light at 25 °C, but adding more light does not raise its rate. Adding CO_2 does. What is the limiting factor?

▼ **Show solution**

1. Light is not limiting (more light had no effect).
2. CO_2 raised the rate.

Answer: Carbon dioxide

PRACTICE

1. Easy Where do the light reactions happen?

   ▼ **Show answer**

   In the thylakoid membranes.

2. Easy Where does the Calvin cycle happen?

   ▼ **Show answer**

   In the stroma.

3. Medium What are the products of the light reactions?

   ▼ **Show answer**

   Oxygen, ATP and NADPH.

COMMON MISTAKES

- Thinking the Calvin cycle needs darkness; it happens in the light too, using light-reaction products.
- Mixing up where each stage happens (thylakoid vs stroma).
- Forgetting that oxygen comes from the light reactions, not the Calvin cycle.

> **Make it a game · Stage Sort.** Write cards: water split, oxygen released, CO_2 fixed, ATP made, sugar built, rubisco, thylakoid, stroma. The student sorts them into light reactions or Calvin cycle.

> **Scripture.** “Every good gift and every perfect gift is from above, and cometh down from the Father of lights, with whom is no variableness, neither shadow of turning.” (James 1:17, KJV)
>
> Every good gift is from the Father of lights. Sunlight captured in leaves feeds the world.

4.3 Cellular Respiration: Krebs and the Citric Acid Cycle (1937)

OBJECTIVES

- Write the overall equation of cellular respiration.
- Describe glycolysis, the Krebs cycle and the electron transport chain.
- Explain why oxygen is needed and how much ATP results.

> **Warm-up.** Breathe out onto a cold mirror and into a cup of red cabbage juice through a straw for one minute. What do you see? What does your breath contain that you didn't breathe in?

WATCH

Cellular Respiration (UPDATED)

Amoeba Sisters · 8:47

https://www.youtube.com/watch?v=eJ9Zjc-jdys

> **WHEN TO WATCH**
> After the overall equation.

BACKUP VIDEO

What is ATP?

Amoeba Sisters · 5:52

https://www.youtube.com/watch?v=23ZzI6WZS28

With the ATP discussion.

KEY TERMS

cellular respiration

The process that releases energy from food by breaking down glucose with oxygen, producing ATP.

glycolysis

The first stage of respiration, splitting glucose into two pyruvate molecules in the cytoplasm.

Krebs cycle

The second stage, in the mitochondria, which breaks pyruvate down to CO_2 and loads energy carriers.

electron transport chain

The final stage, in the inner mitochondrial membrane, which uses oxygen and makes most of the ATP.

aerobic

Requiring oxygen.

ATP synthase

The rotating enzyme that makes ATP.

CORE IDEAS

The story. Hans Krebs, a German Jewish physician, was dismissed by the Nazi government in 1933 and found refuge at Cambridge and then Sheffield. Grinding pigeon breast muscle, which burns fuel quickly for flight, he added different small acids and measured oxygen use. In 1937 he showed that the acids form a cycle: citric acid is made, broken down step by step, and the starting molecule is regenerated to begin again. He won the 1953 Nobel Prize.

How they figured it out. Lavoisier had shown respiration is a slow burning (Chemistry Lesson 9.1). But burning glucose all at once would waste the energy as heat. Cells release it in many small steps, catching it in ATP. In 1961 Peter Mitchell proposed that the electron transport chain pumps protons across the inner membrane and that they flow back through ATP synthase, a tiny rotary motor (Nobel 1978).

The biology. $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy (ATP)}$. (1) Glycolysis, in the cytoplasm: glucose → 2 pyruvate, net 2 ATP, no oxygen needed. (2) Krebs cycle, in the mitochondrial matrix: pyruvate → CO_2, 2 ATP, many NADH and $FADH_2$. (3) Electron transport chain, inner membrane: electrons from NADH pass down a chain to oxygen, forming water; the energy pumps protons that drive ATP synthase, making about 26–34 ATP. Total: about 30–38 ATP per glucose. Without oxygen to accept electrons, the chain stops.

Where it is used. Every heartbeat and thought runs on ATP from respiration. Cyanide kills by blocking the electron transport chain. Endurance athletes train to increase their mitochondria. ATP synthase, spinning at over 100 revolutions per second, is one of the smallest motors known.

LAB

Germinating Peas and CO_2

You will compare carbon dioxide release by germinating and dry peas using cabbage indicator.

You will need

- Dried peas, peas soaked and sprouted for 2 days, glass beads or pebbles (control)
- Red cabbage juice or bromothymol blue (aquarium store), three jars with lids, small mesh bags or cups to hold peas above the liquid

Steps

1. Put 50 mL indicator in each jar.
2. Hang or set germinating peas above the liquid in jar 1, dry peas in jar 2, pebbles in jar 3. Seal.
3. Check the color every 30 minutes for 3 hours.
4. Record and explain.

Check your work

- ☐ Which jar changed color? Why?
- ☐ Why use pebbles as a control?

LAB NOTEBOOK

1. Color observations over time.
2. An explanation using the respiration equation.

> **From history.** Krebs's original paper describing the cycle was rejected by the journal *Nature* in 1937 for lack of space. He published it elsewhere a few weeks later.

WORKED EXAMPLES

Example 1. How many molecules of CO_2 are released for each glucose fully respired?

▼ **Show solution**

1. The equation shows 6 CO_2 per glucose.

Answer: 6

Example 2. Glycolysis gives 2 ATP and full respiration about 32. What fraction of the ATP comes from glycolysis?

▼ **Show solution**

1. 2/32 = 0.0625

Answer: About 6%

PRACTICE

1. Easy Write the overall equation of cellular respiration.

   ▼ **Show answer**

   $$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ATP$$

2. Easy Name the three stages of cellular respiration.

   ▼ **Show answer**

   Glycolysis, Krebs cycle, electron transport chain.

3. Medium Where does glycolysis happen?

   ▼ **Show answer**

   In the cytoplasm.

COMMON MISTAKES

- Thinking only animals respire; plants respire too.
- Thinking respiration means breathing; breathing supplies oxygen for cellular respiration.
- Forgetting glycolysis happens in the cytoplasm, not the mitochondria.

Make it a game · Follow the Glucose. The parent says a location (cytoplasm, matrix, inner membrane). The student names the stage that happens there, its inputs and its outputs.

Scripture. “The Spirit of God hath made me, and the breath of the Almighty hath given me life.” (Job 33:4, KJV)

The breath of the Almighty hath given me life. Every breath supplies the oxygen each cell needs.

4.4 Fermentation: Pasteur, Yeast and Tired Muscles

OBJECTIVES

- Explain fermentation as a way to make ATP without oxygen.
- Compare alcoholic and lactic acid fermentation.
- Describe Pasteur's work on fermentation and its uses.

> **Warm-up.** Mix flour, water and yeast into a small dough ball and put it in a warm place. Mix another without yeast. Check in an hour. What happened?

WATCH

Fermentation

Amoeba Sisters · 8:34

https://www.youtube.com/watch?v=YbdkbCU20_M

> **WHEN TO WATCH**
> After Pasteur's story.

BACKUP VIDEO

A-Level Biology - Anaerobic Respiration | Alcohol & Lactic Acid Fermentation

Cognito · 6:05

https://www.youtube.com/watch?v=OpH6zHIeNxE

With the comparison of the two types.

KEY TERMS

fermentation

A process that makes ATP from glucose without oxygen by glycolysis, regenerating carriers.

anaerobic

Not requiring oxygen.

alcoholic fermentation

Fermentation by yeast that produces ethanol and carbon dioxide.

lactic acid fermentation

Fermentation by muscle cells and some bacteria that produces lactic acid.

yeast

A single-celled fungus used in baking and brewing.

oxygen debt

The extra oxygen needed after hard exercise to process lactate.

CORE IDEAS

The story. In 1856 a manufacturer in Lille asked Louis Pasteur why some of his vats of beet juice turned sour instead of producing alcohol. Under the microscope Pasteur saw round yeast cells in the good vats and rod-shaped bacteria in the sour ones. He showed that fermentation is done by living microbes and that different microbes make different products. He also found that yeast without air ferments sugar, but with air it grows more and makes less alcohol: “fermentation is life without air.”

How they figured it out. In 1897 Eduard Buchner ground yeast with sand, filtered out every cell, and found the juice still fermented sugar. Fermentation was done by molecules (enzymes) made by cells, not by a vital force. He won the 1907 Nobel Prize.

The biology. Without oxygen, the electron transport chain stops and NADH piles up. Fermentation recycles NADH so glycolysis can continue, yielding only 2 ATP per glucose. Yeast: glucose → 2 ethanol + 2 CO_2 (bread rises from the CO_2; the alcohol bakes off). Muscle cells in hard exercise and many bacteria: glucose → 2 lactic acid (lactate). Lactate is carried to the liver and recycled; heavy breathing after a sprint pays back the oxygen debt.

Where it is used. Bread, yogurt, cheese, sauerkraut, pickles, soy sauce and vinegar all depend on fermentation. Sprinters rely on fermentation for short bursts. Industry uses fermentation to make medicines such as insulin and antibiotics.

LAB

Yeast Balloons and Sugar Types

You will measure CO_2 from yeast fed different sugars and temperatures.

You will need

- Dry yeast, five bottles, five balloons, a tape measure
- Table sugar, honey, artificial sweetener, flour, warm and cold water

Steps

1. In each bottle put 1 packet yeast in 1 cup warm water, plus: (1) 2 tsp sugar, (2) 2 tsp honey, (3) sweetener, (4) nothing, (5) sugar in ice water.
2. Stretch a balloon over each.
3. Measure balloon circumference every 15 minutes for 1 hour.
4. Graph the results.

Check your work

- ☐ Which food produced the most gas?
- ☐ Why did the sweetener and the ice water produce little?

LAB NOTEBOOK

1. Data table and graph.
2. A conclusion using the fermentation equation.

> **From history.** Pasteur's fermentation studies saved the French wine and silk industries and led him to suspect that microbes cause disease, the germ theory of Unit 8.

WORKED EXAMPLES

Example 1. How many ATP does a glucose give by fermentation compared with aerobic respiration (about 32)?

▼ **Show solution**

1. Fermentation gives 2.
2. 32/2 = 16.

Answer: 2 ATP; aerobic gives about 16 times more

PRACTICE

1. Easy What is fermentation?

   ▼ **Show answer**

   Making ATP from glucose without oxygen.

2. Easy What are the products of alcoholic fermentation?

   ▼ **Show answer**

   Ethanol and carbon dioxide.

3. Medium What makes bread rise?

   ▼ **Show answer**

   Carbon dioxide from yeast fermentation.

COMMON MISTAKES

- Thinking fermentation makes as much ATP as respiration.
- Thinking muscle soreness the next day is caused by lactic acid; it is mostly tiny muscle damage.
- Thinking yeast is a bacterium; it is a fungus.

> **Make it a game · Fermented or Not?.** The parent names a food (yogurt, apple, sourdough, cheese, rice, sauerkraut, honey, vinegar). The student says whether it is made by fermentation and by what microbe type.

> **Scripture.** “Another parable spake he unto them; The kingdom of heaven is like unto leaven, which a woman took, and hid in three measures of meal, till the whole was leavened.” (Matthew 13:33, KJV)
>
> Jesus compared the kingdom of heaven to leaven hid in three measures of meal until the whole was leavened: fermentation spreading through the dough.

UNIT 4

Energy in Living Things

Every living thing needs energy, and almost all of it starts as sunlight. This unit follows the experiments that discovered photosynthesis, from van Helmont's willow tree to Priestley's mint and Ingenhousz's sunlit leaves, then studies the light reactions and the Calvin cycle, cellular respiration and Hans Krebs's citric acid cycle, and fermentation from Pasteur's yeast to the burn in a sprinter's legs.

The two central equations are learned by heart: photosynthesis and respiration are mirror images.

PREREQUISITES

- Unit 2 (carbohydrates, enzymes, ATP)
- Unit 3 (chloroplasts and mitochondria)

MASTERY CHECKLIST

- ☐ I can describe the experiments of van Helmont, Priestley and Ingenhousz and what each showed.
- ☐ I can write the overall equation of photosynthesis and describe the light reactions and the Calvin cycle.
- ☐ I can write the equation of cellular respiration, describe its three stages and explain the role of ATP.
- ☐ I can compare aerobic respiration with alcoholic and lactic acid fermentation.

LESSONS IN THIS UNIT

4.1 Van Helmont's Willow, Priestley's Mint and Ingenhousz's Sunlight (1648–1779)

4 sessions of 45 minutes

4.2 Photosynthesis: Light Reactions and the Calvin Cycle — 4 sessions of 45 minutes

4.3 Cellular Respiration: Krebs and the Citric Acid Cycle (1937)

4 sessions of 45 minutes

Unit 4 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 4.1**
   Where in the cell does photosynthesis happen?

2. **10 pts** **Lesson 4.1**
   Most of a tree's dry mass comes from where?

3. **10 pts** **Lesson 4.2**
   Why is the Calvin cycle called a cycle?

4. **9 pts** **Lesson 4.2**
   What gas is released by the light reactions?

5. **9 pts** **Lesson 4.3**
   Why do cells release glucose's energy in many small steps?

6. **9 pts** **Lesson 4.3**
   What gas do you breathe out that is made by respiration?

7. **9 pts** **Lesson 4.4**
   Why do you keep breathing hard after a sprint?

8. **9 pts** **Lesson 4.4**
   What kind of organism is yeast?

LAB AND DATA

9. **10 pts**

Elodea sprigs are placed in water with a little baking soda at different distances from a lamp, and bubbles are counted for 5 minutes: 10 cm, 62 bubbles; 20 cm, 35; 40 cm, 12; dark, 0. (a) What gas is in the bubbles? (b) What is the independent variable? (c) Why add baking soda? (d) What do the results show?

SHORT ESSAY

10. **15 pts**

Photosynthesis and cellular respiration are sometimes called mirror images. Write both equations, explain where each happens and what each does with energy, and describe how the two processes link plants and animals.

ANSWER KEY

1. In chloroplasts.
2. Carbon dioxide from the air.
3. The five-carbon starting molecule is regenerated each turn.
4. Oxygen.
5. So the energy can be captured in ATP instead of lost as heat.
6. Carbon dioxide.
7. To repay the oxygen debt by processing lactate and restoring ATP.
8. A single-celled fungus.
9. (a) Oxygen. (b) Light intensity (distance from the lamp). (c) It supplies dissolved CO_2 for photosynthesis. (d) The rate of photosynthesis increases with light intensity; with no light, no photosynthesis.
10. Look for: $6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$ in chloroplasts, storing light energy in sugar; $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{ATP}$ in mitochondria (cytoplasm for glycolysis), releasing energy as ATP; plants do both; the products of one are the reactants of the other; animals depend on plants for food and oxygen; plants use the CO_2 animals release.

Printable answer key (PDF, for the parent)

UNIT 5

Heredity

Why do children resemble their parents, and why do brothers and sisters differ? This unit begins in the garden of an Augustinian monastery in Brno, where Gregor Mendel counted nearly 30,000 pea plants and found the laws of inheritance. Students learn Punnett squares and probability, the patterns beyond Mendel (incomplete dominance, codominance, multiple alleles, sex-linked traits), Thomas Hunt Morgan's white-eyed fruit fly, meiosis and pedigrees.

Every person has two sets of chromosomes, one from the father and one from the mother; males are XY and females XX. The unit teaches this plainly as the biology of sex.

PREREQUISITES

- Unit 3 (chromosomes and mitosis)
- Fractions and simple probability

MASTERY CHECKLIST

- ☐ I can explain Mendel's experiments and his laws of segregation and independent assortment.
- ☐ I can solve monohybrid and dihybrid crosses with Punnett squares and probability.
- ☐ I can solve problems with incomplete dominance, codominance, multiple alleles and sex-linked traits.
- ☐ I can describe meiosis, compare it with mitosis, and read a pedigree.

LESSONS IN THIS UNIT

5.1 The Friar and His Peas: Mendel (1865–1866) and the Rediscovery of 1900

4 sessions of 45 minutes

5.2 Probability, Punnett Squares and Dihybrid Crosses — 4 sessions of 45 minutes

5.3 Beyond Mendel: Incomplete Dominance, Blood Types and Morgan's White-Eyed Fly (1910)

4 sessions of 45 minutes

Unit 5 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 5.1**

   What is a genotype?

2. **8 pts** **Lesson 5.1**

   Why were Mendel's seven traits good choices?

3. **8 pts** **Lesson 5.2**

   Who taught Mendel physics in Vienna?

4. **8 pts** **Lesson 5.2**

   What is a dihybrid cross?

5. **8 pts** **Lesson 5.2**

   In Mendel's peas, round (R) is dominant to wrinkled (r) and yellow (Y) to green (y). Crossing RrYy × RrYy, what fraction of offspring are expected to be wrinkled yellow?

6. **7 pts** **Lesson 5.3**

   What is a polygenic trait? Give an example.

7. **7 pts** **Lesson 5.3**

   Who made the first gene map?

8. **7 pts** **Lesson 5.3**

   A parent with blood genotype $I^A i$ has children with a parent of genotype $I^A i$. What blood types can the children have, and in what proportions?

9. 7 pts Lesson 5.4

A trait appears in an affected father and in all of his daughters but none of his sons. What pattern fits?

10. 7 pts Lesson 5.4

What are homologous chromosomes?

LAB AND DATA

11. 10 pts

A student flips two coins 100 times to model a cross of two Tt pea plants (heads = T, tails = t). Results: TT 22, Tt 53, tt 25. (a) What ratio was expected? (b) What phenotype ratio did she get? (c) Why don’t the results match exactly, and how could she get closer?

SHORT ESSAY

12. 15 pts

Mendel published his results in 1866, but they were ignored until 1900. Explain what Mendel discovered, why his methods were unusual for his time, and why the rediscovery in 1900 mattered.

ANSWER KEY

1. The alleles an organism has.
2. Each had two clear, distinct forms controlled by one gene.
3. Christian Doppler.
4. A cross following two traits.
5. 3/16

   Each trait separately: 3/4 dominant, 1/4 recessive. · Multiply the two probabilities: result 3/16 (the 9:3:3:1 ratio).
6. A trait controlled by many genes; height or skin color.
7. Alfred Sturtevant, 1913.
8. type A: 3/4, type O: 1/4

   Make a 2×2 Punnett square. A and B are codominant; both are dominant to i (O).
9. X-linked dominant.
10. A matched pair, one from each parent, carrying the same genes.
11. (a) 1 TT : 2 Tt : 1 tt (25 : 50 : 25); 3 tall : 1 short. (b) 75 tall : 25 short, 3 : 1. (c) Chance; larger samples come closer to the expected ratio, which is why Mendel counted thousands of plants.
12. Look for: true-breeding parents, seven traits, counting thousands of offspring, 3:1 and 9:3:3:1 ratios; laws of segregation and independent assortment; his use of mathematics and large samples was unusual; biologists of the time thought traits blended; he published in a local journal; de Vries, Correns and Tschermak rediscovered the laws in 1900; chromosomes had by then been observed, so Sutton and Boveri linked Mendel's factors to chromosomes; Mendel's faith and monastic life.

Printable answer key (PDF, for the parent)

5.1 The Friar and His Peas: Mendel (1865–1866) and the Rediscovery of 1900

OBJECTIVES

- Describe Mendel's experiments with pea plants.
- Explain dominant and recessive alleles, genotype and phenotype.
- State the law of segregation.

> **Warm-up.** List three traits you share with a parent and one that neither parent shows. How might a trait skip a generation?

WATCH

GCSE Biology - Gregor Mendel and the History of Genetics

Cognito · 4:22

https://www.youtube.com/watch?v=SOgVM904cPc

> **WHEN TO WATCH**
> After the story.

BACKUP VIDEO

Monohybrids and the Punnett Square Guinea Pigs

Amoeba Sisters · 6:28

https://www.youtube.com/watch?v=i-0rSv6oxSY

With the first Punnett square.

KEY TERMS

gene
A section of DNA that codes for a trait.

allele
One of the different forms of a gene.

dominant
An allele whose trait shows whenever it is present.

recessive
An allele whose trait shows only when two copies are present.

genotype

The alleles an organism has, such as Tt.

phenotype

The trait an organism shows, such as tall.

CORE IDEAS

The story. Gregor Mendel was born to a farming family in Silesia in 1822 and entered the Augustinian abbey of St. Thomas in Brno, where the monks taught science. From 1856 to 1863, in the monastery garden, he grew and counted about 28,000 pea plants. He studied seven traits, each with two clear forms: tall or short, round or wrinkled seeds, yellow or green seeds, purple or white flowers, and others. He presented his results in 1865 and published them in 1866. Hardly anyone noticed. He became abbot in 1868 and died in 1884.

How they figured it out. Mendel began with true-breeding plants. Crossing tall with short gave all tall offspring (F_1). Letting the F_1 self-pollinate gave about 3 tall to 1 short (F_2): 787 tall and 277 short, a ratio of 2.84 to 1. The short trait had not been lost; it was hidden. He reasoned that each plant carries two "factors" for each trait, one from each parent, and that they separate when sex cells form. In 1900 Hugo de Vries, Carl Correns and Erich von Tschermak each independently found the same ratios and discovered that Mendel had been there first.

The biology. Mendel's factors are genes, and their forms are alleles. Use a capital letter for dominant (T, tall) and lowercase for recessive (t, short). TT and tt are homozygous; Tt is heterozygous. Tall plants can be TT or Tt; short plants are always tt. *Law of segregation*: the two alleles separate during the formation of sex cells, so each gamete carries one. A Punnett square shows the possible combinations: Tt × Tt gives 1 TT : 2 Tt : 1 tt, or 3 tall : 1 short.

Where it is used. Plant and animal breeders use Mendel's laws to develop crops and livestock. Genetic counselors use them to estimate risks of inherited conditions such as cystic fibrosis. Mendel's methods (controlled crosses, large samples, mathematical analysis) became a model for biology.

LAB

Coin-Flip Genetics

You will model a Tt × Tt cross with coins and compare your results with Mendel's.

You will need

- Two coins, tape and a marker (label one side T and the other t on each coin)

Steps

1. Each coin is one parent's gamete. Flip both 100 times and record the genotype (TT, Tt or tt).
2. Tally genotypes and phenotypes.
3. Combine results with family members or repeat to reach 400 flips.
4. Compare your ratio with 3 : 1 and with Mendel's 2.84 : 1.

Check your work

- ☐ How close were you after 100 flips? After 400?
- ☐ Why did Mendel count so many plants?

LAB NOTEBOOK

1. Tally tables for 100 and 400 flips.
2. A comparison of ratios.

> **From history.** Mendel also bred bees and kept weather records. Of his work he reportedly said, "My time will come." The statistician R. A. Fisher later suggested Mendel's data were almost too good, but most historians think his methods were sound.

WORKED EXAMPLES

Example 1. Cross a heterozygous purple-flowered pea (Pp) with a white one (pp). Give the expected ratios.

▼ **Show solution**

1. Gametes: P, p × p, p.
2. Square: Pp, Pp, pp, pp.

Answer: 1 Pp : 1 pp; 1 purple : 1 white

Example 2. Mendel got 5,474 round and 1,850 wrinkled seeds in the F_2. Find the ratio.

▼ **Show solution**

1. 5474 ÷ 1850 = 2.96

Answer: 2.96 : 1, close to 3 : 1

PRACTICE

1. Easy What is an allele?

   ▼ **Show answer**

   One form of a gene.

2. Easy What is the phenotype of a Tt pea plant if T (tall) is dominant?

   ▼ **Show answer**

   Tall.

3. Medium Why did the short trait disappear in the F_1 and return in the F_2?

   ▼ **Show answer**

   It was recessive and hidden in Tt plants; Tt × Tt produced tt plants.

COMMON MISTAKES

- Writing the recessive allele as a different letter (T and s) instead of the same letter (T and t).
- Thinking dominant means more common.
- Thinking a 3 : 1 ratio means exactly 3 of every 4 offspring.

Make it a game · Genotype or Phenotype?. The parent says a term (Tt, tall, purple, pp, round, RR). The student says “genotype” or “phenotype” and, for genotypes, the phenotype it gives.

Scripture. “And the earth brought forth grass, and herb yielding seed after his kind, and the tree yielding fruit, whose seed was in itself, after his kind: and God saw that it was good.” (Genesis 1:12, KJV)

Plants yield seed after their kind. Mendel found the laws by which kinds pass on their traits.

5.2 Probability, Punnett Squares and Dihybrid Crosses

OBJECTIVES

- Use probability rules to predict offspring.
- Solve monohybrid crosses and test crosses.
- Solve dihybrid crosses and state the law of independent assortment.

> **Warm-up.** Roll a die and flip a coin at the same time. What is the chance of getting a 6 and heads? List all possible outcomes to check.

WATCH

Dihybrid and Two-Trait Crosses

Amoeba Sisters · 8:32

https://www.youtube.com/watch?v=qIGXTJLrLf8

> **WHEN TO WATCH**
> Before the dihybrid square.

BACKUP VIDEO

A Beginner's Guide to Punnett Squares

Bozeman Science · 12:15

https://www.youtube.com/watch?v=Y1PCwxUDTl8

For extra step-by-step practice (12 minutes).

KEY TERMS

probability
The likelihood that an event will occur, from 0 to 1.

Punnett square
A grid used to predict the genotypes of offspring.

monohybrid cross
A cross involving one trait.

dihybrid cross
A cross involving two traits.

independent assortment

Alleles for different genes separate independently when gametes form.

test cross

Crossing an organism of unknown genotype with a homozygous recessive to find its genotype.

CORE IDEAS

The story. Mendel was trained in physics and mathematics at the University of Vienna, where he studied under Christian Doppler. That training let him see inheritance as a problem in probability. In his second set of experiments he followed two traits at once, seed shape and seed color, and found a 9 : 3 : 3 : 1 ratio in the F_2: 315 round yellow, 108 round green, 101 wrinkled yellow and 32 wrinkled green.

How they figured it out. If seed shape and color are inherited separately, then the chance of round is 3/4 and the chance of yellow is 3/4, so the chance of round and yellow is 3/4 × 3/4 = 9/16. Mendel's numbers matched. This is the *law of independent assortment*. We now know it holds for genes on different chromosomes (or far apart on one chromosome).

The biology. Probability rules: the chance of two independent events both happening is the product of their chances (product rule). A dihybrid cross RrYy × RrYy makes four kinds of gametes (RY, Ry, rY, ry) from each parent, giving a 4 × 4 square with 16 boxes and a 9 : 3 : 3 : 1 phenotype ratio. It is often faster to solve each trait separately and multiply.

Where it is used. Breeders combine traits (disease resistance plus high yield) using these rules. Genetic counselors calculate the chance a couple will have a child with two inherited conditions.

LAB

Dihybrid Beans

You will model a dihybrid cross with two bags of colored beans.

You will need

- Four paper bags, two colors of beans for each gene (for example white/black for shape, red/brown for color)

Steps

1. Bag 1 and 2 (parent 1): one bag of 20 R and 20 r beans, one bag of 20 Y and 20 y beans. Make an identical set for parent 2.
2. Draw one bean from each of parent 1's bags and one from each of parent 2's bags to make an offspring genotype. Replace the beans.
3. Repeat 64 times. Tally phenotypes.
4. Compare with 9 : 3 : 3 : 1 (36 : 12 : 12 : 4).

Check your work

☐ How close did you come?

☐ Why must beans be replaced after each draw?

LAB NOTEBOOK

1. Tally table and comparison with expected numbers.
2. A completed 16-box Punnett square.

> **From history.** Doppler, Mendel's teacher, is famous for the Doppler effect: the change in pitch of a passing siren.

WORKED EXAMPLES

Example 1. In RrYy × RrYy, what fraction of offspring are wrinkled and green (rryy)?

▼ **Show solution**

1. P(rr) = 1/4; P(yy) = 1/4.
2. Multiply: 1/16.

Answer: 1/16

Example 2. What gametes can an RrYy plant make?

▼ **Show solution**

1. Each gamete gets one R-gene allele and one Y-gene allele.
2. RY, Ry, rY, ry.

Answer: RY, Ry, rY, ry (each 1/4)

PRACTICE

1. Easy What is the probability of a heads on a coin flip?

   ▼ **Show answer**

   1/2

2. Easy Two heterozygous purple flowers plants (Pp × Pp) produce 400 offspring. About how many are expected to show the white flowers trait?

   ▼ **Show answer**

   About 100

3. Medium State the law of independent assortment.

   ▼ **Show answer**

   Alleles of different genes separate independently into gametes.

4. Medium In pea plants black fur (B) is dominant to brown fur (b). Cross Bb × bb. Give the genotype ratio and the phenotype ratio.

   ▼ **Show answer**

   Genotypes: 2/4 Bb, 2/4 bb. Phenotypes: 2/4 black fur, 2/4 brown fur.

5. Hard In Mendel's peas, round (R) is dominant to wrinkled (r) and yellow (Y) to green (y). Crossing RrYy × RrYy, what fraction of offspring are expected to be round yellow?

▼ **Show answer**

9/16

COMMON MISTAKES

- Listing gametes with two alleles of the same gene (RR) instead of one of each gene (RY).
- Adding probabilities that should be multiplied.
- Forgetting independent assortment applies to genes on different chromosomes.

Make it a game · Gamete Factory. The parent names a genotype (AaBb, AABb, aaBb). The student lists all possible gametes as fast as possible.

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

The lot is cast into the lap, but the whole disposing thereof is of the LORD. Chance in genetics is never outside God’s rule.

5.3 Beyond Mendel: Incomplete Dominance, Blood Types and Morgan's White-Eyed Fly (1910)

OBJECTIVES

- Solve problems with incomplete dominance and codominance.
- Explain multiple alleles using ABO blood types.
- Explain sex-linked inheritance with Morgan's fruit flies.

> **Warm-up.** A red snapdragon is crossed with a white one, and every offspring is pink. Did the colors blend? What would you predict if two pink ones were crossed?

WATCH

Incomplete Dominance, Codominance, Polygenic Traits, and Epistasis!

Amoeba Sisters · 7:12

https://www.youtube.com/watch?v=YJHGfbW55l0

> **WHEN TO WATCH**
> After incomplete dominance.

BACKUP VIDEO

Multiple Alleles (ABO Blood Types) and Punnett Squares

Amoeba Sisters · 7:05

https://www.youtube.com/watch?v=9O5JQqlngFY

With blood types.

KEY TERMS

incomplete dominance
Neither allele is fully dominant; the heterozygote shows an intermediate trait.

codominance
Both alleles are fully shown in the heterozygote.

multiple alleles
More than two alleles of a gene exist in a population.

sex-linked gene
A gene on the X chromosome (or Y).

carrier

A person with one copy of a recessive allele who does not show the trait.

polygenic trait

A trait controlled by many genes, such as height.

CORE IDEAS

The story. Thomas Hunt Morgan at Columbia University doubted Mendel's laws and the idea that genes sit on chromosomes. In 1908 he began breeding fruit flies, which have a new generation every two weeks, in milk bottles in a cramped laboratory nicknamed the Fly Room. In 1910 he found one male with white eyes instead of red. Crossing it with red-eyed females gave all red-eyed offspring; but in the next generation, every white-eyed fly was male.

How they figured it out. Morgan reasoned that the eye-color gene is on the X chromosome. Females have two X chromosomes (XX); males have one X and one Y (XY). A male with one recessive white allele on his only X shows it; a female needs two. Morgan became convinced that genes are on chromosomes and won the 1933 Nobel Prize. His student Alfred Sturtevant made the first gene map in 1913.

The biology. *Incomplete dominance*: red (RR) × white (WW) → pink (RW). *Codominance*: both show, as in roan cattle with red and white hairs, or AB blood. *Multiple alleles*: blood type has three alleles, I^A, I^B and i; I^A and I^B are codominant and both dominant to i. Types: A (I^AI^A or I^Ai), B, AB (I^AI^B) and O (ii). *Sex-linked*: red-green color blindness and hemophilia are recessive on the X, so they are far more common in males. *Polygenic* traits such as height and skin color are shaped by many genes plus environment.

Where it is used. Blood typing makes transfusions safe. The hemophilia carried by Queen Victoria's descendants affected the royal families of Europe. Genetic counselors trace sex-linked conditions in families.

LAB

Blood Type Mystery (Simulated)

You will solve a family mystery with simulated blood typing (no real blood).

You will need

- Simulated blood typing kit (about $15 from a supplier), or homemade "blood" samples with milk (antigen) and vinegar (antibody) as described in the kit guide
- A family pedigree card prepared by the parent

Steps

1. Test each simulated sample with anti-A and anti-B serum; clumping means that antigen is present.
2. Record each person's blood type.
3. Use Punnett squares to decide which children could belong to which parents.
4. Solve the mystery on the card.

Check your work

- ☐ Which samples clumped with anti-A? With anti-B?
- ☐ Which parent-child pair was impossible?

LAB NOTEBOOK

1. Results table of simulated typing.
2. Punnett squares supporting your solution.

> **From history.** The Fly Room was so small that eight desks were crammed into a space of about 16 by 23 feet. Banana peels were used to feed the flies, and the room swarmed with cockroaches.

WORKED EXAMPLES

Example 1. A color-blind man (X^cY) and a woman with normal vision who is not a carrier (X^CX^C) have children. Predict.

▼ **Show solution**

1. Daughters get X^c from father and X^C from mother: X^CX^c, carriers with normal vision.
2. Sons get Y from father and X^C from mother: normal.

Answer: All children see normally; all daughters are carriers

Example 2. Can parents with type A and type B blood have a type O child?

▼ **Show solution**

1. If they are I^Ai and I^Bi, each can pass i.
2. ii = type O.

Answer: Yes, if both are heterozygous (1/4 chance)

PRACTICE

1. Easy What blood type has the genotype ii?

   ▼ **Show answer**

   Type O.

2. Easy Why are sex-linked recessive traits more common in males?

   ▼ **Show answer**

   Males have only one X, so one recessive allele shows.

3. Medium In snapdragons, red (RR) × white (WW) gives pink (RW) by incomplete dominance. What colors appear, and in what ratio, when two pink plants are crossed?

   ▼ **Show answer**

   1 red : 2 pink : 1 white

4. **Medium** A parent with blood genotype $I^A I^B$ has children with a parent of genotype ii. What blood types can the children have, and in what proportions?

   ▼ **Show answer**

   type A: 2/4, type B: 2/4

5. **Medium** A parent with blood genotype $I^A I^B$ has children with a parent of genotype $I^A I^B$. What blood types can the children have, and in what proportions?

   ▼ **Show answer**

   type A: 1/4, type AB: 2/4, type B: 1/4

COMMON MISTAKES

- Treating codominance as blending.
- Forgetting that males have only one X.
- Writing blood alleles as A, B, O without the gene symbol (use I^A, I^B, i).

Make it a game · Type Match. The parent gives two parents' blood types; the student lists all possible children's types. Then reverse: given a child, which parents are possible?

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

God hath made of one blood all nations of men. All people share one human family and the same genetic system.

5.4 Meiosis, Chromosomes and Pedigrees (Male and Female, XX and XY)

OBJECTIVES

- Describe meiosis and how it halves the chromosome number.
- Compare mitosis and meiosis.
- Explain how meiosis produces variation, and read and draw pedigrees.

> **Warm-up.** Each of your body cells has 46 chromosomes. If a sperm and an egg each had 46, how many would a child have? What must happen to keep the number the same each generation?

WATCH

Meiosis (UPDATED 2026)

Amoeba Sisters · 9:52

https://www.youtube.com/watch?v=I-sucvMV0Ng

> **WHEN TO WATCH**
> After the stages of meiosis.

BACKUP VIDEO

Pedigrees

Amoeba Sisters · 9:38

https://www.youtube.com/watch?v=Gd09V2AkZv4

With pedigrees.

KEY TERMS

meiosis
Cell division that produces four gametes, each with half the chromosome number.

haploid
Having one set of chromosomes (n = 23 in humans).

diploid
Having two sets of chromosomes (2n = 46 in humans).

homologous chromosomes
A pair of chromosomes, one from each parent, carrying the same genes.

crossing over

The exchange of segments between homologous chromosomes in meiosis.

pedigree

A chart showing a trait through generations of a family.

CORE IDEAS

The story. In 1876 Oscar Hertwig watched a sea urchin sperm enter an egg and the two nuclei fuse. In 1883 Edouard van Beneden found that in the roundworm *Ascaris* the egg and sperm each carry half the chromosomes of the body cells. In 1902–1903 Walter Sutton, a graduate student studying grasshopper cells, and Theodor Boveri, working with sea urchins, proposed that chromosomes carry Mendel's factors: the pairs separate in meiosis exactly as Mendel's alleles do.

How they figured it out. Meiosis has two divisions. In meiosis I, homologous chromosomes pair up, exchange pieces (crossing over), and separate into two cells. In meiosis II, sister chromatids separate, as in mitosis. The result is four haploid cells, each genetically different. Fertilization restores the diploid number. In 1905 Nettie Stevens, studying mealworms, discovered that the sex of the offspring depends on whether the sperm carries an X or a Y chromosome.

The biology. Humans have 23 pairs of chromosomes: 22 pairs of autosomes and 1 pair of sex chromosomes. A female is XX; a male is XY. Every egg carries an X; each sperm carries an X or a Y, so the father's sperm determines the child's sex. Variation arises from independent assortment of chromosome pairs (over 8 million combinations per parent) and crossing over. Errors in meiosis can produce an extra chromosome, as in Down syndrome (trisomy 21). In a pedigree, squares are males, circles females; shaded shapes show the trait; half-shaded or dotted shapes show carriers.

Where it is used. Genetic counselors read pedigrees to estimate risks. Karyotypes (pictures of chromosomes) diagnose chromosome conditions. Plant breeders use meiosis to shuffle traits into new varieties.

LAB

Pipe-Cleaner Meiosis and a Family Pedigree

You will model meiosis with crossing over and draw a pedigree for an inherited trait.

You will need

- Pipe cleaners in two colors, beads or tape for alleles, paper plates for cells
- A family trait (attached or free earlobes, tongue rolling, widow's peak) and family photos

Steps

1. Build two pairs of homologous chromosomes (one color from each parent). Copy each (sister chromatids).
2. Pair homologs and twist one segment to show crossing over.
3. Separate homologs (meiosis I) onto two plates, then sister chromatids (meiosis II) onto four plates.
4. Draw a three-generation pedigree for a family trait using standard symbols.

Check your work

- ☐ How many gametes did you make, and how many chromosomes were in each?
- ☐ Were any two gametes identical?

LAB NOTEBOOK

1. Sketches of each stage of your model.
2. Your pedigree with a key.

> **From history.** Nettie Stevens was one of the first American women to make a major discovery in genetics. She earned her doctorate at Bryn Mawr in 1903 and published the X-Y discovery in 1905, about the same time as Edmund Wilson.

WORKED EXAMPLES

Example 1. Compare mitosis and meiosis in a human cell.

▼ **Show solution**

1. Mitosis: 1 division, 2 identical diploid cells (46 chromosomes), for growth and repair.
2. Meiosis: 2 divisions, 4 different haploid cells (23), for gametes.

Answer: See the comparison

Example 2. In a pedigree, two unaffected parents have an affected daughter. Is the trait dominant or recessive?

▼ **Show solution**

1. If dominant, an affected child would need an affected parent.
2. So the trait is recessive, and both parents are carriers.

Answer: Recessive

PRACTICE

1. Easy How many chromosomes are in a human gamete?

   ▼ **Show answer**

   23

2. Easy What are the sex chromosomes of a human male?

   ▼ **Show answer**

   XY

3. Medium How many cells does meiosis produce, and are they identical?

   ▼ **Show answer**

   Four, genetically different.

COMMON MISTAKES

- Thinking meiosis makes two cells (it makes four).
- Confusing homologous chromosomes with sister chromatids.
- Saying the mother determines the child's sex; the father's sperm does.

Make it a game · Mitosis or Meiosis?. The parent reads a statement (makes gametes, two divisions, identical cells, crossing over, used in healing). The student answers mitosis, meiosis or both.

Scripture. “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, KJV)

Male and female created he them. Meiosis and the X and Y chromosomes are the biology of that created distinction.

UNIT 5

Heredity

Why do children resemble their parents, and why do brothers and sisters differ? This unit begins in the garden of an Augustinian monastery in Brno, where Gregor Mendel counted nearly 30,000 pea plants and found the laws of inheritance. Students learn Punnett squares and probability, the patterns beyond Mendel (incomplete dominance, codominance, multiple alleles, sex-linked traits), Thomas Hunt Morgan's white-eyed fruit fly, meiosis and pedigrees.

Every person has two sets of chromosomes, one from the father and one from the mother; males are XY and females XX. The unit teaches this plainly as the biology of sex.

PREREQUISITES

- Unit 3 (chromosomes and mitosis)
- Fractions and simple probability

MASTERY CHECKLIST

- ☐ I can explain Mendel's experiments and his laws of segregation and independent assortment.
- ☐ I can solve monohybrid and dihybrid crosses with Punnett squares and probability.
- ☐ I can solve problems with incomplete dominance, codominance, multiple alleles and sex-linked traits.
- ☐ I can describe meiosis, compare it with mitosis, and read a pedigree.

LESSONS IN THIS UNIT

5.1 The Friar and His Peas: Mendel (1865–1866) and the Rediscovery of 1900

4 sessions of 45 minutes

5.2 Probability, Punnett Squares and Dihybrid Crosses — 4 sessions of 45 minutes

5.3 Beyond Mendel: Incomplete Dominance, Blood Types and Morgan's White-Eyed Fly (1910)

4 sessions of 45 minutes

Unit 5 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 5.1**

   What is a genotype?

2. **8 pts** **Lesson 5.1**

   Why were Mendel's seven traits good choices?

3. **8 pts** **Lesson 5.2**

   Who taught Mendel physics in Vienna?

4. **8 pts** **Lesson 5.2**

   What is a dihybrid cross?

5. **8 pts** **Lesson 5.2**

   In Mendel's peas, round (R) is dominant to wrinkled (r) and yellow (Y) to green (y). Crossing RrYy × RrYy, what fraction of offspring are expected to be wrinkled yellow?

6. **7 pts** **Lesson 5.3**

   What is a polygenic trait? Give an example.

7. **7 pts** **Lesson 5.3**

   Who made the first gene map?

8. **7 pts** **Lesson 5.3**

   A parent with blood genotype $I^A i$ has children with a parent of genotype $I^A i$. What blood types can the children have, and in what proportions?

9. **7 pts** **Lesson 5.4**

   A trait appears in an affected father and in all of his daughters but none of his sons. What pattern fits?

10. **7 pts** **Lesson 5.4**

    What are homologous chromosomes?

LAB AND DATA

11. **10 pts**

    A student flips two coins 100 times to model a cross of two Tt pea plants (heads = T, tails = t). Results: TT 22, Tt 53, tt 25. (a) What ratio was expected? (b) What phenotype ratio did she get? (c) Why don’t the results match exactly, and how could she get closer?

SHORT ESSAY

12. **15 pts**

    Mendel published his results in 1866, but they were ignored until 1900. Explain what Mendel discovered, why his methods were unusual for his time, and why the rediscovery in 1900 mattered.

ANSWER KEY

1. The alleles an organism has.
2. Each had two clear, distinct forms controlled by one gene.
3. Christian Doppler.
4. A cross following two traits.
5. 3/16

   Each trait separately: 3/4 dominant, 1/4 recessive. · Multiply the two probabilities: result 3/16 (the 9:3:3:1 ratio).
6. A trait controlled by many genes; height or skin color.
7. Alfred Sturtevant, 1913.
8. type A: 3/4, type O: 1/4

   Make a 2×2 Punnett square. A and B are codominant; both are dominant to i (O).
9. X-linked dominant.
10. A matched pair, one from each parent, carrying the same genes.
11. (a) 1 TT : 2 Tt : 1 tt (25 : 50 : 25); 3 tall : 1 short. (b) 75 tall : 25 short, 3 : 1. (c) Chance; larger samples come closer to the expected ratio, which is why Mendel counted thousands of plants.
12. Look for: true-breeding parents, seven traits, counting thousands of offspring, 3:1 and 9:3:3:1 ratios; laws of segregation and independent assortment; his use of mathematics and large samples was unusual; biologists of the time thought traits blended; he published in a local journal; de Vries, Correns and Tschermak rediscovered the laws in 1900; chromosomes had by then been observed, so Sutton and Boveri linked Mendel's factors to chromosomes; Mendel's faith and monastic life.

Printable answer key (PDF, for the parent)

UNIT 6

DNA and the Genetic Code

Mendel's factors had to be made of something. This unit follows the detective story that identified DNA as the genetic material (Griffith's mice, Avery's enzymes, Hershey and Chase's blender), the race to its structure (Chargaff's rules, Rosalind Franklin's Photo 51, Watson and Crick's model), the copying of DNA and the reading of its code into proteins (Nirenberg, 1961), and finally mutations, biotechnology and the ethical questions they raise.

Lesson 6.4 discusses bioethics from the conviction that every human being bears the image of God (Genesis 1:27).

PREREQUISITES

- Unit 2 (nucleic acids and proteins)
- Unit 5 (genes and chromosomes)

MASTERY CHECKLIST

- ☐ I can describe the experiments of Griffith, Avery, and Hershey and Chase and what each showed.
- ☐ I can describe the structure of DNA, use base-pairing rules and Chargaff's rules, and explain the contributions of Franklin, Watson and Crick.
- ☐ I can explain replication, transcription and translation and use the codon table.
- ☐ I can classify mutations, describe PCR and gene technology, and discuss ethical questions with care.

LESSONS IN THIS UNIT

6.1 Finding the Genetic Material: Griffith (1928), Avery (1944), Hershey and Chase (1952)

4 sessions of 45 minutes

6.2 The Double Helix: Chargaff, Franklin (Photo 51, 1952), Watson and Crick (1953)

4 sessions of 45 minutes

6.3 Replication, Transcription and Translation: Nirenberg Cracks the Code (1961)

4 sessions of 45 minutes

6.4 Mutations, Biotechnology and Bioethics: Mullis's PCR (1983) and the Image of God

4 sessions of 45 minutes

Unit 6 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 6.1**
   In Griffith's experiment, what was the control that showed heat-killed S cells were harmless?

2. **8 pts** **Lesson 6.1**
   What disease did Griffith study?

3. **8 pts** **Lesson 6.2**
   What ethical lessons does the DNA story teach?

4. **8 pts** **Lesson 6.2**
   How many hydrogen bonds join G and C?

5. **8 pts** **Lesson 6.2**
   A sample of double-stranded DNA is 34% adenine. Using Chargaff's rules, find the percentages of T, G and C.

6. **7 pts** **Lesson 6.3**
   What is the start codon?

7. **7 pts** **Lesson 6.3**
   Name the three stop codons.

8. **7 pts** **Lesson 6.3**

   Using the codon table, translate the mRNA 5′-AUGCGUCUCGAAUAG-3′.

9. **7 pts** **Lesson 6.4**

   Most mutations are harmful or neutral. Why does that matter for discussions of origins?

10. **7 pts** **Lesson 6.4**

    What is bioethics?

LAB AND DATA

11. **10 pts**

    Hershey and Chase grew one batch of viruses with radioactive sulfur (^{35}S, labels protein) and another with radioactive phosphorus (^{32}P, labels DNA). After the viruses infected bacteria, they shook off the virus coats in a blender and spun the bacteria to the bottom. (a) Where was the ^{35}S found? (b) Where was the ^{32}P found? (c) What did this show?

SHORT ESSAY

12. **15 pts**

    The double helix is sometimes told as the story of Watson and Crick alone. Tell the fuller story: what Chargaff, Wilkins and Franklin each contributed, how the model explained base pairing and copying, and what lessons about honesty and credit in science the story teaches.

ANSWER KEY

1. Injecting heat-killed S alone; the mice lived.
2. Pneumonia.
3. Give honest credit; don't use others' data without permission; treat colleagues fairly.
4. Three.
5. T 34%, G 16%, C 16%

   A = T = 34%; G + C = 100 − 68 = 32%, split equally.
6. AUG (methionine).
7. UAA, UAG, UGA.
8. Met–Arg–Leu–Glu (stop)

   Split into codons: AUG CGU CUC GAA UAG
9. It raises the question of how often mutations add useful new information; this is debated (Unit 7).
10. The study of moral questions in biology and medicine.
11. (a) In the liquid with the empty virus coats, outside the bacteria. (b) Inside the bacteria in the pellet. (c) The virus injects DNA, not protein, into the cell; DNA is the genetic material.
12. Look for: Chargaff's rules (A = T, G = C, 1950); Franklin's X-ray images, especially Photo 51 (1952), showing a helix with phosphates outside; Wilkins showed the photo to Watson without Franklin's knowledge; Watson and Crick built the model (1953) with paired bases A–T, G–C; complementary strands suggest a copying mechanism; Nobel 1962 to Watson, Crick and Wilkins (Franklin died in 1958); lessons about giving credit honestly and treating colleagues with respect.

Printable answer key (PDF, for the parent)

6.1 Finding the Genetic Material: Griffith (1928), Avery (1944), Hershey and Chase (1952)

OBJECTIVES

- Describe Griffith's transformation experiment.
- Explain how Avery identified DNA as the transforming principle.
- Explain the Hershey–Chase experiment.

> **Warm-up.** Detectives eliminate suspects one by one. If the genetic material had to be either protein or DNA, what kind of experiment would let you rule one out?

WATCH

Establishing DNA as transformation principle

Khan Academy · 10:18

https://www.youtube.com/watch?v=9X12OVvOznU

> **WHEN TO WATCH**
> After Griffith and Avery.

BACKUP VIDEO

Hershey and Chase conclusively show DNA genetic material

Khan Academy · 8:48

https://www.youtube.com/watch?v=bNsSaxCsIIg

For the Hershey–Chase experiment.

KEY TERMS

transformation
A change in a bacterium caused by taking in genetic material from another bacterium.

bacteriophage
A virus that infects bacteria.

radioactive label
A radioactive atom used to trace a substance.

virulent
Able to cause disease.

genetic material

The substance that carries hereditary information: DNA.

enzyme

A protein catalyst; enzymes that destroy specific molecules were Avery's key tool.

CORE IDEAS

The story. In 1928 the British medical officer Frederick Griffith studied pneumonia bacteria. Smooth (S) strains killed mice; rough (R) strains did not. Heat-killed S bacteria were harmless. But a mix of heat-killed S and live R killed the mice, and live S bacteria were found in their blood. Something from the dead S cells had transformed the R cells. In New York, Oswald Avery, Colin MacLeod and Maclyn McCarty spent a decade purifying the "transforming principle." In 1944 they showed that enzymes destroying protein or RNA did not stop transformation, but an enzyme destroying DNA did.

How they figured it out. Many scientists still thought protein, with its 20 amino acids, was more likely to carry genetic information than DNA, with only four bases. In 1952 Alfred Hershey and Martha Chase used bacteriophages, which are just protein coats around DNA. They labeled protein with radioactive sulfur and DNA with radioactive phosphorus, let the viruses infect bacteria, and knocked off the coats in a kitchen blender. The phosphorus went inside the bacteria; the sulfur stayed outside. DNA was the genetic material.

The biology. Each experiment added to the case: Griffith showed something could transfer heredity; Avery identified it as DNA by elimination; Hershey and Chase confirmed it with a different organism and method. Good science looks for independent lines of evidence that agree.

Where it is used. Bacterial transformation is used every day in laboratories to make bacteria produce human insulin and other medicines. The spread of antibiotic resistance between bacteria also happens partly by transformation.

LAB

The Evidence Board

You will build a detective-style evidence board for the case of the genetic material.

You will need

- Poster board or a large sheet of paper, index cards, string, markers

Steps

1. Make a card for each experiment: Griffith, Avery–MacLeod–McCarty, Hershey–Chase.
2. On each, sketch the setup, the result and what it ruled in or out.
3. Connect cards with string to show how each built on the last.
4. Write a one-paragraph verdict: what is the genetic material, and how sure are we?

Check your work

- ☐ Which experiment ruled out protein most directly?
- ☐ Why was more than one experiment needed?

LAB NOTEBOOK

1. Sketches of each experiment.
2. Your verdict paragraph.

> **From history.** Avery never won a Nobel Prize, though many think he deserved one. Martha Chase was 24 and a laboratory assistant when she co-authored one of the most famous experiments in biology.

WORKED EXAMPLES

Example 1. In Griffith's experiment, what was the result of injecting (a) live R, (b) heat-killed S, (c) heat-killed S + live R?

▼ **Show solution**

1. (a) Mouse lived.
2. (b) Mouse lived.
3. (c) Mouse died; live S found.

Answer: Only the mixture killed: R cells had been transformed

PRACTICE

1. Easy What did Griffith discover?

   ▼ **Show answer**

   Transformation: harmless bacteria became deadly after mixing with heat-killed deadly bacteria.

2. Easy What did Avery identify as the transforming principle?

   ▼ **Show answer**

   DNA.

3. Medium How did Avery show it was DNA?

   ▼ **Show answer**

   Enzymes that destroyed protein or RNA did not stop transformation; an enzyme destroying DNA did.

COMMON MISTAKES

- Thinking Griffith identified DNA; he found transformation but not its cause.
- Mixing up which label marked protein (sulfur) and which DNA (phosphorus).
- Thinking one experiment settles a question; scientists look for agreeing lines of evidence.

> **Make it a game · Which Label?.** The parent names a molecule or element (sulfur, phosphorus, protein coat, DNA, amino acid, nucleotide). The student says which Hershey–Chase label it goes with.

> **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)
>
> It is the honour of kings to search out a matter. The search for the genetic material took decades of patient detective work.

6.2 The Double Helix: Chargaff, Franklin (Photo 51, 1952), Watson and Crick (1953)

OBJECTIVES

- Describe the structure of DNA.
- Apply base-pairing and Chargaff's rules.
- Explain the contributions of Chargaff, Franklin, Wilkins, Watson and Crick.

> **Warm-up.** Twist a ladder made of paper strips. Which parts would be the sugar-phosphate backbone and which the rungs? What holds the rungs together?

WATCH

The discovery of the double helix structure of DNA

Khan Academy · 8:56

https://www.youtube.com/watch?v=hCUce36Ganc

> **WHEN TO WATCH**
> After the story.

BACKUP VIDEO

(OLD VIDEO) DNA Structure and Function

Amoeba Sisters · 8:54

https://www.youtube.com/watch?v=_POdWsii7AI

With the structure.

KEY TERMS

double helix

The twisted-ladder shape of DNA, two strands wound around each other.

base pairing

A pairs with T and G pairs with C by hydrogen bonds.

Chargaff's rules

In DNA, the amount of A equals T and G equals C.

complementary

Matching by base-pairing rules.

X-ray crystallography

Using X-ray patterns to find the arrangement of atoms in a molecule.

antiparallel

Running in opposite directions (5′ → 3′ and 3′ → 5′).

CORE IDEAS

The story. In 1950 Erwin Chargaff, an Austrian-born biochemist at Columbia, measured the bases in DNA from many species and found that A always equals T and G equals C. At King's College London, Rosalind Franklin took sharp X-ray photographs of DNA fibers; her Photo 51 (May 1952), taken with her student Raymond Gosling, showed a clear X, the signature of a helix. Without her knowledge, her colleague Maurice Wilkins showed it to James Watson. Watson and Francis Crick at Cambridge had also seen her data in a report. On February 28, 1953, they finished a cardboard and metal model.

How they figured it out. The model fit everything: two sugar-phosphate backbones on the outside, running in opposite directions; bases paired inside, A with T (two hydrogen bonds) and G with C (three); a uniform width of 2 nm; one full turn every 10 base pairs. Their one-page paper in *Nature* (April 25, 1953) ended: "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material." Franklin's own paper appeared in the same issue.

The biology. Base pairing means each strand determines the other: if one strand reads ATGC, its partner reads TACG. Chargaff's rules follow from pairing. The sequence of bases is the information; the human genome has about 3 billion base pairs in each set of chromosomes.

Where it is used. DNA sequencing, forensic DNA profiles, paternity tests and genetic medicine all rest on base pairing. Franklin died of ovarian cancer in 1958 at 37; the 1962 Nobel Prize went to Watson, Crick and Wilkins. The story is now a lesson in giving honest credit.

LAB

Build a DNA Model

You will build a double helix model and use it to show base pairing.

You will need

- Licorice or pipe cleaners (backbones), four colors of gummy candies or beads (bases), toothpicks

Steps

1. Assign a color to A, T, G and C.
2. Build one strand of 10 nucleotides with any sequence.
3. Build the complementary strand, pairing A–T and G–C.
4. Join the strands and twist gently into a helix, about one full turn.

Check your work

- ☐ How did the first strand determine the second?
- ☐ Why are all the rungs the same length?

LAB NOTEBOOK

1. Your sequences for both strands.
2. A labeled sketch of your model.

> **From history.** Photo 51 took about 62 hours of X-ray exposure. Franklin later did pioneering work on the structure of viruses before her early death.

WORKED EXAMPLES

Example 1. A DNA sample is 30% guanine. Find the percentages of the other bases.

▼ **Show solution**

1. G = C = 30%.
2. A + T = 40%, so A = T = 20%.

Answer: C 30%, A 20%, T 20%

Example 2. Write the complementary strand for 5′-ATTGCAC-3′.

▼ **Show solution**

1. Pair A–T, G–C; the new strand runs antiparallel.

Answer: 3′-TAACGTG-5′

PRACTICE

1. Easy What shape is DNA?

   ▼ **Show answer**

   A double helix.

2. Easy Which base pairs with adenine in DNA?

   ▼ **Show answer**

   Thymine.

3. Easy Write the complementary DNA strand for 5′-ACGGAGCAG-3′.

   ▼ **Show answer**

   3′-TGCCTCGTC-5′

4. Medium A sample of double-stranded DNA is 19% adenine. Using Chargaff's rules, find the percentages of T, G and C.

   ▼ **Show answer**

   T 19%, G 31%, C 31%

5. Medium A sample of double-stranded DNA is 31% adenine. Using Chargaff's rules, find the percentages of T, G and C.

   ▼ **Show answer**

   T 31%, G 19%, C 19%

COMMON MISTAKES

- Pairing A with G or C with T.
- Forgetting the strands run in opposite directions.
- Giving Watson and Crick sole credit and forgetting Franklin, Wilkins and Chargaff.

Make it a game · Speed Pairing. The parent reads a strand of 8 bases aloud; the student calls back the complementary strand. Increase the length each round.

Scripture. “My substance was not hid from thee, when I was made in secret, and curiously wrought in the lowest parts of the earth. 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 139:15–16, KJV)

David speaks of being curiously wrought and written in God’s book. The DNA double helix is a written code in every cell.

6.3 Replication, Transcription and Translation: Nirenberg Cracks the Code (1961)

OBJECTIVES

- Describe DNA replication.
- Describe transcription and translation.
- Use the genetic code to translate mRNA into a protein.

> **Warm-up.** A library keeps its rare books in a vault. To use one, you make a photocopy, take it to the workshop and follow the instructions. How is this like a cell making a protein?

WATCH

Protein Synthesis: Transcription and Translation (Updated)

Amoeba Sisters · 8:47

https://www.youtube.com/watch?v=oefAI2x2CQM

> **WHEN TO WATCH**
> After the central dogma.

BACKUP VIDEO

DNA Replication (Updated)

Amoeba Sisters · 8:12

https://www.youtube.com/watch?v=Qqe4thU-os8

For replication.

KEY TERMS

replication

Copying DNA before a cell divides.

transcription

Making an mRNA copy of a gene.

translation

Building a protein from the mRNA message at a ribosome.

codon

A three-base sequence of mRNA that codes for one amino acid or a stop signal.

anticodon

The three bases on a tRNA that pair with a codon.

mRNA

Messenger RNA, which carries the gene's message to the ribosome.

CORE IDEAS

The story. If DNA holds the instructions, how are they read? Crick proposed the "central dogma": DNA → RNA → protein. In 1958 Matthew Meselson and Franklin Stahl showed, with heavy nitrogen, that DNA copies itself semi-conservatively: each new double helix keeps one old strand. Then in May 1961, Marshall Nirenberg and Heinrich Matthaei at the National Institutes of Health added an artificial RNA made only of uracil (UUU…) to a cell-free extract. It made a protein made only of phenylalanine. UUU means phenylalanine: the first word of the genetic code. By 1966 all 64 codons were known.

How they figured it out. Four bases taken one at a time could code only 4 amino acids; two at a time, 16; three at a time, 64, enough for 20 amino acids plus stop signals. Crick and Sydney Brenner showed in 1961 that the code is read in triplets without gaps. Nirenberg, Har Gobind Khorana and Robert Holley worked out the rest (Nobel 1968).

The biology. *Replication*: the enzyme helicase unzips DNA; DNA polymerase builds new strands by base pairing. *Transcription* (nucleus): RNA polymerase copies a gene into mRNA, using U in place of T. *Translation* (ribosome): the mRNA is read in codons starting at AUG (methionine); each tRNA brings one amino acid and matches its anticodon to the codon; the ribosome links amino acids until a stop codon (UAA, UAG, UGA). The code is nearly universal: the same codons mean the same amino acids in bacteria, plants and people.

Where it is used. Because the code is shared, bacteria can read a human insulin gene and make insulin. Some antibiotics block bacterial ribosomes. The code is often compared to written language: a message of letters, words and punctuation. Many see such a code as evidence of a Designer.

LAB

Decode a Secret Protein

You will transcribe and translate DNA messages using a codon table, then design your own.

You will need

- A printed codon table, the parent's secret DNA messages (each amino acid's one-letter code spells a word)
- Paper beads or paper clips in colors for a chain model

Steps

1. Transcribe each DNA template into mRNA.
2. Find the start codon and translate codon by codon.
3. Write the one-letter amino acid codes; they spell a word.
4. Design your own DNA message for a family member to decode.

Check your work

- ☐ What happened when you started reading one base too late?
- ☐ Why does a stop codon matter?

LAB NOTEBOOK

1. Worked decoding of each message.
2. Your own coded message with answer.

> **From history.** Nirenberg announced the UUU result at a conference in Moscow in August 1961 to a small audience. Crick heard about it and arranged for him to give the talk again to the whole congress.

WORKED EXAMPLES

Example 1. Transcribe and translate the DNA template strand 3′-TACAAACCGATT-5′.

▼ **Show solution**

1. mRNA: 5′-AUGUUUGGCUAA-3′.
2. Codons: AUG UUU GGC UAA.
3. Met – Phe – Gly – stop.

Answer: Met–Phe–Gly

Example 2. How many amino acids are coded by an mRNA of 300 bases (not counting the stop codon)?

▼ **Show solution**

1. 300/3 = 100 codons, one is stop.

Answer: 99

PRACTICE

1. Easy What is the central dogma?

   ▼ **Show answer**

   DNA → RNA → protein.

2. Easy Where does transcription happen in eukaryotes?

   ▼ **Show answer**

   In the nucleus.

3. Medium Using the codon table, translate the mRNA 5′-AUGGCAUUAAGAUAG-3′.

   ▼ **Show answer**

   Met–Ala–Leu–Arg (stop)

4. Medium Using the codon table, translate the mRNA 5′-AUGCUGGGGCUUUAA-3′.

   ▼ **Show answer**

   Met–Leu–Gly–Leu (stop)

5. Hard A DNA template strand reads 3′-TACAGACCGGCGATT-5′. Write the mRNA, then use the codon table to give the amino acid sequence.

   ▼ **Show answer**

   mRNA 5′-AUGUCUGGCCGCUAA-3′; protein Met–Ser–Gly–Arg (then stop)

COMMON MISTAKES

- Using T in mRNA instead of U.
- Translating the DNA directly instead of the mRNA.
- Starting before AUG or reading past the stop codon.

Make it a game · Codon Bingo. Make bingo cards with amino acid names. The parent calls codons; the student finds the amino acid on the codon table and marks it.

Scripture. “Thy word is a lamp unto my feet, and a light unto my path.” (Psalm 119:105, KJV)

Thy word is a lamp unto my feet. The genetic code is a written word inside every cell, read faithfully every moment.

6.4 Mutations, Biotechnology and Bioethics: Mullis's PCR (1983) and the Image of God

OBJECTIVES

- Classify gene and chromosome mutations and their effects.
- Describe PCR, gel electrophoresis and genetic engineering.
- Discuss bioethical questions from the conviction that every human being bears God's image.

> **Warm-up.** Change one letter in the sentence THE CAT ATE THE RAT. Then delete one letter and regroup the letters into threes. Which change damaged the message more?

WATCH

PCR (Polymerase Chain Reaction)

Amoeba Sisters · 7:54

https://www.youtube.com/watch?v=a5jmdh9AnS4

> **WHEN TO WATCH**
> After the PCR story.

BACKUP VIDEO

Mutations (Updated)

Amoeba Sisters · 7:14

https://www.youtube.com/watch?v=vl6Vlf2thvI

With the types of mutation.

KEY TERMS

mutation

A change in the DNA sequence.

point mutation

A change in a single base.

frameshift mutation

An insertion or deletion that shifts the reading frame.

PCR

Polymerase chain reaction: a method to copy a DNA segment millions of times.

gel electrophoresis

Separating DNA fragments by size with an electric current through a gel.

bioethics

The study of moral questions raised by biology and medicine.

CORE IDEAS

The story. One night in 1983 the biochemist Kary Mullis was driving along a mountain road in California when he realized how to copy a single piece of DNA over and over: heat the DNA to separate the strands, cool it so short primers bind, let DNA polymerase build new strands, and repeat. Each cycle doubles the DNA; 30 cycles make about a billion copies. Using a heat-resistant polymerase from bacteria found in Yellowstone's hot springs, PCR became one of the most widely used methods in biology. Mullis won the 1993 Nobel Prize.

How they figured it out. Mutations are changes in DNA from copying errors, radiation or chemicals. A *substitution* changes one base; it may be silent (same amino acid), missense (a different amino acid, as in sickle-cell disease, where one base change alters hemoglobin) or nonsense (a premature stop). Insertions and deletions shift the reading frame and usually wreck the protein. Most mutations are harmful or neutral; cells have repair systems that fix most errors.

The biology. Biotechnology tools: PCR copies DNA; gel electrophoresis sorts fragments by size (small ones travel farther), making DNA fingerprints; genetic engineering inserts a gene into another organism (human insulin from bacteria since 1982); CRISPR (2012) edits genes precisely. Gene therapy has treated some inherited diseases such as sickle-cell disease (approved 2023).

Bioethics and the image of God. Scripture teaches that every human being is made in God's image (Genesis 1:27) and is therefore of great worth, whatever his health, abilities or stage of life. That conviction guides how Christians weigh new technologies: treating disease in a patient is a work of mercy, as Jesus healed the sick; experiments that destroy or manufacture human embryos, or that try to "design" children, treat persons as products. In 2018 a scientist in China edited the genes of twin girls as embryos; scientists around the world condemned it, and he was imprisoned. Students should be able to state the arguments carefully and charitably.

Safety first. Adult connects the batteries. Do not touch the electrodes while running. 45 V from batteries in series can shock.

LAB

Candy Electrophoresis and a Mutation Model

You will separate food dyes on a gel (a safe model of DNA electrophoresis) and model mutations with paper strips.

You will need

- Agar powder, baking soda buffer, a small plastic box, aluminum foil electrodes, five 9 V batteries in series (adult)
- Food coloring or candy dyes dissolved in water, a dropper
- Paper strips with a printed DNA sequence

Steps

1. With an adult, make a 1% agar gel in baking soda solution with wells cut at one end.
2. Load drops of different dyes in the wells; connect foil electrodes to the batteries.
3. Run for 20–30 minutes and record how far each dye moved.
4. Mutation model: cut and tape the paper sequences to make a substitution, an insertion and a deletion, then translate each.

Check your work

- ☐ Which dyes moved farthest? Why?
- ☐ Which mutation changed the protein the most?

LAB NOTEBOOK

1. Distances moved by each dye.
2. Translations of the normal and mutated sequences.

From history. The heat-resistant polymerase used in PCR, Taq, comes from *Thermus aquaticus*, a bacterium discovered in 1966 by Thomas Brock in Yellowstone's Mushroom Spring.

WORKED EXAMPLES

Example 1. In the hemoglobin gene, one mRNA codon GAG (glutamic acid) mutates to GUG. What happens?

▼ **Show solution**

1. mRNA codon GAG → GUG.
2. Glu → Val: a missense mutation.
3. This is the sickle-cell mutation in hemoglobin.

Answer: Missense: glutamic acid → valine, causing sickle-cell disease

Example 2. Starting from one DNA molecule, how many copies after 10 PCR cycles?

▼ **Show solution**

1. Each cycle doubles: 2^{10}.

Answer: 1,024

PRACTICE

1. Easy What is a mutation?

   ▼ **Show answer**

   A change in the DNA sequence.

2. Easy What does PCR do?

   ▼ **Show answer**

   Copies a DNA segment millions of times.

3. Medium Why is a frameshift usually more harmful than a substitution?

   ▼ **Show answer**

   It changes every codon after it.

COMMON MISTAKES

- Thinking all mutations are harmful (many are neutral) or that mutations commonly add new useful information.
- Thinking small DNA fragments move slower; they move faster.
- Confusing gene therapy in a patient with editing embryos.

Make it a game · Mutation Detective. The parent writes a sentence of three-letter words and secretly mutates it. The student identifies the type (substitution, insertion, deletion) and its effect.

Scripture. “Whoso sheddeth man’s blood, by man shall his blood be shed: for in the image of God made he man.” (Genesis 9:6, KJV)

After the Flood, God grounded the protection of human life in this: in the image of God made he man. Every human being, healthy or sick, at every stage of life, carries that dignity.

UNIT 6

DNA and the Genetic Code

Mendel's factors had to be made of something. This unit follows the detective story that identified DNA as the genetic material (Griffith's mice, Avery's enzymes, Hershey and Chase's blender), the race to its structure (Chargaff's rules, Rosalind Franklin's Photo 51, Watson and Crick's model), the copying of DNA and the reading of its code into proteins (Nirenberg, 1961), and finally mutations, biotechnology and the ethical questions they raise.

Lesson 6.4 discusses bioethics from the conviction that every human being bears the image of God (Genesis 1:27).

PREREQUISITES

- Unit 2 (nucleic acids and proteins)
- Unit 5 (genes and chromosomes)

MASTERY CHECKLIST

- ☐ I can describe the experiments of Griffith, Avery, and Hershey and Chase and what each showed.
- ☐ I can describe the structure of DNA, use base-pairing rules and Chargaff's rules, and explain the contributions of Franklin, Watson and Crick.
- ☐ I can explain replication, transcription and translation and use the codon table.
- ☐ I can classify mutations, describe PCR and gene technology, and discuss ethical questions with care.

LESSONS IN THIS UNIT

6.1 Finding the Genetic Material: Griffith (1928), Avery (1944), Hershey and Chase (1952)

4 sessions of 45 minutes

6.2 The Double Helix: Chargaff, Franklin (Photo 51, 1952), Watson and Crick (1953)

4 sessions of 45 minutes

6.3 Replication, Transcription and Translation: Nirenberg Cracks the Code (1961)

4 sessions of 45 minutes

6.4 Mutations, Biotechnology and Bioethics: Mullis's PCR (1983) and the Image of God

4 sessions of 45 minutes

Unit 6 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 6.1**
   In Griffith's experiment, what was the control that showed heat-killed S cells were harmless?

2. **8 pts** **Lesson 6.1**
   What disease did Griffith study?

3. **8 pts** **Lesson 6.2**
   What ethical lessons does the DNA story teach?

4. **8 pts** **Lesson 6.2**
   How many hydrogen bonds join G and C?

5. **8 pts** **Lesson 6.2**
   A sample of double-stranded DNA is 34% adenine. Using Chargaff's rules, find the percentages of T, G and C.

6. **7 pts** **Lesson 6.3**
   What is the start codon?

7. **7 pts** **Lesson 6.3**
   Name the three stop codons.

8. **7 pts** **Lesson 6.3**

   Using the codon table, translate the mRNA 5′-AUGCGUCUCGAAUAG-3′.

9. **7 pts** **Lesson 6.4**

   Most mutations are harmful or neutral. Why does that matter for discussions of origins?

10. **7 pts** **Lesson 6.4**

    What is bioethics?

LAB AND DATA

11. **10 pts**

    Hershey and Chase grew one batch of viruses with radioactive sulfur (^{35}S, labels protein) and another with radioactive phosphorus (^{32}P, labels DNA). After the viruses infected bacteria, they shook off the virus coats in a blender and spun the bacteria to the bottom. (a) Where was the ^{35}S found? (b) Where was the ^{32}P found? (c) What did this show?

SHORT ESSAY

12. **15 pts**

    The double helix is sometimes told as the story of Watson and Crick alone. Tell the fuller story: what Chargaff, Wilkins and Franklin each contributed, how the model explained base pairing and copying, and what lessons about honesty and credit in science the story teaches.

ANSWER KEY

1. Injecting heat-killed S alone; the mice lived.
2. Pneumonia.
3. Give honest credit; don't use others' data without permission; treat colleagues fairly.
4. Three.
5. T 34%, G 16%, C 16%

   A = T = 34%; G + C = 100 − 68 = 32%, split equally.
6. AUG (methionine).
7. UAA, UAG, UGA.
8. Met–Arg–Leu–Glu (stop)

   Split into codons: AUG CGU CUC GAA UAG
9. It raises the question of how often mutations add useful new information; this is debated (Unit 7).
10. The study of moral questions in biology and medicine.
11. (a) In the liquid with the empty virus coats, outside the bacteria. (b) Inside the bacteria in the pellet. (c) The virus injects DNA, not protein, into the cell; DNA is the genetic material.
12. Look for: Chargaff's rules (A = T, G = C, 1950); Franklin's X-ray images, especially Photo 51 (1952), showing a helix with phosphates outside; Wilkins showed the photo to Watson without Franklin's knowledge; Watson and Crick built the model (1953) with paired bases A–T, G–C; complementary strands suggest a copying mechanism; Nobel 1962 to Watson, Crick and Wilkins (Franklin died in 1958); lessons about giving credit honestly and treating colleagues with respect.

Printable answer key (PDF, for the parent)

UNIT 7

Variation, Adaptation and Origins

This unit takes up the most debated question in biology: where did the variety of living things come from? It begins with what Charles Darwin actually observed on the voyage of the *Beagle*, studies the variation and adaptation that everyone agrees we can see (finch beaks, peppered moths, antibiotic resistance), sets out the case for universal common descent as its defenders make it along with the open questions critics raise, and closes by comparing young-earth creation, old-earth creation, intelligent design and Darwinian theory fairly, each in its own best terms.

The rule of the unit is Proverbs 18:17: "He that is first in his own cause seemeth just; but his neighbour cometh and searcheth him." Students should be able to state every view so that its own holders would say "yes, that is what we believe," before weighing it. Observations come first; claims about the unobserved past are labeled as interpretations. A parent should read the whole unit before the student begins.

PREREQUISITES

- Units 5–6 (genes, mutations, DNA)

MASTERY CHECKLIST

- ☐ I can describe what Darwin observed on the Beagle voyage and how he reasoned to his theory.
- ☐ I can explain natural selection and give observed examples of adaptation within kinds, including Blyth's view of conserving selection.
- ☐ I can state the evidence offered for universal common descent and the main open questions about it.
- ☐ I can fairly compare young-earth creation, old-earth creation, intelligent design and Darwinian theory, stating each in terms its holders would accept.

LESSONS IN THIS UNIT

7.1 Darwin's Voyage (1831–1836) and What He Observed — 4 sessions of 45 minutes

7.2 Variation Within Kinds: Finch Beaks, Peppered Moths, Antibiotic Resistance and Blyth's Conserving Selection (1835)

4 sessions of 45 minutes

7.3 Common Descent: The Claim, the Evidence Offered and the Open Questions

4 sessions of 45 minutes

7.4 Origins Fairly Told: Creation, Intelligent Design and Darwinian Theory Compared

4 sessions of 45 minutes

Unit 7 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 7.1**
   In the beak lab, why did no single beak do best on every food?

2. **10 pts** **Lesson 7.1**
   What did Darwin study at Cambridge before the voyage?

3. **10 pts** **Lesson 7.2**
   Does selection create new traits?

4. **9 pts** **Lesson 7.2**
   How did the beak depths change after the wet year of 1983?

5. **9 pts** **Lesson 7.3**
   What were Haeckel's embryo drawings, and what was wrong with them?

6. **9 pts** **Lesson 7.3**
   Why must a Christian student understand the case for common descent accurately?

7. 9 pts **Lesson 7.4**

What does Romans 1:20 say about creation?

8. 9 pts **Lesson 7.4**

Why does this unit ask you to state each view as its holders would?

LAB AND DATA

9. 10 pts

In a bean-hunt simulation, red and white beans are scattered on a red cloth. A "predator" picks up beans for 30 seconds each round; survivors "reproduce" (each surviving bean adds one of its color). Start: 50 red, 50 white. After round 1: 38 red, 12 white survived. (a) What will the population be at the start of round 2? (b) Which color is favored, and why? (c) Has a new kind of bean appeared? What does this model show and not show?

SHORT ESSAY

10. 15 pts

Using Proverbs 18:17 as your guide, state the strongest case for Darwinian common descent and the strongest case for one other view of origins (young-earth creation, old-earth creation or intelligent design), each as its own advocates would. Then explain which evidence you find most important and why, and where you think more research is needed.

ANSWER KEY

1. Each shape suits some foods better than others; traits are advantageous only in certain environments.
2. Theology, preparing for the Anglican ministry.
3. No; it acts on existing variation.
4. Smaller beaks were favored again.
5. Drawings showing embryos as nearly identical; they exaggerated similarities and were inaccurate.
6. To answer it fairly and honestly; misrepresenting a view breaks Proverbs 18:17 and the ninth commandment.
7. God's invisible attributes are clearly seen through the things He made.
8. Fairness and honesty (Proverbs 18:17, the ninth commandment); you cannot fairly judge a view you misstate.
9. (a) 76 red, 24 white. (b) Red: camouflage on the red cloth makes red beans harder to find. (c) No new kind appeared; existing variation was sorted by selection. The model shows how selection changes the frequency of existing traits; it does not show the origin of new traits or new kinds.
10. Grade on fairness first (rubric): (1) Darwinian case stated accurately (variation, heredity, selection, deep time, fossils, homology, DNA similarity) – 4 pts; (2) the other view stated accurately in its own terms (for YEC: Genesis read as history, created kinds, variation within kinds, a young earth and a global Flood; for OEC: created kinds over long ages; for ID: detectable design such as irreducible complexity and information) – 4 pts; (3) a reasoned judgment that distinguishes observation from interpretation – 4 pts; (4) a sensible question for further research – 3 pts. Do not grade the student's conclusion, only the fairness and quality of reasoning.

Printable answer key (PDF, for the parent)

7.1 Darwin's Voyage (1831–1836) and What He Observed

OBJECTIVES

- Describe the Beagle voyage and what Darwin observed in South America and the Galápagos.
- Explain the influences of Lyell and Malthus on Darwin's thinking.
- Distinguish Darwin's observations from the theory he built on them.

> **Warm-up.** Look at the beaks of birds at a feeder or in a field guide: a cardinal, a hummingbird, a woodpecker, a duck. What does each beak seem suited to?

WATCH

Conversations with Michael Denton: The Galapagos Finches

Discovery Science · 3:01

https://www.youtube.com/watch?v=xgeIpkTpBJo

> **WHEN TO WATCH**
> After the story.

BACKUP VIDEO

Alfred Russel Wallace and His Friendly Battle with Darwin

Discovery Science · 11:35

https://www.youtube.com/watch?v=Eg9nPEMNUyo

For Wallace's side of the story.

KEY TERMS

naturalist

A person who studies plants and animals in their natural settings.

adaptation

An inherited trait that helps an organism survive and reproduce in its environment.

artificial selection

Breeding by humans who choose which animals or plants reproduce.

natural selection

The process by which individuals with traits better suited to their environment survive and reproduce more.

theory

In science, a broad explanation of many observations; it can be strong or weak and is always open to testing.

uniformitarianism

Lyell's idea that past geological change happened by the same slow processes seen today.

CORE IDEAS

The story. In December 1831 Charles Darwin, 22 years old and a recent Cambridge graduate who had studied for the Anglican ministry, sailed on HMS *Beagle* as a gentleman naturalist. The voyage lasted almost five years. He collected fossils of giant ground sloths and armadillo-like glyptodonts in Argentina, felt an earthquake in Chile raise the shore several feet, and in September 1835 spent five weeks in the Galápagos Islands. There he noticed that mockingbirds differed from island to island, and the vice-governor told him he could tell which island a tortoise came from by its shell.

How he reasoned. Darwin carried Charles Lyell's *Principles of Geology*, which taught that the earth had been shaped slowly over vast ages. Back in England, ornithologist John Gould told him his Galápagos finches were a group of distinct species. In 1838 Darwin read Thomas Malthus on population: living things produce more offspring than can survive. Darwin reasoned that in that struggle, individuals with helpful variations would survive and pass them on, and over immense time this could produce new species and, he proposed, all the diversity of life from a few original forms. He worked on the idea privately for twenty years. In 1858 Alfred Russel Wallace sent him a paper with the same idea, and their papers were read together. *On the Origin of Species* appeared in November 1859.

The biology. Darwin's argument has parts that can be observed today: (1) individuals vary; (2) much variation is inherited; (3) more offspring are born than survive; (4) those with favorable traits tend to survive and reproduce more. These lead to natural selection, which changes populations over generations. His further claim, that this

process over long ages produced all living things from one or a few ancestors (universal common descent), is an inference about the unobserved past, discussed in Lessons 7.3 and 7.4. Darwin himself closed the *Origin* by speaking of life "having been originally breathed by the Creator into a few forms or into one."

Where it is used. Darwin's observations of variation and selection are used by breeders, farmers fighting pests and doctors fighting resistant bacteria. His idea of common descent became the framework of most modern biology textbooks, which is why students need to understand it accurately.

> **THINKING ABOUT TIME**
>
> **What the sign says.** Textbooks often say Darwin proved that all life evolved from a common ancestor over millions of years.
>
> **What we observe.** Darwin observed variation among island populations, fossils of extinct animals and the power of breeders to change domestic animals. He did not observe one kind changing into another; he inferred it, relying on Lyell's long ages.
>
> **How Christians read it.** Young-earth creationists accept variation and selection within created kinds but read Genesis as history and reject deep time and universal common descent. Old-earth creationists accept long ages but hold that God created distinct kinds. Some Christians (theistic evolutionists) accept common descent as God's method. All agree that what Darwin saw in the Galápagos is real.
>
> **Try it.** Make two columns in your notebook: things Darwin saw, and things Darwin concluded. Sort ten statements from this lesson.
>
> *Proverbs 18:17*

LAB

Beak Buffet

You will model how beak shape affects feeding success on different foods.

You will need

- “Beaks”: tweezers, clothespin, spoon, chopsticks, binder clip
- “Foods”: sunflower seeds, rice, marbles or dried beans, small pasta, water in a cup
- Paper cups as “stomachs,” a timer

Steps

1. Each family member chooses a beak.
2. Spread one food type on a tray. In 30 seconds, collect as much as possible into your cup.
3. Count and record. Repeat for each food type.
4. Which beak did best on which food?

Check your work

- ☐ Did one beak do best on everything?
- ☐ If only small seeds were available in a drought, which beaks would “survive”?

LAB NOTEBOOK

1. Data table: beak × food.
2. Two columns: Darwin’s observations and his inferences.

> **From history.** Darwin was so seasick on the Beagle that he spent as much time as possible ashore. He later suffered decades of illness. His wife Emma, a devout Christian, wrote to him of her fear that his doubts would separate them; he kept her letter all his life.

WORKED EXAMPLES

Example 1. Sort these into observation or inference: (a) Galápagos mockingbirds differ between islands. (b) All Galápagos finches descend from one mainland species. (c) Animals produce more young than survive. (d) All life descends from one ancestor.

▼ **Show solution**

1. (a) and (c) can be seen and counted.
2. (b) is an inference about the past (though many creationists also accept it, as variation within a kind).
3. (d) is a much larger inference about the distant past.

Answer: Observations: a, c. Inferences: b, d

PRACTICE

1. Easy On what ship did Darwin sail, and when?

   ▼ **Show answer**

   HMS Beagle, 1831–1836.

2. Easy What islands are most associated with Darwin?

   ▼ **Show answer**

   The Galápagos Islands.

3. Medium What did Darwin notice about Galápagos mockingbirds and tortoises?

   ▼ **Show answer**

   They differed from island to island.

COMMON MISTAKES

- Thinking Darwin was the first to notice variation or selection; Blyth and others wrote about it earlier (Lesson 7.2).
- Confusing a scientific theory with a guess, or with a proven fact; theories are explanations of varying strength.
- Thinking the finches were the key to Darwin's idea at the time; he did not label them carefully, and the mockingbirds and tortoises struck him first.

Make it a game · Observed or Inferred?. The parent reads statements about Darwin and living things. The student says “observed” or “inferred.” Discuss any disagreements.

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

This verse is the rule for this unit: hear every side out fully before judging.

7.2 Variation Within Kinds: Finch Beaks, Peppered Moths, Antibiotic Resistance and Blyth's Conserving Selection (1835)

OBJECTIVES

- Explain natural selection with observed examples.
- Describe the Grants' finch studies, the peppered moth and antibiotic resistance.
- Explain Edward Blyth's idea of natural selection as conserving created kinds.

> **Warm-up.** Dog breeds range from Chihuahuas to Great Danes, yet all are one species. Where did all that variety come from? Was any new information added, or was existing variety sorted?

WATCH

Natural Selection

Amoeba Sisters · 7:23

https://www.youtube.com/watch?v=7VM9YxmULuo

> **WHEN TO WATCH**
> After the core ideas; it presents the standard explanation clearly.

BACKUP VIDEO

The Rapid Adaptation of the Hawaiian Stick Spider | Creation on Location

Institute for Creation Research · 3:12

https://www.youtube.com/watch?v=g-3e7BaVl54

For a creationist look at rapid adaptation.

KEY TERMS

variation

Differences among individuals of the same species.

allele frequency

How common an allele is in a population.

antibiotic resistance

The ability of bacteria to survive an antibiotic.

kind

In creation biology, an originally created group whose members can vary and sometimes interbreed (often near the family level).

microevolution

Small changes within a population, such as changes in allele frequencies.

macroevolution

Large-scale change, such as the origin of new body plans, proposed over long ages.

CORE IDEAS

The story. In 1835, while Darwin was still at sea, the English naturalist Edward Blyth published articles describing natural selection. Blyth saw it as a *conserving* force: it weeds out weak or deformed individuals and keeps each species fit for its place, within limits set by the Creator. Darwin read Blyth and cited him on other points. Many creationists today follow Blyth: selection is real and powerful, but it works within created kinds.

What everyone has observed. *Finches:* on the Galápagos island of Daphne Major, Peter and Rosemary Grant measured thousands of finches from 1973 onward. After a drought in 1977 left only large, hard seeds, birds with deeper beaks survived better, and the next generation's average beak depth rose about 4%. After heavy rains in 1983, smaller beaks were favored again. *Peppered moths:* in industrial England dark moths became common on soot-darkened trees, and light moths returned after clean-air laws; Michael Majerus's careful study (2001–2007) confirmed bird predation as a main cause, after earlier photos were criticized for being staged. *Antibiotic resistance:* bacteria with resistance genes survive treatment and multiply, which is why patients must finish their antibiotics and doctors avoid overprescribing them.

The biology. In each case, existing variation is sorted by the environment and allele frequencies change. Biologists call this microevolution, and creationists and evolutionists agree it happens. The dispute is whether such processes, given long ages, can produce entirely new organs and body plans (macroevolution). Note that the finch beaks oscillated, the moths stayed moths, and bacteria stayed bacteria;

resistance often comes from genes the bacteria already had or obtained from other bacteria, or from mutations that damage a target the antibiotic binds to.

Where it is used. Farmers rotate pesticides to slow resistance in insects and weeds. Hospitals track resistant "superbugs" such as MRSA. Breeders use selection to develop crops and livestock. Wildlife managers watch how populations adapt to changing habitats.

LAB

Bean Hunt: Natural Selection in Action

You will model selection by a predator on camouflaged prey.

You will need

- A patterned cloth or carpet, 50 each of two or three colors of dried beans or paper dots
- A timer, a data table

Steps

1. Scatter 50 of each color on the cloth.
2. A "predator" picks up beans one at a time for 30 seconds.
3. Count survivors of each color. Each survivor "reproduces": add one bean of the same color for each survivor.
4. Repeat for four generations and graph the percent of each color.

Check your work

- ☐ Which color increased? Why?
- ☐ Did a new color ever appear? What does that tell you about what selection can and cannot do?

LAB NOTEBOOK

1. Data for four generations and a graph.
2. A paragraph on what the model shows and what it does not.

> **From history.** The Grants spent about 40 years on Daphne Major and recorded a new breeding population founded by a hybrid “Big Bird” finch in 1981. Debate continues over whether Darwin’s finches are separate species or varieties of one interbreeding kind, since many hybridize.

WORKED EXAMPLES

Example 1. A population of beetles is 80% green and 20% brown. Birds eat green beetles on brown soil, so 50% of green and 10% of brown beetles are eaten each generation. What are the percents after one generation?

▼ **Show solution**

1. Green survivors: 80 × 0.5 = 40. Brown: 20 × 0.9 = 18.
2. Total 58. Green: 40/58 = 69%; brown 31%.

Answer: About 69% green, 31% brown

PRACTICE

1. Easy What is natural selection?

   ▼ **Show answer**

   Individuals with traits better suited to the environment survive and reproduce more, so those traits become more common.

2. Easy Who described natural selection in 1835 as a conserving force?

   ▼ **Show answer**

   Edward Blyth.

3. Medium What did the Grants observe after the 1977 drought?

   ▼ **Show answer**

   Finches with deeper beaks survived better; average beak depth rose in the next generation.

COMMON MISTAKES

- Thinking individuals adapt during their lives; populations change over generations.
- Thinking selection creates new traits; it acts on variation that is already present.

- Treating every example of microevolution as proof of macroevolution, or denying that microevolution happens.

Make it a game · Selection or Not?. The parent describes a change (a dog breed developed, a lizard's legs lengthening on a new island, a person tanning, bacteria surviving penicillin). The student says whether it is natural selection, artificial selection or not inherited at all.

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. 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 1:24–25, KJV)

God made beasts and creeping things after their kind. Variation within kinds is part of the richness He built in.

7.3 Common Descent: The Claim, the Evidence Offered and the Open Questions

OBJECTIVES

- State the claim of universal common descent.
- Summarize the main lines of evidence offered for it, as its defenders present them.
- Summarize the main open questions and alternative explanations.

> **Warm-up.** Two sentences are nearly identical, with the same spelling mistakes. Did one writer copy the other, or did both copy a third? Could a single author have written both? What evidence would help decide?

WATCH

Evolution

Amoeba Sisters · 9:27

https://www.youtube.com/watch?v=fI7IV3x-dGI

> **WHEN TO WATCH**
> After the core ideas; it presents the standard case. Pause to note which statements are observations and which are interpretations.

BACKUP VIDEO

Is Homology Evidence for Evolution? (Long Story Short, Ep. 1)

Discovery Science · 8:00

https://www.youtube.com/watch?v=lk1gDk1wGhQ

For a critique of one line of evidence (homology).

KEY TERMS

common descent

The claim that different species share ancestors; universal common descent holds that all life comes from one original ancestor.

homologous structures

Structures with similar arrangement in different organisms, such as the bones of a human arm and a bat wing.

vestigial structure

A structure claimed to have lost most of its original function.

fossil record

The fossils found in the earth's rock layers and their order.

Cambrian explosion

The sudden appearance of most major animal body plans in the lowest fossil-bearing layers.

common design

The view that similarities reflect one Designer reusing good plans.

CORE IDEAS

The claim. Universal common descent holds that all living things are related through a branching tree of ancestors reaching back to a single original cell, roughly 3.5–4 billion years ago in the standard timescale. Darwin drew the first such tree in his notebook in 1837 with the words "I think."

The evidence offered (as defenders present it). (1) *Fossil sequences*: simpler organisms in lower layers and transitional forms such as *Tiktaalik* (fish to tetrapod) and the series of whale ancestors. (2) *Homology*: the same bone pattern in the human arm, the whale flipper and the bat wing. (3) *Molecular similarity*: the closer two organisms are in body plan, the more similar their DNA and proteins; humans and chimpanzees share a high percentage of aligned DNA sequences. (4) *Biogeography*: island species resemble those on the nearest mainland. (5) *Vestigial structures* and shared DNA "mistakes" such as broken genes in similar places. Supporters say these lines agree with one another and form a nested pattern best explained by descent.

The open questions (as critics present them). (1) *Sudden appearance*: in the Cambrian explosion most animal body plans appear abruptly without clear ancestors, a problem Darwin himself acknowledged. (2) *Homology and common design*: similar structures can reflect a common Designer, and some homologous structures develop from different genes or embryonic tissues. (3) *Vestigial and "junk" claims* have often been revised: the appendix has immune functions, and much DNA once called junk has been found to have regulatory roles. (4) *Information*: building new proteins and organs requires vast amounts of new genetic information, and whether mutation and selection can supply it is debated (Michael Behe, Douglas Axe). (5) *Origin of life*: no known natural process produces a living cell from chemicals. (6) *Timescales*: young-earth creationists dispute the deep-time dates on which the case depends.

How to weigh it. Separate what is seen (fossils in rock, bones, DNA sequences) from what is inferred about the unseen past (who descended from whom, and when). The same observations can sometimes be fit into more than one framework. Ask of every argument: what would we expect to see if this were true, and if the alternative were true?

> **THINKING ABOUT TIME**
>
> **What the sign says.** The fossil record shows life evolving over 3.5 billion years.
>
> **What we observe.** We observe fossils in rock layers, generally with simpler marine organisms lower and land plants and mammals higher, and with many gaps. The ages assigned to layers come from radiometric dating and the assumption of slow deposition.
>
> **How Christians read it.** Young-earth creationists read much of the fossil record as the result of Noah's Flood and its aftermath, with the order reflecting habitat, mobility and burial, not millions of years. Old-earth creationists accept the ages but see fresh acts of creation at points such as the Cambrian. Theistic evolutionists accept common descent as God's means. All Christians affirm that God is Creator.
>
> **Try it.** Pick one line of evidence and write what a Darwinist would predict, what a creationist would predict, and what we actually observe.
>
> *See High School Geology, Units 5 and 6, for fossils, rock layers and the Flood.*

LAB

Comparing Skeletons and Sequences

You will compare limb skeletons and a short protein sequence across several animals, then evaluate two explanations.

You will need

- Printed drawings of human, cat, whale, bat and bird forelimbs (from a library book or the course packet)
- A short printed segment of cytochrome c amino acid sequences for human, chimpanzee, horse, chicken and yeast (from a reference)

Steps

1. Color matching bones the same color across the five limbs.
2. Count differences in the cytochrome c segments between human and each organism.
3. Make a table ranking organisms by number of differences.
4. Write how common descent and common design would each explain the pattern.

Check your work

- ☐ Did the protein differences match how similar the animals look?
- ☐ What observation, if any, could help decide between the two explanations?

LAB NOTEBOOK

1. Colored limb drawings.
2. The table of differences and two written explanations.

> **From history.** The 1859 Origin contained a single diagram, a branching tree. The German biologist Ernst Haeckel later drew embryo diagrams supporting it that were shown, even in his own day, to be inaccurate; some textbooks used them for over a century.

WORKED EXAMPLES

Example 1. The bones of a human arm, a bat wing and a whale flipper share one pattern (one upper bone, two lower bones, wrist bones and digits). State how a Darwinist and a design proponent each explain the similarity.

▼ **Show solution**

1. Darwinist: inherited from a common ancestor and modified.
2. Design proponent: a Designer reused an excellent plan for different jobs, as engineers reuse proven parts.
3. Test: do the same genes and embryonic tissues build them? (Sometimes yes, sometimes no.)

Answer: Common ancestry vs common design; both explain the pattern; further evidence is needed to choose

PRACTICE

1. Easy What is universal common descent?

   ▼ **Show answer**

   The claim that all living things descend from one original ancestor.

2. Easy What are homologous structures? Give an example.

   ▼ **Show answer**

   Structures with similar arrangements in different organisms; a human arm, bat wing and whale flipper.

3. Medium Name three lines of evidence offered for common descent.

   ▼ **Show answer**

   Fossil sequences, homology, molecular similarity, biogeography, vestigial structures or shared DNA errors.

COMMON MISTAKES

- Treating the case for common descent as weak or foolish; it is the view of most biologists and must be understood accurately.
- Treating every similarity as proof of descent; similarity is consistent with more than one explanation.

- Confusing the origin of life with the diversification of life; they are separate questions.

Make it a game · Steelman. The parent states one view of origins in one sentence. The student restates it better, as its strongest supporter would. Then swap views.

Scripture. “Through faith we understand that the worlds were framed by the word of God, so that things which are seen were not made of things which do appear.” (Hebrews 11:3, KJV)

Through faith we understand that the worlds were framed by the word of God. Every view of origins includes beliefs about events no one observed.

7.4 Origins Fairly Told: Creation, Intelligent Design and Darwinian Theory Compared

OBJECTIVES

- State the main claims of young-earth creation, old-earth creation, intelligent design and Darwinian theory, as their holders would.
- Explain irreducible complexity and the main responses to it.
- Compare the views on key questions and evaluate arguments fairly.

> **Warm-up.** Find something in your house that was obviously designed (a mousetrap, a zipper, a watch). How do you know it was designed? Could you tell if you had never seen one before?

WATCH

What Is Irreducible Complexity?

Discovery Science · 2:39

https://www.youtube.com/watch?v=0cN-aIXNQrc

> **WHEN TO WATCH**
> After the intelligent design section.

BACKUP VIDEO

Are Natural Selection and Evolution the Same? | Creation Q&A: Campus Edition

Institute for Creation Research · 6:58

https://www.youtube.com/watch?v=0kwtYmsoaho

As a summary of a creationist distinction.

KEY TERMS

young-earth creation

The view that God created the universe and distinct kinds of life in six ordinary days, thousands of years ago, as Genesis records, with a global Flood.

old-earth creation

The view that God created distinct kinds of life by special acts over long ages, reading the Genesis days as long periods or in another non-literal way.

intelligent design

The view that some features of living things are best explained by an intelligent cause, detectable by scientific evidence.

irreducible complexity

A system of several parts that all must be present for it to work at all (Behe, 1996).

theistic evolution

The view that God used common descent and natural processes to create life.

methodological naturalism

The rule that science explains things only by natural causes.

CORE IDEAS

Young-earth creation. Genesis 1–11 is history. God created in six ordinary days, about 6,000–10,000 years ago; He made distinct kinds that reproduce after their kind and vary within limits; death entered after the Fall; a global Flood in Noah's day laid down most fossil-bearing rock. Researchers such as those at the Institute for Creation Research and creation biologists such as Todd Wood (who studies how to identify created kinds) work in this framework. Strengths cited: a plain reading of Scripture, the abrupt appearance of kinds in the fossil record, rapid adaptation within kinds, and evidence of catastrophic deposition.

Old-earth creation. The universe and earth are billions of years old, but God created life and distinct kinds by special acts over that time; humans were specially created, not descended from apes. Hugh Ross (Reasons to Believe) is a well-known advocate. Strengths cited: agreement with mainstream dating and astronomy while affirming special creation and Adam and Eve.

Intelligent design. ID makes a narrower claim: design is detectable. Michael Behe (*Darwin's Black Box*, 1996) argued that the bacterial flagellum, a rotary motor of some 40 protein parts, is irreducibly complex: remove one part and it does not work, so it is hard to build step by step. William Dembski and Stephen Meyer argue that the specified information in DNA points to intelligence, as information in a book does. ID does not itself identify the designer or the age of the earth; its advocates include young-earth, old-earth and other views. Critics reply that parts of the flagellum have other uses (the type III secretion system), that "we can't yet explain it" is not

evidence for design, and that ID breaks the rule of methodological naturalism. ID advocates answer that the rule assumes the answer in advance.

Darwinian theory. All life descends from a common ancestor over billions of years by natural processes, chiefly mutation and natural selection, without the need for design. It is the majority view of biologists and the framework of most textbooks. Strengths cited: the lines of evidence in Lesson 7.3 and its usefulness in organizing biological data. Some Christians, such as Francis Collins, hold it as theistic evolution, seeing God working through it; others, including Darwin later in life and many today, see it as removing the need for God. *Where the views agree:* variation and natural selection are real; the living world shows astonishing order. *Where they differ:* the age of the earth, the reach of natural processes, the origin of new kinds and humans, and how to read Genesis.

> **THINKING ABOUT TIME**
>
> **What the sign says.** Many textbooks present Darwinian evolution as the only scientific view and creation as religion only.
>
> **What we observe.** Every view interprets the same observations (fossils, DNA, rock layers, living systems) within a framework about the unobserved past. Each framework includes starting beliefs: about God, about Scripture, about whether science may consider design.
>
> **How Christians read it.** Christians hold a range of views but agree that God is Creator, that man is made in His image, and that Scripture is true. This course presents the young-earth reading alongside the others and asks students to know every view well.
>
> **Try it.** Write one question you would ask an advocate of each view, as respectfully as you would want to be asked.
>
> *Romans 1:20; Proverbs 18:17*

LAB

Structured Debate

You will prepare and present the strongest case for a view you may not hold, then switch.

You will need

- Index cards, this unit's lessons, a timer, a family audience

Steps

1. Draw a view at random: young-earth creation, old-earth creation, intelligent design or Darwinian theory.
2. Prepare a 3-minute case with three pieces of evidence, stated as that view's advocates would.
3. Present it. The audience then asks one question each.
4. Switch to a different view and repeat. Finish with a written reflection on what you learned.

Check your work

- ☐ Could a supporter of the view you presented recognize it as fair?
- ☐ Which question was hardest to answer?

LAB NOTEBOOK

1. Your index-card outlines for both views.
2. A one-page reflection.

> **From history.** William Paley's *Natural Theology* (1802) argued that a watch found on a heath implies a watchmaker. Darwin, who studied Paley at Cambridge, said he had almost memorized it. The modern design debate is, in part, a renewed conversation with Paley.

WORKED EXAMPLES

Example 1. A mousetrap has a base, spring, hammer, catch and holding bar. Explain irreducible complexity with it, and give the main critic's reply.

▼ **Show solution**

1. Remove any part and the trap catches no mice; all parts are needed at once (Behe).
2. Critic: the parts could have served other functions first (a tie clip, a key ring) and been co-opted.
3. Reply: co-option still needs the parts to be modified and assembled in the right order; whether that is plausible for molecular machines is the question.

Answer: Behe's argument and the co-option response

PRACTICE

1. Easy What does young-earth creation teach about the age of the earth?

   ▼ **Show answer**

   About 6,000–10,000 years, from a historical reading of Genesis.

2. Easy What is irreducible complexity?

   ▼ **Show answer**

   A system whose parts must all be present for it to work.

3. Medium How does old-earth creation differ from young-earth creation?

   ▼ **Show answer**

   It accepts billions of years but holds God created distinct kinds by special acts.

COMMON MISTAKES

- Caricaturing any view, including Darwinism (for example, "evolution says a monkey turned into a man").
- Thinking ID is the same as young-earth creation.
- Thinking that a gap in present knowledge is by itself proof of either design or evolution.

Make it a game · Who Believes That?. The parent reads a statement (the earth is billions of years old; kinds were created separately; design is detectable; selection explains all life). The student names every view that holds it.

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 invisible things of God are clearly seen, being understood by the things that are made. Every view must reckon with that claim.

UNIT 7

Variation, Adaptation and Origins

This unit takes up the most debated question in biology: where did the variety of living things come from? It begins with what Charles Darwin actually observed on the voyage of the *Beagle*, studies the variation and adaptation that everyone agrees we can see (finch beaks, peppered moths, antibiotic resistance), sets out the case for universal common descent as its defenders make it along with the open questions critics raise, and closes by comparing young-earth creation, old-earth creation, intelligent design and Darwinian theory fairly, each in its own best terms.

The rule of the unit is Proverbs 18:17: "He that is first in his own cause seemeth just; but his neighbour cometh and searcheth him." Students should be able to state every view so that its own holders would say "yes, that is what we believe," before weighing it. Observations come first; claims about the unobserved past are labeled as interpretations. A parent should read the whole unit before the student begins.

PREREQUISITES

- Units 5–6 (genes, mutations, DNA)

MASTERY CHECKLIST

- ☐ I can describe what Darwin observed on the Beagle voyage and how he reasoned to his theory.
- ☐ I can explain natural selection and give observed examples of adaptation within kinds, including Blyth's view of conserving selection.
- ☐ I can state the evidence offered for universal common descent and the main open questions about it.
- ☐ I can fairly compare young-earth creation, old-earth creation, intelligent design and Darwinian theory, stating each in terms its holders would accept.

LESSONS IN THIS UNIT

7.1 Darwin's Voyage (1831–1836) and What He Observed — 4 sessions of 45 minutes

7.2 Variation Within Kinds: Finch Beaks, Peppered Moths, Antibiotic Resistance and Blyth's Conserving Selection (1835)

4 sessions of 45 minutes

7.3 Common Descent: The Claim, the Evidence Offered and the Open Questions

4 sessions of 45 minutes

7.4 Origins Fairly Told: Creation, Intelligent Design and Darwinian Theory Compared

4 sessions of 45 minutes

Unit 7 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 7.1**
   In the beak lab, why did no single beak do best on every food?

2. **10 pts** **Lesson 7.1**
   What did Darwin study at Cambridge before the voyage?

3. **10 pts** **Lesson 7.2**
   Does selection create new traits?

4. **9 pts** **Lesson 7.2**
   How did the beak depths change after the wet year of 1983?

5. **9 pts** **Lesson 7.3**
   What were Haeckel's embryo drawings, and what was wrong with them?

6. **9 pts** **Lesson 7.3**
   Why must a Christian student understand the case for common descent accurately?

7. 9 pts **Lesson 7.4**

What does Romans 1:20 say about creation?

8. 9 pts **Lesson 7.4**

Why does this unit ask you to state each view as its holders would?

LAB AND DATA

9. 10 pts

In a bean-hunt simulation, red and white beans are scattered on a red cloth. A "predator" picks up beans for 30 seconds each round; survivors "reproduce" (each surviving bean adds one of its color). Start: 50 red, 50 white. After round 1: 38 red, 12 white survived. (a) What will the population be at the start of round 2? (b) Which color is favored, and why? (c) Has a new kind of bean appeared? What does this model show and not show?

SHORT ESSAY

10. 15 pts

Using Proverbs 18:17 as your guide, state the strongest case for Darwinian common descent and the strongest case for one other view of origins (young-earth creation, old-earth creation or intelligent design), each as its own advocates would. Then explain which evidence you find most important and why, and where you think more research is needed.

ANSWER KEY

1. Each shape suits some foods better than others; traits are advantageous only in certain environments.
2. Theology, preparing for the Anglican ministry.
3. No; it acts on existing variation.
4. Smaller beaks were favored again.
5. Drawings showing embryos as nearly identical; they exaggerated similarities and were inaccurate.
6. To answer it fairly and honestly; misrepresenting a view breaks Proverbs 18:17 and the ninth commandment.
7. God's invisible attributes are clearly seen through the things He made.
8. Fairness and honesty (Proverbs 18:17, the ninth commandment); you cannot fairly judge a view you misstate.
9. (a) 76 red, 24 white. (b) Red: camouflage on the red cloth makes red beans harder to find. (c) No new kind appeared; existing variation was sorted by selection. The model shows how selection changes the frequency of existing traits; it does not show the origin of new traits or new kinds.
10. Grade on fairness first (rubric): (1) Darwinian case stated accurately (variation, heredity, selection, deep time, fossils, homology, DNA similarity) – 4 pts; (2) the other view stated accurately in its own terms (for YEC: Genesis read as history, created kinds, variation within kinds, a young earth and a global Flood; for OEC: created kinds over long ages; for ID: detectable design such as irreducible complexity and information) – 4 pts; (3) a reasoned judgment that distinguishes observation from interpretation – 4 pts; (4) a sensible question for further research – 3 pts. Do not grade the student's conclusion, only the fairness and quality of reasoning.

Printable answer key (PDF, for the parent)

UNIT 8

The Diversity of Life

This unit tours the living world group by group, following the people who first looked closely: Jenner's cowpox and Pasteur's rabies vaccine, Koch proving that one germ causes one disease, Fleming's moldy plate and the penicillin that Florey and Chain turned into a medicine, Grew, Malpighi and Hales opening up plants, and Cuvier comparing animal skeletons until he could reconstruct a whole creature from a single bone. Viruses are taught through history: smallpox, rabies, polio and the 1918 influenza.

The labs are the busiest of the year: sealed agar plates, a bread-mold time-lapse, spore prints, a flower dissection and an earthworm and then a perch or frog dissection (real or virtual). The unit ends with a **lab practical**: identifying slides and specimens and labeling a dissection. Agar plates are sealed with tape and never reopened; they are destroyed with bleach.

PREREQUISITES

- Unit 1 (the microscope and classification)
- Unit 3 (prokaryotic and eukaryotic cells)

MASTERY CHECKLIST

- ☐ I can compare bacteria and viruses and explain how vaccines and antibiotics work, using Jenner, Koch and Pasteur.
- ☐ I can describe protists and fungi and tell the story of penicillin from Fleming to Florey and Chain.
- ☐ I can name the main plant groups, label a flower and explain transpiration from Hales's experiments.
- ☐ I can describe the main animal phyla and body plans, explain Cuvier's comparative anatomy, and identify the organs of a dissected specimen.

LESSONS IN THIS UNIT

8.1 **Bacteria and Viruses: Jenner (1796), Koch's Postulates (1884) and Pasteur's Rabies Vaccine (1885)**

4 sessions of 45 minutes

8.2 **Protists and Fungi: Fleming's Penicillin (1928)** 4 sessions of 45 minutes

8.3 **Plants: Grew, Malpighi and Hales's Vegetable Staticks (1727)**

4 sessions of 45 minutes

8.4 **Animals: Cuvier's Comparative Anatomy and the Dissection Lab**

4 sessions of 45 minutes

Unit 8 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 8.1**
   Why must sealed agar plates never be reopened?

2. **10 pts** **Lesson 8.1**
   How do bacteria reproduce?

3. **10 pts** **Lesson 8.2**
   What warning did Fleming give in 1945?

4. **9 pts** **Lesson 8.2**
   How does a paramecium move?

5. **9 pts** **Lesson 8.3**
   What part of the flower becomes the fruit?

6. **9 pts** **Lesson 8.3**
   Why should gardeners water in the morning rather than at midday?

7. **9 pts** **Lesson 8.4**

What percentage of animal species are invertebrates, roughly?

8. **9 pts** **Lesson 8.4**

How did Cuvier’s fossil opossum demonstration test his principle?

LAB AND DATA

9. **10 pts**

Three sealed agar plates were swabbed and kept at room temperature for 3 days: A, a clean kitchen counter (4 colonies); B, a phone screen (31 colonies); C, a hand after washing with soap for 20 seconds (2 colonies). (a) Which surface carried the most bacteria? (b) Why must the plates stay taped shut? (c) What would make this a fairer test?

SHORT ESSAY

10. **15 pts**

Choose two of these scientists: Jenner, Koch, Pasteur, Fleming, Hales or Cuvier. For each, describe the observation or experiment that made his name, what it changed in biology or medicine, and one question it left for those who came after.

ANSWER KEY

1. Colonies contain billions of cells, possibly pathogens; opening could spread them.
2. By binary fission: one cell copies its DNA and splits in two.
3. Careless use of penicillin could make bacteria resistant.
4. By beating its cilia.
5. The ovary.
6. Less water evaporates before roots absorb it, and the plant has water for the hot, high-transpiration hours.
7. Over 95%.
8. From the jaw he predicted marsupial bones in the pelvis, then uncovered them before witnesses.
9. (a) The phone screen. (b) Colonies contain billions of cells, some possibly harmful; opening the plate could spread them, so plates are sealed, never reopened and destroyed with bleach. (c) Same swab technique, same area swabbed, same time and temperature, a control plate swabbed with a sterile swab, and repeated trials.
10. Look for: accurate details (Jenner: cowpox and James Phipps, 1796; Koch: anthrax and tuberculosis, his postulates; Pasteur: the rabies vaccine and Joseph Meister, 1885; Fleming: the Penicillium plate, 1928, and Florey and Chain's purification; Hales: measuring transpiration and root pressure, 1727; Cuvier: comparative anatomy and extinction); a clear statement of what changed; a sensible open question; clear organization.

Printable answer key (PDF, for the parent)

PORTFOLIO PIECE: UNIT 8 LAB PRACTICAL

The practical is set up by a parent at stations around a table, one minute per station, like a high-school or college biology practical. Typical stations: (1) a prepared slide of bacteria (name the shape: coccus, bacillus or spiral); (2) a pond-water or prepared protist slide (amoeba, paramecium or euglena); (3) a bread-mold sample under magnification (hyphae, sporangia); (4) a mushroom spore print (gills or pores); (5) a flower with pins in five parts (sepal, petal, anther, stigma, ovary); (6) a moss, a fern frond and a pine cone (name the plant group); (7) shells, insects or photos of animals (name the phylum); (8) the opened earthworm with pins in five organs (crop, gizzard, hearts, nerve cord, intestine); (9) the perch or frog with pins in five organs (heart, liver, stomach, gills or lungs, swim bladder or kidney).

Score one point per correct label, about 40 points in all, and count it with the labs. A student who used a virtual dissection labels printed screenshots instead.

8.1 Bacteria and Viruses: Jenner (1796), Koch's Postulates (1884) and Pasteur's Rabies Vaccine (1885)

OBJECTIVES

- Compare the structure, size and reproduction of bacteria and viruses.
- Explain Koch's postulates and how vaccines work, using Jenner and Pasteur.
- Explain why antibiotics work against bacteria but not viruses, and describe the many helpful roles of bacteria.

> **Warm-up.** Yogurt, sourdough, pickles and cheese are all made with the help of microbes. A strep throat and a cold are both caused by microbes too. What do you think the difference is between the microbe that makes yogurt and the one that causes strep throat?

WATCH

Bacteria (Updated)

Amoeba Sisters · 7:31

https://www.youtube.com/watch?v=ORB866QSGv8

> **WHEN TO WATCH**
> After the history of Jenner, Koch and Pasteur.

BACKUP VIDEO

(OLD VIDEO) Viruses

Amoeba Sisters · 7:22

https://www.youtube.com/watch?v=PHp6iYDi9ko

With the comparison of viruses and bacteria.

KEY TERMS

bacterium

A single-celled prokaryote with no nucleus; most are 1–10 micrometers long.

virus

A tiny particle of DNA or RNA in a protein coat that can reproduce only inside a living cell.

pathogen

A microbe that causes disease.

vaccine

A preparation of a weakened, killed or partial pathogen that trains the immune system to resist it.

antibiotic

A substance that kills bacteria or stops their growth without harming the patient's cells.

Koch's postulates

Four tests for proving that a particular microbe causes a particular disease.

CORE IDEAS

The story. Smallpox killed millions in every century. Country people in England said that milkmaids who caught cowpox, a mild disease from cows, never caught smallpox. In May 1796 the country doctor Edward Jenner scratched matter from a cowpox sore on the milkmaid Sarah Nelmes into the arm of eight-year-old James Phipps; weeks later he exposed the boy to smallpox, and he did not fall ill. Jenner called the method vaccination, from *vacca*, Latin for cow. In 1876 the German doctor Robert Koch showed that a rod-shaped bacterium caused anthrax, and in 1882 he found the bacterium of tuberculosis. In July 1885 Louis Pasteur gave a series of injections of weakened rabies to nine-year-old Joseph Meister, bitten by a rabid dog; the boy lived.

How they figured it out. Koch's rules, published by his student Friedrich Loeffler in 1884 and known as Koch's postulates, are still the logic of medical microbiology: (1) the microbe is found in every case of the disease; (2) it can be grown in pure culture; (3) the pure culture causes the disease in a healthy host; (4) the same microbe is recovered from that host. Koch's assistants invented the tools he needed: Julius Petri's dish (1887) and agar, a seaweed jelly suggested by Fanny Hesse from her kitchen. Viruses were found later: in 1892 Dmitri Ivanovsky showed that tobacco mosaic disease passed through filters fine enough to stop every bacterium, and the first virus was photographed with an electron microscope in 1939.

The biology. Bacteria are prokaryotes: a cell membrane, usually a cell wall, ribosomes and a loop of DNA but no nucleus. They come in three main shapes, cocci (spheres), bacilli (rods) and spirilla (spirals), and reproduce by binary fission, some every 20 minutes. Viruses are much smaller (20–300 nanometers), have no cell parts

of their own, and copy themselves only by taking over a host cell's machinery. Antibiotics attack structures bacteria have and our cells do not, such as their cell walls, so they are useless against viruses. A vaccine shows the immune system a harmless form of a pathogen so it can make antibodies and memory cells ahead of time.

Where it is used. Most bacteria are helpful: they make yogurt, cheese, sauerkraut and vinegar, help digest food in our intestines and make vitamin K, decompose dead things and return nitrogen to the soil (Lesson 9.2). Vaccination ended smallpox, the last natural case of which was in 1977; the World Health Organization declared it eradicated in 1980. The polio vaccines of Jonas Salk (1955) and Albert Sabin made a disease that once paralyzed thousands of American children every summer rare. The influenza of 1918–1919, before any flu vaccine existed, killed tens of millions worldwide.

Try it. In the lab you will swab household surfaces onto sealed agar plates, count colonies, and look at yogurt bacteria under the microscope.

> **Safety first.** Never open a grown agar plate: colonies contain billions of cells and some could be harmful. An adult handles bleach. Wash hands after the lab.

LAB

Sealed Agar Plates and Yogurt Bacteria

You will compare the bacteria on household surfaces, test handwashing, and see real bacteria under the microscope.

You will need

- 4 pre-poured nutrient agar plates (about $15 for 10), sterile cotton swabs, clear tape, a marker
- Plain yogurt with live cultures, a slide and cover slip, methylene blue stain (optional) and a microscope at 400–1000×
- Household bleach (adult) for disposal

Steps

1. Label the bottom of each plate. Swab one surface per plate in a zigzag: a sterile swab only (control), a phone screen, a doorknob and a washed hand.
2. Close each plate at once and tape it shut around the edge. Store upside down at room temperature for 2–4 days. Never open the plates again.
3. Count and describe colonies (color, size, shape) through the lid.
4. Smear a tiny dab of yogurt thinned with a drop of water on a slide, let it dry, add a drop of methylene blue if you have it, cover and view at the highest power. Sketch the rods and spheres.
5. Disposal: an adult pours a little bleach around the taped lid edge into a sealed zip bag with the plates, closes the bag and leaves it for an hour before putting it in the trash.

Check your work

- ☐ Which surface grew the most colonies? Did the control stay clear?
- ☐ What shapes did you see in the yogurt?
- ☐ Why must the plates never be opened?

LAB NOTEBOOK

1. A data table of colony counts and descriptions with a sketch of each plate.
2. Sketches of yogurt bacteria with the magnification.

From history. Jenner never patented vaccination, and the method spread around the world within a few years; in 1801 Thomas Jefferson vaccinated his family and neighbors at Monticello with vaccine sent by the Boston doctor Benjamin Waterhouse. Pasteur's first rabies patient, Joseph Meister, later worked as a caretaker at the Pasteur Institute in Paris.

WORKED EXAMPLES

Example 1. A bacterium divides every 20 minutes with unlimited food. Starting with one cell, how many cells are there after 3 hours?

▼ **Show solution**

1. 3 hours = 180 min = 9 divisions
2. $2^9 = 512$

Answer: 512 cells

Example 2. A virus is 100 nm across and a bacterium 2 micrometers long. How many virus widths fit along the bacterium?

▼ **Show solution**

1. 2 µm = 2000 nm
2. 2000/100 = 20

Answer: 20

PRACTICE

1. Easy Name the three common shapes of bacteria.

   ▼ **Show answer**

   Cocci (spheres), bacilli (rods) and spirilla (spirals).

2. Easy What did Jenner use to protect James Phipps from smallpox?

   ▼ **Show answer**

   Matter from a cowpox sore (1796).

3. Easy Where does the word vaccine come from?

   ▼ **Show answer**

   Latin *vacca*, cow, from cowpox.

COMMON MISTAKES

- Taking antibiotics for a cold or the flu; antibiotics do not work on viruses.
- Thinking all bacteria are harmful; most are harmless or helpful.
- Calling viruses cells; they have no cell parts and cannot reproduce on their own.

Make it a game · Bacteria or Virus?. The parent names a disease or product (strep throat, the common cold, yogurt, smallpox, tuberculosis, chickenpox, cheese, rabies). The student says bacterium or virus and whether an antibiotic would help.

Scripture. "All the days wherein the plague shall be in him he shall be defiled; he is unclean: he shall dwell alone; without the camp shall his habitation be." (Leviticus 13:46, KJV)

The law of Moses separated people with contagious skin diseases from the camp, the first written rule of quarantine, more than three thousand years before anyone saw a germ.

8.2 Protists and Fungi: Fleming's Penicillin (1928)

OBJECTIVES

- Describe the main kinds of protists and how they move and feed.
- Describe the structure of fungi and their role as decomposers.
- Tell the story of penicillin from Fleming's plate to Florey and Chain's medicine.

> **Warm-up.** Leave a slice of bread (without preservatives) in a sealed bag for a week and you will see fuzzy spots. Where did they come from? Is the mold a plant, an animal or something else?

WATCH

Protists and Fungi

Amoeba Sisters · 8:50

https://www.youtube.com/watch?v=zK7Ckmxxqds

> **WHEN TO WATCH**
> After the protists and fungi tour.

BACKUP VIDEO

Kingdom Fungi- The Decomposers

MooMooMath and Science · 3:15

https://www.youtube.com/watch?v=ao1SM_YH9Ws

With the decomposers discussion.

KEY TERMS

protist
A eukaryote that is not a plant, animal or fungus; most are single-celled, such as amoebas, paramecia, euglenas and diatoms.

pseudopod
A "false foot," a flowing extension an amoeba uses to move and engulf food.

cilia and flagella

Hairlike structures that beat to move a cell: many short cilia (paramecium) or a few long flagella (euglena).

fungus

A eukaryote with cell walls of chitin that absorbs food from its surroundings; yeasts, molds and mushrooms.

hypha and mycelium

A hypha is one threadlike filament of a fungus; a mycelium is the whole tangled mass.

spore

A tiny reproductive cell that can grow into a new organism.

CORE IDEAS

The story. In September 1928 Alexander Fleming returned to his cluttered laboratory at St Mary's Hospital in London after a holiday and began sorting a stack of culture dishes of *Staphylococcus* bacteria. On one, a blue-green mold had landed, and all around it the bacterial colonies had dissolved. He identified the mold as *Penicillium* and named its bacteria-killing juice penicillin. He could not purify it, and for a decade it was a curiosity. In 1939–1941 Howard Florey and Ernst Chain at Oxford, with Norman Heatley's homemade apparatus of bedpans and milk churns, purified enough to save mice and then the first patients. American factories took up the work, and large supplies were ready for the wounded of the D-Day landings in 1944. Fleming, Florey and Chain shared the 1945 Nobel Prize.

How they figured it out. Fleming's gift was noticing: many would have thrown the spoiled dish away. He then tested the mold juice against many kinds of bacteria and found it killed some but not others, and that it did not harm white blood cells. Florey and Chain's gift was persistence: they grew the mold in hundreds of vessels, extracted the tiny amounts of penicillin, and proved in careful experiments that it cured infected mice. A moldy cantaloupe from a market in Peoria, Illinois, later gave a strain that made far more penicillin, and it became the ancestor of most production strains.

The biology. *Protists* are a mixed group of mostly single-celled eukaryotes: animal-like protists such as amoebas (pseudopods) and paramecia (cilia); plantlike algae such as euglena (flagellum and chloroplasts), diatoms in glass shells and seaweeds; and funguslike slime molds. The protist *Plasmodium*, carried by mosquitoes, causes

malaria, as Ronald Ross showed in 1897. *Fungi* have cell walls of chitin, feed by releasing enzymes and absorbing the digested food, and grow as threadlike hyphae forming a mycelium; a mushroom is only the spore-making fruiting body of a much larger mycelium underground. Yeasts are single-celled fungi (Lesson 4.4).

Where it is used. Fungi and bacteria are the great decomposers, returning the matter of dead plants and animals to the soil. Yeast raises bread; molds make blue cheese and soy sauce; mushrooms are food. Diatoms and other algae make a large share of the oxygen produced on earth. Penicillin and the antibiotics that followed it, many of them from soil fungi and bacteria, turned pneumonia, infected wounds and blood poisoning from death sentences into treatable illnesses. Some fungi cause disease: athlete's foot, ringworm and crop rusts.

Try it. In the lab you will watch bread mold grow in a sealed bag, make a spore print from a store mushroom, and look for protists in pond water.

> **Safety first.** Never eat wild mushrooms; many deadly species look like edible ones. Do not open moldy bags or sniff mold, especially if anyone has asthma or allergies. Wash hands after handling pond water.

LAB

Bread Mold, Spore Prints and Pond-Water Protists

You will observe the growth of a fungus, the spores of a mushroom and the movement of protists.

You will need

- Bread without preservatives, a zip bag, a few drops of water, a ruler
- Store-bought mushrooms with open gills (portobello is easy), white and black paper, a bowl
- Pond water with a little bottom mud or scum, a slide and cover slip, a microscope; a few cotton fibers to slow fast swimmers

Steps

1. Dampen the bread, rub it on a dusty windowsill, seal it in the bag and tape it shut. Measure and photograph the mold every day for a week. Do not open the bag; throw it away sealed.
2. Cut the stem off a mushroom and set the cap gills-down on half white, half black paper under a bowl overnight. Lift it and look at the pattern.
3. Put a drop of pond water with a few cotton fibers on a slide. Search at 40× and 100× for moving protists. Sketch them and note how each moves.

Check your work

- ☐ How fast did the mold grow? Graph its diameter.
- ☐ How many spores do you think made the print?
- ☐ Which protists moved with cilia, which with a flagellum, which with pseudopods?

LAB NOTEBOOK

1. A mold growth table and graph with daily sketches.
2. The spore print (spray with hairspray to keep it) and protist sketches with magnifications.

> **From history.** When the Oxford team made their first penicillin they ran so short that they recovered it from the first patient's urine to reuse. Fleming warned in his Nobel lecture in 1945 that bacteria could become resistant if penicillin were used carelessly, as Lesson 7.2 described.

WORKED EXAMPLES

Example 1. A mold colony on bread is 2 mm across on day 1 and its diameter doubles every day. How wide is it on day 5?

▼ **Show solution**

1. 4 doublings after day 1: 2×2^4

Answer: 32 mm

Example 2. A paramecium is 0.2 mm long. How long does it look at 40× magnification?

▼ **Show solution**

1. 0.2×40

Answer: 8 mm, easy to see as a moving speck at low power

PRACTICE

1. Easy What did Fleming notice in 1928?

   ▼ **Show answer**

   Bacteria around a *Penicillium* mold on a culture dish had been killed.

2. Easy What are fungal cell walls made of?

   ▼ **Show answer**

   Chitin.

3. Easy How does an amoeba move?

   ▼ **Show answer**

   With pseudopods.

COMMON MISTAKES

- Calling fungi plants; they have no chlorophyll, have chitin walls and absorb their food.

- Thinking the mushroom is the whole fungus; it is the fruiting body of a mycelium.
- Saying Fleming alone made penicillin a medicine; Florey, Chain and Heatley purified and tested it.

Make it a game · Kingdom Sort. Write names on cards: yeast, amoeba, mushroom, kelp, paramecium, bread mold, euglena, athlete's foot, diatom, morel. The student sorts them into protists and fungi as fast as possible, then explains two tricky ones.

Scripture. "A man's heart deviseth his way: but the LORD directeth his steps." (Proverbs 16:9, KJV)

A spoiled dish and a moldy melon changed medicine. A man's heart deviseth his way, but the LORD directeth his steps.

8.3 Plants: Grew, Malpighi and Hales's Vegetable Staticks (1727)

OBJECTIVES

- Classify plants into mosses, ferns, conifers and flowering plants and describe their differences.
- Describe the structure and function of roots, stems, leaves and flowers, including xylem, phloem and stomata.
- Explain transpiration and how Stephen Hales measured it.

> **Warm-up.** Put a stalk of celery with leaves in a glass of water with red or blue food coloring. Look at it after a few hours and again tomorrow. What path did the color take?

WATCH

Angiosperm (Flowering Plants) Reproduction UPDATED

Amoeba Sisters · 8:16

https://www.youtube.com/watch?v=QMBGMUgAqCs

> **WHEN TO WATCH**
> After the flower and plant structure.

BACKUP VIDEO

Plant Structure and Diversity: Before the Bell Biology

Amoeba Sisters · 8:04

https://www.youtube.com/watch?v=iJ0cO5VwBXg

With the four plant groups.

KEY TERMS

vascular tissue

Tubes that carry water and food through a plant: xylem and phloem.

xylem

Vascular tissue that carries water and minerals up from the roots.

phloem

Vascular tissue that carries sugars from the leaves to the rest of the plant.

stoma (plural stomata)

A tiny pore in a leaf, opened and closed by two guard cells, that lets in carbon dioxide and lets out water vapor.

transpiration

The loss of water vapor from leaves, which pulls water up through the xylem.

angiosperm and gymnosperm

Angiosperms are flowering plants with seeds in fruits; gymnosperms, such as pines, bear naked seeds in cones.

CORE IDEAS

The story. In the 1670s two men, working separately, first opened plants with the microscope. In Bologna the physician Marcello Malpighi described the tubes and pores of stems and leaves in his *Anatome Plantarum* (1675–1679). In London Nehemiah Grew, a physician from a Puritan family, published *The Anatomy of Plants* (1682), with beautiful engravings of wood and pith, and suggested that the stamens of a flower are its male parts. Fifty years later Stephen Hales, the parish minister of Teddington near London, measured how plants drink. In *Vegetable Staticks* (1727) he weighed a potted sunflower morning and evening for weeks and found how much water it gave off through its leaves, and he fixed gauges to cut grapevine stems in spring and found the root pressure could push sap up the equivalent of more than 20 feet.

How they figured it out. Hales was a careful measurer: he sealed the pot so water could leave only through the plant, compared the sunflower's water loss with the area of its leaves, and found it lost far more on hot, sunny days. From his numbers he concluded that water rises through the plant chiefly because leaves give it off at the top. He also showed that leaves take something from the air, which Priestley and Ingenhousz would explain (Lesson 4.1). Hales went on to measure blood pressure in a horse and invented ventilators that cleared foul air from ships and prisons.

The biology. Biologists group plants by four features. *Mosses* have no vascular tissue and must live in damp places. *Ferns* have xylem and phloem but reproduce by spores. *Gymnosperms* (pines, firs, cedars) have seeds in cones. *Angiosperms*, the flowering plants, have seeds enclosed in fruits. Roots anchor and absorb water and minerals; stems support and carry; leaves make food by photosynthesis. Water

enters the root, rises in the xylem, and leaves as vapor through stomata; this transpiration pulls a continuous column of water up even the tallest trees. A flower's parts are the sepals, the petals, the stamens (anther and filament, making pollen) and the pistil (stigma, style and ovary, holding the ovules that become seeds).

Where it is used. Farmers and gardeners use this every day: watering in the morning, mulching to reduce evaporation, grafting fruit trees so the xylem and phloem of two plants join, and taking cuttings. Lumber is xylem; maple syrup is boiled-down sap; cotton and linen are plant fibers. Plant breeders cross-pollinate flowers by hand to produce better wheat, corn and fruit, using the flower parts Grew first described.

Try it. In the lab you will dissect a flower, follow the color in celery, and measure transpiration from a leafy branch in a bag.

> **Safety first.** An adult handles the blade. Some flowers (lilies especially) are poisonous to cats; keep scraps away from pets.

LAB

Flower Dissection and Transpiration

You will identify the parts of a flower and measure how much water a branch transpires.

You will need

- A large simple flower (lily, tulip, alstroemeria or gladiolus from a grocery bouquet), a razor blade or craft knife (adult), tape, a hand lens
- Celery with leaves, food coloring, a glass
- A clear plastic bag, a twist tie, a leafy branch on a shrub in the sun and one in the shade

Steps

1. Remove and tape onto paper, in order from outside to inside, the sepals, petals and stamens, labeling each. Cut the ovary crosswise and count the ovules with a hand lens.
2. Cut a celery stalk crosswise after it has stood in colored water; sketch the colored dots (xylem bundles).
3. Tie a clear bag over a leafy branch in the sun and another in the shade in the morning. After 4 hours, collect the water in each bag with a syringe or measure the drops.
4. Compare the amounts.

Check your work

- ☐ How many stamens and ovules did your flower have?
- ☐ Where was the color in the celery, and what does it show?
- ☐ Which branch transpired more, and why?

LAB NOTEBOOK

1. The taped, labeled flower dissection.
2. Celery sketch and transpiration data for both branches.

> **From history.** Stephen Hales served as the parish minister of Teddington for more than fifty years, measured nature as a way of honoring its Maker, and was elected to the Royal Society and the French Academy of Sciences. Grew later wrote *Cosmologia Sacra* (1701), a defense of the wisdom of God shown in the creation.

WORKED EXAMPLES

Example 1. A potted plant weighs 1,250 g at 8 a.m. and 1,190 g at 6 p.m., with the soil sealed. How much water did it transpire per hour?

▼ **Show solution**

1. Loss = 60 g over 10 h
2. 60/10 = 6 g/h

Answer: 6 g of water per hour, about 6 mL

Example 2. A leaf has 250 stomata per square millimeter. How many are on a 3,000 mm^2 leaf?

▼ **Show solution**

1. 250×3000

Answer: 750,000 stomata

PRACTICE

1. Easy Name the four main groups of plants.

   ▼ **Show answer**

   Mosses, ferns, gymnosperms (conifers) and angiosperms (flowering plants).

2. Easy What does xylem carry?

   ▼ **Show answer**

   Water and minerals up from the roots.

3. Easy What does phloem carry?

   ▼ **Show answer**

   Sugars from the leaves to the rest of the plant.

COMMON MISTAKES

- Mixing up xylem (water up) and phloem (sugar to all parts).

- Thinking plants take in their food from the soil; soil gives water and minerals, while leaves make sugar from air and light.
- Calling a pine's cone a fruit; gymnosperm seeds are not enclosed in a fruit.

Make it a game · Plant Group Hunt. Walk the yard, a park or a garden center for 15 minutes. Find and photograph one moss, one fern, one conifer and five different flowering plants. Score a bonus point for each one you can name.

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)

Consider the lilies of the field. Jesus pointed to the flower as a lesson in God's care, and a dissected lily shows how finely it is made.

8.4 Animals: Cuvier's Comparative Anatomy and the Dissection Lab

OBJECTIVES

- Describe the main animal phyla by body plan and symmetry.
- Explain Cuvier's principle of the correlation of parts and his demonstration of extinction (1796).
- Identify the major organs of an earthworm and a perch or frog by dissection, real or virtual.

> **Warm-up.** A paleontologist finds a single sharp, curved tooth in a riverbank. What can she guess about the animal's jaws, its stomach, its legs and its claws? Why?

WATCH

Animals: Tour of 9 Phyla

Amoeba Sisters · 12:21

https://www.youtube.com/watch?v=3y1dTsyfNQ4

> **WHEN TO WATCH**
> After the tour of the animal phyla.

Note: Runs about 12 minutes; worth watching whole as a survey.

BACKUP VIDEO

Animals

Bozeman Science · 8:08

https://www.youtube.com/watch?v=wd-QnKlfZHI

With symmetry and body plans.

KEY TERMS

invertebrate and vertebrate

Animals without a backbone (over 95% of animal species) and animals with one.

phylum

A major group of animals sharing a basic body plan, such as arthropods or mollusks.

symmetry

Body balance: radial (like a wheel, as in jellyfish) or bilateral (matching left and right halves, as in worms and people).

exoskeleton

A hard outer covering that supports and protects, as in insects and crabs.

comparative anatomy

The study of how the structures of different animals compare.

dissection

Careful cutting apart of a specimen to study its internal structure.

CORE IDEAS

The story. Georges Cuvier, a Lutheran from Montbéliard near the Swiss border, who became the leading naturalist of Napoleon's Paris, could look at a single bone and describe the animal it came from. In 1796 he compared the jaws and teeth of living Indian and African elephants with fossil mammoth bones from Siberia and the bones of the American mastodon and showed they were distinct species, not found alive anywhere: animals could go extinct. Cuvier organized the whole animal kingdom by internal anatomy in *Le Règne Animal* (1817) and argued throughout his life that each animal is a coordinated whole, against Lamarck's idea that species gradually transform into others.

How they figured it out. Cuvier's *correlation of parts* says that every organ fits every other: an animal with teeth for tearing flesh must also have jaws to hold prey, claws to seize it, legs to chase it and a gut to digest meat; a hoofed animal will have flat grinding teeth and a long gut for plants. Comparing thousands of skeletons in the Paris museum let him predict, and then find, hidden bones in fossils. His famous demonstration was a fossil opossum in gypsum: from its jaw he predicted marsupial bones in the pelvis, and in front of witnesses he chipped away the rock and found them.

The biology. Biologists group animals by body plan. *Sponges* have no true tissues. *Cnidarians* (jellyfish, corals) have radial symmetry and stinging cells. *Flatworms*, *roundworms* and *annelids* (segmented worms such as the earthworm) have bilateral symmetry. *Mollusks* (snails, clams, octopuses) have a soft body and often a shell. *Arthropods* (insects, spiders, crustaceans) have jointed legs and an exoskeleton and are the largest phylum. *Echinoderms* (sea stars) have spiny skin and tube feet. *Chordates* include the vertebrates: fish, amphibians, reptiles, birds and mammals.

Dissection shows the organ systems for feeding, breathing, circulation, excretion and nerves in each.

Where it is used. Comparative anatomy underlies veterinary medicine, the testing of medicines in animals before people, and the recognition of fossil bones. Knowing body plans helps farmers fight pests (arthropods) and parasites (roundworms and flatworms), and helps beekeepers, fishermen and ranchers care for the animals in their keeping. Surgeons first learn the organs by dissection.

Try it. In the lab you will dissect an earthworm and then a perch or frog (real or virtual), and prepare for the unit's lab practical.

> **Safety first.** Wear gloves and goggles. Cut away from your body and your fingers, and let an adult handle the scalpel if you prefer. Work in a ventilated room; wash hands well afterward. Families who prefer not to dissect can use a virtual dissection and label printed screenshots for the practical.

LAB

Earthworm and Perch or Frog Dissection

You will identify the external and internal anatomy of an annelid and a vertebrate and compare their organ systems.

You will need

- A dissection kit (scalpel, scissors, forceps, probe, pins), a dissecting tray or a foam plate, gloves and goggles
- A preserved earthworm and a preserved perch or frog from a science supplier (about $40–70 for the kit and specimens), or a free virtual dissection online
- Paper towels, a zip bag for disposal

Steps

1. Earthworm: find the front end, the clitellum and the bristles (setae). Pin it dorsal side up, cut gently along the back with scissors, pin the skin open and find the pharynx, the five pairs of hearts (aortic arches), the crop, the gizzard, the intestine and the nerve cord.
2. Perch or frog: describe the outside (fins or limbs, eyes, gills or eardrum). With a parent, open the body cavity along the belly and find the heart, liver, stomach, intestine, gills or lungs and, in the perch, the swim bladder.
3. Sketch and label each specimen. Compare how each one takes in oxygen, moves blood and digests food.
4. Wrap the remains in paper towels, seal them in a bag and put them in the trash; clean the tools with soap and water.

Check your work

- ☐ Which organs did both animals have? Which were different?
- ☐ How does the earthworm breathe without lungs or gills?
- ☐ Why does the worm need a gizzard?

LAB NOTEBOOK

1. Labeled sketches of both dissections with at least eight organs each.

2. A comparison table of the two animals' organ systems.

> **From history.** Cuvier once settled an argument in a Paris salon by pointing out that a guest dressed as a horned, hoofed devil who threatened to eat him could do no such thing: horns and hooves mean a plant-eater. The story may be embellished, but it shows his principle. Louis Agassiz, his student, brought Cuvier's comparative method to Harvard and remained a lifelong critic of Darwin.

WORKED EXAMPLES

Example 1. A tooth has a sharp, blade-like edge, and a leg bone has a narrow foot with claws. Using the correlation of parts, what did the animal eat?

▼ **Show solution**

1. Blade teeth and claws go with seizing and slicing flesh.

Answer: Meat: it was a carnivore

Example 2. An animal has jointed legs, an exoskeleton, three body sections and six legs. Name its phylum and class.

▼ **Show solution**

1. Jointed legs and exoskeleton: arthropod
2. Three body sections and six legs: insect

Answer: Phylum Arthropoda, class Insecta

PRACTICE

1. Easy What is the largest animal phylum?

   ▼ **Show answer**

   Arthropods.

2. Easy What did Cuvier show in 1796?

   ▼ **Show answer**

   Mammoths and mastodons were distinct species not living anywhere: animals can go extinct.

3. **Medium** State Cuvier's principle of the correlation of parts.

   ▼ **Show answer**

   Every part of an animal fits every other, so one part shows what the others must be like.

COMMON MISTAKES

- Calling all invertebrates bugs; insects are only one class of one phylum.
- Thinking an earthworm has one heart; it has five pairs of aortic arches.
- Confusing radial and bilateral symmetry.

Make it a game · Phylum Twenty Questions. One player thinks of an animal; the other may ask only yes-or-no questions about its body (Does it have a backbone? Jointed legs? A shell? Radial symmetry?) and must name its phylum, then the animal, within twenty questions.

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)

But ask now the beasts, and they shall teach thee. Comparative anatomy is a long lesson in listening to what animals show about how they are made.

UNIT 8

The Diversity of Life

This unit tours the living world group by group, following the people who first looked closely: Jenner's cowpox and Pasteur's rabies vaccine, Koch proving that one germ causes one disease, Fleming's moldy plate and the penicillin that Florey and Chain turned into a medicine, Grew, Malpighi and Hales opening up plants, and Cuvier comparing animal skeletons until he could reconstruct a whole creature from a single bone. Viruses are taught through history: smallpox, rabies, polio and the 1918 influenza.

The labs are the busiest of the year: sealed agar plates, a bread-mold time-lapse, spore prints, a flower dissection and an earthworm and then a perch or frog dissection (real or virtual). The unit ends with a **lab practical**: identifying slides and specimens and labeling a dissection. Agar plates are sealed with tape and never reopened; they are destroyed with bleach.

PREREQUISITES

- Unit 1 (the microscope and classification)
- Unit 3 (prokaryotic and eukaryotic cells)

MASTERY CHECKLIST

- ☐ I can compare bacteria and viruses and explain how vaccines and antibiotics work, using Jenner, Koch and Pasteur.
- ☐ I can describe protists and fungi and tell the story of penicillin from Fleming to Florey and Chain.
- ☐ I can name the main plant groups, label a flower and explain transpiration from Hales's experiments.
- ☐ I can describe the main animal phyla and body plans, explain Cuvier's comparative anatomy, and identify the organs of a dissected specimen.

LESSONS IN THIS UNIT

8.1 **Bacteria and Viruses: Jenner (1796), Koch's Postulates (1884) and Pasteur's Rabies Vaccine (1885)**

4 sessions of 45 minutes

8.2 **Protists and Fungi: Fleming's Penicillin (1928)** 4 sessions of 45 minutes

8.3 **Plants: Grew, Malpighi and Hales's Vegetable Staticks (1727)**

4 sessions of 45 minutes

8.4 **Animals: Cuvier's Comparative Anatomy and the Dissection Lab**

4 sessions of 45 minutes

Unit 8 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **10 pts** **Lesson 8.1**
   Why must sealed agar plates never be reopened?

2. **10 pts** **Lesson 8.1**
   How do bacteria reproduce?

3. **10 pts** **Lesson 8.2**
   What warning did Fleming give in 1945?

4. **9 pts** **Lesson 8.2**
   How does a paramecium move?

5. **9 pts** **Lesson 8.3**
   What part of the flower becomes the fruit?

6. **9 pts** **Lesson 8.3**
   Why should gardeners water in the morning rather than at midday?

7. **9 pts** **Lesson 8.4**

What percentage of animal species are invertebrates, roughly?

8. **9 pts** **Lesson 8.4**

How did Cuvier’s fossil opossum demonstration test his principle?

LAB AND DATA

9. **10 pts**

Three sealed agar plates were swabbed and kept at room temperature for 3 days: A, a clean kitchen counter (4 colonies); B, a phone screen (31 colonies); C, a hand after washing with soap for 20 seconds (2 colonies). (a) Which surface carried the most bacteria? (b) Why must the plates stay taped shut? (c) What would make this a fairer test?

SHORT ESSAY

10. **15 pts**

Choose two of these scientists: Jenner, Koch, Pasteur, Fleming, Hales or Cuvier. For each, describe the observation or experiment that made his name, what it changed in biology or medicine, and one question it left for those who came after.

ANSWER KEY

1. Colonies contain billions of cells, possibly pathogens; opening could spread them.
2. By binary fission: one cell copies its DNA and splits in two.
3. Careless use of penicillin could make bacteria resistant.
4. By beating its cilia.
5. The ovary.
6. Less water evaporates before roots absorb it, and the plant has water for the hot, high-transpiration hours.
7. Over 95%.
8. From the jaw he predicted marsupial bones in the pelvis, then uncovered them before witnesses.
9. (a) The phone screen. (b) Colonies contain billions of cells, some possibly harmful; opening the plate could spread them, so plates are sealed, never reopened and destroyed with bleach. (c) Same swab technique, same area swabbed, same time and temperature, a control plate swabbed with a sterile swab, and repeated trials.
10. Look for: accurate details (Jenner: cowpox and James Phipps, 1796; Koch: anthrax and tuberculosis, his postulates; Pasteur: the rabies vaccine and Joseph Meister, 1885; Fleming: the Penicillium plate, 1928, and Florey and Chain's purification; Hales: measuring transpiration and root pressure, 1727; Cuvier: comparative anatomy and extinction); a clear statement of what changed; a sensible open question; clear organization.

Printable answer key (PDF, for the parent)

PORTFOLIO PIECE: UNIT 8 LAB PRACTICAL

The practical is set up by a parent at stations around a table, one minute per station, like a high-school or college biology practical. Typical stations: (1) a prepared slide of bacteria (name the shape: coccus, bacillus or spiral); (2) a pond-water or prepared protist slide (amoeba, paramecium or euglena); (3) a bread-mold sample under magnification (hyphae, sporangia); (4) a mushroom spore print (gills or pores); (5) a flower with pins in five parts (sepal, petal, anther, stigma, ovary); (6) a moss, a fern frond and a pine cone (name the plant group); (7) shells, insects or photos of animals (name the phylum); (8) the opened earthworm with pins in five organs (crop, gizzard, hearts, nerve cord, intestine); (9) the perch or frog with pins in five organs (heart, liver, stomach, gills or lungs, swim bladder or kidney).

Score one point per correct label, about 40 points in all, and count it with the labs. A student who used a virtual dissection labels printed screenshots instead.

UNIT 9

Ecology and Stewardship

The last unit studies living things together: who eats whom and how energy flows (Elton's pyramid), how water, carbon and nitrogen cycle through air, soil, oceans and living things, how populations grow and are limited (Gause's paramecia), and how people can exercise the dominion of Genesis 1:28 as careful keepers of the garden (Genesis 2:15). Ecology is taught as observation and measurement; conservation is told through its successes: the bison, the wood duck, the whooping crane and the bluebird, many of them paid for by hunters and anglers through the Duck Stamp and the Pittman–Robertson Act.

The labs go outdoors: a hula-hoop quadrat survey of the yard, a Berlese funnel for soil animals, nitrate and pH tests of a pond or stream, a duckweed population count and a bird count you can report to Project FeederWatch or eBird.

PREREQUISITES

- Unit 4 (photosynthesis and respiration)
- Unit 8 (the groups of living things)
- Algebra I for growth and percentage problems

MASTERY CHECKLIST

- ☐ I can describe food chains, food webs and trophic levels and use the 10% rule.
- ☐ I can trace the water, carbon and nitrogen cycles and name the living things that drive them.
- ☐ I can explain exponential and logistic growth, carrying capacity, limiting factors and Gause's competitive exclusion.
- ☐ I can explain dominion as stewardship and describe successful examples of wildlife management.

LESSONS IN THIS UNIT

9.1 **Ecosystems, Food Webs and Elton's Pyramid (1927)** — 4 sessions of 45 minutes

9.2 **Cycles of Matter: Water ("All the Rivers Run into the Sea"), Carbon and Nitrogen**

4 sessions of 45 minutes

9.3 Populations: Growth, Carrying Capacity and Gause's Experiments (1934)

4 sessions of 45 minutes

9.4 Dominion and Care: Game Management, the Bison and the Duck Stamp (1934)

4 sessions of 45 minutes

Unit 9 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 9.1**
   Why can an acre of grain feed more people than an acre of pasture used for beef?

2. **8 pts** **Lesson 9.1**
   Is a rabbit a primary or secondary consumer?

3. **8 pts** **Lesson 9.1**
   Producers in a meadow capture 10,000 kcal of energy. Using the 10% rule, about how much reaches trophic level 5?

4. **8 pts** **Lesson 9.2**
   What role do decomposers play in the nitrogen cycle?

5. **8 pts** **Lesson 9.2**
   Explain how a water molecule in the ocean could end up in a tree leaf.

6. **7 pts** **Lesson 9.3**
   Who proposed the logistic equation, and when?

7. **7 pts** **Lesson 9.3**

   In the logistic model, why is growth slow both when the population is very small and when it is near K?

8. **7 pts** **Lesson 9.3**

   A population of 100 yeast cells doubles every 3 hours with unlimited food. How many cells after 12 hours?

9. **7 pts** **Lesson 9.4**

   What is a bag limit?

10. **7 pts** **Lesson 9.4**

    How do citizen scientists help wildlife management?

LAB AND DATA

11. **10 pts**

    A student counts plants in five 1 m^2 quadrats in a meadow: 12, 9, 15, 11, 13 clover plants. The meadow is 400 m^2. (a) Find the mean per square meter. (b) Estimate the clover in the whole meadow. (c) Why use several quadrats placed at random?

SHORT ESSAY

12. **15 pts**

    Genesis 1:28 gives man dominion over the creatures, and Genesis 2:15 says God put the man in the garden “to dress it and to keep it.” Using two examples from this unit (such as the bison, the wood duck, the Duck Stamp or a farm or ranch you know), explain what wise dominion looks like in practice and how science helps people exercise it.

ANSWER KEY

1. Eating at a lower trophic level avoids the roughly 90% energy loss at each step.
2. Primary consumer (herbivore).
3. About 1 kcal

   Each step passes about 10%: 10,000 × 0.1^4 = 1 kcal
4. They break down proteins in dead things and wastes, returning ammonia to the soil.
5. Evaporation, condensation into a cloud, precipitation on land, soaking into soil, uptake by roots and rise through xylem.
6. Pierre-François Verhulst, 1838.
7. When small, few individuals reproduce; near K, the factor (K − N)/K is close to zero.
8. 1,600

   12/3 = 4 doublings; 100 × 2^4 = 1,600
9. The number of animals of a species a hunter or angler may legally take.
10. Their counts (FeederWatch, eBird, the Christmas Bird Count) track populations across large areas and many years.
11. (a) 60/5 = 12 per m^2. (b) 12 × 400 = 4,800 clover plants. (c) A single quadrat might land on an unusually thick or thin patch; random placement and several samples give a fairer average.
12. Look for: accurate quotations; dominion understood as responsible rule and care, not exploitation or neglect; two accurate examples (bison recovery from fewer than about a thousand to hundreds of thousands; wood duck recovery with hunting limits and nest boxes; the Duck Stamp funding wetlands); a clear role for measurement (counts, carrying capacity, harvest limits); balanced tone without alarm.

Printable answer key (PDF, for the parent)

9.1 Ecosystems, Food Webs and Elton's Pyramid (1927)

OBJECTIVES

- Define ecosystem, habitat, niche, producer, consumer and decomposer.
- Build food chains and webs and explain trophic levels.
- Use the 10% rule to explain Elton's pyramid of numbers and energy.

> **Warm-up.** List everything you ate yesterday. For each item, trace it back step by step until you reach a plant. How many steps did the longest chain have? Did any chain end with something other than a plant?

WATCH

Food Webs and Energy Pyramids: Bedrocks of Biodiversity

Amoeba Sisters · 5:49

https://www.youtube.com/watch?v=-oVavgmveyY

> **WHEN TO WATCH**
> After Elton's pyramid.

BACKUP VIDEO

Energy Flow in Ecosystems

Bozeman Science · 7:46

https://www.youtube.com/watch?v=lnAKICtJIA4

With energy flow and the 10% rule.

KEY TERMS

ecosystem

All the living things in an area together with the nonliving parts of their environment: soil, water, air and sunlight.

producer

An organism that makes its own food, usually by photosynthesis.

consumer

An organism that eats other organisms: herbivores, carnivores and omnivores.

decomposer

An organism, such as a fungus or bacterium, that breaks down dead matter and returns nutrients to the soil.

trophic level

A feeding step in a food chain: producers, primary consumers, secondary consumers and so on.

niche

The role of a species in its ecosystem: what it eats, where it lives and how it interacts with others.

CORE IDEAS

The story. In 1921, as a 21-year-old Oxford student, Charles Elton sailed to Spitsbergen, an Arctic island with very few kinds of plants and animals, and recorded who ate whom: plants, insects, birds, Arctic foxes, polar bears. In 1927 he published *Animal Ecology*, which introduced the food chain, the food web, the niche, and the pyramid of numbers: many small animals at the bottom support fewer and larger animals above them. Later, Elton studied the fur records of the Hudson's Bay Company and found regular ten-year cycles in lynx and snowshoe hares (Lesson 9.3).

How they figured it out. Elton counted and watched; in an ecosystem with few species the connections were easy to see. In 1942 Raymond Lindeman, studying a Minnesota lake, measured energy at each feeding step and explained the pyramid: at each step only a small part of the energy, roughly a tenth, is built into the next level's bodies. The rest is used for living, lost as heat, or never eaten. That is why food chains seldom have more than four or five links.

The biology. Energy enters ecosystems as sunlight captured by producers (plants, algae). Primary consumers (herbivores) eat producers; secondary consumers eat herbivores; tertiary consumers eat them. Decomposers recycle the dead of every level. A food chain is one path; a food web shows all the overlapping paths. Energy flows one way, from the sun through the levels and out as heat; matter cycles (Lesson 9.2). Each species has a niche, and two species cannot hold exactly the same niche for long (Gause, Lesson 9.3).

Where it is used. Ranchers use the same arithmetic when they set stocking rates: an acre of pasture can feed only so much cattle. Fish and game managers protect the producers and prey that support the animals people hunt and fish. Eating lower on the food chain, grains and vegetables, feeds more people per acre than meat, which is why famine relief begins with grain.

Try it. In the lab you will survey the plants and animals in a hula-hoop quadrat, collect soil animals with a Berlese funnel and draw the food web of your own yard.

> **Safety first.** Wear gloves when handling soil and leaf litter. Keep the lamp from touching the bottle or paper. Do not handle stinging insects or spiders.

LAB

Quadrat Survey and Berlese Funnel

You will sample the living things in your yard and build its food web.

You will need

- A hula hoop (or a 1 m square of string and stakes), a notebook, a field guide or plant-identification app
- A Berlese funnel: a plastic soda bottle cut in half (top half inverted as a funnel), a piece of window screen, a desk lamp, a jar with a little rubbing alcohol or water
- A trowel, a cup of leaf litter or topsoil, a hand lens

Steps

1. Toss the hoop at random three times in the yard. In each, list every kind of plant and count individuals of the most common two. Note insects, worms and other animals.
2. Put a cup of leaf litter on the screen in the funnel over the jar, and set the lamp 10–15 cm above for 24 hours. The heat drives soil animals down into the jar.
3. Examine the jar with a hand lens and sort the animals (mites, springtails, beetles, centipedes, worms).
4. Draw a food web for your yard with at least ten organisms, including decomposers.

Check your work

- ☐ Which plant was most common? Why there?
- ☐ How many kinds of soil animals did you find?
- ☐ Which organism in your web would affect the most others if it disappeared?

LAB NOTEBOOK

1. Quadrat data tables and sketches of three soil animals.
2. Your yard food web with arrows pointing from food to eater.

> **From history.** Elton founded the Bureau of Animal Population at Oxford in 1932 and spent decades studying a single wood near Oxford, Wytham Woods, which is still one of the most-studied patches of land on earth.

WORKED EXAMPLES

Example 1. Grass in a field captures 50,000 kcal. About how much energy reaches the hawks that eat snakes that eat mice that eat the grass?

▼ **Show solution**

1. Grass → mice: 5,000 kcal
2. Mice → snakes: 500 kcal
3. Snakes → hawks: 50 kcal

Answer: About 50 kcal

Example 2. Why are there far fewer hawks than mice in a field?

▼ **Show solution**

1. Each step passes only about 10% of the energy.
2. The hawk level receives about 1% of the energy of the mouse level.

Answer: There is far less energy available at the top of the pyramid

PRACTICE

1. Easy What is a producer? Give an example.

   ▼ **Show answer**

   An organism that makes its own food, such as grass or algae.

2. Easy What do decomposers do?

   ▼ **Show answer**

   Break down dead matter and return nutrients to the soil.

3. Medium Producers in a meadow capture 50,000 kcal of energy. Using the 10% rule, about how much reaches trophic level 4?

   ▼ **Show answer**

   About 50 kcal

4. **Medium** Producers in a meadow capture 20,000 kcal of energy. Using the 10% rule, about how much reaches trophic level 5?

   ▼ **Show answer**

   About 2 kcal

5. **Medium** Producers in a meadow capture 50,000 kcal of energy. Using the 10% rule, about how much reaches trophic level 5?

   ▼ **Show answer**

   About 5 kcal

COMMON MISTAKES

- Drawing food-web arrows backward; the arrow points from the food to the eater (the direction energy flows).
- Thinking energy is recycled like matter; it flows through once and leaves as heat.
- Leaving decomposers out of food webs.

> **Make it a game · Food Web Yarn.** Each family member holds a card with an organism (sun, grass, oak, rabbit, deer, fox, hawk, mushroom). Pass a ball of yarn from food to eater to make a web, then tug one string: everyone who feels it is affected.

> **Scripture.** “These wait all upon thee; that thou mayest give them their meat in due season.” (Psalm 104:27, KJV)
>
> These wait all upon thee; that thou mayest give them their meat in due season. The psalmist saw the whole food web as provided for by God.

9.2 Cycles of Matter: Water ("All the Rivers Run into the Sea"), Carbon and Nitrogen

OBJECTIVES

- Trace the water cycle: evaporation, transpiration, condensation, precipitation and runoff.
- Trace the carbon cycle through photosynthesis, respiration, decomposition, combustion, oceans and rocks.
- Trace the nitrogen cycle and explain the role of nitrogen-fixing bacteria and fertilizer.

> **Warm-up.** Every atom of water you drank today has been somewhere before: in a cloud, a river, an ocean, a plant, perhaps an animal. Trace one possible journey for a water molecule over the last year.

WATCH

How the Earth Recycles Elements: Biogeochemical Cycles

MooMooMath and Science · 2:59

https://www.youtube.com/watch?v=UVg-8-ueM_8

> **WHEN TO WATCH**
> After the three cycles.

BACKUP VIDEO

Water Cycle Diagram A Demonstration for Each Step of the Water Cycle

MooMooMath and Science · 3:38

https://www.youtube.com/watch?v=YqiVRPMKR6Y

With the water cycle demonstration.

KEY TERMS

evaporation and condensation

Evaporation turns liquid water to vapor; condensation turns vapor back to liquid droplets, forming clouds and dew.

precipitation

Water falling from clouds as rain, snow, sleet or hail.

photosynthesis and respiration

Photosynthesis takes carbon dioxide from the air to make sugar; respiration releases it again.

nitrogen fixation

Turning nitrogen gas from the air into ammonia that plants can use, done by certain bacteria, by lightning, and in factories.

legume

A plant of the pea and bean family, whose root nodules house nitrogen-fixing bacteria.

decomposition

The breakdown of dead matter by fungi and bacteria, returning carbon and nitrogen to the soil and air.

CORE IDEAS

The story. Solomon described the water cycle three thousand years ago: "All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again" (Ecclesiastes 1:7). In 1674 the French lawyer Pierre Perrault measured the rain and snow falling on the basin of the upper Seine for three years and showed it was several times the river's flow, enough to feed the springs and rivers: the first measured water budget. Farmers had known for two thousand years that peas, beans and clover enrich the soil; in 1886 the German chemists Hermann Hellriegel and Hermann Wilfarth showed why: bacteria in the root nodules of legumes take nitrogen from the air.

How they figured it out. Hellriegel and Wilfarth grew peas and grain in sterilized sand without nitrogen. The grain starved; the peas starved too, unless the experimenters added a little water from fertile soil, after which nodules formed on the roots and the peas grew well. Something living in soil let legumes use the nitrogen of the air. Martinus Beijerinck isolated the bacterium, *Rhizobium*, in 1888. In 1909 Fritz Haber found how to fix nitrogen in a factory (Chemistry Lesson 9.3), and today fertilizer made by his process helps feed billions of people.

The biology. *Water:* the sun evaporates water from oceans, lakes and soil, and plants transpire it (Lesson 8.3); vapor condenses into clouds, falls as precipitation, and returns by runoff and groundwater to the sea. *Carbon:* plants and algae take carbon dioxide from the air and build it into sugars (Unit 4); animals eat them; respiration and decomposition return carbon dioxide; burning wood, coal, oil and gas releases carbon stored long ago; oceans dissolve carbon dioxide, and shells and limestone

store it. *Nitrogen:* air is 78% nitrogen gas, which most living things cannot use. Nitrogen-fixing bacteria and lightning turn it into ammonia and nitrates; plants build them into proteins and DNA; animals eat plants; decomposers return ammonia to the soil; other bacteria return nitrogen gas to the air.

Where it is used. Farmers rotate corn with soybeans or clover to put nitrogen back into the soil, and test soil to apply just the fertilizer a crop needs, since excess nitrate washing into streams feeds algae that can choke ponds. Greenhouse growers raise carbon dioxide to make plants grow faster. Wells, irrigation and city water systems depend on knowing how fast rain recharges groundwater.

Try it. In the lab you will build a sealed water-cycle jar and test a pond or stream for nitrate and pH.

> **Safety first.** Collect water samples with an adult; stay back from steep or slippery banks and fast water. Wash hands after handling pond water.

LAB

A Water-Cycle Jar and Water-Quality Tests

You will watch the water cycle in a sealed jar and measure nitrate and pH in natural water.

You will need

- A large clear jar with a lid, gravel, potting soil, small plants or moss, a spray bottle
- Water-test strips for nitrate, nitrite and pH (aquarium or pool strips, about $10–15)
- Clean jars for samples from a pond, a stream, rain and the tap

Steps

1. Layer gravel and soil in the jar, plant moss or small plants, water lightly, close the lid and set it in bright light (not hot direct sun). Observe twice a day for a week and record where water collects.
2. Collect samples of pond or stream water, rainwater and tap water. Dip a strip in each and read nitrate, nitrite and pH against the chart.
3. If you can, sample a stream above and below a farm field or pasture.

Check your work

- ☐ Where did you see evaporation, condensation and precipitation in the jar?
- ☐ Which sample had the most nitrate? Why might that be?
- ☐ How does the jar show that matter cycles?

LAB NOTEBOOK

1. Daily observations of the jar with a labeled diagram of the cycle.
2. A water-test results table with your explanations.

> **From history.** George Washington Carver at Tuskegee taught Southern farmers worn out by cotton to plant peanuts, cowpeas and sweet potatoes, restoring nitrogen to their soil, and found hundreds of uses for those crops so that they could be sold. He credited God with revealing to him the secrets of the peanut.

WORKED EXAMPLES

Example 1. A 1-acre field receives 36 inches of rain a year. If 25% soaks into groundwater, how many inches recharge the aquifer?

▼ **Show solution**

1. 36×0.25

Answer: 9 inches a year

Example 2. Air is 78% nitrogen by volume. How many liters of nitrogen are in a 10 L bottle of air?

▼ **Show solution**

1. 10×0.78

Answer: 7.8 L

PRACTICE

1. Easy Name four processes in the water cycle.

   ▼ **Show answer**

   Evaporation, condensation, precipitation and runoff (also transpiration).

2. Easy What percent of the air is nitrogen?

   ▼ **Show answer**

   About 78%.

3. Medium Which process removes carbon dioxide from the air, and which processes return it?

   ▼ **Show answer**

   Photosynthesis removes it; respiration, decomposition and burning return it.

COMMON MISTAKES

- Thinking plants get their carbon from the soil; it comes from carbon dioxide in the air.
- Thinking plants can use nitrogen gas directly; they need it fixed as ammonia or nitrate.
- Leaving transpiration out of the water cycle.

Make it a game · Cycle Path Dice. Make stations around the house: ocean, cloud, rain, river, plant, animal, soil, groundwater. At each station roll a die to see where the water molecule goes next (write the options on a card at each station). Record the journey and compare paths.

Scripture. “All the rivers run into the sea; yet the sea is not full; unto the place from whence the rivers come, thither they return again.” (Ecclesiastes 1:7, KJV)

All the rivers run into the sea; yet the sea is not full. Solomon described the water cycle long before anyone measured it.

9.3 Populations: Growth, Carrying Capacity and Gause's Experiments (1934)

OBJECTIVES

- Distinguish exponential and logistic growth and define carrying capacity.
- Name density-dependent and density-independent limiting factors, including predation and competition.
- Explain Gause's competitive exclusion principle and the lynx–hare cycle.

> **Warm-up.** If one pair of rabbits had eight young every season and all of them survived and bred, how many rabbits would there be after five seasons? Why doesn't the earth fill up with rabbits?

WATCH

Population Ecology

Bozeman Science · 12:09

https://www.youtube.com/watch?v=PQ-CQ3CQE3g

> **WHEN TO WATCH**
> After the growth curves.

Note: Runs about 12 minutes; watch it whole or in two sittings.

BACKUP VIDEO

Logistic Growth

Bozeman Science · 10:56

https://www.youtube.com/watch?v=rXlyYFXyfIM

With the logistic model and carrying capacity.

KEY TERMS

population
All the members of one species living in one area.

exponential growth
Growth by a constant percentage each period, giving a J-shaped curve, possible only while resources are unlimited.

carrying capacity (K)

The largest population an environment can support over time.

logistic growth

Growth that slows as the population approaches carrying capacity, giving an S-shaped curve.

limiting factor

Anything that holds a population down: food, water, space, disease, predators, weather.

competitive exclusion

Gause's principle that two species competing for exactly the same resources cannot coexist indefinitely.

CORE IDEAS

The story. In the early 1930s the young Russian biologist Georgii Gause, in Moscow, grew two species of the protist *Paramecium* in test tubes of oat medium fed with bacteria and counted them every day under the microscope. Alone, each species rose quickly and then leveled off. Together, *P. aurelia* always won and *P. caudatum* died out. In 1934 he published *The Struggle for Existence*, setting out the principle that two species with exactly the same needs cannot share one niche for long. When he gave *P. caudatum* a species that fed in a different part of the tube, both survived.

How they figured it out. Gause tested an old mathematical idea. In 1838 the Belgian mathematician Pierre-François Verhulst had proposed the logistic equation: growth slows as a population fills its environment. Gause's counts traced Verhulst's S-shaped curve almost exactly. Elton, meanwhile, had found in the Hudson's Bay Company's fur records nearly a century of lynx and snowshoe hare pelts rising and falling together about every ten years: more hares feed more lynx; more lynx eat down the hares; then the lynx starve and the hares recover.

The biology. With unlimited resources a population grows exponentially: it doubles at a steady interval. Real environments push back: as numbers rise, food, space and nesting sites run short and disease and predators increase (density-dependent factors), while floods, freezes and fires strike regardless of density (density-independent factors). The logistic model writes growth as $\Delta N = rN\dfrac{K-N}{K}$: fast when N is small, zero when N reaches the carrying capacity K. Species that seem to compete for the same food often split it: warblers feeding in different parts of the same spruce tree, as Robert MacArthur showed in 1958.

Where it is used. Game managers set hunting seasons and bag limits from population counts and carrying capacity, so the harvest takes the surplus a habitat would not support through winter. Fisheries set catch limits the same way. Farmers manage pests by encouraging their predators (ladybugs against aphids) and by rotating crops. Doctors use growth curves for bacteria in infections and for the time an antibiotic needs to work.

Try it. In the lab you will grow duckweed in jars at different starting densities, count it every few days and graph the growth curves.

LAB

Duckweed Population Growth

You will measure population growth in duckweed, a tiny floating plant that reproduces by budding, and compare it with the exponential and logistic models.

You will need

- A small cup of duckweed (*Lemna*) from a pond or a pet or aquarium store
- Four clear cups or jars, aged tap water or pond water, a pinch of houseplant fertilizer (optional)
- A hand lens, a sunny window or grow light, graph paper

Steps

1. Fill four cups with the same amount of water. Put 5 fronds in two cups and 20 fronds in the other two.
2. Keep them in the same light. Every 2–3 days for three weeks, count the fronds in each cup.
3. Graph frond count against time for all four cups.
4. Mark where growth slows and estimate the carrying capacity of a cup.

Check your work

- ☐ Did growth look exponential at first? When did it slow?
- ☐ Did the cups starting with 20 fronds level off at the same number as the cups starting with 5?
- ☐ What limited the population in each cup?

LAB NOTEBOOK

1. Count tables for all four cups and the growth graph.
2. Your estimate of carrying capacity and the limiting factors.

KEY FORMULAS

$$\Delta N = rN \qquad \text{(exponential)}$$

$$\Delta N = rN\frac{K - N}{K} \qquad \text{(logistic)}$$

From history. The Hudson's Bay Company, chartered in 1670, kept careful records of every pelt bought from trappers. Those business ledgers became one of the longest-running data sets in ecology.

WORKED EXAMPLES

Example 1. A population of 500 yeast cells doubles every 2 hours. How many cells are there after 10 hours with unlimited food?

▼ **Show solution**

1. 10/2 = 5 doublings
2. $500 \times 2^5 = 16{,}000$

Answer: 16,000 cells

Example 2. A deer herd of 600 has carrying capacity 1,000 and $r = 0.30$ per year. Estimate this year's growth.

▼ **Show solution**

1. $\Delta N = (0.30)(600)(1000 - 600)/1000$
2. $= 180 \times 0.40 = 72$

Answer: About 72 deer; a manager might allow a harvest near that number

PRACTICE

1. Easy What is carrying capacity?

   ▼ **Show answer**

   The largest population an environment can support over time.

2. Easy What shape is an exponential growth curve? A logistic curve?

   ▼ **Show answer**

   J-shaped; S-shaped.

3. Medium A population of 200 yeast cells doubles every 3 hours with unlimited food. How many cells after 12 hours?

▼ **Show answer**

3,200

4. Hard A deer herd of 752 has carrying capacity K = 1000 and r = 0.5 per year. Using $\Delta N = rN(K - N)/K$, estimate the growth this year.

▼ **Show answer**

About 93 deer

5. Hard A deer herd of 508 has carrying capacity K = 1000 and r = 0.15 per year. Using $\Delta N = rN(K - N)/K$, estimate the growth this year.

▼ **Show answer**

About 37 deer

COMMON MISTAKES

- Thinking carrying capacity is fixed forever; it changes with weather, food supply and habitat.
- Assuming exponential growth can continue; every real population meets limits.
- Confusing density-dependent and density-independent factors.

Make it a game · Oh Deer!. A classic wildlife-management game for a group: players are deer or habitat (food, water, shelter). Each round, deer run to find a matching resource; those without one become habitat. Record the number of deer each round and graph the rise and fall.

Scripture. “And God blessed them, saying, Be fruitful, and multiply, and fill the waters in the seas, and let fowl multiply in the earth.” (Genesis 1:22, KJV)

God blessed the creatures and said, Be fruitful, and multiply. Every population has the power to grow, and every environment sets its limits.

9.4 Dominion and Care: Game Management, the Bison and the Duck Stamp (1934)

OBJECTIVES

- Explain dominion (Genesis 1:28) and keeping the garden (Genesis 2:15) as the Christian basis of stewardship.
- Describe the near loss and recovery of the bison, the wood duck, the whooping crane and the eastern bluebird.
- Explain how hunters, anglers and landowners fund and carry out American wildlife management, including the Duck Stamp (1934) and the Pittman–Robertson Act (1937).

> **Warm-up.** A family has a pond with bass and bluegill. Every summer they catch fish for supper. What rules should they make so that their grandchildren can fish in the same pond?

WATCH

Wood Duck: Bird in the Spotlight

Cornell Lab of Ornithology · 2:29

https://www.youtube.com/watch?v=PINj-sj_-9M

> **WHEN TO WATCH**
> After the conservation history.

Note: A short Cornell Lab of Ornithology spotlight; the wood duck's recovery is the story of this lesson.

BACKUP VIDEO

Eastern Bluebird: Bird in the Spotlight

Cornell Lab of Ornithology · 2:56

https://www.youtube.com/watch?v=PQlRkqnFdPM

With the bluebird nest-box discussion.

KEY TERMS

dominion

Rule given by God to mankind over the creatures (Genesis 1:28), to be exercised as a faithful steward answerable to Him.

stewardship

Caring for and wisely using what belongs to another, here the creation that belongs to God.

game management

The science and practice of keeping wildlife populations healthy and productive by managing habitat and harvest.

habitat

The place where an organism lives and finds food, water, shelter and space.

bag limit

The number of a species a hunter or angler may legally take in a day or season.

Duck Stamp

The federal Migratory Bird Hunting and Conservation Stamp, required of waterfowl hunters since 1934, whose sales buy wetlands for wildlife refuges.

CORE IDEAS

The story. In 1800 tens of millions of bison roamed the plains. Market hunting for hides and the building of the railroads cut them to fewer than about a thousand by the late 1880s. Ranchers and hunters saved them: a handful of private herds, a small wild herd protected in Yellowstone, and the American Bison Society founded in 1905 with President Theodore Roosevelt as honorary president. Today about half a million bison live in North America, most on private ranches. The wood duck was nearly gone by 1900; protected by the Migratory Bird Treaty Act of 1918 and helped by thousands of nest boxes built by hunters and farm families, it is again one of the most common ducks in the East. In 1934 Congress created the Duck Stamp, first drawn by the cartoonist and conservationist Jay “Ding” Darling, and in 1937 the Pittman–Robertson Act put a tax on guns and ammunition to pay for state wildlife agencies.

How they figured it out. Aldo Leopold, a forester who loved to hunt, wrote the first textbook of the new science, *Game Management* (1933): populations could be counted, carrying capacity measured and habitat improved, and harvests set so that

the land produced a lasting surplus. Biologists banded ducks to learn their flyways, counted deer on winter range, and studied what each species needed: the wood duck, a cavity nester, needed tree holes near water, so nest boxes worked. The whooping crane fell to 15 or 16 birds in the winter of 1941; refuges on its Texas wintering ground, protection along its route and captive breeding have brought the population to around 800.

The biology and the Bible. Genesis 1:28 gives mankind dominion over every living thing, and Genesis 2:15 says "the LORD God took the man, and put him into the garden of Eden to dress it and to keep it." Dominion is not ownership: "the earth is the LORD's" (Psalm 24:1). It means using the creatures for food, work and delight while keeping them for the next generation, the way a good farmer keeps his soil and a good rancher his range. Ecology supplies the measurements (counts, carrying capacity, habitat needs) that make wise rule possible. Neglect and waste are failures of dominion, and so is treating people as intruders in a creation God gave them to tend.

Where it is used. Hunting and fishing licenses and the excise taxes on hunting and fishing gear pay for most state wildlife management in America. Duck Stamp sales have bought or leased more than six million acres of wetlands for the National Wildlife Refuge System. Farmers leave field borders and wetlands for quail and ducks; ranchers rotate grazing to keep grass healthy; families put up bluebird boxes, and citizen scientists count birds each winter for Project FeederWatch and the Christmas Bird Count, begun in 1900.

Try it. In the lab you will count the birds at a feeder or in a park and report them, and plan a habitat improvement for your own yard.

LAB

Bird Count and a Habitat Plan

You will count birds as citizen scientists do and plan one improvement to your yard's habitat.

You will need

- A bird feeder or a window view of a yard or park, a field guide or the free Merlin Bird ID app, binoculars if you have them
- A timer, a notebook, graph paper for a yard map

Steps

1. On two days, watch the same spot for 15 minutes. For each species, record the largest number seen at one time (this avoids counting the same bird twice).
2. Optional: enter your count in Project FeederWatch or eBird with an adult's help.
3. Map your yard or a nearby park: trees, shrubs, water, open grass, nest sites.
4. Choose one improvement (a nest box of the right size for a local species, a brush pile, a water dish, native plants with seeds or berries) and write a one-page plan explaining how it meets a species' needs.

Check your work

- ☐ Which species was most common? Why does your area suit it?
- ☐ What does your chosen species need that your yard lacks?
- ☐ How does counting birds help wildlife managers?

LAB NOTEBOOK

1. Bird count tables for both days.
2. Your yard map and habitat plan.

> **From history.** Jay "Ding" Darling won two Pulitzer Prizes for his newspaper cartoons and drew the first Duck Stamp, of two mallards landing on a marsh, in 1934. The J. N. "Ding" Darling National Wildlife Refuge on Sanibel Island, Florida, is named for him.

WORKED EXAMPLES

Example 1. A state sells 400,000 hunting licenses at 30*andreceives*15 million from the Pittman–Robertson fund. What is the total available for wildlife management?

▼ **Show solution**

1. Licenses: 400,000 × 30 =12 million
2. 12*million*+15 million

Answer: $27 million

Example 2. A bison herd grows from 500 to 1,000 in 6 years. If growth stayed steady, how long would it take to reach 4,000?

▼ **Show solution**

1. Doubling time = 6 years
2. 1,000 → 2,000 → 4,000 is two more doublings

Answer: 12 more years (18 years in all)

PRACTICE

1. Easy Which two verses describe man's dominion and his care of the garden?

   ▼ **Show answer**

   Genesis 1:28 and Genesis 2:15.

2. Easy What is the Duck Stamp, and when did it begin?

   ▼ **Show answer**

   A federal stamp required of waterfowl hunters since 1934; its sales buy wetlands.

3. Medium How low did the bison fall, and how many are there today?

   ▼ **Show answer**

   Fewer than about a thousand by the late 1880s; about half a million today.

COMMON MISTAKES

- Thinking conservation means keeping people out; most American wildlife recovery was done by hunters, anglers, farmers and ranchers managing land.

- Confusing dominion with doing as we please; Scripture makes man a steward answerable to God.
- Counting the same bird many times; record the most seen at once.

> **Make it a game · Habitat Match.** The parent names an animal (wood duck, bluebird, deer, bass, honeybee, quail). The student names its food, water, shelter and space needs and one thing a family or farmer could do to help it.

> **Scripture.** “A righteous man regardeth the life of his beast: but the tender mercies of the wicked are cruel.” (Proverbs 12:10, KJV)
>
> A righteous man regardeth the life of his beast. Care for animals is part of righteousness, not a modern invention.

UNIT 9

Ecology and Stewardship

The last unit studies living things together: who eats whom and how energy flows (Elton's pyramid), how water, carbon and nitrogen cycle through air, soil, oceans and living things, how populations grow and are limited (Gause's paramecia), and how people can exercise the dominion of Genesis 1:28 as careful keepers of the garden (Genesis 2:15). Ecology is taught as observation and measurement; conservation is told through its successes: the bison, the wood duck, the whooping crane and the bluebird, many of them paid for by hunters and anglers through the Duck Stamp and the Pittman–Robertson Act.

The labs go outdoors: a hula-hoop quadrat survey of the yard, a Berlese funnel for soil animals, nitrate and pH tests of a pond or stream, a duckweed population count and a bird count you can report to Project FeederWatch or eBird.

PREREQUISITES

- Unit 4 (photosynthesis and respiration)
- Unit 8 (the groups of living things)
- Algebra I for growth and percentage problems

MASTERY CHECKLIST

- ☐ I can describe food chains, food webs and trophic levels and use the 10% rule.
- ☐ I can trace the water, carbon and nitrogen cycles and name the living things that drive them.
- ☐ I can explain exponential and logistic growth, carrying capacity, limiting factors and Gause's competitive exclusion.
- ☐ I can explain dominion as stewardship and describe successful examples of wildlife management.

LESSONS IN THIS UNIT

9.1 **Ecosystems, Food Webs and Elton's Pyramid (1927)** — 4 sessions of 45 minutes

9.2 **Cycles of Matter: Water ("All the Rivers Run into the Sea"), Carbon and Nitrogen**

4 sessions of 45 minutes

9.3 Populations: Growth, Carrying Capacity and Gause's Experiments (1934)

4 sessions of 45 minutes

9.4 Dominion and Care: Game Management, the Bison and the Duck Stamp (1934)

4 sessions of 45 minutes

Unit 9 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 9.1**
   Why can an acre of grain feed more people than an acre of pasture used for beef?

2. **8 pts** **Lesson 9.1**
   Is a rabbit a primary or secondary consumer?

3. **8 pts** **Lesson 9.1**
   Producers in a meadow capture 10,000 kcal of energy. Using the 10% rule, about how much reaches trophic level 5?

4. **8 pts** **Lesson 9.2**
   What role do decomposers play in the nitrogen cycle?

5. **8 pts** **Lesson 9.2**
   Explain how a water molecule in the ocean could end up in a tree leaf.

6. **7 pts** **Lesson 9.3**
   Who proposed the logistic equation, and when?

7. **7 pts** **Lesson 9.3**

   In the logistic model, why is growth slow both when the population is very small and when it is near K?

8. **7 pts** **Lesson 9.3**

   A population of 100 yeast cells doubles every 3 hours with unlimited food. How many cells after 12 hours?

9. **7 pts** **Lesson 9.4**

   What is a bag limit?

10. **7 pts** **Lesson 9.4**

    How do citizen scientists help wildlife management?

LAB AND DATA

11. **10 pts**

    A student counts plants in five 1 m^2 quadrats in a meadow: 12, 9, 15, 11, 13 clover plants. The meadow is 400 m^2. (a) Find the mean per square meter. (b) Estimate the clover in the whole meadow. (c) Why use several quadrats placed at random?

SHORT ESSAY

12. **15 pts**

    Genesis 1:28 gives man dominion over the creatures, and Genesis 2:15 says God put the man in the garden “to dress it and to keep it.” Using two examples from this unit (such as the bison, the wood duck, the Duck Stamp or a farm or ranch you know), explain what wise dominion looks like in practice and how science helps people exercise it.

ANSWER KEY

1. Eating at a lower trophic level avoids the roughly 90% energy loss at each step.
2. Primary consumer (herbivore).
3. About 1 kcal

   Each step passes about 10%: 10,000 × 0.1^4 = 1 kcal
4. They break down proteins in dead things and wastes, returning ammonia to the soil.
5. Evaporation, condensation into a cloud, precipitation on land, soaking into soil, uptake by roots and rise through xylem.
6. Pierre-François Verhulst, 1838.
7. When small, few individuals reproduce; near K, the factor (K − N)/K is close to zero.
8. 1,600

   12/3 = 4 doublings; 100 × 2^4 = 1,600
9. The number of animals of a species a hunter or angler may legally take.
10. Their counts (FeederWatch, eBird, the Christmas Bird Count) track populations across large areas and many years.
11. (a) 60/5 = 12 per m^2. (b) 12 × 400 = 4,800 clover plants. (c) A single quadrat might land on an unusually thick or thin patch; random placement and several samples give a fairer average.
12. Look for: accurate quotations; dominion understood as responsible rule and care, not exploitation or neglect; two accurate examples (bison recovery from fewer than about a thousand to hundreds of thousands; wood duck recovery with hunting limits and nest boxes; the Duck Stamp funding wetlands); a clear role for measurement (counts, carrying capacity, harvest limits); balanced tone without alarm.

Printable answer key (PDF, for the parent)

UNIT 10 · OPTIONAL

The Human Body (Optional Bonus Unit)

This optional bonus unit is for students headed toward medicine, nursing, athletic training or veterinary work, or anyone who wants a closer look at the body God made. It follows four great discoveries: Vesalius dissecting the body himself and correcting fourteen centuries of textbook errors (1543), Harvey measuring the heart and proving that the blood circulates (1628), the army surgeon William Beaumont watching digestion through a hole in a fur trader's stomach (1822–1833), and Raymond Damadian imagining the MRI scanner (1970s).

The unit is not included in the midterm or final. Families can use it after the final, in a longer year, or alongside Unit 8. Labs use a chicken leg, a stethoscope or a cardboard tube, a stopwatch, crackers and a few simple reaction-time and sense tests.

PREREQUISITES

- Unit 3 (cells and tissues)
- Unit 4 (respiration)
- Unit 8 (comparative anatomy and dissection)

MASTERY CHECKLIST

- ☐ I can name the main bones and kinds of joints and describe the work of Vesalius.
- ☐ I can trace the path of blood through the heart and body and explain how Harvey proved circulation.
- ☐ I can describe mechanical and chemical digestion and Beaumont's experiments.
- ☐ I can describe neurons, reflexes and the senses, and explain the basic idea of MRI.

LESSONS IN THIS UNIT

10.1 Vesalius and the Skeleton: De Humani Corporis Fabrica (1543)

4 sessions of 45 minutes

10.2 Harvey and the Circulation of the Blood (1628): "The Life of the Flesh Is in the Blood"

10.3 Beaumont and Digestion (1822–1833) 4 sessions of 45 minutes

10.4 Nerves, Senses and Damadian's MRI (1970s) 4 sessions of 45 minutes

Unit 10 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **9 pts** **Lesson 10.1**
   Why does weight-bearing exercise strengthen bones?

2. **9 pts** **Lesson 10.1**
   Which joints in the skull move?

3. **9 pts** **Lesson 10.2**
   What do platelets do?

4. **8 pts** **Lesson 10.2**
   Why do pulmonary arteries carry oxygen-poor blood?

5. **8 pts** **Lesson 10.2**
   A resting heart beats 77 times a minute and pumps 78 mL per beat. What is the cardiac output in liters per minute?

6. **8 pts** **Lesson 10.3**
   Why are villi important?

7. **8 pts** **Lesson 10.3**
   What is peristalsis?

8. **8 pts** **Lesson 10.4**
   Why do you have a blind spot?

9. **8 pts** **Lesson 10.4**

How does the ear turn sound into nerve signals?

LAB AND DATA

10. **10 pts**

A student measures resting pulse four times: 68, 72, 70, 70 beats per minute. After 2 minutes of jumping jacks: 128 beats per minute. After 3 minutes of rest: 84. (a) Find the average resting pulse. (b) By what percent did the pulse rise with exercise? (c) Why does the heart beat faster during exercise?

SHORT ESSAY

11. **15 pts**

Vesalius, Harvey and Beaumont each overturned an older idea by looking and measuring for himself. Choose two. For each, describe the old idea, what he observed or measured, and how he persuaded others. What do their stories teach about honest observation?

ANSWER KEY

1. Bone is living tissue that rebuilds itself thicker where it is stressed.
2. None of the sutures move in adults; only the jaw moves.
3. Help blood clot.
4. They carry blood from the heart to the lungs, before it picks up oxygen; arteries are defined by direction, not oxygen.
5. 6.01 L/min

   77 × 78 = 6006 mL/min = 6.01 L/min
6. They hugely increase the surface area for absorbing nutrients into the blood.
7. Waves of muscle contraction that push food through the digestive tract.
8. Where the optic nerve leaves the retina there are no rods or cones.
9. The eardrum and three small bones vibrate; the cochlea's fluid and hair cells turn the vibrations into nerve signals.
10. (a) 70 beats per minute. (b) (128 − 70)/70 = 0.83, an 83% rise. (c) Working muscles need more oxygen and glucose and must get rid of more carbon dioxide; a faster heart pumps more blood per minute.
11. Look for: Vesalius (Galen's anatomy, partly based on animals; Vesalius dissected human bodies himself and showed errors such as the rete mirabile and the jawbone; the *Fabrica*'s drawings persuaded); Harvey (Galen's idea that blood is made in the liver and consumed; Harvey's calculation of blood pumped per hour, valves in veins, ligature experiments); Beaumont (digestion as grinding or rotting; his experiments with gastric juice in and out of the stomach); a thoughtful conclusion about observation, measurement and humility.

Printable answer key (PDF, for the parent)

10.1 Vesalius and the Skeleton: De Humani Corporis Fabrica (1543)

OBJECTIVES

- Describe the functions of the skeleton and the structure of bone.
- Name major bones and classify joints.
- Explain how Vesalius corrected Galen by dissecting and drawing the human body himself.

> **Warm-up.** Make a fist and then open your hand slowly. How many places did your fingers bend? Now feel your elbow, wrist and shoulder as you move them. Which ones can turn in a circle and which only bend one way?

WATCH

Skeletal System

Amoeba Sisters · 9:05

https://www.youtube.com/watch?v=m26gr04HIVE

> **WHEN TO WATCH**
> After the Vesalius story.

BACKUP VIDEO

All about the Skeleton System

MooMooMath and Science · 4:07

https://www.youtube.com/watch?v=hSo6of15PBA

With the bones and joints review.

KEY TERMS

skeleton

The framework of bones that supports the body, protects organs, allows movement, stores minerals and makes blood cells.

compact and spongy bone

Compact bone is the dense outer layer; spongy bone is the lighter, honeycombed inner bone that often holds red marrow.

bone marrow

Soft tissue inside bones: red marrow makes blood cells; yellow marrow stores fat.

joint

A place where two bones meet: hinge (knee), ball-and-socket (hip), pivot (neck), gliding (wrist) and fixed (skull).

ligament and tendon

Ligaments join bone to bone; tendons join muscle to bone.

cartilage

Smooth, flexible tissue that cushions joints and forms the nose, ears and the ends of growing bones.

CORE IDEAS

The story. For fourteen hundred years medical students learned anatomy from the books of Galen, a Greek physician of the second century who had dissected apes, pigs and dogs because human dissection was forbidden in Rome. Professors read Galen aloud from a high chair while a barber-surgeon cut. In Padua, Andreas Vesalius, a young Flemish professor, did the dissections himself and found that Galen was often wrong about humans: the human jawbone is one bone, not two; the breastbone has three parts, not seven; there is no network of vessels at the base of the human brain as there is in cattle. In 1543, at age 28, he published *De Humani Corporis Fabrica* (On the Fabric of the Human Body), seven books with more than two hundred woodcuts, among the most beautiful science books ever made.

How they figured it out. Vesalius trusted what he saw over what he had read. He boiled and reassembled skeletons, compared them with animal skeletons to find where Galen's descriptions came from, and hired artists trained in the workshop of Titian to draw exactly what he showed them, so readers could check his claims for themselves. Older professors attacked him, but the drawings could not be argued away, and within a generation anatomy was taught from the body.

The biology. The adult skeleton has 206 bones (a newborn has about 300 that later fuse). It supports the body, protects the brain, heart and lungs, works with muscles to move, stores calcium and phosphorus, and makes about two million red blood cells every second in its red marrow. Bone is living tissue: hard compact bone outside, spongy bone inside, blood vessels and nerves throughout, and cells that constantly remove and rebuild it. Joints are classified by movement: hinge (elbow, knee), ball-and-socket (shoulder, hip), pivot (the top of the neck), gliding (wrist and

ankle bones) and fixed (the skull's sutures). Ligaments hold joints together; cartilage cushions them.

Where it is used. Orthopedic surgeons set fractures, replace worn-out hips and knees and repair torn ligaments. Physical therapists and athletic trainers rebuild strength around injured joints. Weight-bearing exercise and enough calcium and vitamin D keep bones strong and prevent osteoporosis. Forensic scientists can tell age, sex and height from a skeleton.

Try it. In the lab you will dissect a chicken leg and wing to find bone, cartilage, tendons, ligaments and muscle, and soak a bone in vinegar to see what minerals do.

> **Safety first.** Raw chicken can carry Salmonella: wear gloves, keep it on one cutting board, wash the board, scissors and your hands with hot soapy water and wipe the counter afterward.

LAB

Chicken Wing and Leg Dissection and the Rubber Bone

You will find the parts of a real joint and see how minerals make bone hard.

You will need

- A raw chicken wing and a drumstick-thigh from the grocery, a cutting board, kitchen scissors, gloves, paper towels
- A cooked and cleaned chicken leg bone, a jar of vinegar

Steps

1. Put the cooked, cleaned bone in a jar of vinegar for 3–5 days, changing the vinegar once.
2. With gloves, peel the skin from the raw wing. Find the muscles and pull on each to see which way it moves the wing.
3. Follow a muscle to its shiny white tendon and the tendon to the bone. Bend the joint and find the ligaments holding it together.
4. Cut through the joint and find the smooth cartilage on the bone ends. Sketch and label.
5. After several days, remove the vinegar bone, rinse it and try to bend it.

Check your work

- ☐ What attaches muscle to bone? Bone to bone?
- ☐ What did the cartilage feel like, and why is that useful?
- ☐ Why did the vinegar bone become rubbery?

LAB NOTEBOOK

1. Labeled sketches of the wing joint with muscles, tendons, ligaments and cartilage.
2. Before-and-after notes on the vinegar bone.

> **From history.** The *Fabrica* appeared in 1543, the same year Copernicus published his book on the motion of the earth. Vesalius became physician to the Emperor Charles V and then to King Philip II of Spain, and died in 1564 on the way home from a pilgrimage to Jerusalem.

WORKED EXAMPLES

Example 1. A newborn has about 300 bones and an adult 206. How many bones fuse or join during growth?

▼ **Show solution**

1. 300 − 206

Answer: About 94

Example 2. Femur length is about 26% of a person's height. Estimate the height of a person whose femur is 47 cm.

▼ **Show solution**

1. Height ≈ 47/0.26

Answer: About 181 cm (5 ft 11 in)

PRACTICE

1. Easy How many bones are in the adult skeleton?

   ▼ **Show answer**

   206.

2. Easy Name four jobs of the skeleton.

   ▼ **Show answer**

   Support, protection, movement, mineral storage and making blood cells.

3. Easy What does a tendon connect? A ligament?

   ▼ **Show answer**

   Tendon: muscle to bone. Ligament: bone to bone.

COMMON MISTAKES

- Thinking bone is dead; it is living tissue with blood vessels and cells.
- Mixing up ligaments (bone to bone) and tendons (muscle to bone).
- Thinking Vesalius rejected all of Galen; he corrected him where human bodies showed otherwise.

Make it a game · Simon Says Bones. The leader calls "Simon says touch your femur (patella, clavicle, sternum, scapula, tibia, radius, mandible)." Players who touch the wrong bone sit down. Speed up as you go.

Scripture. "So I prophesied as I was commanded: and as I prophesied, there was a noise, and behold a shaking, and the bones came together, bone to his bone." (Ezekiel 37:7, KJV)

In Ezekiel's vision the bones came together, bone to his bone. The skeleton is a framework of joints, every bone fitted to its neighbor.

10.2 Harvey and the Circulation of the Blood (1628): "The Life of the Flesh Is in the Blood"

OBJECTIVES

- Trace the path of blood through the four chambers of the heart, the lungs and the body.
- Explain how Harvey proved that blood circulates, using calculation, valves and ligature experiments.
- Calculate cardiac output and describe blood, blood vessels and blood pressure.

> **Warm-up.** Find your pulse in your wrist or neck and count it for 15 seconds. Multiply by 4. If your heart pumps about 70 mL with each beat, how much blood does it pump in a minute? In an hour?

WATCH

Circulatory System and Pathway of Blood Through the Heart

Amoeba Sisters · 8:14

https://www.youtube.com/watch?v=_vZ0lefPg_0

> **WHEN TO WATCH**
> After the path of blood through the heart.

BACKUP VIDEO

A-Level Biology - Blood - Red & White Blood Cells | Platelets | Plasma

Cognito · 4:54

https://www.youtube.com/watch?v=wW1NiCQvkDg

With the parts of the blood.

KEY TERMS

atrium and ventricle

The heart's upper receiving chambers (atria) and lower pumping chambers (ventricles).

artery, vein and capillary

Arteries carry blood away from the heart; veins carry it back; capillaries are the tiny vessels between, where exchange happens.

valve

A flap that lets blood flow only one way, in the heart and in the veins.

pulmonary and systemic circulation

The loop through the lungs (pulmonary) and the loop through the rest of the body (systemic).

cardiac output

The volume of blood the heart pumps per minute: heart rate × stroke volume.

red and white blood cells, platelets

Red cells carry oxygen with hemoglobin; white cells fight infection; platelets help blood clot.

CORE IDEAS

The story. Galen taught that blood was made continually in the liver from food, flowed out to the body and was used up there, and that some blood seeped through invisible pores in the wall between the heart's two sides. William Harvey, an English physician trained at Padua and later physician to King James I and King Charles I, spent years dissecting dozens of kinds of animals and watching their hearts beat. In 1628 he published a small book, *De Motu Cordis* (On the Motion of the Heart and Blood), which argued that the same blood goes round and round, pumped out through the arteries and returning through the veins.

How they figured it out. Harvey's strongest argument was arithmetic. He estimated that the heart's left ventricle sends out as much as two ounces with each beat and beats more than a thousand times in half an hour, so in one hour it pumps hundreds of pounds of blood, several times a man's weight. The liver could not possibly make that much from food; the blood must circulate. He showed that the valves in the veins (described by his teacher Fabricius, who thought they only kept blood from pooling in the limbs) let it flow only toward the heart, and with a tight band around the arm he made the arteries swell above it and the veins below it. He could not see how blood got from arteries to veins; in 1661 Marcello Malpighi saw the capillaries in a frog's lung with a microscope.

The biology. Blood from the body returns through the veins to the right atrium, passes to the right ventricle, and is pumped through the pulmonary arteries to the lungs, where it picks up oxygen and gives off carbon dioxide. It returns to the left atrium, passes to the left ventricle, the thickest and strongest chamber, and is pumped out through the aorta to the whole body. Valves keep it moving one way; the

“lub-dub” of the heartbeat is the sound of valves closing. An adult has about 5 liters of blood: plasma, red blood cells, white blood cells and platelets. Cardiac output is heart rate times stroke volume, about 5 liters per minute at rest.

Where it is used. Nurses and doctors take pulse and blood pressure in nearly every visit; a reading such as 120/80 gives the pressure when the ventricles contract and when they relax. Blood transfusions depend on blood typing (Lesson 5.3). Paramedics use CPR to push blood through the circulation by hand when the heart stops. Regular exercise strengthens the heart so it pumps more per beat and beats more slowly at rest.

Try it. In the lab you will listen to the heart with a stethoscope or a cardboard tube, measure your pulse at rest and after exercise, and calculate cardiac output.

> **Safety first.** Anyone with a heart condition, asthma or an injury should skip the exercise step or check with a doctor first. Stop if you feel dizzy.

LAB

Heart Sounds, Pulse and Exercise

You will listen to the heart and measure how exercise changes the pulse and cardiac output.

You will need

- A stethoscope (about $10) or a cardboard paper-towel tube
- A stopwatch or phone timer, a partner, graph paper

Steps

1. Listen to a partner's chest just left of the breastbone with the stethoscope or tube. Describe the lub-dub.
2. Count the resting pulse at the wrist for 30 seconds and double it. Repeat three times and average.
3. Do jumping jacks for 2 minutes. Count the pulse immediately, then every minute for 5 minutes as it recovers.
4. Graph pulse against time. Calculate cardiac output at rest and after exercise assuming 70 mL per beat at rest and 100 mL per beat after exercise.

Check your work

- ☐ How much did the pulse rise, and how fast did it recover?
- ☐ Why does a fit person's pulse recover faster?
- ☐ What makes the lub and the dub?

LAB NOTEBOOK

1. Pulse data table and recovery graph.
2. Cardiac output calculations and a labeled diagram of blood flow through the heart.

KEY FORMULAS

$$\text{cardiac output} = \text{heart rate} \times \text{stroke volume}$$

From history. Harvey dedicated *De Motu Cordis* to King Charles I and compared the heart to the king of the body. During the English Civil War his London rooms were ransacked and years of notes on the development of animals were lost. He gave a library and later his family estate to the College of Physicians.

WORKED EXAMPLES

Example 1. A resting heart beats 72 times a minute and pumps 70 mL per beat. Find the cardiac output in liters per minute, and in liters per day.

▼ **Show solution**

1. 72 × 70 = 5,040 mL/min = 5.04 L/min
2. 5.04 × 60 × 24 = 7,258 L/day

Answer: About 5.0 L/min, over 7,000 liters a day

Example 2. Make an estimate in Harvey's style: 2 ounces per beat, 72 beats per minute. How many pounds of blood per hour? (16 oz = 1 lb)

▼ **Show solution**

1. 2 × 72 × 60 = 8,640 oz
2. 8,640/16 = 540 lb

Answer: About 540 pounds an hour, several times a person's weight

PRACTICE

1. Easy Name the four chambers of the heart.

   ▼ **Show answer**

   Right atrium, right ventricle, left atrium, left ventricle.

2. Easy Which vessels carry blood away from the heart?

   ▼ **Show answer**

   Arteries.

3. Medium A resting heart beats 86 times a minute and pumps 67 mL per beat. What is the cardiac output in liters per minute?

   ▼ **Show answer**

   5.76 L/min

4. **Medium** A resting heart beats 90 times a minute and pumps 90 mL per beat. What is the cardiac output in liters per minute?

   ▼ **Show answer**

   8.10 L/min

5. **Medium** A resting heart beats 69 times a minute and pumps 83 mL per beat. What is the cardiac output in liters per minute?

   ▼ **Show answer**

   5.73 L/min

COMMON MISTAKES

- Saying arteries always carry oxygen-rich blood; the pulmonary arteries carry oxygen-poor blood to the lungs. Arteries carry blood away from the heart.
- Mixing up the right and left sides of a heart diagram, which is drawn as if facing you.
- Thinking blood in veins is blue; it is dark red.

> **Make it a game · Blood Cell Relay.** Set up stations around the house: right atrium, right ventricle, lungs, left atrium, left ventricle, body. The "red blood cell" carries a red card (oxygen) from the lungs to the body and a blue card (carbon dioxide) from the body to the lungs, naming each station and valve as it passes.

> **Scripture.** "For the life of the flesh is in the blood: and I have given it to you upon the altar to make an atonement for your souls: for it is the blood that maketh an atonement for the soul." (Leviticus 17:11, KJV)
>
> For the life of the flesh is in the blood. Moses wrote it long before Harvey showed how blood carries life to every part of the body.

10.3 Beaumont and Digestion (1822–1833)

OBJECTIVES

- Describe the organs of the digestive system and the path of food.
- Distinguish mechanical and chemical digestion and name key enzymes.
- Explain Beaumont's experiments on Alexis St. Martin and what they showed about gastric juice.

> **Warm-up.** Chew a plain saltine cracker slowly for two full minutes without swallowing. How does the taste change? What do you think is happening?

WATCH

Digestive System

Amoeba Sisters · 8:43

https://www.youtube.com/watch?v=1UvuBYUbFk0

> **WHEN TO WATCH**
> After the path of food.

BACKUP VIDEO

Path of Food Through the Digestive System

MooMooMath and Science · 3:19

https://www.youtube.com/watch?v=vqblT6haSKM

With the review of the digestive organs.

KEY TERMS

mechanical digestion

Breaking food into smaller pieces by chewing and by the churning of the stomach.

chemical digestion

Breaking food molecules into smaller molecules with enzymes and acid.

gastric juice

The stomach's digestive fluid of hydrochloric acid and the enzyme pepsin.

small intestine

The long, coiled tube where most digestion and absorption take place, through millions of villi.

liver and pancreas

The liver makes bile to break up fats; the pancreas makes enzymes and bicarbonate for the small intestine.

villi

Tiny fingerlike projections lining the small intestine that absorb nutrients into the blood.

CORE IDEAS

The story. On June 6, 1822, at the trading post on Mackinac Island in Michigan, a musket went off by accident and blew a hole in the side of a young French-Canadian voyageur, Alexis St. Martin. The army surgeon William Beaumont treated him and, to everyone's surprise, St. Martin survived, but the wound healed with an opening into his stomach, a fistula, covered by a flap of tissue. Beaumont realized he could look directly into a living human stomach. Over the next eleven years, on and off, he performed some 238 experiments, and in 1833 published *Experiments and Observations on the Gastric Juice and the Physiology of Digestion*.

How they figured it out. Some physicians thought the stomach digested food by grinding, others by fermenting or rotting it. Beaumont tied bits of meat, bread and vegetables to silk strings, lowered them into St. Martin's stomach, and pulled them out at intervals to see how fast each digested. He drew out gastric juice and showed that it digested meat in a vial kept at body temperature, outside the body, though more slowly: digestion was chemical. He found that the stomach makes juice only when food arrives, that anger and fear slowed digestion, and that the juice contained hydrochloric acid, as William Prout had found in 1824. In 1836 Theodor Schwann isolated pepsin, the stomach's protein-digesting enzyme.

The biology. Digestion begins in the mouth: teeth chew (mechanical digestion) and saliva's amylase starts breaking starch into sugar (chemical digestion), which is why a cracker tastes sweeter as you chew. The esophagus pushes food to the stomach by waves of muscle (peristalsis). The stomach churns food with acid and pepsin for protein. In the small intestine, bile from the liver breaks fat into droplets and pancreatic enzymes finish digesting starch, protein and fat; millions of villi absorb sugars, amino acids and fats into the blood. The large intestine absorbs water and houses helpful bacteria (Lesson 8.1).

Where it is used. Dietitians plan meals for diabetes, food allergies and athletes using this knowledge. Doctors treat ulcers, reflux and gallstones, and use endoscopes, cameras on flexible tubes, to see inside the stomach as Beaumont did through his

patient's wound. Food scientists design foods for infants and the elderly that are easy to digest.

Try it. In the lab you will test the action of saliva on starch, model the stomach in a zip bag, and repeat a version of Beaumont's timed digestion with pineapple or meat tenderizer enzymes.

> **Safety first.** Iodine tincture is poisonous if swallowed and stains skin and clothing; an adult handles it and the cups are not for eating. Each person tastes only his own cracker.

LAB

Saliva, Starch and a Stomach in a Bag

You will see chemical digestion of starch and protein and model mechanical digestion.

You will need

- Saltine crackers, iodine tincture (it stains; adult), small cups, a dropper
- A zip bag, a slice of bread, a little vinegar or lemon juice (stomach acid model)
- Unflavored gelatin made in two cups, fresh pineapple (or meat tenderizer powder with papain) and canned pineapple

Steps

1. Crush half a cracker in a cup with a spoon of water; chew the other half for one minute and spit it into a second cup. Add a drop of iodine to each: dark blue-black means starch. Compare.
2. Put bread and a little vinegar in the zip bag, seal it and squeeze for 2 minutes: the stomach churning food with acid.
3. Lay fresh pineapple on one gelatin cup and canned pineapple on the other. Check every 30 minutes for 2 hours, as Beaumont checked his strings.
4. Record which gelatin liquefied, and when.

Check your work

- ☐ Which cracker sample had less starch? Why?
- ☐ Why did the fresh pineapple digest the gelatin and the canned one did not?
- ☐ How was your timing experiment like Beaumont's?

LAB NOTEBOOK

1. Results table for each test with times.
2. A labeled diagram of the digestive system tracing a bite of food.

> **From history.** Alexis St. Martin married, raised a family and outlived Beaumont (who died in 1853) by more than a quarter of a century, dying in Quebec in 1880. Beaumont is often called the father of gastric physiology.

WORKED EXAMPLES

Example 1. The small intestine is about 6 m long and food moves through it in about 4 hours. What is the average speed in cm per minute?

▼ **Show solution**

1. 600 cm / 240 min

Answer: 2.5 cm per minute

Example 2. Villi and microvilli increase the small intestine's surface area to about 30 m^2, roughly the floor of a small room. If a tube of the same length were smooth, with an inner surface of 0.5 m^2, by what factor do the folds increase the area?

▼ **Show solution**

1. 30 / 0.5

Answer: About 60 times

PRACTICE

1. Easy Name the organs food passes through, in order.

   ▼ **Show answer**

   Mouth, esophagus, stomach, small intestine, large intestine.

2. Easy What happened to Alexis St. Martin in 1822?

   ▼ **Show answer**

   A musket wound left an opening into his stomach.

3. Medium What did Beaumont show by digesting meat in a vial of gastric juice?

   ▼ **Show answer**

   Digestion is chemical; it can occur outside the body.

COMMON MISTAKES

- Thinking most digestion happens in the stomach; most digestion and nearly all absorption happen in the small intestine.
- Forgetting that digestion starts in the mouth.
- Thinking enzymes are used up; they are catalysts and can act again (Lesson 2.3).

Make it a game · Digestive Tour Guide. The student is a tour guide on a bus that starts as a bite of a sandwich. Narrate the trip from mouth to large intestine, naming each organ, what happens there and which enzyme or juice is at work. The parent rings a bell for each mistake.

Scripture. “Whether therefore ye eat, or drink, or whatsoever ye do, do all to the glory of God.” (1 Corinthians 10:31, KJV)

Whether therefore ye eat, or drink, or whatsoever ye do, do all to the glory of God. Even digestion is part of the daily life Paul says to offer to God.

10.4 Nerves, Senses and Damadian's MRI (1970s)

OBJECTIVES

- Describe neurons, synapses, the brain and spinal cord, and reflex arcs.
- Explain how the eye, ear and other senses gather information.
- Explain the basic idea of magnetic resonance imaging and Raymond Damadian's role in it.

> **Warm-up.** Have a partner drop a ruler between your open thumb and finger without warning, and catch it as fast as you can. Note the centimeter mark. Try five times. Did you improve?

WATCH

Nervous System

Amoeba Sisters · 11:32

https://www.youtube.com/watch?v=RNLceVI8jcc

> **WHEN TO WATCH**
> After neurons and reflexes.

Note: Runs about 11½ minutes.

BACKUP VIDEO

GCSE Biology - The Nervous System | Reflex Arcs Explained

Cognito · 5:08

https://www.youtube.com/watch?v=BnsZo4j1YvU

With the reflex arc.

KEY TERMS

neuron

A nerve cell that carries electrical signals: dendrites receive, the axon sends.

synapse

The tiny gap between neurons, crossed by chemical messengers called neurotransmitters.

central nervous system

The brain and spinal cord; the peripheral nervous system is all the nerves branching from them.

reflex arc

A fast, automatic pathway from a sense receptor through the spinal cord to a muscle, without waiting for the brain.

retina

The layer at the back of the eye with rod cells (dim light) and cone cells (color).

magnetic resonance imaging (MRI)

Imaging the body's soft tissues using a strong magnet and radio waves to detect hydrogen nuclei in water.

CORE IDEAS

The story. In the 1880s the Spanish physician Santiago Ramón y Cajal stained brain tissue with Camillo Golgi's silver method and drew thousands of nerve cells by hand. He showed that the nervous system is made of separate cells, neurons, not a continuous net, and shared the 1906 Nobel Prize with Golgi. In 1897 the English physiologist Charles Sherrington named the gap between neurons the synapse. A century later, in 1971, Raymond Damadian, a physician at the State University of New York in Brooklyn, reported in the journal *Science* that cancerous tissue gives a different nuclear magnetic resonance signal from healthy tissue, and proposed scanning the whole body. On July 3, 1977, his team made the first whole-body MRI scan of a human being with a machine they built themselves and named *Indomitable*, now in the Smithsonian.

How they figured it out. The body is about 60% water, and every water molecule has two hydrogen nuclei that behave like tiny magnets. In a strong magnetic field they line up; a pulse of radio waves tips them over, and as they relax back they give off a faint radio signal. Damadian found that the time to relax differs between tissues, and especially between tumors and healthy tissue. Paul Lauterbur (1973) and Peter Mansfield showed how to use changing magnetic fields to locate the signals and build a sharp image; they received the 2003 Nobel Prize. Damadian, who was not included, protested publicly, and many colleagues agreed that his work deserved recognition. He was also an outspoken Christian who believed in the creation account of Genesis.

The biology. A neuron receives signals on its dendrites and sends an electrical impulse down its axon at up to about 120 meters per second; at the synapse,

neurotransmitters carry the message to the next cell. The brain's cerebrum handles thought, speech and voluntary movement; the cerebellum balance and coordination; the brainstem breathing and heartbeat. In a reflex arc, such as jerking your hand from a hot stove, the signal goes from the skin to the spinal cord and straight back to the muscle before the brain even feels the pain. The eye focuses light with the cornea and lens onto the retina's rods and cones; the ear turns sound into vibrations of the eardrum and three tiny bones, then into nerve signals in the fluid-filled cochlea; taste, smell and touch have their own receptors.

Where it is used. MRI shows the brain, spinal cord, joints and organs in fine detail without X-rays, and tens of millions of scans are made each year. Neurologists test reflexes with a rubber hammer; eye doctors fit glasses and contact lenses; audiologists fit hearing aids and cochlear implants. Seat belts, helmets and safe diving rules protect the brain and spinal cord, which heal poorly when injured.

Try it. In the lab you will measure reaction time with a falling ruler, test reflexes, find your eye's blind spot and map the touch receptors on your skin.

> **Safety first.** Tap knees gently. Use toothpick tips lightly and never near the eyes.

LAB

Reaction Time, Reflexes and the Senses

You will measure how fast your nervous system works and test several senses.

You will need

- A 30 cm ruler, a partner, a calculator
- An index card, a marker, two toothpicks or a bent paper clip, a ruler
- A rubber hammer or the side of a hand

Steps

1. Reaction time: catch a dropped ruler five times with each hand. Convert each distance to time with $t = \sqrt{2d/g}$ and average.
2. Knee-jerk reflex: sit with legs dangling; a partner taps just below the kneecap. Observe. Try while you clench your hands together.
3. Blind spot: draw an X and a dot 8 cm apart on a card. Close your left eye, stare at the X with your right eye, and move the card toward you until the dot disappears.
4. Two-point touch: with eyes closed, have a partner touch your fingertip, palm, forearm and back with one or two points at different spacings. Record the smallest spacing at which you feel two points.

Check your work

- ☐ Which hand was faster? Did practice help?
- ☐ Why does the knee jerk happen without your deciding?
- ☐ Why do you have a blind spot, and why don’t you notice it every day?
- ☐ Where are touch receptors closest together, and why?

LAB NOTEBOOK

1. Reaction-time data and calculations.
2. Results and explanations for each sense test.

KEY FORMULAS

$$d = \tfrac{1}{2} g t^2 \;\Rightarrow\; t = \sqrt{\frac{2d}{g}} \qquad g = 9.8\ \text{m/s}^2$$

From history. Damadian's first attempt in 1977 failed because his colleague Lawrence Minkoff fit inside the magnet but Damadian himself was too large; Minkoff volunteered and sat for nearly five hours for the first scan. Cajal, the son of a country doctor, wanted as a boy to be an artist, and his drawings of neurons are still reprinted in textbooks.

WORKED EXAMPLES

Example 1. A ruler falls 0.18 m before you catch it. What is your reaction time?

▼ **Show solution**

1. $t = \sqrt{2d/g} = \sqrt{2(0.18)/9.8}$
2. $= \sqrt{0.0367}$

Answer: About 0.19 s

Example 2. A nerve impulse travels 100 m/s. How long does it take to go 1.5 m from a toe to the brain?

▼ **Show solution**

1. $t = 1.5/100$

Answer: 0.015 s, 15 milliseconds

PRACTICE

1. Easy What are the two parts of the central nervous system?

   ▼ **Show answer**

   The brain and spinal cord.

2. Easy What is a synapse?

   ▼ **Show answer**

   The gap between neurons, crossed by neurotransmitters.

3. **Medium** What did Cajal show about the nervous system?

▼ **Show answer**

It is made of separate cells, neurons, not a continuous net.

COMMON MISTAKES

- Thinking reflexes go through the brain first; the spinal cord handles the reflex.
- Saying MRI uses X-rays; it uses a magnet and radio waves.
- Thinking the eye sees an image directly; the brain builds the picture from nerve signals.

Make it a game · Reflex or Choice?. The parent names an action (blinking at a puff of air, catching a ball, sneezing, writing your name, pulling a hand from a hot pan, knee jerk, choosing a cookie). The student says reflex or voluntary and whether the brain or spinal cord controls it.

Scripture. “The hearing ear, and the seeing eye, the LORD hath made even both of them.” (Proverbs 20:12, KJV)

The hearing ear, and the seeing eye, the LORD hath made even both of them.

UNIT 10 · OPTIONAL

The Human Body (Optional Bonus Unit)

This optional bonus unit is for students headed toward medicine, nursing, athletic training or veterinary work, or anyone who wants a closer look at the body God made. It follows four great discoveries: Vesalius dissecting the body himself and correcting fourteen centuries of textbook errors (1543), Harvey measuring the heart and proving that the blood circulates (1628), the army surgeon William Beaumont watching digestion through a hole in a fur trader's stomach (1822–1833), and Raymond Damadian imagining the MRI scanner (1970s).

The unit is not included in the midterm or final. Families can use it after the final, in a longer year, or alongside Unit 8. Labs use a chicken leg, a stethoscope or a cardboard tube, a stopwatch, crackers and a few simple reaction-time and sense tests.

PREREQUISITES

- Unit 3 (cells and tissues)
- Unit 4 (respiration)
- Unit 8 (comparative anatomy and dissection)

MASTERY CHECKLIST

- ☐ I can name the main bones and kinds of joints and describe the work of Vesalius.
- ☐ I can trace the path of blood through the heart and body and explain how Harvey proved circulation.
- ☐ I can describe mechanical and chemical digestion and Beaumont's experiments.
- ☐ I can describe neurons, reflexes and the senses, and explain the basic idea of MRI.

LESSONS IN THIS UNIT

10.1 Vesalius and the Skeleton: De Humani Corporis Fabrica (1543)

4 sessions of 45 minutes

10.2 Harvey and the Circulation of the Blood (1628): "The Life of the Flesh Is in the Blood"

4 sessions of 45 minutes

10.3 Beaumont and Digestion (1822–1833)	4 sessions of 45 minutes
10.4 Nerves, Senses and Damadian's MRI (1970s)	4 sessions of 45 minutes

Unit 10 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **9 pts** **Lesson 10.1**
   Why does weight-bearing exercise strengthen bones?

2. **9 pts** **Lesson 10.1**
   Which joints in the skull move?

3. **9 pts** **Lesson 10.2**
   What do platelets do?

4. **8 pts** **Lesson 10.2**
   Why do pulmonary arteries carry oxygen-poor blood?

5. **8 pts** **Lesson 10.2**
   A resting heart beats 77 times a minute and pumps 78 mL per beat. What is the cardiac output in liters per minute?

6. **8 pts** **Lesson 10.3**
   Why are villi important?

7. **8 pts** **Lesson 10.3**
   What is peristalsis?

8. **8 pts** **Lesson 10.4**
   Why do you have a blind spot?

9. **8 pts** **Lesson 10.4**

How does the ear turn sound into nerve signals?

LAB AND DATA

10. **10 pts**

A student measures resting pulse four times: 68, 72, 70, 70 beats per minute. After 2 minutes of jumping jacks: 128 beats per minute. After 3 minutes of rest: 84. (a) Find the average resting pulse. (b) By what percent did the pulse rise with exercise? (c) Why does the heart beat faster during exercise?

SHORT ESSAY

11. **15 pts**

Vesalius, Harvey and Beaumont each overturned an older idea by looking and measuring for himself. Choose two. For each, describe the old idea, what he observed or measured, and how he persuaded others. What do their stories teach about honest observation?

ANSWER KEY

1. Bone is living tissue that rebuilds itself thicker where it is stressed.
2. None of the sutures move in adults; only the jaw moves.
3. Help blood clot.
4. They carry blood from the heart to the lungs, before it picks up oxygen; arteries are defined by direction, not oxygen.
5. 6.01 L/min

   77 × 78 = 6006 mL/min = 6.01 L/min
6. They hugely increase the surface area for absorbing nutrients into the blood.
7. Waves of muscle contraction that push food through the digestive tract.
8. Where the optic nerve leaves the retina there are no rods or cones.
9. The eardrum and three small bones vibrate; the cochlea's fluid and hair cells turn the vibrations into nerve signals.
10. (a) 70 beats per minute. (b) (128 − 70)/70 = 0.83, an 83% rise. (c) Working muscles need more oxygen and glucose and must get rid of more carbon dioxide; a faster heart pumps more blood per minute.
11. Look for: Vesalius (Galen's anatomy, partly based on animals; Vesalius dissected human bodies himself and showed errors such as the rete mirabile and the jawbone; the *Fabrica*'s drawings persuaded); Harvey (Galen's idea that blood is made in the liver and consumed; Harvey's calculation of blood pumped per hour, valves in veins, ligature experiments); Beaumont (digestion as grinding or rotting; his experiments with gastric juice in and out of the stomach); a thoughtful conclusion about observation, measurement and humility.

Printable answer key (PDF, for the parent)

COURSE EXAM

Midterm Exam

Covers Units 1–5. Time: 100 minutes.

You have 100 minutes. No notes or books. Answer in complete sentences where asked, show the work for any calculation, and label diagrams clearly. The exam has 5 problems worth a total of 100 points.

---

1. **23 pts** **Lesson 1.3**

   At 40× total (4× objective) the field of view is 4.5 mm across. At 400× (40× objective), what is the field diameter? If 10 cells fit across it end to end, how long is one cell in micrometers?

2. **23 pts** **Lesson 3.3**

   A potato core weighed 3.11 g before soaking and 2.88 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

3. **22 pts** **Lesson 5.2**

   In Mendel's peas, round (R) is dominant to wrinkled (r) and yellow (Y) to green (y). Crossing RrYy × RrYy, what fraction of offspring are expected to be wrinkled green?

4. **22 pts** **Lesson 5.3**

   In snapdragons, red (RR) × white (WW) gives pink (RW) by incomplete dominance. What colors appear, and in what ratio, when two pink plants are crossed?

ESSAY

5. **10 pts**

   Choose one scientist from Units 1–5 (Redi, Pasteur, Hooke, Leeuwenhoek, Linnaeus, Virchow, Krebs or Mendel). Describe his key experiment or observation, what it changed in biology, and how later scientists built on it.

ANSWER KEY

1. 0.45 mm; about 45 µm per cell
2. -7.4%; hypertonic (water moved out)
3. 1/16
4. 1 red : 2 pink : 1 white
5. Look for: accurate dates and details; the experiment described in the student's own words, including its controls where relevant (Redi's covered jars, Pasteur's swan-neck flasks, Mendel's counted crosses); a clear statement of what changed; one connection to later work; correct vocabulary.

Printable answer key (PDF, for the parent)

COURSE EXAM

Final Exam

Covers Units 1–9. Time: 100 minutes.

You have 100 minutes. No notes or books. Answer in complete sentences where asked, show the work for any calculation, and label diagrams clearly. The exam has 9 problems worth a total of 100 points.

---

1. **12 pts** **Lesson 1.3**

   At 40× total (4× objective) the field of view is 5.0 mm across. At 100× (10× objective), what is the field diameter? If 5 cells fit across it end to end, how long is one cell in micrometers?

2. **12 pts** **Lesson 3.3**

   A potato core weighed 5.25 g before soaking and 5.38 g after 24 hours in a salt solution. Find the percent change in mass and say whether the solution was hypotonic or hypertonic to the potato cells.

3. **11 pts** **Lesson 5.2**

   In Mendel's peas, round (R) is dominant to wrinkled (r) and yellow (Y) to green (y). Crossing RrYy × RrYy, what fraction of offspring are expected to be round green?

4. **11 pts** **Lesson 5.3**

   A parent with blood genotype $I^B i$ has children with a parent of genotype ii. What blood types can the children have, and in what proportions?

5. **11 pts** **Lesson 6.2**

   A sample of double-stranded DNA is 34% adenine. Using Chargaff's rules, find the percentages of T, G and C.

6. **11 pts** **Lesson 6.3**

   A DNA template strand reads 3′-TACCTGGCTGTAATC-5′. Write the mRNA, then use the codon table to give the amino acid sequence.

7. **11 pts** **Lesson 9.1**

   Producers in a meadow capture 10,000 kcal of energy. Using the 10% rule, about how much reaches trophic level 3?

8. **11 pts** **Lesson 9.3**

   A population of 200 yeast cells doubles every 2 hours with unlimited food. How many cells after 6 hours?

ESSAY

9. **10 pts**

   Trace the discovery that living things inherit their traits through DNA, from Mendel (1866) to the genetic code (1961). Name at least four scientists and the evidence each contributed, and explain how scientists learned about structures far too small to see.

ANSWER KEY

1. 2.0 mm; about 400 µm per cell
2. +2.5%; hypotonic (water moved in)
3. 3/16
4. type B: 2/4, type O: 2/4
5. T 34%, G 16%, C 16%
6. mRNA 5′-AUGGACCGACAUUAG-3′; protein Met–Asp–Arg–His (then stop)
7. About 100 kcal
8. 1,600
9. Look for: Mendel (factors and ratios), Morgan (genes on chromosomes), Griffith and Avery (DNA as the transforming principle), Hershey and Chase, Chargaff, Franklin, Watson and Crick, Nirenberg; the point that careful, repeatable experiments build a reliable picture of the invisible; clear organization.

Printable answer key (PDF, for the parent)