



SCHOLAR COACH

Boutique Academic Coaching & Tutoring

AP BIOLOGY · COURSE REVIEW AND PRACTICE

AP Biology Mastery.

Every unit on the exam: concise concept review, worked examples, exam-style writing, practice problems with full explanations, a mixed practice test, and a reference section.

INSIDE

Words in Context · Inferences · Command of Evidence · Central Ideas and Details · Function of a Sentence · Algebra · Advanced Math · Problem-Solving and Data Analysis · Geometry and Trigonometry · Three Full-Length Practice Exams with Explanations



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Course review, practice, and a mixed test.

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Start Here: The Exam, Your Plan, and Your Tools

How the AP Biology exam is built, how points are earned, and how to use this book.

F Start Here: The Exam, Your Plan, and Your Tools

How AP Biology is structured and scored, what each free-response type rewards, how to plan your weeks, and the math tools you will use.

Why This Matters

Knowing the shape of the exam before you study saves weeks. This chapter explains how AP Biology is built and scored, which units carry the most weight, what each free-response type rewards, how to pace your study, and the math you must handle.

The 2027 Exam

The exam is on **Monday, May 3, 2027 (Session 2)**. Hybrid digital. Section I: 60 multiple-choice questions, 90 minutes, 50%. Section II: 6 free-response questions, 90 minutes, 50% (2 long questions worth 9 points each and 4 short questions worth 4 points each). Calculator permitted; reference information provided. Next, the unit map, with multiple-choice weightings (they do not apply to free-response points):

Unit	Topic	Weighting
1	Chemistry of Life	8-11%
2	Cells	10-13%
3	Cellular Energetics	12-16%
4	Cell Communication and Cell Cycle	10-15%
5	Heredity	8-11%
6	Gene Expression and Regulation	12-16%
7	Natural Selection	13-20%
8	Ecology	10-15%

Format at a glance

Section I: 60 multiple choice, 90 minutes, 50%. Section II: 6 free response, 90 minutes, 50%. Long questions: 2 at 9 points. Short questions: 4 at 4 points. Total 34 free-response points.

Every unit is built around four big ideas: evolution, energetics, information storage and transmission, and systems interactions. Questions often combine units, for example a data set about an enzyme that also asks about a mutation. Expect about a quarter of your course time in hands-on investigations, and expect the exam to ask about experimental design even when you did not run that exact lab.

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Six Science Practices

Practice	What it looks like	MC share
Concept Explanation	Define, describe and explain processes	25-33%
Visual Representations	Read or draw models, diagrams, cycles	16-24%
Questions and Methods	Identify variables, controls, and designs	8-14%
Representing and Describing Data	Build graphs, describe trends	8-14%
Statistical Tests and Data Analysis	Mean, error bars, chi-square, calculations	8-14%
Argumentation	Claim, evidence, reasoning, predictions	20-26%

How Free-Response Points Are Earned

Slot	Type	What earns points
1	Long: interpret and evaluate experimental results	Name variables; describe trends with direction and magnitude; justify controls specifically; link to mechanism
2	Long: results with graphing	Labeled axes, sensible scale, accurate plotting, error bars
3	Short: scientific investigation	Precise terms: control, null hypothesis; reasoned claims
4	Short: conceptual analysis	Correct evolutionary terms; cause before effect
5	Short: model or visual	Read symbols accurately, then predict downstream effects
6	Short: data analysis	Use the specified data set; use error bars; link genotype, protein, phenotype

Readers repeatedly see the same losses: a control defined as "same conditions" instead of the group lacking the independent variable, a null hypothesis that predicts a direction, data restated without reasoning, and a pathway disruption predicted without tracing the steps. Write claim, evidence, then reasoning, using the task verb (identify, describe, explain, justify, predict, calculate).

Study Plans

Week	4-week plan	8-week plan
1	Units 1, 2, 3	Start Here and Unit 1
2	Units 4, 5, 6	Unit 2
3	Units 7, 8	Unit 3
4	Full practice test and FRQ review	Unit 4
5		Unit 5
6		Unit 6
7		Unit 7
8		Unit 8, full practice test, FRQ review

Pacing and Test-Day Habits

- ◆ Multiple choice: 60 questions in 90 minutes is about 90 seconds each. Mark long set questions and return after the quick ones.
- ◆ Free response: 6 questions in 90 minutes. Spend about 20 minutes on each long question and 8 to 10 on each short one, and read all parts first.
- ◆ Use the task verb: identify is a name, describe is what happens, explain is why, justify is evidence plus reasoning.
- ◆ On graphs, label axes with units, choose an even scale, plot every point, draw bars or lines as the data type requires, and include error bars when given.

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How to Use This Book

- ◆ Read Why This Matters and Core Ideas, then try each Worked Example before reading the solution.
- ◆ Do the practice items in order; read every explanation, even for correct answers.
- ◆ Study the Write It Like a 5 model, then write your own version from memory.
- ◆ Use Common traps and Quick Check as a last review.

Key Math

Formulas you should be able to set up

Hardy-Weinberg: $p + q = 1$ and $p^2 + 2pq + q^2 = 1$; the frequency of the recessive phenotype is q^2 .

Rate: $\text{rate} = \Delta \text{quantity} / \Delta \text{time}$; read the slope of a graph over a stated interval.

Water potential: $\Psi = \Psi_P + \Psi_S$, with $\Psi_S = -iCRT$; water moves from higher to lower Ψ .

Chi-square: $\chi^2 = \sum \frac{(o-e)^2}{e}$, with $df = \text{categories} - 1$; reject the null if χ^2 exceeds the critical value at $p = 0.05$ (3.84 for 1 df, 5.99 for 2, 7.81 for 3, 9.49 for 4).

Standard error: $SE = s / \sqrt{n}$; error bars of 2 SE approximate a 95% confidence interval.

In your own words: Hardy-Weinberg splits a gene pool into allele frequencies (p and q) and genotype frequencies, and it holds only with no selection, mutation, migration, drift or nonrandom mating. A rate is simply how much something changed divided by how long it took. Water potential tells you which way water will flow. Chi-square measures how far observed counts stray from expected counts, relative to the expected size. The standard error shrinks as sample size grows, so error bars show how well a mean is estimated, not how spread out individuals are.

Always write the equation, substitute with units, and interpret the result in words. Error bars that overlap widely suggest no real difference; non-overlapping bars suggest one, but this is a rule of thumb, so say "suggests."

Practice

PRACTICE Start Here Check

Show your work. A calculator is allowed.

- In a population at Hardy-Weinberg equilibrium, 16% of individuals show a recessive trait. What is the frequency of heterozygotes?
(A) 0.24 (B) 0.48 (C) 0.40 (D) 0.16
- A chi-square test compares observed and expected counts across four phenotype categories. How many degrees of freedom are used?
(A) 4 (B) 2 (C) 3 (D) 1
- A cross is expected to give a 3:1 ratio. Among 120 offspring, 100 are purple and 20 are white.
(a) State a null hypothesis.
(b) Calculate chi-square.
(c) Using the critical value 3.84, state your conclusion.
- A treated group has mean 12.0, standard deviation 6.0, and $n = 9$. The control mean is 22.0 with $SE = 2.0$.
(a) Calculate the standard error of the treated group.
(b) Give the approximate 95% interval for each group.
(c) State what the intervals suggest.

Answers and Explanations

F Start Here: The Exam, Your Plan, and Your Tools

PRACTICE · START HERE CHECK

- B. $q^2 = 0.16$, so $q = 0.4$ and $p = 0.6$. Heterozygotes $= 2pq = 2(0.6)(0.4) = 0.48$. Choice C is just q .
- C. $df = 4 - 1 = 3$. Choice A forgets to subtract 1.
- (a) The observed counts do not differ from a 3:1 ratio except by chance.
(b) Expected: 90 purple, 30 white. $\chi^2 = (100 - 90)^2/90 + (20 - 30)^2/30 = 1.11 + 3.33 = 4.44$.
(c) 4.44 exceeds 3.84 (1 df, $p = 0.05$), so reject the null; the data do not fit a 3:1 ratio.

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4. (a) $SE = 6.0/\sqrt{9} = 2.0$.
(b) Treated: $12 \pm 4 = 8$ to 16. Control: $22 \pm 4 = 18$ to 26.
(c) The intervals do not overlap, which suggests a real difference between the groups.

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Unit 1: Chemistry of Life

Exam weighting: about 8-11% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

1 Chemistry of Life

Water, the elements of life, and the four classes of biological macromolecules: the structures and bonds that explain how living systems work.

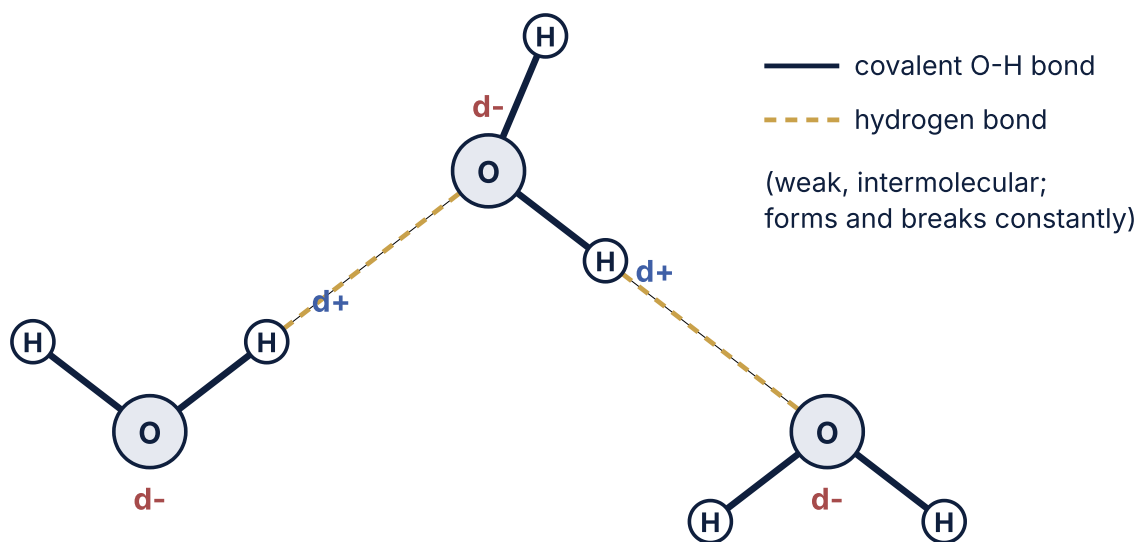
Why This Matters

Unit 1 carries the lightest weighting on the exam (8-11% of multiple choice), but nearly every later unit leans on it. Membrane transport needs water and lipids, enzymes are proteins, and gene expression depends on nucleic acids. Students lose points here by mixing up bond types, calling water a "universal solvent," and naming a property without linking it to polarity.

Core Ideas

1.1 Structure of Water and Hydrogen Bonding

A water molecule is polar: oxygen pulls shared electrons harder than hydrogen does, so oxygen is slightly negative and each hydrogen slightly positive. The positive hydrogen of one molecule is attracted to the negative oxygen of another, forming a **hydrogen bond**.



Three water molecules. Oxygen carries a partial negative charge (d^-) and hydrogen a partial positive charge (d^+). Each dashed hydrogen bond joins an H of one molecule to the O of a neighbor.

Hydrogen bond versus covalent bond

Covalent O-H bonds inside a molecule are strong and do not break when water melts, freezes, or boils.

Hydrogen bonds are weak attractions between molecules. In liquid water they constantly break and re-form; in ice they hold a fixed open lattice.

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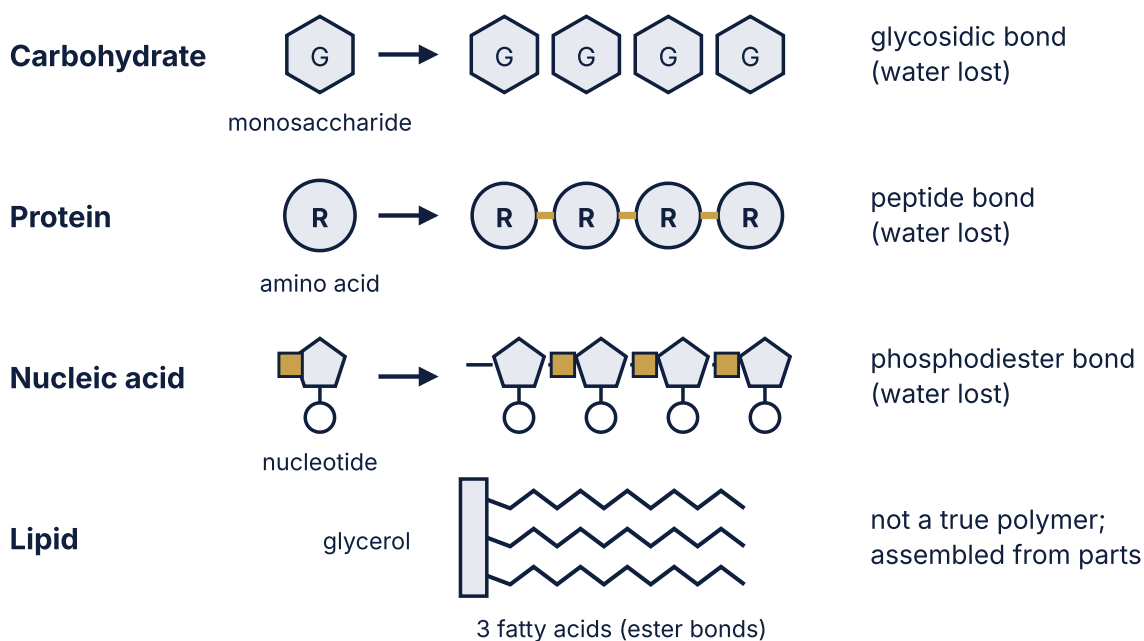
Property	Cause	Biological example
Cohesion	H bonds between water molecules	Water columns rise in plant xylem
Adhesion	H bonds to polar surfaces	Water climbs the walls of narrow vessels
Surface tension	Cohesion at the surface	Insects walk on ponds
High specific heat	Heat must first break H bonds	Oceans and cells resist temperature swings
High heat of vaporization	Breaking H bonds to enter the gas phase	Sweating cools the body
Ice floats	Lattice holds molecules farther apart	Ponds freeze from the top down

Water dissolves **polar and ionic** substances well (sugars, salts, amino acids) because it surrounds charges. It does not dissolve nonpolar substances such as oils; avoid the phrase "universal solvent." Remember that NaCl is an ionic lattice, not a molecule. Free H⁺ in water is shorthand for hydronium, and pH = -log[H⁺], so each pH unit is a tenfold change.

1.2 Elements of Life

Living matter is built mostly from **C, H, O, N, P, and S**. Carbon forms four covalent bonds and long chains, which makes it the backbone of organic molecules. Carbohydrates contain C, H, O; lipids mostly C, H, O (phospholipids add P); proteins C, H, O, N and often S; nucleic acids C, H, O, N, P. Trace elements such as iron or magnesium serve specific roles in proteins and pigments.

1.3 Introduction to Macromolecules



Monomers and the bonds that join them. G = glucose unit, R = variable side chain. In the nucleotide, the gold square is phosphate, the pentagon is sugar, and the small circle is the base.

Building and breaking polymers

Dehydration synthesis joins monomers and releases one water per bond; it requires energy input.

Hydrolysis adds one water to break a bond. A chain of n monomers has $n - 1$ bonds.

1.4 Carbohydrates

Monosaccharides (glucose, fructose) join by glycosidic bonds into disaccharides and polysaccharides. **Starch** (plant storage) and **glycogen** (animal storage) use alpha linkages and can be digested by common enzymes. **Cellulose** uses beta linkages, giving straight, hydrogen-bonded fibers in plant cell walls that most animals cannot digest. Chitin forms fungal walls and arthropod exoskeletons. Same monomer, different linkage, different function.

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1.5 Lipids

Lipids are nonpolar and hydrophobic, defined by solubility rather than by a repeating monomer. A **triglyceride** is glycerol plus three fatty acids joined by ester bonds and stores energy. **Saturated** fatty acids have no C=C double bonds and pack tightly (often solid at room temperature); **unsaturated** ones have kinks from double bonds and stay liquid. A **phospholipid** has a polar phosphate head and two nonpolar tails, so it is amphipathic and forms bilayers. Steroids, such as cholesterol, have four fused rings.

1.6 Nucleic Acids

A nucleotide has a phosphate, a pentose sugar, and a nitrogenous base. Nucleotides join by **phosphodiester bonds** between the sugar of one and the phosphate of the next, giving a chain with 5' and 3' ends. DNA has deoxyribose and bases A, T, G, C; RNA has ribose and uses uracil in place of thymine. The two strands of DNA are **antiparallel** and pair A-T (two hydrogen bonds) and G-C (three). Purines (A, G) have two rings; pyrimidines (C, T, U) have one.

1.7 Proteins

Twenty amino acids share an amino group, a carboxyl group, and a central carbon, and differ in the **R group** (nonpolar, polar, charged). They join by peptide bonds to make a polypeptide with an N-terminus and a C-terminus.

Level	What defines it	Held by
Primary	Amino acid sequence	Peptide bonds
Secondary	Alpha helices, beta sheets	H bonds between backbone atoms
Tertiary	3-D fold of one chain	R-group interactions: hydrophobic, ionic, H bonds, disulfide bridges
Quaternary	Several chains together	Same R-group interactions

Structure determines function

Sequence sets the folding; folding sets the shape; shape sets function. **Denaturation** (heat, extreme pH, salt) breaks the weak interactions of secondary through quaternary structure but leaves the primary sequence intact. Changing one amino acid can alter folding and function.

Worked Examples

EXAMPLE 1: PH AS A LOGARITHM

Gastric fluid has $[H^+] = 0.010$ M. Find its pH and compare its acidity with a solution at pH 5.

SOLUTION

$$\text{pH} = -\log(0.010) = 2.$$

The difference is $5 - 2 = 3$ pH units, and each unit is a factor of 10, so gastric fluid has $10^3 = 1000$ times the H^+ concentration of the pH 5 solution.

EXAMPLE 2: COUNTING WATER

A protein has 120 amino acids. How many water molecules are released when it forms, and how many are needed to hydrolyze it fully?

SOLUTION

Bonds in a linear chain: $120 - 1 = 119$ peptide bonds.

One water is released per bond, so 119 are released by dehydration synthesis and 119 are consumed by complete hydrolysis.

EXAMPLE 3: SPECIFIC HEAT

An energy input of 4000 J goes into 200 g of water ($c = 4.18$ J/g per degree C) and, separately, 200 g of oil ($c = 2.0$). Find each temperature rise and explain the difference.

SOLUTION

$$\Delta T = q/(mc). \text{ Water: } 4000/(200 \times 4.18) = 4.8 \text{ degrees C. Oil: } 4000/(200 \times 2.0) = 10 \text{ degrees C.}$$

Water warms less because added energy first disrupts hydrogen bonds instead of only speeding molecules. This buffers organisms and environments against temperature change.

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EXAMPLE 4: BASE PAIRING

A double-stranded DNA fragment of 1000 base pairs is 22% guanine. Find the percent of each base and the number of hydrogen bonds.

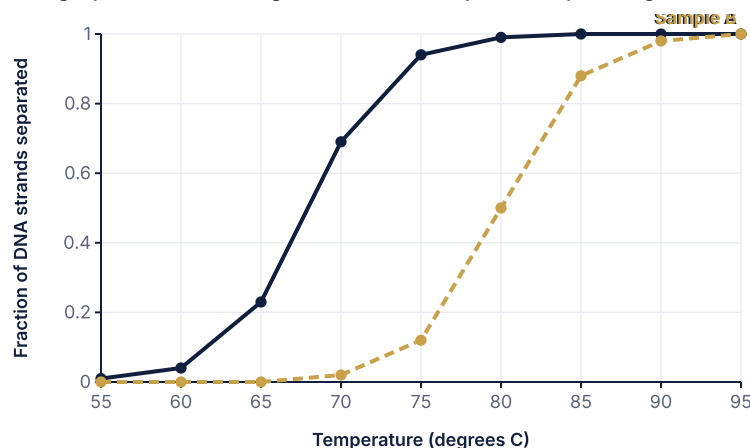
SOLUTION

$G = 22\%$ so $C = 22\%$ (G pairs with C). $A + T = 100 - 44 = 56\%$, so $A = T = 28\%$.

The fragment has 2000 bases: 440 G-C pairs and 560 A-T pairs. Hydrogen bonds: $440 \times 3 + 560 \times 2 = 2440$.

EXAMPLE 5: READING A MELTING CURVE

The graph shows heating of two DNA samples of equal length. Which sample has more G-C pairs? Justify.



Heating curves for two DNA samples of equal length.

SOLUTION

Sample B separates at a higher temperature (about 80 degrees C versus 68 degrees C).

G-C pairs have three hydrogen bonds and A-T pairs have two, so more energy is needed to separate strands rich in G-C. Sample B therefore has the higher G-C content.

Write It Like a 5**Model Response**

Prompt: A mutation replaces a polar amino acid inside the folded core of an enzyme with a nonpolar one, with no change elsewhere. Predict the effect on primary and tertiary structure and justify. The primary structure changes by one amino acid, because the sequence has changed. The R groups of the core normally interact with each other by hydrogen bonds or ionic bonds, and the new nonpolar R group cannot form those interactions, so the tertiary structure is likely to change. A changed fold alters the shape of the active site, so substrate may bind poorly and the enzyme may have reduced activity. Because sequence determines folding and folding determines shape, a single substitution can alter function.

What the grader looks for

(1) Identifies a change in primary structure. (2) Links the change to loss of specific R-group interactions. (3) Connects altered tertiary structure to altered shape or active site. (4) States a consequence in terms of function. Restating "the protein changes" without naming the level or interaction earns nothing.

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Coach's Playbook

- ◆ Always name the bond: covalent inside a molecule, hydrogen bond between molecules.
- ◆ For any "explain why" about water, write polarity, then hydrogen bonds, then the property.
- ◆ For macromolecules ask: what is the monomer, what bond joins it, what is released?
- ◆ For proteins, say which level of structure changed, then shape, then function.

Common traps

1) Saying boiling water breaks covalent bonds in H₂O; it breaks hydrogen bonds. 2) Calling water a "universal solvent" or saying it dissolves oils. 3) Saying hydrogen bonds in ice never break, or that liquid water has none. 4) Saying denaturation destroys the amino acid sequence or peptide bonds.

Quick Check

Q: How many water molecules are released making a 30-monomer polymer? A: 29. Q: Which base pair has three hydrogen bonds? A: G-C. Q: What differs between starch and cellulose? A: The type of glycosidic linkage (alpha versus beta).

Challenge Corner

A tripeptide of Ser-Cys-Ala forms from three free amino acids. (a) How many peptide bonds and water molecules? (b) Two Cys residues on separate chains can form a disulfide bridge. At which level of structure does that matter? (a) Two peptide bonds, two waters released. (b) A bridge between R groups of different regions of one chain stabilizes tertiary structure; between two separate chains it stabilizes quaternary structure.

Practice

PRACTICE Unit 1 Practice

Show your work. A calculator is allowed. Justify conclusions.

- Water rises through narrow tubes in plant stems against gravity. Which pair of properties best explains this?
 - (A) High specific heat and surface tension
 - (B) Cohesion between water molecules and adhesion to the tube wall
 - (C) Ice floating and high heat of vaporization
 - (D) Nonpolar character and hydrophobic exclusion
- Which bond directly links two amino acids in a polypeptide?
 - (A) Hydrogen bond between R groups
 - (B) Glycosidic bond
 - (C) Peptide bond, a covalent bond
 - (D) Phosphodiester bond
- A student identifies the elements in four unknown biological molecules. Which molecule is most likely a nucleic acid?

Molecule	Elements detected
W	C, H, O
X	C, H, O, N, S
Y	C, H, O, N, P
Z	C, H, O

(A) W

(B) X

(C) Y

(D) Z

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4. Cellulose and starch are both polymers of glucose, yet humans digest starch but not cellulose. Which statement best explains this?
- (A) Cellulose contains a different monomer
 - (B) Cellulose has beta glycosidic linkages that human enzymes cannot break
 - (C) Starch is hydrophobic and cellulose is hydrophilic
 - (D) Cellulose lacks hydrogen bonds
5. A solution changes from pH 7 to pH 5. How does the H^+ concentration change?
- (A) It doubles
 - (B) It increases 100-fold
 - (C) It decreases 100-fold
 - (D) It increases 2 units
6. Compared with a saturated fatty acid, an unsaturated fatty acid is most likely to
- (A) be a straight chain that packs tightly and is solid at room temperature
 - (B) contain one or more $C=C$ double bonds that kink the chain, keeping it liquid at room temperature
 - (C) contain more hydrogen atoms per carbon
 - (D) lack a carboxyl group
7. A student wants to compare how quickly 100 mL of water and 100 mL of vegetable oil heat on a hot plate.
- (a) Identify the independent and dependent variables.
 - (b) Give two variables to hold constant.
 - (c) Predict the result and justify using hydrogen bonding.
8. A double-stranded DNA fragment of 500 base pairs is 18% adenine.
- (a) Calculate the percent of T, G, and C.
 - (b) Calculate the total number of hydrogen bonds in the fragment.
9. Fictional solubility in water at 25 degrees C: substance 1 is glucose (polar, many -OH groups), 90 g per 100 mL; substance 2 is table salt (ionic), 36 g per 100 mL; substance 3 is a hexane-like oil (nonpolar), less than 0.01 g per 100 mL.
- (a) Describe the relationship between polarity and solubility shown.
 - (b) Explain why substance 3 dissolves poorly using molecular structure.
 - (c) Explain why dissolving glucose does not break its covalent bonds.
10. An enzyme loses activity after being heated to 90 degrees C for 10 minutes, although its amino acid sequence is unchanged.
- (a) Explain what happened to the protein.
 - (b) Identify which levels of structure were disrupted and which was not.
 - (c) Explain why activity was lost.

Answers Unit 1: Answers and Explanations

Read every explanation, including the ones for problems you answered correctly.

1 Chemistry of Life

PRACTICE · UNIT 1 PRACTICE

1. B. Cohesion holds water molecules together in a column and adhesion attaches them to the polar wall. Choice A (specific heat) concerns temperature buffering, the tempting wrong choice.
2. C. A peptide bond is a covalent bond between the carboxyl carbon of one amino acid and the amino nitrogen of the next. Hydrogen bonds between R groups stabilize folding but do not link the chain.
3. C. Nucleic acids contain phosphorus and nitrogen. Molecule X has N and S, typical of a protein, but no P. W and Z lack N.
4. B. The beta linkages of cellulose are not recognized by human digestive enzymes, while alpha linkages in starch are. Choice A fails because both are glucose polymers.
5. B. pH is logarithmic; a drop of two units means $10^2 = 100$ times more H^+ . Choice A treats the scale as linear.
6. B. Double bonds put kinks in the hydrocarbon tail, preventing tight packing, so unsaturated fats tend to be liquid. Choice C is backward: unsaturated chains have fewer hydrogens.
7. (a) Independent: type of liquid. Dependent: temperature rise (or time to reach a set temperature).
(b) Any two: same volume or mass, same starting temperature, same hot plate setting, same container.
(c) Water warms more slowly. Heating must first disrupt the many hydrogen bonds between water molecules, so a given energy input raises water's temperature less than oil, which lacks hydrogen bonding.
8. (a) $A = T = 18\%$. $G + C = 64\%$, so $G = C = 32\%$.
(b) 1000 bases: $A = T = 180$ each, so 180 A-T pairs; G-C pairs = 320. Hydrogen bonds: $180 \times 2 + 320 \times 3 = 360 + 960 = 1320$.

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9. (a) Polar and ionic substances dissolve readily in water; the nonpolar substance barely dissolves.
(b) Substance 3 is nonpolar and cannot form hydrogen bonds or ion-dipole attractions with water, so water molecules bond to each other and exclude it.
(c) Dissolving separates molecules from each other by forming hydrogen bonds with water; the covalent bonds within each glucose molecule are far stronger and remain intact.
10. (a) The protein denatured: heat broke the weak interactions (hydrogen bonds, ionic and hydrophobic interactions) and the chain unfolded.
(b) Secondary, tertiary and quaternary structure were disrupted. Primary structure (sequence, held by peptide bonds) was not.
(c) Function depends on 3-D shape; with the active site distorted, substrate cannot bind properly, so the reaction is not catalyzed.

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Unit 2: Cells

Exam weighting: about 10-13% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

2 Cells

Cell structure, size limits, the fluid mosaic membrane, transport, water potential, compartmentalization, and the endosymbiotic origin of organelles.

Why This Matters

Unit 2 is worth 10-13% of multiple choice and gives the shapes and gradients that Units 3 and 4 depend on. Typical lost points: treating the membrane as a wall instead of a selective, fluid structure; mixing up tonicity (a comparison of solutions) with water potential (a property of each system); and saying "water moves toward where there is less water" instead of from higher to lower water potential.

Core Ideas

2.1 Cell Structure and Function

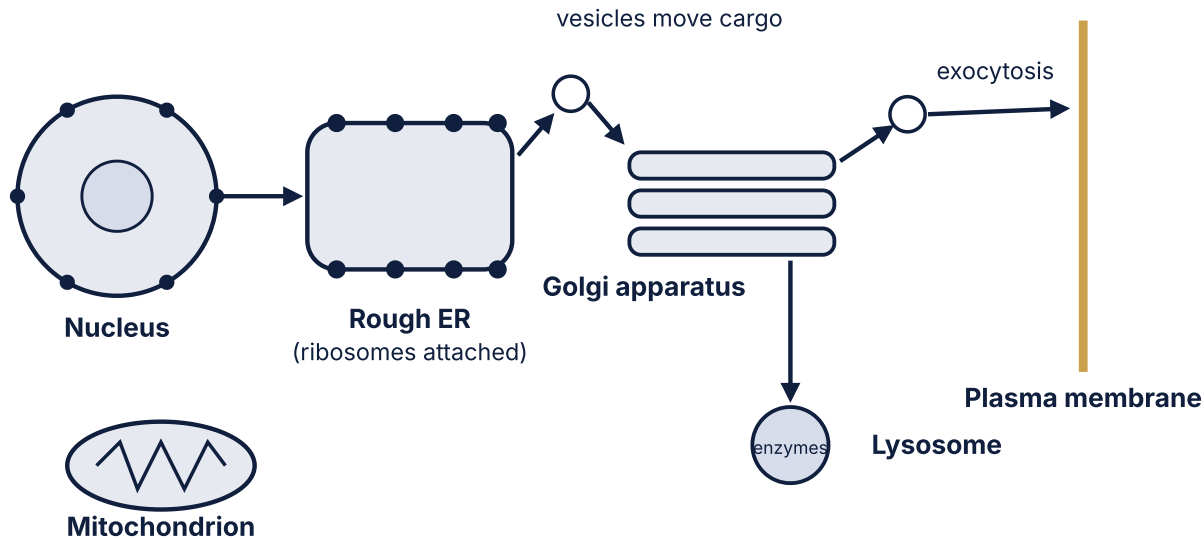
Prokaryotes (bacteria and archaea) have DNA in a nucleoid, ribosomes, and a plasma membrane, but no membrane-bound organelles. **Eukaryotes** compartmentalize functions in membrane-bound organelles.

Structure	Function
Nucleus	Stores DNA; site of transcription; nuclear pores regulate traffic
Ribosome	Translates mRNA into protein; free ribosomes make cytosolic proteins, bound ones make secreted or membrane proteins (same ribosomes)
Rough ER	Folds proteins entering the secretory pathway
Smooth ER	Lipid synthesis, detoxification, calcium storage
Golgi	Modifies, sorts and packages proteins into vesicles
Lysosome	Hydrolytic enzymes digest macromolecules and worn organelles
Mitochondrion	Aerobic respiration; ATP production
Chloroplast	Photosynthesis (plants and algae)
Vacuole	Storage; large central vacuole maintains plant turgor
Cytoskeleton	Support, shape, vesicle and organelle movement
Cell wall	Protection and support in plants, fungi, many prokaryotes

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Endomembrane pathway. Proteins made on rough ER ribosomes move by vesicles to the Golgi, then to the membrane (exocytosis) or lysosomes. The mitochondrion has a folded inner membrane.

2.2 Cell Size

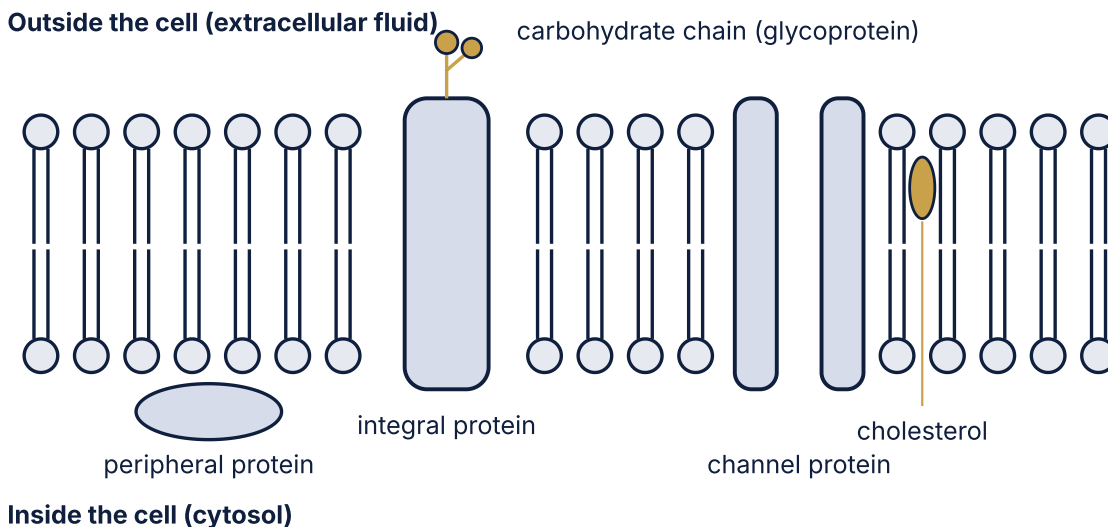
Materials enter and wastes leave through the surface, but needs scale with volume. As a cell grows, volume increases faster than surface area, so the **surface area-to-volume ratio** falls and diffusion across the cell becomes too slow. Small size, flattened shapes, and folds (microvilli) keep the ratio high.

Surface area and volume

Sphere: $SA = 4\pi r^2$, $V = \frac{4}{3}\pi r^3$, so $SA/V = 3/r$. Cube of side s : $SA = 6s^2$, $V = s^3$, $SA/V = 6/s$.

Larger cell, smaller ratio, slower exchange per unit volume.

2.3 Plasma Membrane



Fluid mosaic model. Each phospholipid is a polar head (circle) with two nonpolar tails; tails face inward. Proteins float in the bilayer, and cholesterol (gold) sits between tails.

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The **fluid mosaic model**: a phospholipid bilayer with embedded proteins that can move laterally. Phospholipids are amphipathic: polar heads face water, nonpolar tails face inward. Cholesterol moderates fluidity (it prevents tight packing in cold and restrains movement in heat). Integral proteins span the bilayer and have nonpolar regions in contact with the tails; peripheral proteins sit on the surface. Carbohydrate chains on the outer face aid cell recognition. Nonpolar regions interact with nonpolar regions; opposite polarities do not "attract" to hold proteins in the membrane.

2.4 Membrane Permeability

The bilayer's core is nonpolar, so small nonpolar molecules (O_2 , CO_2 , steroids) cross easily. Small uncharged polar molecules cross slowly (water mostly uses aquaporins), while ions and large polar molecules (glucose) need transport proteins.

2.5 Membrane Transport and 2.6 Facilitated Diffusion

Passive transport moves substances down their concentration gradient with no energy input: simple diffusion, osmosis, and **facilitated diffusion** through channel or carrier proteins. Facilitated diffusion is passive but specific and can saturate when all carriers are busy.

Active transport moves substances against their gradient, using ATP directly (primary) or the gradient of another ion (secondary, or cotransport).

Water potential

$\Psi = \Psi_P + \Psi_S$ and $\Psi_S = -iCRT$ (i = ionization constant, 1 for sucrose; C = molarity; R = 0.0831 L bar per mol K; T in kelvin).

Water moves from higher to lower Ψ . Pure water in an open container: $\Psi = 0$. Adding solute lowers Ψ_S ; pressure adds to Ψ_P .

2.7 Tonicity and Osmoregulation

Tonicity compares solute concentration of the surrounding solution to the cell. In a **hypotonic** solution an animal cell gains water and may lyse; in a **hypertonic** solution it loses water and shrinks; in an **isotonic** solution there is no net movement. A plant cell in hypotonic solution becomes turgid (pressure Ψ_P rises until net movement stops), and in hypertonic solution undergoes plasmolysis. Freshwater protists use contractile vacuoles to pump out excess water.

2.8 Mechanisms of Transport

Large particles cross via vesicles. **Exocytosis** fuses vesicles with the membrane to export contents. **Endocytosis** brings material in: phagocytosis (cell eating, a type of endocytosis), pinocytosis (fluid), and receptor-mediated endocytosis (specific ligands). The sodium-potassium pump uses ATP to move 3 Na^+ out and 2 K^+ in against their gradients, building the gradient that cotransporters use.

2.9 Cell Compartmentalization and 2.10 Origins

Internal membranes separate incompatible reactions (digestion in lysosomes), concentrate enzymes and substrates, and add surface for reactions (cristae, thylakoids). The **endosymbiotic theory** says mitochondria and chloroplasts descend from free-living prokaryotes engulfed by an ancestral cell. Evidence: double membranes, their own circular DNA, bacteria-like ribosomes, and reproduction by binary fission. The nucleus and ER likely arose through infolding of the plasma membrane.

Worked Examples

EXAMPLE 1: CELL SIZE

Compare two cube-shaped cells with sides of 2 micrometers and 6 micrometers. Which exchanges materials more efficiently per unit volume?

SOLUTION

$SA/V = 6/s$. Cell A: $6/2 = 3$ per micrometer. Cell B: $6/6 = 1$ per micrometer.

Cell A has a ratio three times larger, so diffusion supplies each unit of volume faster.

EXAMPLE 2: WATER POTENTIAL

A solution of 0.25 M sucrose in an open beaker at 22 degrees C is used to bathe a plant cell with $\Psi_S = -11.0$ bar and $\Psi_P = +2.0$ bar. Predict the direction of net water movement.

SOLUTION

Solution: $T = 295$ K, $\Psi_P = 0$, $\Psi_S = -(1)(0.25)(0.0831)(295) = -6.13$ bar, so $\Psi = -6.13$ bar.

Cell: $\Psi = -11.0 + 2.0 = -9.0$ bar.

Water moves from higher to lower Ψ : from the solution (-6.13) into the cell (-9.0).

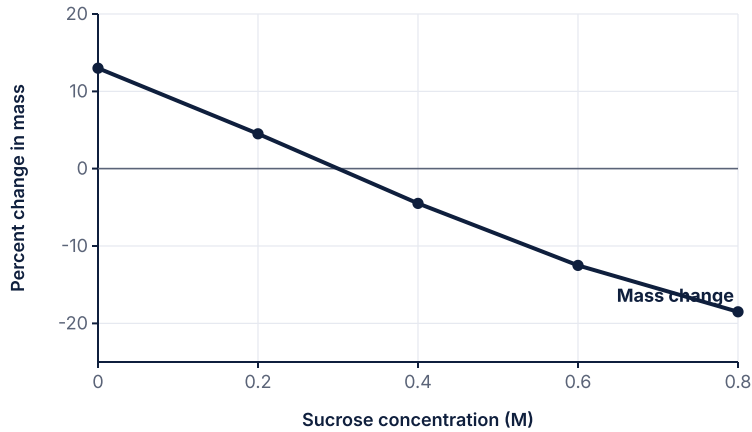
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EXAMPLE 3: POTATO CORES

Potato cores (4.00 g each) were placed in sucrose solutions. Use the graph to estimate the solute concentration of the potato tissue and its water potential at 25 degrees C.



Potato cores after 24 hours (fictional data).

SOLUTION

Percent change = $(\text{final} - \text{initial}) / \text{initial} \times 100$; e.g. $(4.52 - 4.00) / 4.00 = +13.0\%$.

The curve crosses 0 between 0.2 M (+4.5%) and 0.4 M (-4.5%), so by linear interpolation at 0.30 M. At this concentration there is no net water movement.

$\Psi_s = -(1)(0.30)(0.0831)(298) = -7.4 \text{ bar}$; the tissue has $\Psi \approx -7.4 \text{ bar}$.

EXAMPLE 4: TONICITY

An animal cell has 0.30 M nonpenetrating solutes. Predict what happens in solutions of 0.10 M, 0.30 M and 0.50 M of nonpenetrating solute.

SOLUTION

0.10 M is hypotonic to the cell: water enters, the cell swells and may lyse.

0.30 M is isotonic: no net movement; water moves in and out equally.

0.50 M is hypertonic: net water loss, the cell shrinks. If the solute were able to cross the membrane (urea), the prediction changes.

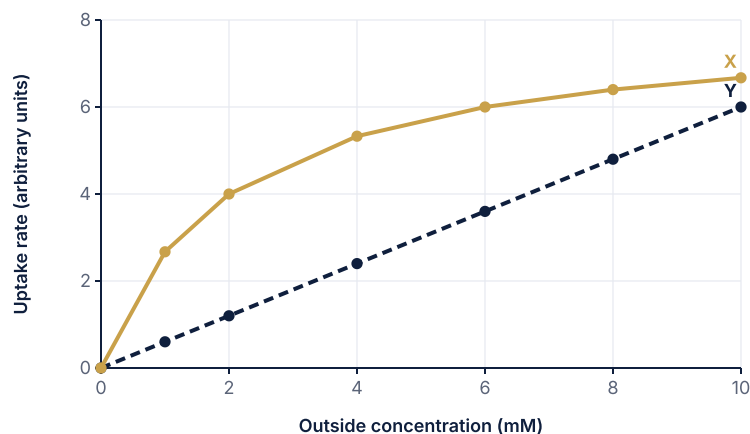
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EXAMPLE 5: READING TRANSPORT DATA

The graph shows uptake of solutes X and Y. Which uses a protein carrier? What does ATP depletion do?



Uptake of two solutes.

SOLUTION

X rises steeply and then flattens (6.4 to 6.7 units at 8 to 10 mM) while Y rises linearly. Saturation shows a limited number of carriers, so X uses facilitated diffusion (or active transport).

Y is simple diffusion because rate is proportional to concentration.

ATP depletion would not affect X if it is passive, so a test with an ATP inhibitor distinguishes facilitated diffusion from active transport.

Write It Like a 5**Model Response**

Prompt: Describe two pieces of evidence that mitochondria arose by endosymbiosis, and explain one advantage of compartmentalization. Mitochondria have their own circular DNA, like bacterial chromosomes, rather than linear DNA in the nucleus. They also have a double membrane, consistent with a prokaryote engulfed by vesicle formation, and divide by binary fission. Compartmentalization benefits eukaryotic cells because enzymes and substrates for a pathway are concentrated in one organelle; for example, lysosomes keep hydrolytic enzymes away from the cytosol, so digestion does not damage other cell components.

What the grader looks for

(1) Two specific, accurate evidence statements (DNA, ribosomes, membranes, fission). (2) A named advantage. (3) A linking explanation: why the feature supports the claim, not only that it exists.

Coach's Playbook

- ◆ For any transport question ask: which direction relative to the gradient, and is energy used?
- ◆ Draw the cell and label which solution has higher Ψ before choosing the direction of water movement.
- ◆ Write the formula before substituting; convert to kelvin; solute potential is negative.
- ◆ In permeability questions, name polarity and size.

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Common traps

1) Saying water moves toward "less water" without using water potential. 2) Treating hypertonic as a property of the cell rather than the solution. 3) Saying phagocytosis and endocytosis are the same thing. 4) Claiming facilitated diffusion needs ATP.

Quick Check

Q: What happens to SA/V when radius doubles? A: It halves. Q: Which uses ATP, facilitated diffusion or the Na⁺/K⁺ pump? A: The pump. Q: Name one piece of evidence for endosymbiosis. A: Circular DNA in mitochondria.

Challenge Corner

A plant cell has $\Psi_s = -8.0$ bar and is bathed in pure water in an open dish. At equilibrium what is Ψ_p ? Pure water: $\Psi = 0$. At equilibrium cell $\Psi = 0 = \Psi_p + (-8.0)$, so $\Psi_p = +8.0$ bar. The cell wall resists further swelling, so the cell becomes turgid.

Practice**PRACTICE Unit 2 Practice**

Show your work. A calculator is allowed. Justify conclusions.

- Which organelle modifies and packages proteins into vesicles for secretion?
 (A) Smooth ER (B) Lysosome (C) Golgi apparatus
 (D) Nucleolus
- A spherical cell doubles its radius. What happens to its surface area-to-volume ratio?
 (A) It is cut in half (B) It doubles (C) It does not change
 (D) It increases fourfold
- Which substance crosses a pure phospholipid bilayer most readily without a transport protein?
 (A) Sodium ions (B) Glucose (C) Sucrose
 (D) Oxygen gas
- A dialysis bag (impermeable to sucrose) filled with 0.5 M sucrose is placed in a beaker of 0.2 M sucrose. What is most likely to occur?
 (A) The bag loses mass as sucrose leaves (B) The bag gains mass as water enters
 (C) Nothing; the solutions are in equilibrium (D) The bag gains mass as sucrose enters
- A cell accumulates a nutrient from dilute surroundings to a higher cytoplasmic concentration, and uptake stops when ATP production is blocked. This is best described as
 (A) Simple diffusion (B) Facilitated diffusion through a channel
 (C) Active transport by a carrier protein (D) Osmosis
- Which observation best supports the claim that mitochondria originated from an engulfed prokaryote?
 (A) They contain ribosomes
 (B) They contain circular DNA similar to bacterial DNA
 (C) They have a single membrane
 (D) They are found in all cells
- Design an experiment to estimate the solute concentration of onion tissue using sucrose solutions.
 (a) Identify the independent and dependent variables.
 (b) Describe a control and explain what it shows.
 (c) Describe how you would determine the concentration and predict the result for a solution more concentrated than the tissue.
- Two spherical cells have radii of 4 and 12 micrometers.
 (a) Calculate the surface area, volume, and SA/V of each ($SA = 4\pi r^2$, $V = \frac{4}{3}\pi r^3$).
 (b) Explain which cell is more limited in exchange and how a cell could compensate.

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9. In an experiment, cells were given molecules P and Q at the same external concentration. Without treatment, uptake was 100 units for P and 100 units for Q. With a metabolic inhibitor that blocks ATP production, uptake was 8 units for P and 98 units for Q.
- (a) Identify the transport type for P and for Q and justify.
 - (b) Predict the effect of adding a protein inhibitor that blocks carriers if Q is facilitated.
 - (c) Explain why P can accumulate to a higher concentration inside than outside.
10. Explain how internal membranes and the origin of eukaryotic organelles are related.
- (a) Describe two benefits of compartmentalization.
 - (b) Describe the endosymbiotic origin of chloroplasts and give two lines of evidence.

Answers Unit 2: Answers and Explanations

Read every explanation, including the ones for problems you answered correctly.

2 Cells

PRACTICE · UNIT 2 PRACTICE

1. C. The Golgi modifies, sorts and packages proteins. Smooth ER (A) makes lipids; lysosomes (B) digest.
2. A. $SA/V = 3/r$, so doubling r halves it. Choice B confuses SA with V.
3. D. O_2 is small and nonpolar and crosses a lipid bilayer. Sodium ions, glucose and sucrose need proteins.
4. B. The bag has higher solute concentration (lower water potential), so water enters by osmosis and mass increases. Choice D fails because sucrose cannot cross the tubing.
5. C. Movement against the gradient that requires ATP is active transport. Facilitated diffusion (B) is passive.
6. B. Circular DNA like bacterial chromosomes supports bacterial origin. Ribosomes (A) are in all cells.
7. (a) Independent: sucrose concentration. Dependent: percent change in mass of tissue (or length).
(b) Control: tissue in distilled water or a replicate set, or equal initial mass for each piece; it shows changes result from the solute and not from handling.
(c) Plot percent change vs concentration and find where it is zero: no net water movement, so the solution is isotonic to the tissue. A more concentrated solution makes the tissue lose mass (hypertonic).
8. (a) Radius 4: $SA = 4\pi(16) = 201.1$ square micrometers, $V = \frac{4}{3}\pi(64) = 268.1$ cubic micrometers, $SA/V = 0.75$. Radius 12: $SA = 1809.6$, $V = 7238.2$, $SA/V = 0.25$.
(b) The larger cell has one-third the ratio, so exchange per unit volume is slower. It can flatten, elongate, or add folds such as microvilli to raise surface area.
9. (a) P is active transport: uptake fell from 100 to 8 when ATP was blocked. Q is passive (simple or facilitated diffusion) because uptake was unchanged.
(b) Uptake of Q would drop and level off because the carriers are blocked.
(c) Active transport uses ATP to move against the concentration gradient, so P can build a higher internal concentration; passive transport stops at equilibrium.
10. (a) Examples: separating incompatible reactions (lysosome enzymes); concentrating enzymes and substrates; increasing membrane surface for reactions (cristae, thylakoids).
(b) Chloroplasts descend from photosynthetic bacteria engulfed by an ancestral eukaryote. Evidence: double membrane, own circular DNA, bacteria-like ribosomes, binary fission.

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Unit 3: Cellular Energetics

Exam weighting: about 12-16% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

3 Cellular Energetics

Enzymes and their regulation, free energy and ATP, photosynthesis, and cellular respiration, with the stage-by-stage logic the exam uses to test them.

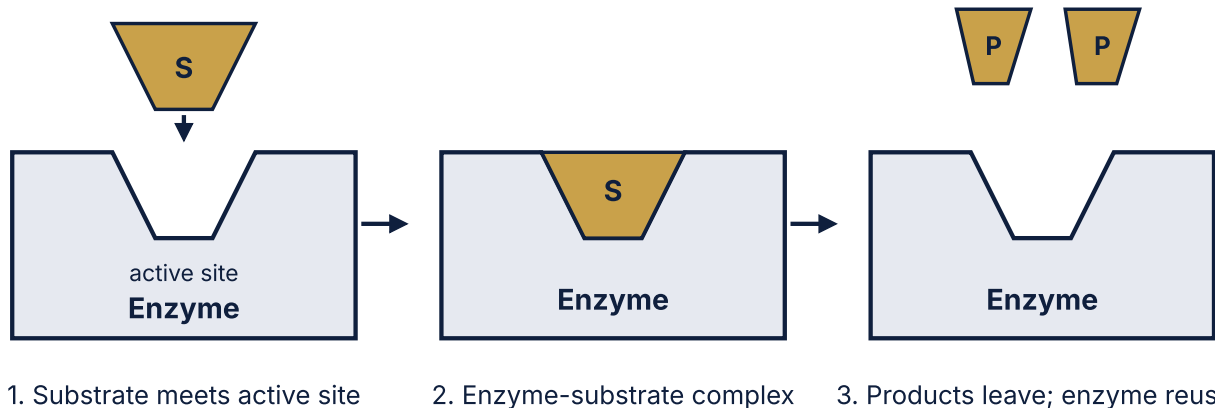
Why This Matters

Unit 3 is the heaviest of the first three, at 12-16% of multiple choice, and it is also where free-response questions ask you to read a model or pathway and predict what happens when a step is disrupted. Students lose points by mixing inhibitor types, stopping at "the enzyme denatures," and mislocating the steps of photosynthesis and respiration.

Core Ideas

3.1 Enzymes

Enzymes are biological catalysts, mostly proteins. Each has an **active site** whose shape and chemistry match its substrate. On binding, the enzyme adjusts slightly (induced fit), and the reaction proceeds with a lower **activation energy**. The enzyme is not consumed and does not change the overall ΔG or the equilibrium.



Enzyme action. The substrate binds the active site (induced fit), the reaction occurs at lower activation energy, and unchanged enzyme is released.

Enzyme essentials

Enzymes lower activation energy; they do not supply energy, change ΔG , or get used up.

Specificity comes from active-site shape and chemistry. Cofactors (metal ions) and coenzymes (vitamin-derived) help many enzymes.

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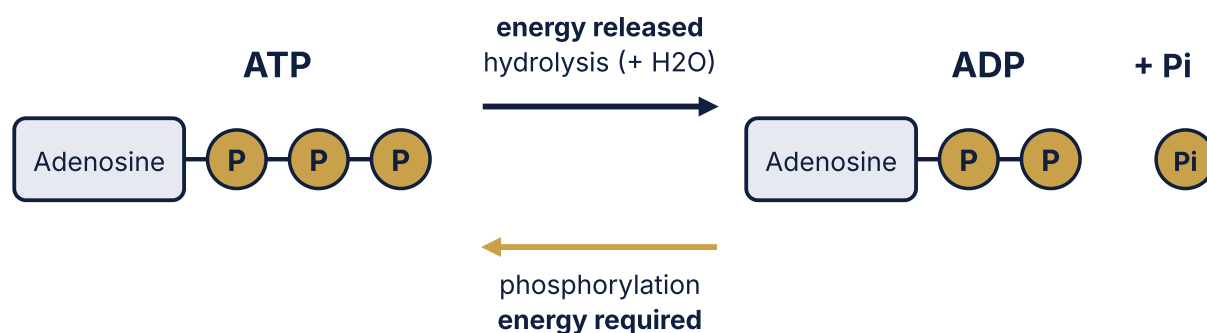
3.2 Environmental Impacts on Enzyme Function

Rate rises with temperature because collisions are more frequent and energetic, until heat breaks the weak interactions that hold the tertiary structure; the active site loses its shape and the substrate no longer fits. Each enzyme has an optimum pH because pH changes the ionization of R groups and so the fold. Rate also rises with substrate concentration until all active sites are busy (saturation).

Competitive inhibitors resemble the substrate and bind the active site; extra substrate can outcompete them. **Allosteric (noncompetitive) inhibitors** bind another site, change the enzyme's shape, and lower the maximum rate even with excess substrate. In **feedback inhibition** an end product inhibits an early enzyme, a negative feedback that prevents overproduction.

3.3 Cellular Energy

Living systems are open and need continuous energy input; energy flows from the sun through producers to consumers and is lost as heat. A reaction is **exergonic** if $\Delta G < 0$ and **endergonic** if $\Delta G > 0$. **Coupling** pairs an endergonic reaction with ATP hydrolysis so the net ΔG is negative. ATP is an energy currency regenerated from ADP and P_i , not a long-term store.



Energy from catabolism (respiration) or light drives the lower arrow;
the upper arrow powers transport, synthesis and movement.

The ATP cycle. ATP hydrolysis is exergonic and is coupled to endergonic cell work; ATP is regenerated from ADP and P_i using energy from fuel molecules or light.

Free energy

$\Delta G = \Delta H - T\Delta S$ with T in kelvin. Negative ΔG means energy is released and the reaction is favorable; it does not say how fast.

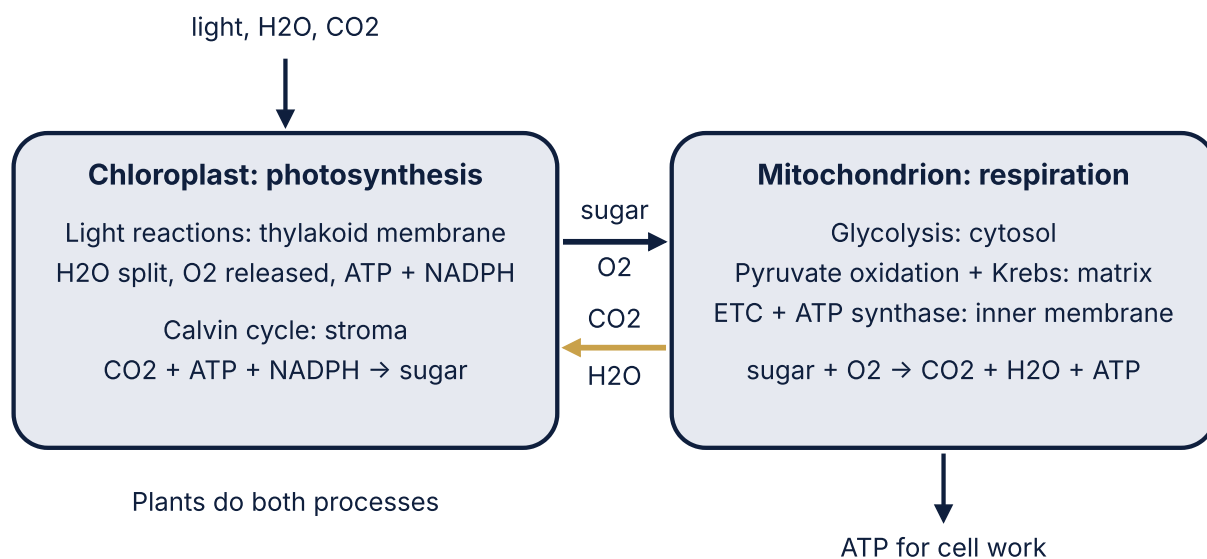
3.4 Photosynthesis

In the **light reactions** (thylakoid membranes) chlorophyll absorbs light; photosystem II splits water, releasing O_2 (the oxygen comes from water) and electrons. Electrons pass along a chain, pumping H^+ into the thylakoid lumen; H^+ flows back through ATP synthase to make ATP (chemiosmosis), and photosystem I helps reduce $NADP^+$ to NADPH. In the **Calvin cycle** (stroma), rubisco fixes CO_2 onto RuBP, ATP and NADPH reduce 3-PGA to G3P, and some G3P regenerates RuBP. Photorespiration, when rubisco binds O_2 instead, wastes energy; C4 and CAM plants separate CO_2 capture in space or time to reduce it.

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Energy capture and release. Photosynthesis stores light energy in sugar and releases O₂; respiration transfers sugar energy to ATP. The two are linked by the exchange of products and reactants.

3.5 Cellular Respiration

Stage	Location	Main outputs per glucose
Glycolysis	Cytosol	2 pyruvate, net 2 ATP, 2 NADH
Pyruvate oxidation	Mitochondrial matrix	2 acetyl CoA, 2 CO ₂ , 2 NADH
Krebs cycle	Matrix	4 CO ₂ , 2 ATP, 6 NADH, 2 FADH ₂
ETC and chemiosmosis	Inner membrane	H ₂ O; about 26-28 ATP

NADH and FADH₂ deliver electrons to the electron transport chain; O₂ is the final electron acceptor, forming water. The chain pumps H⁺ into the intermembrane space, and the gradient drives ATP synthase. Without O₂, the chain stops, NAD⁺ is not regenerated, and **fermentation** (lactic acid or alcohol) regenerates NAD⁺ so glycolysis continues with only 2 ATP per glucose.

Worked Examples

EXAMPLE 1: FREE ENERGY

A reaction has $\Delta H = +12 \text{ kJ/mol}$ and $\Delta S = +0.060 \text{ kJ/mol per K}$ at 298 K. Find ΔG . Then a different reaction with $\Delta G = +14 \text{ kJ/mol}$ is coupled to ATP hydrolysis (-30.5 kJ/mol). Find the net.

SOLUTION

$\Delta G = 12 - (298)(0.060) = 12 - 17.88 = -5.88 \text{ kJ/mol}$: favorable, driven by entropy.

Coupled: $14 + (-30.5) = -16.5 \text{ kJ/mol}$, so the pair proceeds.

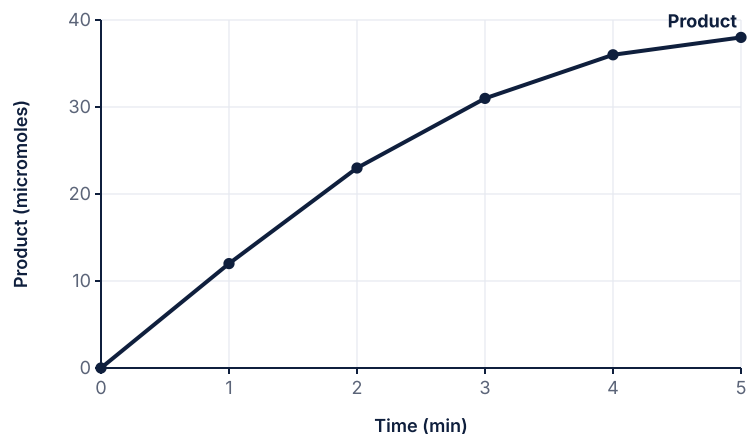
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EXAMPLE 2: REACTION RATE

Use the graph to find the initial rate over 0 to 2 minutes and explain the curve.



Product formed by an enzyme (fictional).

SOLUTION

Initial rate = $(23 - 0)/(2 - 0) = 11.5$ micromoles per minute.

The curve flattens because substrate is used up (and product may accumulate), so the rate falls; the enzyme has not been used up.

EXAMPLE 3: TEMPERATURE

Use the table to state the optimum and explain the data.

Temperature (degrees C)	10	20	30	40	50	60
Rate (micromoles per min)	2	4	7	10	3	0.2

SOLUTION

The highest rate (10) occurs at 40 degrees C, the optimum.

From 20 to 30 degrees C the rate rises by a factor of $7/4 = 1.75$ because molecules collide more often.

At 50 and 60 degrees C the rate collapses as heat disrupts hydrogen bonds and other weak interactions, changing the active-site shape; substrate can no longer bind.

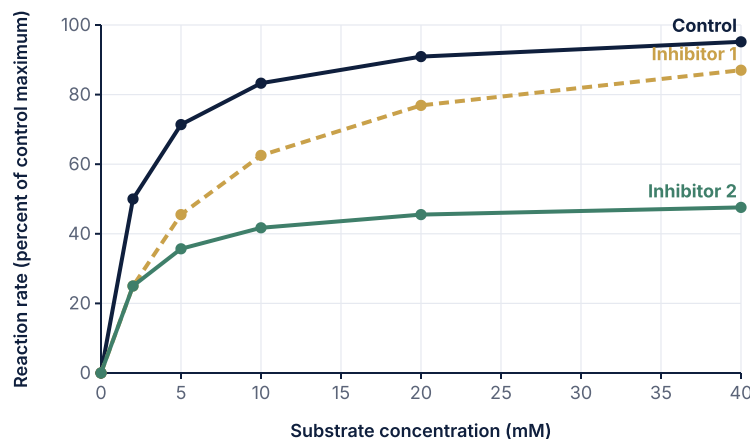
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EXAMPLE 4: INHIBITORS

The graph shows rates with two inhibitors. Identify each type and justify.



Enzyme activity with and without inhibitors (fictional).

SOLUTION

The curve for inhibitor 1 converges toward the control as substrate rises (87 versus 95 percent at 40 mM), so extra substrate overcomes it: competitive, binding the active site.

Inhibitor 2 lowers the maximum rate, and added substrate cannot fix that: noncompetitive/allosteric, binding elsewhere and reducing the number of working enzymes.

EXAMPLE 5: ATP ACCOUNTING

Estimate the ATP from one glucose using 2.5 ATP per NADH and 1.5 per FADH₂.

Stage	NADH	FADH ₂	ATP made directly
Glycolysis	2	0	2 (net)
Pyruvate oxidation	2	0	0
Krebs cycle	6	2	2
Total	10	2	4

SOLUTION

Totals: NADH = 2 + 2 + 6 = 10; FADH₂ = 2; direct ATP = 4.

Oxidative phosphorylation: $10(2.5) + 2(1.5) = 28$. Total = $28 + 4 = 32$ ATP, an upper estimate; real yields are somewhat lower.

Write It Like a 5**Model Response**

Prompt: A herbicide blocks ATP synthase in chloroplast thylakoid membranes. Predict the effect on the light reactions and Calvin cycle. If ATP synthase is blocked, protons cannot flow from the thylakoid lumen into the stroma, so the gradient builds and ATP is not made. The high gradient slows electron transport, so less NADPH forms. In the Calvin cycle, reduction of 3-PGA to G3P needs ATP and NADPH, and regenerating RuBP needs ATP, so sugar synthesis decreases. Light is still absorbed, but the energy is not captured as ATP.

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What the grader looks for

(1) States that H^+ cannot flow and ATP is not made. (2) Links to NADPH and ATP being limiting. (3) Connects to a Calvin cycle step and its outcome. Saying only "photosynthesis stops" earns no credit because it lacks the chain of cause and effect.

Coach's Playbook

- ◆ For pathway diagrams: trace each step in order, then state what blocking one step does to the products downstream.
- ◆ Name the site: active vs allosteric; lumen vs stroma; matrix vs inner membrane.
- ◆ For graphs: compare maximum rate and the substrate level at which it is reached.
- ◆ When asked about denaturation, add: shape changes, substrate cannot bind, product not formed.

Common traps

1) Mixing competitive and allosteric inhibition, or equating allosteric site with active site. 2) Stopping at "it denatures" without explaining why the product does not form. 3) Saying enzymes are used up or change the energy of reactants and products. 4) Saying O_2 in photosynthesis comes from CO_2 (it comes from water).

Quick Check

Q: Where is the proton gradient in the chloroplast? A: Higher in the thylakoid lumen. Q: What is the final electron acceptor in aerobic respiration? A: O_2 . Q: Is glycolysis aerobic? A: It does not need O_2 ; it occurs in the cytosol.

Challenge Corner

How many ATP and NADPH does the Calvin cycle need to fix 6 CO_2 into one glucose? Also account for carbon. Each CO_2 fixed takes 3 ATP and 2 NADPH, so 6 CO_2 take 18 ATP and 12 NADPH. Carbon: 6 CO_2 + 6 RuBP (30 C) gives 12 3-PGA (36 C) and 12 G3P; 2 G3P (6 C) leave as glucose and 10 (30 C) regenerate 6 RuBP.

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Practice

PRACTICE Unit 3 Practice

Show your work. A calculator is allowed. Justify conclusions.

- An enzyme speeds up a reaction by
 - raising the temperature of the reactants
 - lowering the activation energy without changing overall free-energy change
 - making the reaction more exergonic
 - supplying energy that substrates lack
- The table shows activity of an enzyme at different pH values. Which best explains the low activity at pH 12?

pH	4	6	8	10	12
Rate (percent of maximum)	10	60	100	35	2

- The substrate has been used up
 - The enzyme is competitively inhibited
 - The enzyme's R groups are fully saturated with substrate
 - Extreme pH alters ionization of R groups, changing the active site shape
- When more substrate is added, an inhibitor's effect disappears and the original maximum rate is reached. The inhibitor is most likely
 - a competitive inhibitor that binds the active site
 - an allosteric inhibitor that binds elsewhere
 - a denaturing agent
 - a coenzyme
 - During the light reactions, protons accumulate in the
 - stroma
 - intermembrane space
 - thylakoid lumen
 - cytosol
 - In aerobic respiration, most ATP per glucose is produced by
 - substrate-level phosphorylation in glycolysis
 - the Krebs cycle in the matrix
 - pyruvate oxidation
 - chemiosmosis at the inner mitochondrial membrane
 - The oxygen released during photosynthesis comes from
 - carbon dioxide
 - water
 - glucose
 - ATP
 - Design an experiment using floating leaf disks to test the effect of light intensity on photosynthetic rate.
 - Identify the independent and dependent variables.
 - Describe a control and the purpose of each control.
 - Predict the results and explain using the light reactions.
 - An enzyme reaction produced the following product (micromoles): 0 at 0 min, 8 at 1 min, 15 at 2 min, 20 at 3 min, 22 at 4 min.
 - Calculate the rate from 0 to 2 minutes and from 3 to 4 minutes.
 - Explain the change in rate.
 - Cyanide blocks the final step of the electron transport chain.
 - Calculate the maximum ATP from one glucose with the chain working, using 2.5 ATP per NADH, 1.5 per FADH₂, 10 NADH, 2 FADH₂ and 4 ATP made directly.
 - Predict and explain what happens to ATP production, NADH, and the Krebs cycle after cyanide.
 - Explain how fermentation helps.

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10. In a metabolic pathway, A is converted to B, B to C, and C to the end product D by enzymes 1, 2 and 3. D binds to enzyme 1 at a site away from the active site and inhibits it.
- Identify the type of regulation.
 - Explain how it works.
 - Predict the effect of a mutation in the binding site for D.
 - Explain one advantage to the cell.

Answers Unit 3: Answers and Explanations

Read every explanation, including the ones for problems you answered correctly.

3 Cellular Energetics

PRACTICE · UNIT 3 PRACTICE

- B. Catalysts lower activation energy and leave ΔG unchanged. Choice C is tempting but enzymes do not change the energy of reactants and products.
- D. Extreme pH changes ionization of R groups, altering interactions that maintain shape, so the active site no longer fits. Choice A is tempting but low rate at high pH is not substrate depletion.
- A. A competitive inhibitor can be outcompeted by more substrate. An allosteric inhibitor (B) would lower the maximum rate.
- C. The electron transport chain pumps H^+ into the lumen. The stroma (A) is lower in H^+ .
- D. Oxidative phosphorylation produces most ATP. Glycolysis (A) yields only a net 2.
- B. Photosystem II splits water to produce O_2 . Choice A is the common error; CO_2 carbon ends up in sugar.
- Independent: light intensity (distance of lamp). Dependent: number of disks floating or time to float.
 - Controls: disks in a dark setup, and disks in buffer without bicarbonate show the need for light and CO_2 ; same leaf and number of disks.
 - Brighter light produces more O_2 and faster floating, because more light drives more electron flow, ATP and NADPH, and O_2 from splitting water.
- 0 to 2 min: $15/2 = 7.5$ micromoles per minute. 3 to 4 min: $(22 - 20)/1 = 2$ micromoles per minute.
 - The rate falls because substrate is depleted and the reaction slows as substrate concentration decreases; the enzyme remains active.
- $10(2.5) + 2(1.5) = 28$; plus 4 direct gives 32 ATP.
 - With the chain blocked, oxidative phosphorylation stops, so ATP production falls greatly. NADH accumulates and NAD^+ is not regenerated, so pyruvate oxidation and the Krebs cycle slow down.
 - Fermentation regenerates NAD^+ so glycolysis continues, giving 2 ATP per glucose.
- Feedback (negative) inhibition by allosteric regulation.
 - D binds an allosteric site on enzyme 1, changing the shape of the active site and reducing activity, so less A is converted.
 - If D cannot bind, enzyme 1 stays active and D is overproduced.
 - It prevents waste of resources by shutting down production when enough D exists.

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Unit 4: Cell Communication and Cell Cycle

Exam weighting: about 10-15% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

4 Cell Communication and Cell Cycle

Trace signals from receptor to response, tell positive feedback from negative, and follow a cell through the cycle and its checkpoints.

Why This Matters

Unit 4 carries about 10-15% of the multiple-choice score and powers the signaling and model-analysis free-response questions. Points are lost when students name a pathway but never trace what a disruption does step by step, or when they swap positive and negative feedback. Learn to move through a model one arrow at a time.

Core Ideas

Cell Communication

Cells coordinate by sending and receiving signals. **Direct contact** uses gap junctions (animal cells) or plasmodesmata (plants) and cell-surface recognition molecules. **Local signaling** is **autocrine** (the cell responds to its own signal), **paracrine** (nearby cells), or **synaptic** (a neurotransmitter crossing a synapse). **Long-distance signaling** is **endocrine**: hormones travel in the blood. Single-celled organisms also signal: yeast mating pheromones and bacterial quorum sensing coordinate behavior once a population is dense enough.

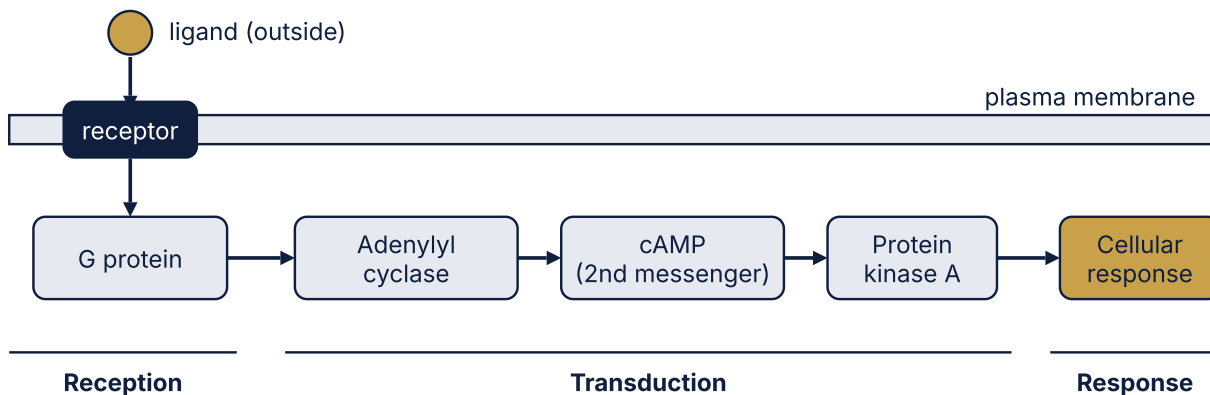
Introduction to Signal Transduction

Three Stages of a Signal

Reception: a ligand binds a specific receptor protein; the fit depends on shape and chemistry.

Transduction: the message is relayed and often amplified inside the cell.

Response: a change in enzyme activity, gene expression, cell shape, or survival (apoptosis).



A G protein-coupled pathway. Binding of the ligand to its receptor starts a chain of relays that ends in a cellular response.

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Receptors differ by location. Water-soluble ligands cannot cross the membrane, so they bind **membrane receptors** such as G protein-coupled receptors (GPCRs), receptor tyrosine kinases, and ligand-gated ion channels. Small nonpolar ligands such as steroid hormones diffuse through the membrane and bind **intracellular receptors**; the complex often acts directly as a transcription factor. Do not confuse the two vocabulary pairs: a receptor is a protein that binds a *ligand*, whereas an enzyme binds a *substrate*.

Signal Transduction Pathways

Pathways use **phosphorylation cascades**: a protein kinase adds phosphate to the next kinase, and phosphatases remove it to switch the pathway off. **Second messengers** (cAMP, Ca^{2+} , IP_3) are small molecules that spread the message quickly. One active receptor can activate many G proteins, so each step **amplifies** the signal. In a GPCR pathway the G protein is active when it holds GTP and returns to its inactive state when it hydrolyzes GTP to GDP.

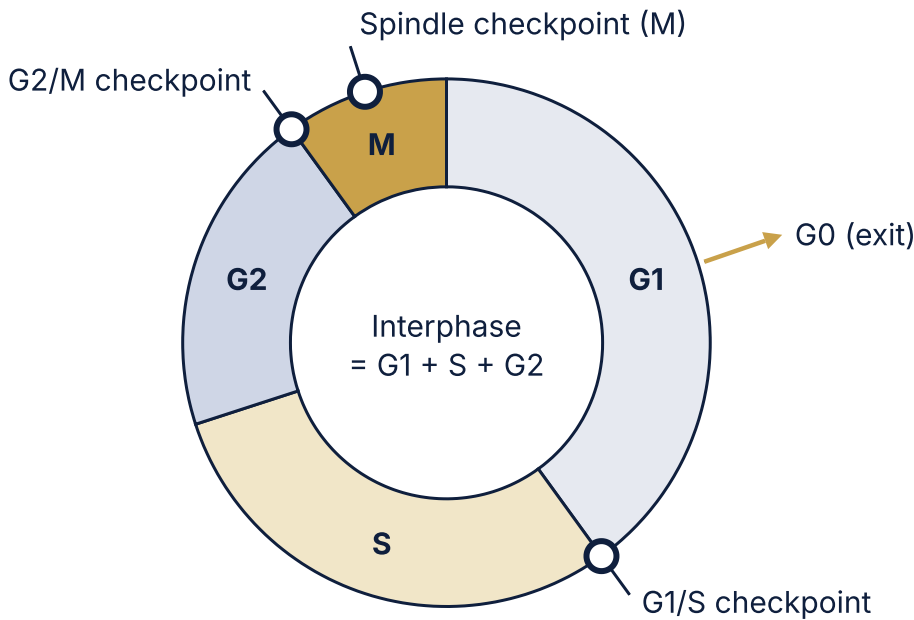
Pathways can be changed. A mutated receptor that is always active gives a response with no ligand; an **inhibitor** or a missing kinase blocks everything downstream while leaving upstream steps normal. Always predict a mutation by naming the step it affects, then each later step.

Feedback

	Negative feedback	Positive feedback
Effect on the change	Opposes it; returns the system toward a set point	Amplifies it; pushes the system further
Typical role	Homeostasis (blood glucose, body temperature, hormone levels)	Rapid completion of a process (oxytocin in labor, blood clotting, fruit ripening)
Symbol in a model	T-bar means inhibition; arrow means stimulation	A loop of stimulation that reinforces itself

Judge the type by what the output does to the input, not by whether the arrow is up or down. If more product shuts off its own production, it is negative feedback.

Cell Cycle



The cell cycle drawn clockwise. Wedge sizes show a typical cell: interphase takes most of the time and mitosis is short.

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Counting Chromosomes and DNA

Count **chromosomes** by centromeres. Count **chromatids** as two per replicated chromosome.

A diploid cell with $2n = 6$ has 6 chromosomes in G1, 6 replicated chromosomes (12 chromatids) after S, and 6 chromosomes per daughter after mitosis.

Sister chromatids separate in **anaphase**; chromosome number is unchanged by mitosis.

Interphase is G1 (growth), S (DNA replication), and G2 (preparation). Mitosis has prophase, metaphase, anaphase, and telophase, then **cytokinesis**: a cleavage furrow in animal cells, a cell plate in plant cells. Prokaryotes divide by binary fission with no spindle.

Regulation of Cell Cycle

Cyclins rise and fall, and **cyclin-dependent kinases (CDKs)** are active only when bound to a cyclin. Checkpoints at G1/S, G2/M, and in metaphase (spindle assembly) test for damaged DNA, complete replication, and attachment of every chromosome to the spindle. Cells that stop dividing sit in **G0**. Tumor suppressors such as p53 and Rb brake the cycle or trigger apoptosis; mutated proto-oncogenes push it forward, so cancer arises from loss of control, not from faster division timing alone.

Checkpoint Logic

Problem detected, so the checkpoint holds the cycle (or triggers apoptosis if damage is severe).

Loss of a checkpoint protein lets damaged cells continue, so mutations accumulate.

Worked Examples

EXAMPLE 1: TIME IN EACH PHASE

In a root-tip squash 500 cells were counted: 410 interphase, 40 prophase, 20 metaphase, 10 anaphase, 20 telophase. The cycle lasts 20 hours. Estimate the time in prophase and in all of mitosis.

SOLUTION

Fraction of cells in a phase estimates the fraction of time spent there.

Prophase: $\frac{40}{500} \times 20 = 1.6$ h.

Mitosis: $\frac{90}{500} \times 20 = 3.6$ h, leaving 16.4 h for interphase.

EXAMPLE 2: AMPLIFICATION

One ligand activates one receptor. The receptor activates 25 G proteins, and each G protein activates an adenylyl cyclase that makes 80 cAMP. (a) How many cAMP form? (b) Predict the effect of a G protein that cannot hydrolyze GTP.

SOLUTION

(a) $25 \times 80 = 2000$ cAMP from one binding event.

(b) The G protein stays active, so adenylyl cyclase keeps producing cAMP and the response continues after the ligand leaves; amplification is unregulated.

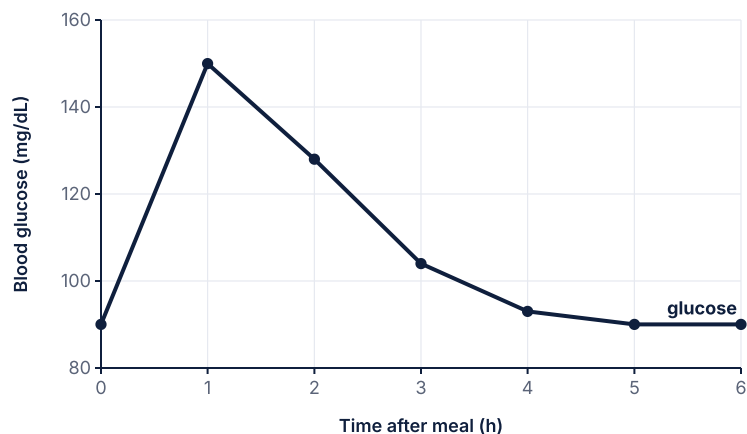
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EXAMPLE 3: FEEDBACK FROM DATA

Use the graph. (a) Identify the feedback type and justify. (b) Find the percent decrease from the peak to hour 3.



Fictional patient data.

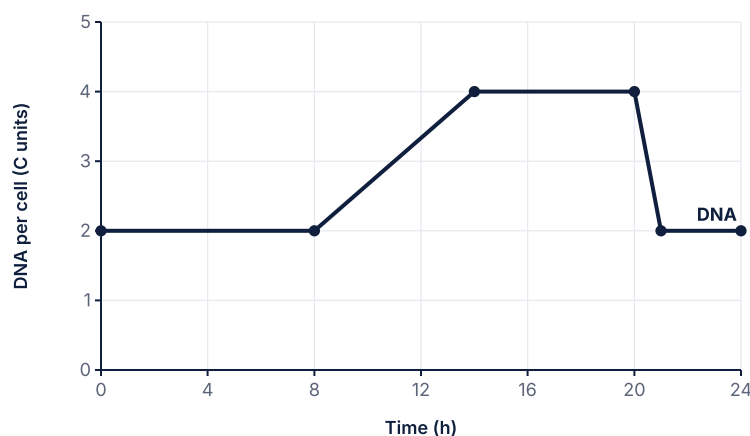
SOLUTION

(a) Negative feedback: the rise in glucose triggers a response that lowers glucose back to about 90 mg/dL, the set point.

(b) $\frac{150-104}{150} \times 100 = 30.7\%$ decrease.

EXAMPLE 4: DNA CONTENT

Use the graph for a cell with $2n = 6$. (a) Which hours are S phase? (b) How many chromatids at 16 h and at 22 h? (c) What would a block at the G₂/M checkpoint do to the curve?



DNA content of one dividing cell (2C = unreplicated amount).

SOLUTION

(a) 8 to 14 h: DNA rises from 2C to 4C.

(b) At 16 h the cell is in G₂ with 6 replicated chromosomes, so 12 chromatids. At 22 h it is a daughter cell with 6 chromosomes (6 unreplicated chromatids).

(c) DNA would stay at 4C past 20 h because the cell cannot enter mitosis, so no drop to 2C.

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EXAMPLE 5: CHECKPOINT FAILURE

Twenty-four hours after DNA damage, the percent of cells in G1, S, and G2/M was 68, 12, 20 in line A and 22, 38, 40 in line B (nonfunctional p53). Explain the difference.

Line	G1	S	G2/M
A (normal)	68%	12%	20%
B (no p53)	22%	38%	40%

SOLUTION

Claim: line B lacks a working G1/S checkpoint.

Evidence: line B has about 3.2 times as many S-phase cells (38/12) and far fewer in G1.

Reasoning: functional p53 halts cells in G1 or triggers apoptosis; without it, damaged DNA is replicated and mutations accumulate.

Write It Like a 5**Model Response**

Prompt: A drug blocks adenylyl cyclase in liver cells exposed to a hormone that binds a GPCR. Predict and justify the effect on glycogen breakdown. Response: The hormone still binds its receptor and the G protein is still activated, because the drug acts later. Adenylyl cyclase cannot convert ATP to cAMP, so cAMP stays low, protein kinase A is not activated, and the kinase cascade that activates glycogen phosphorylase does not occur. Therefore glycogen breakdown will decrease even though the hormone is present.

What the grader looks for

A correct prediction with direction; the step affected; each downstream consequence in order; the unaffected upstream steps; a linking word such as therefore or because.

Coach's Playbook

- 1 Mark the model.** Circle each arrow type. T-bar means inhibits.
- 2 Find the broken step.** Write what it normally does.
- 3 Trace forward.** State each later effect in order.
- 4 Check the data.** Quote numbers with units for your claim.

Common traps

1) Calling a ligand a substrate or a receptor an enzyme. 2) Mixing up positive and negative feedback. 3) Saying a mutated protein is nonfunctional instead of reduced or altered. 4) Defining a control as matching conditions rather than the group without the treatment.

Quick Check

Q: What returns a G protein to the inactive state? A: Hydrolysis of GTP to GDP. Q: At which phase do sister chromatids separate? A: Anaphase. Q: Which checkpoint confirms spindle attachment? A: The metaphase spindle assembly checkpoint.

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Challenge Corner

A cell needs a cyclin-CDK complex to pass G2/M. A mutation makes cyclin never degrade. Predict the result. Solution: cyclin level normally falls at the end of mitosis, inactivating the CDK. If cyclin persists, the CDK stays active and cells stay in a mitotic state, unable to complete exit from mitosis and return to G1.

Practice**PRACTICE Unit 4 Practice**

Show your work. A calculator is allowed. Justify conclusions.

1. Cortisol is a steroid hormone. Which statement best describes how a cell responds to it?
(A) It binds a membrane GPCR and activates cAMP
(B) It diffuses across the membrane and binds an intracellular receptor that affects transcription
(C) It must be taken up by endocytosis before binding
(D) It opens a ligand-gated channel
2. A mutation locks a G protein in its GTP-bound form. In the absence of ligand, which result is most likely?
(A) No cAMP forms
(B) The receptor degrades
(C) The response is decreased
(D) cAMP is made continuously
3. During labor, oxytocin triggers contractions that cause more oxytocin release. This is an example of:
(A) positive feedback because the output amplifies the stimulus
(B) negative feedback because it maintains homeostasis
(C) a second messenger
(D) a checkpoint
4. A plant cell with $2n = 8$ is at metaphase of mitosis. How many chromatids are present?
(A) 8
(B) 4
(C) 16
(D) 32
5. In a sample of 200 onion cells, 30 are in mitosis. The cycle lasts 18 hours. About how long is mitosis?
(A) 1.2 h
(B) 5.4 h
(C) 15.3 h
(D) 2.7 h
6. A drug prevents spindle microtubules from forming. Where will dividing cells arrest?
(A) Metaphase (spindle checkpoint)
(B) G1/S checkpoint
(C) Telophase
(D) G0
7. A researcher wants to test whether a hormone acts through cAMP in cultured liver cells. (a) State the independent and dependent variables. (b) Describe a control group and justify it. (c) Predict the results if an adenylyl cyclase inhibitor is added to hormone-treated cells and explain.
8. Blood calcium rises and the body releases a hormone that lowers it. (a) Identify the feedback and justify. (b) Predict what happens if the receptor for that hormone is nonfunctional. (c) Explain why a positive feedback loop would be unsuitable here.
9. An onion root-tip count of 600 cells gives: interphase 504, prophase 48, metaphase 18, anaphase 12, telophase 18. The cycle lasts 22 hours. (a) Calculate hours in each stage. (b) Calculate total mitosis time. (c) Explain why this method assumes cells are not synchronized.
10. Cells with a mutated p53 gene were irradiated. (a) Predict how the percent in G1 compares with normal cells. (b) Explain with the G1/S checkpoint. (c) Argue why the mutation raises cancer risk.

Answers Unit 4: Answers and Explanations

Read every explanation, including the ones for problems you answered correctly.

4 Cell Communication and Cell Cycle

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1. B. Steroids are nonpolar and cross the membrane. The choice "It binds a membrane GPCR and activates cAMP" treats every ligand as water-soluble, the tempting mistake.
2. D. A GTP-locked G protein keeps activating adenylyl cyclase. The choice "No cAMP forms" assumes the G protein needs ligand to act.
3. A. The output reinforces the input. The choice "negative feedback because it maintains homeostasis" confuses homeostasis with all feedback.
4. C. Eight replicated chromosomes contain 16 chromatids. The choice "8" forgets that S phase doubled the chromatids.
5. D. $\frac{30}{200} \times 18 = 2.7$ h. The choice "5.4 h" uses 30% instead of 15%.
6. A. The spindle checkpoint senses unattached chromosomes. The choice "G1/S checkpoint" is tempting because drug action is often assumed to affect DNA replication.
7. (a) Independent: presence of hormone (and inhibitor). Dependent: cAMP concentration or glycogen breakdown. (b) Control: cells given buffer only (no hormone); this group lacks the treatment so any change in treated cells is due to the hormone. (c) cAMP and glycogen breakdown stay near control levels because the inhibitor prevents cAMP production even though the receptor and G protein are active.
8. (a) Negative feedback: the response reduces the original stimulus. (b) The hormone cannot act, so calcium stays high. (c) Positive feedback would drive calcium further from the set point, causing instability.
9. (a) Interphase 18.48 h, prophase 1.76 h, metaphase 0.66 h, anaphase 0.44 h, telophase 0.66 h (fraction of cells $\times$ 22 h). (b) $\frac{96}{600} \times 22 = 3.52$ h. (c) The fraction of cells in a stage equals the fraction of time only if cells are spread randomly through the cycle.
10. (a) Lower: fewer cells arrest in G1. (b) Normal p53 detects DNA damage and halts the cycle or triggers apoptosis; without it the cell passes G1/S. (c) Damaged DNA is copied and mutations accumulate, so more cells carry oncogenic changes and divide without control.

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Unit 5: Heredity

Exam weighting: about 8-11% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

5 Heredity

Follow chromosomes through meiosis, predict inheritance patterns from simple to complex, and test results with chi-square.

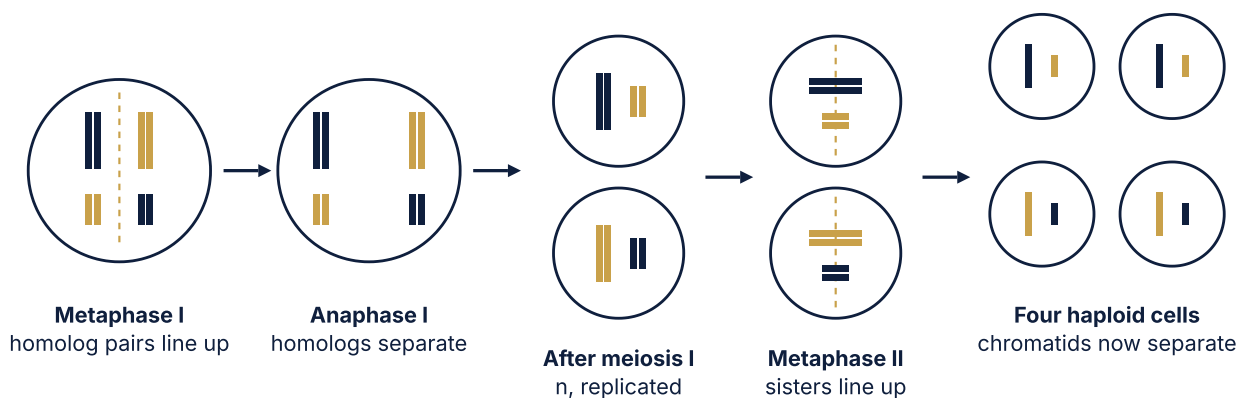
Why This Matters

Heredity is about 8-11% of the multiple-choice score but supplies calculation items that are easy to lose: probability, chi-square, and linkage. Points disappear when students confuse chromosomes with chromatids, skip the null hypothesis, or restate data instead of linking genotype to phenotype.

Core Ideas

Meiosis

Meiosis makes four genetically different haploid cells from one diploid cell through two divisions after one round of DNA replication. In **meiosis I** homologous chromosomes pair (synapsis) and separate, so the number of chromosomes per cell is halved. In **meiosis II** sister chromatids separate, much like mitosis.



Meiosis in a cell with $2n = 4$ (crossing over omitted). Dark and gold bars mark the two parents' chromosomes. Anaphase II is not drawn separately.

- ◆ **Prophase I**: chromosomes condense, homologs synapse, and crossing over occurs.
- ◆ **Metaphase I**: homologous pairs align at the plate; orientation of each pair is random.
- ◆ **Anaphase I**: homologs move to opposite poles; sister chromatids stay together.
- ◆ **Meiosis II**: like mitosis; sister chromatids separate, giving four haploid cells with unreplicated chromosomes.

Feature	Mitosis	Meiosis
Divisions	1	2
Daughter cells	2, diploid, identical	4, haploid, different
Homologs pair	No	Yes, in prophase I
Purpose	Growth, repair, asexual reproduction	Gametes or spores

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Meiosis and Genetic Diversity

Three Sources of Variation

Crossing over (prophase I) exchanges segments between nonsister chromatids of homologs.

Independent assortment (metaphase I): a cell with n pairs can make 2^n gamete types without crossing over.

Random fertilization: any sperm can fuse with any egg. For humans $(2^{23})^2 \approx 7.0 \times 10^{13}$ combinations.

Nondisjunction is failure of chromosomes to separate. If homologs fail to separate in meiosis I, all four gametes are abnormal (two $n + 1$, two $n - 1$). If sister chromatids fail in meiosis II, two gametes are normal. A gamete with an extra chromosome 21 gives trisomy 21.

Mendelian Genetics

Law of **segregation**: the two alleles of a gene separate into different gametes. Law of **independent assortment**: genes on different chromosomes assort independently. A **testcross** (unknown $\times$ homozygous recessive) reveals genotype from offspring phenotypes.

		Parent 2: Aa		
		A	a	
Parent 1: Aa	A	AA	Aa	
	a	Aa	aa	Genotypes 1 AA : 2 Aa : 1 aa Phenotypes 3 dominant : 1 recessive Gold square = aa (recessive)

Punnett square for Aa $\times$ Aa. Each gamete is 1/2 A and 1/2 a, so each box has probability 1/4.

Probability Rules

Multiplication rule: $P(A \text{ and } B) = P(A) \times P(B)$ for independent events.

Addition rule: $P(A \text{ or } B) = P(A) + P(B)$ for mutually exclusive events.

For several genes, multiply gene by gene.

Non-Mendelian Genetics

- ◆ **Incomplete dominance:** the heterozygote is intermediate (red $\times$ white gives pink; pink $\times$ pink gives 1:2:1).
- ◆ **Codominance:** both alleles are expressed (human AB blood type).
- ◆ **Polygenic traits:** many genes give continuous variation.
- ◆ **Pleiotropy:** one gene affects several traits.
- ◆ **Epistasis:** one gene masks another, changing a 9:3:3:1 ratio (for example 9:3:4).
- ◆ **Sex linkage:** X-linked recessive traits appear more in males, who have one X.
- ◆ **Extranuclear inheritance:** mitochondrial and chloroplast genes pass from the maternal parent.

Linkage: genes close together on one chromosome tend to be inherited together. In a testcross the recombinant classes are small; recombination frequency = recombinants / total offspring, and 1% equals one map unit. Maximum recombination is 50%, the same as independent assortment.

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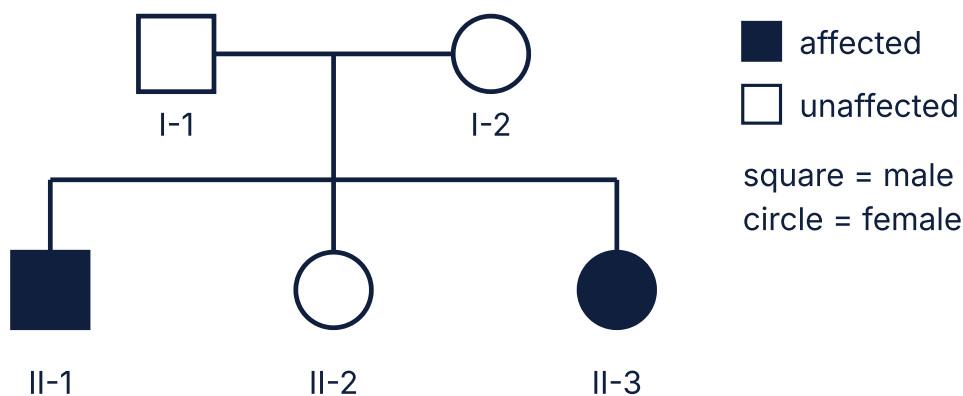
Pattern in a pedigree	Suggests
Affected child, both parents unaffected	Recessive (parents are carriers)
Every affected person has an affected parent	Dominant
Affected father never passes it to sons; more males affected	X-linked recessive
Trait appears only through mothers, in all children	Mitochondrial

Environmental Effects on Phenotype

Phenotype = genotype + environment. When asked why identical genotypes differ, name the environmental factor and the mechanism, such as temperature changing an enzyme's activity. Examples: Himalayan rabbit fur is dark only where the body is cool; hydrangea flower color shifts with soil pH; identical twins differ by diet and experience. Genotype sets a range, and environment determines where in the range an individual falls.

Pedigrees and Chi-Square

A pedigree is read by asking which inheritance patterns it makes impossible. One contradiction rules a pattern out; consistency only makes a pattern possible.



Pedigree for a rare trait. A horizontal line joins mates; the vertical line descends to their children.

Chi-Square Goodness of Fit

$$\chi^2 = \sum \frac{(O - E)^2}{E} \text{ with } df = \text{categories} - 1.$$

Null hypothesis: observed counts fit the expected ratio. Reject if $\chi^2 > \text{critical value}$ ($p = 0.05$).

Critical values: $df = 1$: 3.84; $df = 2$: 5.99; $df = 3$: 7.81; $df = 4$: 9.49.

- 1 State the null: the observed counts fit the expected ratio.
- 2 Compute expected counts from the ratio and total.
- 3 Add $(O - E)^2 / E$ for every category.
- 4 Compare with the critical value for df and decide.

Rejecting the null means the difference is unlikely to be chance alone. Failing to reject does not prove the model, only that the data are consistent with it.

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Worked Examples

EXAMPLE 1: THREE GENES

AaBbCc x AaBbCc. Find the probability of an offspring that is dominant for A, recessive for B, dominant for C.

SOLUTION

Each gene is independent: $P(A_) = \frac{3}{4}$, $P(bb) = \frac{1}{4}$, $P(C_) = \frac{3}{4}$.

$$\frac{3}{4} \times \frac{1}{4} \times \frac{3}{4} = \frac{9}{64} \approx 0.14.$$

EXAMPLE 2: MEIOSIS COUNTS

A species has $2n = 10$. (a) How many gamete types are possible by independent assortment alone? (b) A gamete with 6 chromosomes fertilizes a normal gamete. What is the zygote's chromosome number, and what kind of error occurred?

SOLUTION

(a) $n = 5$, so $2^5 = 32$.

(b) $6 + 5 = 11$ chromosomes, trisomy ($2n + 1$), caused by nondisjunction in one parent's meiosis. The abnormal gamete had one extra chromosome, so it came from an error that left both members of a pair (or both chromatids) in one cell.

EXAMPLE 3: PEDIGREE

Use the pedigree above. (a) Rule out X-linked recessive inheritance. (b) II-2 is unaffected and her partner is a known carrier. What is the probability their child is affected?

SOLUTION

(a) II-3 is an affected daughter. An X-linked recessive daughter needs an affected father, but I-1 is unaffected. So the trait is autosomal recessive.

(b) I-1 and I-2 are carriers (Aa), so II-2 is Aa with probability $\frac{2}{3} \cdot \frac{2}{3} \times \frac{1}{4} = \frac{1}{6} \approx 0.17$.

EXAMPLE 4: LINKAGE

A testcross AaBb x aabb gives 420 AB, 80 Ab, 90 aB, 410 ab (1000 total). Test independent assortment and estimate map distance.

SOLUTION

Expected under independent assortment: 250 each.

$$\chi^2 = \frac{170^2 + 170^2 + 160^2 + 160^2}{250} = 436.0, df = 3, \text{critical } 7.81. \text{ Reject: the genes are linked.}$$

Recombinants are Ab + aB = 170, so $\frac{170}{1000} = 0.17$, or 17 map units.

EXAMPLE 5: EPISTASIS AND CHI-SQUARE

In mice, B gives black and bb brown, but cc blocks pigment (white). BbCc x BbCc gave 192 pups: 101 black, 44 brown, 47 white. Is a 9:3:4 ratio supported?

Class	Observed	Expected
Black	101	108
Brown	44	36
White	47	48

SOLUTION

Expected ratio 9:3:4 of 192 gives 108, 36, 48.

$$\chi^2 = \frac{49}{108} + \frac{64}{36} + \frac{1}{48} = 2.25, df = 2, \text{critical } 5.99.$$

$2.25 < 5.99$: fail to reject the null; the data are consistent with 9:3:4 epistasis.

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Write It Like a 5

Model Response

Prompt: Explain how meiosis produces genetic variation. Response: During prophase I, homologous chromosomes synapse and nonsister chromatids exchange segments, creating new allele combinations. At metaphase I each homologous pair lines up independently, so maternal and paternal chromosomes are distributed randomly; a cell with n pairs gives 2^n gamete types. Finally, random fertilization combines any sperm with any egg, multiplying the possibilities again.

What the grader looks for

The stage named for each source; the mechanism, not just the term; a number or ratio when asked; the word therefore or because linking mechanism to variation.

Coach's Playbook

- 1 **Define alleles.** Write the symbols and what each means.
- 2 **List parent genotypes.** Deduce from phenotypes or pedigree.
- 3 **Choose a tool.** Punnett for one gene, multiplication for several.
- 4 **Test data.** Chi-square with $df = \text{categories} - 1$.

Common traps

1) Writing a null hypothesis with a direction or a result. 2) Using df equal to the number of categories. 3) Counting chromatids as chromosomes. 4) Saying a heterozygote makes only the dominant protein.

Quick Check

Q: When do homologs separate? A: Anaphase I. Q: Maximum recombination frequency? A: 50%. Q: Which phase of meiosis holds crossing over? A: Prophase I.

Challenge Corner

A carrier mother ($X^H X^h$) and unaffected father ($X^H Y$) have a child. For X-linked hemophilia (recessive) find $P(\text{affected child})$ and $P(\text{affected son given the child is a son})$. Solution: Offspring are $X^H X^H$, $X^H X^h$, $X^H Y$, $X^h Y$, each $1/4$. $P(\text{affected child}) = 1/4$; among sons, $1/2$ are affected.

Practice

PRACTICE Unit 5 Practice

Show your work. A calculator is allowed. Justify conclusions.

1. A cell with $2n = 12$ completes meiosis I. How many chromosomes (each with two chromatids) are in each daughter cell?
 (A) 12 (B) 24 (C) 6 (D) 3
2. An organism has 5 pairs of chromosomes. Ignoring crossing over, how many gamete types are possible?
 (A) 32 (B) 5 (C) 10 (D) 25
3. $AaBb \times aabb$. What fraction of offspring is $aabb$ if the genes assort independently?
 (A) $1/16$ (B) $1/2$ (C) $1/8$ (D) $1/4$

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4. Two unaffected parents have an affected daughter. The trait is most likely:
 (A) X-linked recessive (B) autosomal recessive (C) autosomal dominant
 (D) mitochondrial
5. A 3:1 cross yielded 140 dominant and 60 recessive of 200. What is χ^2 for the 3:1 expectation?
 (A) 2.67 (B) 0.67 (C) 5.33 (D) 1.33
6. Pink snapdragons (incomplete dominance) are crossed with white ones. What fraction of offspring is pink?
 (A) 1/4 (B) 3/4 (C) all (D) 1/2
7. A hydrangea grower has genetically identical plants. (a) Design an experiment to test whether soil pH affects flower color. (b) State the null hypothesis. (c) Identify the control and justify.
8. A testcross AaBb x aabb gave 410 AB, 405 ab, 90 Ab, and 95 aB (1000 total). (a) Calculate the recombination frequency. (b) Calculate χ^2 against 1:1:1:1 and conclude. (c) Explain why recombination is below 50%.
9. A woman has a child with Down syndrome from an egg with an extra chromosome 21. (a) Name the error. (b) Explain two meiotic stages where it can occur. (c) Calculate the chromosome number of the zygote.
10. An X-linked recessive allele causes color blindness. A carrier woman and a man with normal vision have children. (a) Give the genotypes of the parents. (b) Find the probability that a child is a color-blind son. (c) Explain why a mitochondrial trait would not follow this pattern.

Answers**Unit 5: Answers and Explanations**

Read every explanation, including the ones for problems you answered correctly.

5 Heredity**PRACTICE · UNIT 5 PRACTICE**

1. C. Homologs separate in meiosis I, halving the number to 6. The choice "12" is tempting because the DNA is not yet halved.
2. A. $2^5 = 32$. The choice "10" adds instead of multiplying.
3. D. Gametes ab pair with each of AB, Ab, aB, ab equally, giving aaBb 1/4. The choice "1/16" uses an AaBb x AaBb cross.
4. B. Both parents are carriers, and a daughter with an unaffected father rules out X-linked recessive. The choice "autosomal dominant" fails because dominant traits appear in a parent.
5. A. $\frac{(140-150)^2}{150} + \frac{(60-50)^2}{50} = 2.67$ (df = 1, critical 3.84, fail to reject). The choice "0.67" omits the second class.
6. D. Rr x rr gives 1/2 Rr (pink) and 1/2 rr (white). The choice "all" assumes pink x white gives all pink.
7. (a) Grow clones in soil at several pH values with all other conditions (light, water, temperature) constant; record flower color. (b) Soil pH has no effect on flower color. (c) Plants in unaltered soil lack the pH treatment, so any difference in treated plants is due to pH; clones show genotype is not the cause.
8. (a) $\frac{185}{1000} = 0.185$, or 18.5 map units. (b) Expected 250 each: $\chi^2 = \frac{160^2 + 155^2 + 160^2 + 155^2}{250} = 397.0$ with df = 3, above 7.81, so reject independent assortment. (c) Genes are close on one chromosome, so crossing over separates them less often than independent assortment would.
9. (a) Nondisjunction. (b) Homologs fail to separate in anaphase I, or sister chromatids fail to separate in anaphase II. (c) $24 + 23 = 47$ chromosomes.
10. (a) $X^c X^c$ and $X^c Y$. (b) 1/4 of all children ($X^c Y$); 1/2 of sons. (c) Mitochondria come from the egg, so all children of an affected mother inherit the trait and none of the children of an affected father do, whatever the sex.

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Unit 6: Gene Expression and Regulation

Exam weighting: about 12-16% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

6 Gene Expression and Regulation

How cells copy, read, regulate and change their genetic information, and how scientists exploit these processes.

Why This Matters

Unit 6 is worth about 12-16% of the multiple-choice score, and the 'information flow' reasoning here shows up in free-response questions about experiments, mutations and regulation. Points are lost by mixing up the jobs of polymerase, ribosomes and tRNA and by miscounting nucleotides versus amino acids.

Core Ideas

6.1 DNA and RNA Structure

A **nucleotide** has a five-carbon sugar, a phosphate and a nitrogen base. DNA uses deoxyribose and the bases A, T, G, C; RNA uses ribose and replaces T with **U** (uracil). DNA is a double helix of two **antiparallel** strands (one runs 5' to 3', its partner 3' to 5') held together by hydrogen bonds: A-T (2 bonds) and G-C (3 bonds). RNA is usually single-stranded; the main types are mRNA (carries the message), tRNA (adapter) and rRNA (ribosome part). Eukaryotic DNA is linear; prokaryotes have a circular chromosome plus **plasmids**.

Base-pairing rules

DNA: A pairs with T, G pairs with C. RNA: A pairs with U.

In double-stranded DNA, %A = %T and %G = %C, so purines (A+G) equal pyrimidines (T+C).

New nucleotides are always added to the 3' end of a growing strand.

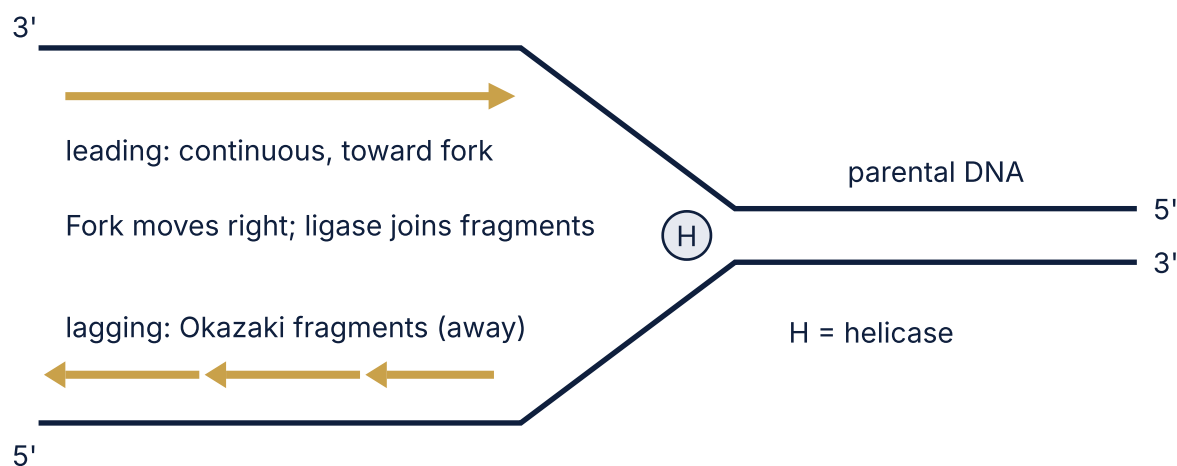
6.2 DNA Replication

Replication is **semiconservative**: each new double helix keeps one old (template) strand and one new strand. **Helicase** unwinds and separates the strands; **primase** lays down a short RNA primer; **DNA polymerase** extends the primer 5' to 3'; **ligase** seals gaps. Because polymerase can only add to a 3' end, one strand (leading) is made continuously while the other (lagging) is made as **Okazaki fragments**. Polymerase also proofreads, so errors are rare but not zero.

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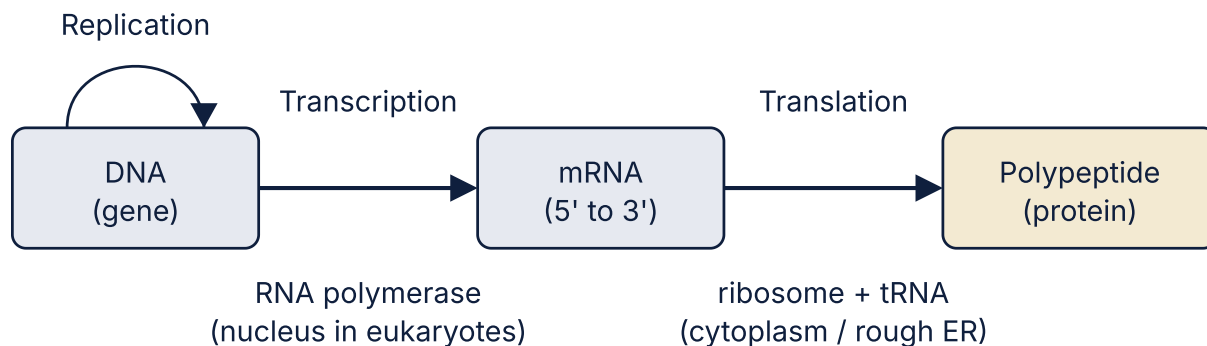
Replication fork. Gold = new DNA, always extended at its 3' end by DNA polymerase.

6.3 Transcription and RNA Processing

Transcription makes RNA from a DNA template. RNA polymerase binds a **promoter**, separates the strands and builds RNA 5' to 3', reading the template strand 3' to 5'. The mRNA matches the non-template (coding) strand with U for T. In eukaryotes the pre-mRNA is processed: a 5' cap and poly-A tail protect it and aid export, and **introns** are spliced out so **exons** are joined. Alternative splicing lets one gene make several proteins. Bacteria lack introns, so translation can start before transcription ends.

6.4 Translation

Translation builds a polypeptide at a ribosome. mRNA is read in **codons** (three nucleotides). Each tRNA carries one amino acid and an **anticodon** that pairs with a codon. Translation begins at the start codon AUG (Met) and ends at a stop codon (UAA, UAG, UGA), which codes for no amino acid. The code is redundant (several codons per amino acid) but never ambiguous, and it is nearly universal. Ribosomes assemble the chain; they do not make amino acids or transport proteins.



Central dogma: information flows from DNA to RNA to protein; DNA also copies itself.

Counting rule

Coding nucleotides / 3 = codons. Amino acids = codons minus the stop codon.

Never divide by 2, and remember mature mRNA is shorter than the gene (introns removed).

6.5 Regulation of Gene Expression

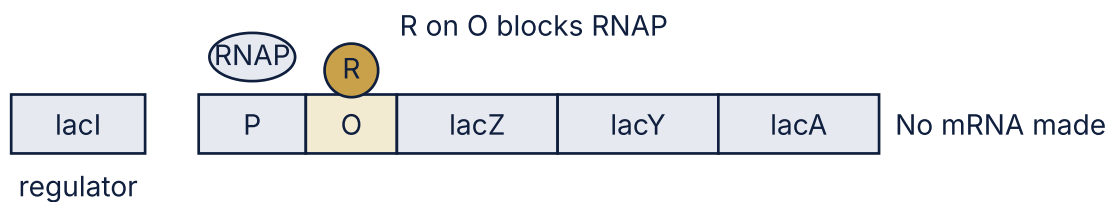
Prokaryotes control genes in **operons**. In the inducible **lac operon**, the repressor binds the operator and blocks RNA polymerase; allolactose binds the repressor, which releases the operator, so the genes are expressed. In a repressible operon such as *trp*, the end product acts as a corepressor that switches the genes off. Eukaryotes regulate with transcription factors, activators binding enhancers, chromatin changes (DNA methylation, histone acetylation) and small regulatory RNAs.

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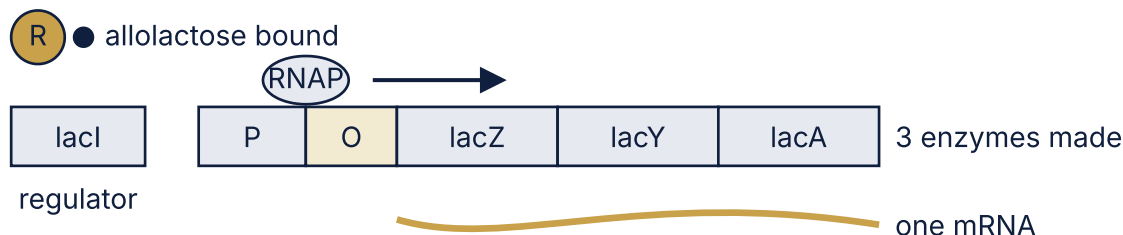
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A. Lactose absent: operon OFF



B. Lactose present, glucose low: operon ON



Lac operon: lacI makes the repressor (R); P = promoter, O = operator; lacZ, lacY, lacA code for lactose-use proteins.

6.6 Gene Expression and Cell Specialization

Nearly all cells in an organism hold the same genome. Specialization arises because different **transcription factors** and signals turn different genes on, so a neuron and a liver cell make different mRNAs and proteins. Master regulators and homeotic genes set body plans during development.

6.7 Mutations

A **mutation** is a heritable change in DNA sequence. Point mutations are **silent** (same amino acid), **missense** (different amino acid) or **nonsense** (new stop codon). Insertions or deletions that are not multiples of three cause a **frameshift**, which usually alters every later codon. Mutations arise from replication errors and mutagens; they supply new alleles, so they are a source of variation, and effects can be harmful, neutral or beneficial depending on environment. Meiotic crossing over and, in microbes, transformation, transduction and conjugation also shuffle genes.

6.8 Biotechnology

Gel electrophoresis separates DNA by size: negatively charged fragments move toward the positive electrode, and smaller pieces travel farther. **Restriction enzymes** cut at specific sequences; **ligase** joins pieces, producing recombinant plasmids that **transformation** puts into bacteria, with an antibiotic-resistance gene to select cells that took the plasmid. **PCR** copies a target region through cycles of denaturing, primer annealing and extension, doubling the amount each cycle. Sequencing, BLAST comparison and CRISPR gene editing are other key tools.

Gel rule and PCR rule

Smaller fragments migrate farther from the wells; fragment sizes should add up to the original piece.

Copies after n cycles from one template = 2^n .

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Worked Examples

EXAMPLE 1: BASE PAIRING

A DNA sample is 28% adenine. Give the percentage of each other base, and state why RNA from this gene could not be tested the same way.

SOLUTION

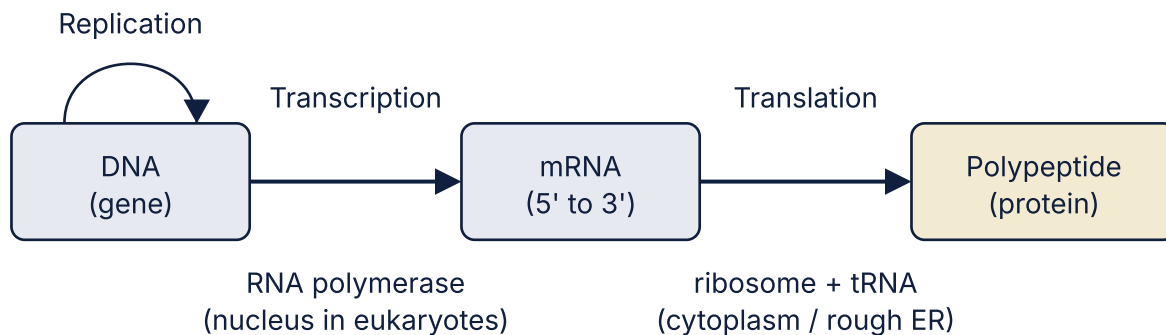
In double-stranded DNA, $A = T$, so $T = 28\%$.

$A + T = 56\%$, leaving 44% for $G + C$; $G = C = 22\%$.

Single-stranded RNA has no complementary strand, so there is no rule forcing $\%A = \%U$.

EXAMPLE 2: GENE TO PROTEIN

The template strand reads 3'-TACCCTGGAATT-5'. Write the mRNA and the peptide.



Central dogma: information flows from DNA to RNA to protein; DNA also copies itself.

SOLUTION

mRNA is complementary and antiparallel: 5'-AUGGGACCUUAA-3'.

Codons: AUG (Met), GGA (Gly), CCU (Pro), UAA (stop).

Peptide: Met-Gly-Pro. Four codons, but only 3 amino acids because the stop codon codes for none.

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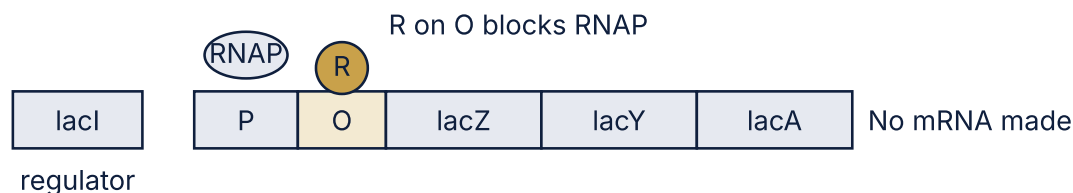
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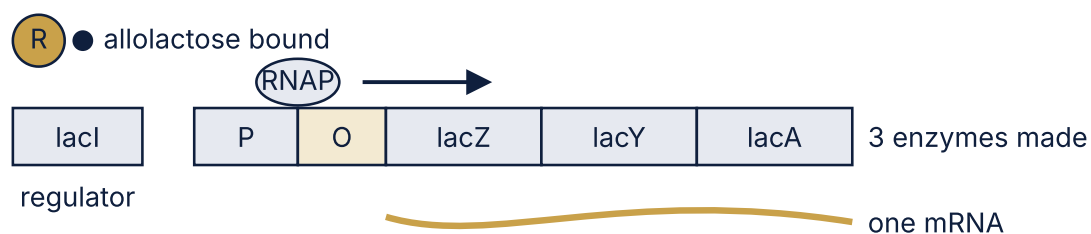
EXAMPLE 3: LAC OPERON PREDICTION

Predict lac gene expression in each condition and justify: (i) no lactose; (ii) lactose present; (iii) a mutant whose repressor cannot bind the operator, no lactose.

A. Lactose absent: operon OFF



B. Lactose present, glucose low: operon ON



Lac operon: lacI makes the repressor (R); P = promoter, O = operator; lacZ, lacY, lacA code for lactose-use proteins.

SOLUTION

(i) Off: the repressor binds the operator and blocks RNA polymerase.

(ii) On: allolactose binds the repressor, changing its shape so it leaves the operator; RNA polymerase transcribes lacZYA.

(iii) On all the time: with no operator binding, nothing blocks transcription even without lactose. This is a loss of regulation, not a loss of protein function.

EXAMPLE 4: CLASSIFYING MUTATIONS

A coding region of 1,350 nucleotides (including the stop codon) makes how many amino acids? Then classify GAG (Glu) changing to (a) GAA, (b) GUG (Val), (c) UAG.

SOLUTION

$1,350 / 3 = 450$ codons; minus the stop codon gives 449 amino acids.

(a) GAA still codes Glu: silent. (b) Val replaces Glu: missense; effect depends on the position and the properties of the amino acid.

(c) UAG is a stop codon: nonsense, so the protein is cut short.

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EXAMPLE 5: GEL AND PCR

A 6.0 kb plasmid is cut by a restriction enzyme into fragments of 3.5, 2.0 and 0.5 kb. Predict their order on a gel and check the digest. If one template starts a PCR, how many copies exist after 10 cycles?

Fragment (kb)	Relative distance moved
3.5	shortest
2.0	medium
0.5	longest

SOLUTION

Smaller pieces move farther: from the wells, 3.5 kb is closest, then 2.0, then 0.5 kb farthest.

Check: $3.5 + 2.0 + 0.5 = 6.0$ kb, so the digest is consistent with one circular 6.0 kb plasmid cut at three sites.

PCR doubles each cycle: $2^{10} = 1024$ copies.

Write It Like a 5**Model Response**

Prompt: Bacteria with a mutation in the lac repressor gene make lacZ enzyme even when only glucose is available. Explain. Response: The repressor normally binds the operator and prevents RNA polymerase from transcribing the lac genes unless allolactose is present. A mutation in the repressor gene that changes the protein's shape so it cannot bind the operator removes that block, so RNA polymerase transcribes lacZ, the mRNA is translated, and enzyme is made constitutively. The DNA sequence of lacZ is unchanged; only regulation is lost.

What the grader looks for

Names repressor and operator; states what the mutation changes (binding); links to RNA polymerase access, mRNA and protein; distinguishes regulatory mutation from a mutation in the structural gene.

Coach's Playbook

- 1 Label every strand 5' and 3' before you transcribe; the mRNA is complementary and antiparallel to the template.
- 2 Say which molecule does each job: polymerase builds nucleic acids, tRNA matches codons, ribosomes catalyze peptide bonds.
- 3 For regulation, trace: signal, then regulator protein shape, then DNA binding, then RNA polymerase, then protein.
- 4 Describe mutation effects as reduced, altered or lost function and reason from the change in amino acid properties.

Common traps

1) Saying ribosomes transport proteins, make amino acids or carry out transcription. 2) Dividing nucleotides by 2, or forgetting the stop codon. 3) Writing 'T' in mRNA or copying the template instead of its complement. 4) Calling every mutation harmful or 'nonfunctional' instead of describing altered function.

Quick Check

Q: Which enzyme joins Okazaki fragments? A: DNA ligase. Q: What does a gene's promoter bind? A: RNA polymerase (with factors). Q: Does a silent mutation change the DNA? A: Yes, the DNA changes but the amino acid does not.

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Challenge Corner

A pre-mRNA is 3,000 nucleotides; after splicing, exons total 900 nucleotides, all coding and ending in a stop codon. How many amino acids? Solution: $900 / 3 = 300$ codons; minus the stop codon = 299 amino acids. The 2,100 intron nucleotides are removed and do not count.

Practice

PRACTICE Unit 6 Practice

Show your work. A calculator is allowed. Justify conclusions.

- A double-stranded DNA sample contains 24% thymine. What percentage of its bases is guanine?
(A) 24% (B) 26% (C) 48% (D) 52%
- Which statement about the lagging strand is correct?
(A) It is made continuously toward the fork.
(B) It is made 3' to 5' by polymerase.
(C) It does not need a primer.
(D) It is made in short fragments because polymerase only extends 3' ends.
- A template strand reads 3'-TACGGT-5'. The mRNA is:
(A) 5'-AUGCCA-3' (B) 5'-TACGGT-3' (C) 5'-ATGCCA-3'
(D) 3'-AUGCCA-5'
- In a bacterium, a mutation in the lac operator prevents the repressor from binding. With no lactose present the cell will:
(A) not transcribe lacZYA (B) make no repressor
(C) transcribe lacZYA (D) make the repressor but destroy it
- The mRNA codon UAC is changed to UAG in the early part of a gene. The most likely result is:
(A) a shortened protein (B) a protein with one amino acid changed
(C) a protein with no change (D) a protein longer than normal
- A plasmid is cut into the fragments shown. Which fragment is nearest the wells after electrophoresis?

Fragment	Size (kb)
1	5.0
2	3.0
3	1.2
4	0.4

- (A) 0.4 kb (B) 5.0 kb (C) 1.2 kb (D) 3.0 kb
- An investigator grows E. coli in four media: (1) glucose only, (2) lactose only, (3) glucose plus lactose, (4) no sugar. She measures beta-galactosidase (lacZ product) activity.
(a) Identify the independent and dependent variables.
(b) Predict the medium with the highest activity and justify with the operon model.
(c) Explain why medium 4 is a necessary control.
- The mRNA 5'-GCAUGGAAGUCUAAUG-3' is translated. Use these codons: AUG Met; GAA, GAG Glu; GUC Val; UCU Ser; AAU Asn; UAA Stop.
(a) Give the polypeptide.
(b) Predict the effect of GAA changing to GAG.
(c) Predict the effect of deleting the first A of GAA.
- A student transforms bacteria with a plasmid carrying an ampicillin-resistance gene and a gene of interest, then plates cells on agar with and without ampicillin.
(a) Explain why only transformed cells grow on ampicillin plates.
(b) State the purpose of the plate without ampicillin.
(c) A PCR starts with one DNA template. Calculate the number of copies after 12 cycles.

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10. A liver cell and a neuron from the same person are compared. Both have identical genomes, but only the liver cell makes the enzyme albumin.
- (a) Explain how this is possible.
 - (b) A eukaryotic pre-mRNA has 3,000 nucleotides; exons total 900 nucleotides including the stop codon. Calculate the number of amino acids.
 - (c) Explain why alternative splicing allows one gene to give several proteins.

Answers**Unit 6: Answers and Explanations**

Read every explanation, including the ones for problems you answered correctly.

6 Gene Expression and Regulation**PRACTICE · UNIT 6 PRACTICE**

1. B. $A = T = 24\%$, so $G + C = 52\%$ and $G = 26\%$. Choice A treats G as equal to T; choice D is $G + C$ together.
2. D. Polymerase adds nucleotides only to a 3' end, so the strand copied away from the fork is built in Okazaki fragments, each needing a primer. Choice B is wrong because no polymerase works 3' to 5'.
3. A. mRNA is complementary to the template, uses U in place of T, and runs 5' to 3'. Choice C uses T; choice D has the wrong polarity.
4. C. The repressor is still made, but without operator binding RNA polymerase is not blocked, so the genes are expressed. Choice A is the normal uninduced state.
5. A. UAG is a stop codon, so translation ends early (nonsense). Choice A would describe a missense change, the tempting error.
6. B. Larger fragments move more slowly, so 5.0 kb stays closest to the wells. Choice A is the farthest traveller.
7. (a) Independent: sugar in the medium. Dependent: beta-galactosidase activity. (b) Medium 2: lactose gives allolactose, which binds the repressor so it leaves the operator, and with glucose low the operon is fully active so RNA polymerase transcribes lacZ. (c) Medium 4 shows baseline activity with neither inducer nor glucose, so any rise in other media can be attributed to the sugar rather than to the growth conditions.
8. (a) Translation starts at the first AUG: Met-Glu-Val, then UAA stops. (b) GAG also codes Glu, so the change is silent and the protein is unchanged. (c) Deleting one nucleotide shifts the reading frame after AUG G: the codons become AUG GAG UCU AAU, so the peptide is Met-Glu-Ser-Asn: every amino acid after Met is read in a new frame (frameshift) and the stop codon is missed, so function is probably lost.
9. (a) Only cells that took up the plasmid express the resistance gene, so only they survive the antibiotic. (b) It is a control showing that the cells are viable and the transformation procedure itself did not kill them. (c) Copies = $2^{12} = 4096$.
10. (a) Different transcription factors are active in each cell type, so RNA polymerase transcribes the albumin gene in the liver but not in the neuron, even though both carry the gene. (b) $900 / 3 = 300$ codons; subtracting the stop codon gives 299 amino acids. (c) Different combinations of exons can be joined, producing different mature mRNAs and therefore different polypeptides.

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Unit 7: Natural Selection

Exam weighting: about 13-20% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

7 Natural Selection

How populations change through selection, drift and gene flow, how scientists reconstruct relationships, and how species and life itself arose.

Why This Matters

Unit 7 is the heaviest unit, about 13-20% of the multiple-choice score, and evolution is also the thread through the whole course. Points are lost by saying individuals evolve and by swapping allele and phenotype frequency.

Core Ideas

7.1 Introduction to Natural Selection

Evolution is a change in allele frequencies in a population over generations. Natural selection needs four things: heritable variation, more offspring than can survive, differences in survival and reproduction, and an environment that favors some traits. **Fitness** is reproductive success. An **adaptation** is a heritable trait that raises fitness in a given environment. Individuals do not evolve; populations do. Variation arises from mutation and from meiosis and sexual reproduction, and organisms do not mutate 'on purpose' to meet a need.

7.2 Natural Selection

Selection acts on phenotypes, and the allele frequencies change if the phenotype is heritable. Modes: **stabilizing** (favors the middle), **directional** (favors one extreme) and **disruptive** (favors both extremes). **Sexual selection** favors traits that improve mating success even at some survival cost. A trait helpful in one habitat may be harmful in another.

7.3 Artificial Selection

In **artificial selection** humans choose which individuals breed (crops, dogs, livestock). The mechanism is identical to natural selection; only the selecting agent differs. Intense breeding can lower genetic diversity.

7.4 Population Genetics

A population's **gene pool** is all its alleles. Five processes change allele frequencies: natural selection, **genetic drift** (chance changes, strongest in small populations, including the **bottleneck** and **founder** effects), **gene flow** (migration), mutation, and nonrandom mating (which changes genotype but not allele frequency by itself).

7.5 Hardy-Weinberg Equilibrium

The Hardy-Weinberg model gives expected genotype frequencies if allele frequencies are not changing. Conditions: very large population, random mating, no mutation, no gene flow, no selection. A population that fits the data is not evolving at that gene; a mismatch only shows that at least one condition fails, so identify which with evidence.

Hardy-Weinberg equations

$p + q = 1$ (allele frequencies, with p = dominant allele, q = recessive allele)

$p^2 + 2pq + q^2 = 1$ (genotype frequencies: homozygous dominant, heterozygous, homozygous recessive)

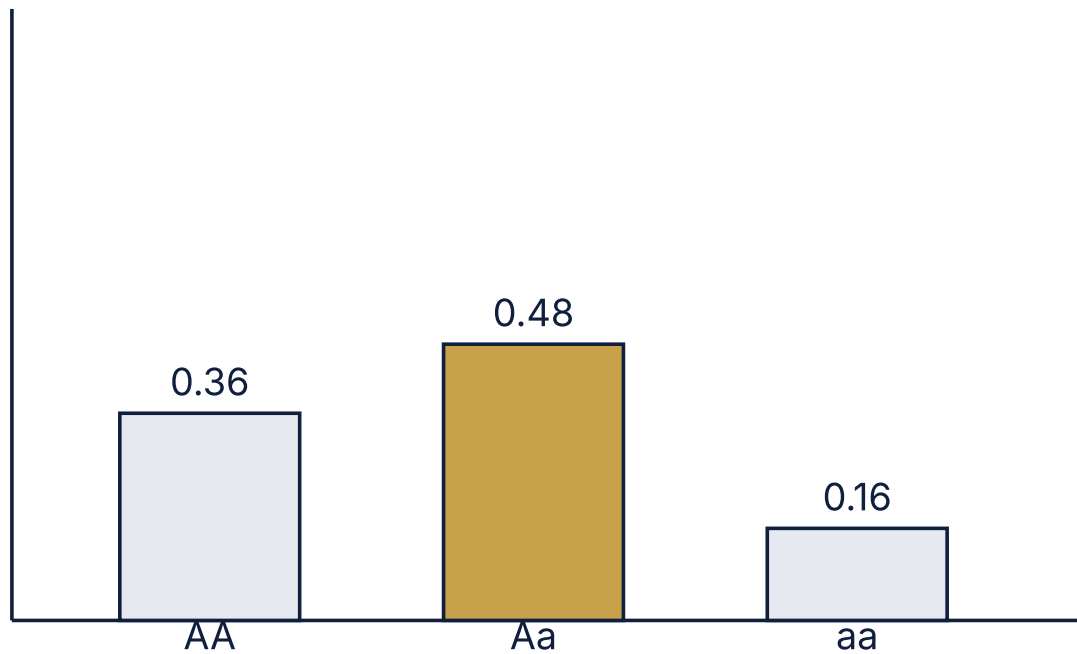
Start from the recessive phenotype: $q = \sqrt{q^2}$. Frequencies are proportions of alleles, not of individuals showing a trait.

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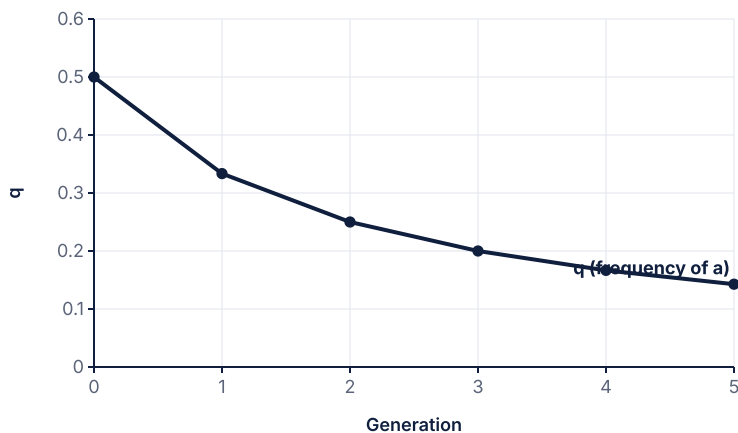
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Expected genotype frequencies when $p = 0.6$, $q = 0.4$



Hardy-Weinberg expectations. Bar heights are frequencies (sum = 1).

When selection acts, allele frequencies shift each generation. The graph below follows a recessive allele a under complete selection against aa .



Selection against aa lowers q ever more slowly because most a alleles hide in carriers.

7.6 Evidence of Evolution

Evidence comes from the **fossil record**, biogeography, **homologous structures** (shared ancestry, different function), **vestigial** structures, embryology, and molecular data: similar DNA and protein sequences between close relatives. Analogous structures (wings of bats and insects) show convergent evolution, not close ancestry.

7.7 Common Ancestry

All life shares DNA as genetic material, a nearly universal genetic code, ribosomes, ATP use and core pathways such as glycolysis. These shared features are best explained by descent from a common ancestor.

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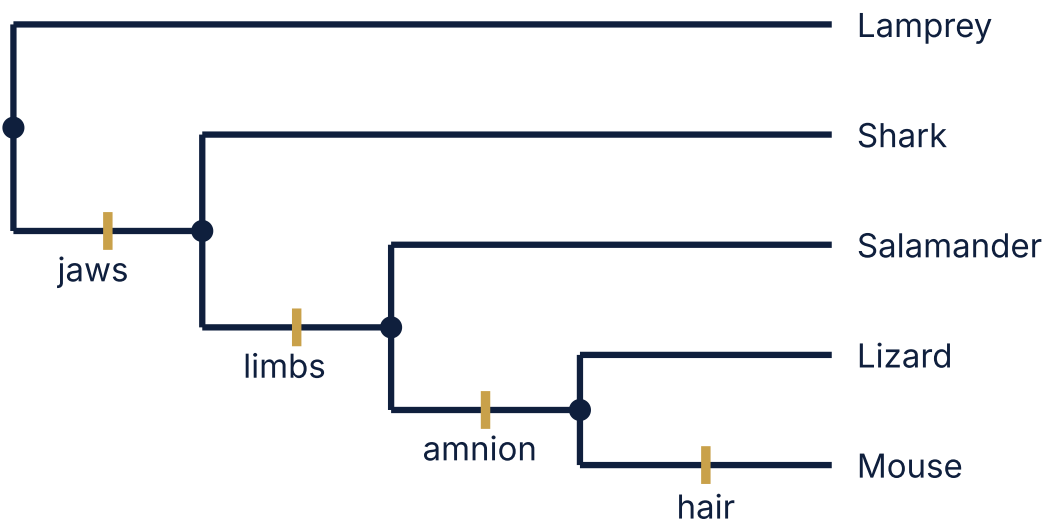
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7.8 Continuing Evolution

Evolution is ongoing: antibiotic-resistant bacteria, pesticide-resistant insects and seasonal changes in viruses all show populations changing under selection. Resistance alleles already exist; the drug removes susceptible individuals.

7.9 Phylogeny

A **cladogram** shows branching order. Each node is a common ancestor; sister taxa share the most recent ancestor. Groups are built from **shared derived characters**, and an **outgroup** roots the tree. A **monophyletic** group contains an ancestor and all its descendants. Molecular data (sequence differences) support or refine trees; a **molecular clock** converts divergence to time using a mutation-rate estimate.



Reading a cladogram

Closeness of relationship = recency of a shared node, not distance along the page.

Rotating branches at a node does not change relationships.

Convergent traits can mislead; use many characters.

7.10 Speciation

Under the **biological species concept**, species are populations that interbreed and produce fertile offspring but are reproductively isolated from others. Prezygotic barriers act before fertilization (habitat, temporal, behavioral, mechanical, gametic); postzygotic barriers act afterward (hybrid inviability or sterility). **Allopatric** speciation starts with geographic isolation, then divergence by selection and drift; **sympatric** speciation occurs without separation, as in polyploidy. Speciation is not the same as adaptation.

7.11 Variations in Populations

Genetic diversity gives a population more chances that some members survive a changing environment; small populations that lose alleles to drift are more vulnerable.

7.12 Origins of Life on Earth

Earth is about 4.5 billion years old, and early life appeared more than 3.5 billion years ago in a low-oxygen world. Experiments simulating early conditions made amino acids and other small organic molecules, supporting **abiotic synthesis**. In the **RNA world** hypothesis, RNA could store information and act as a catalyst (ribozyme), so it may have preceded DNA and proteins. Lipid vesicles may have formed protocells, and endosymbiosis later produced eukaryotes. These are scientific hypotheses supported by evidence, not settled history.

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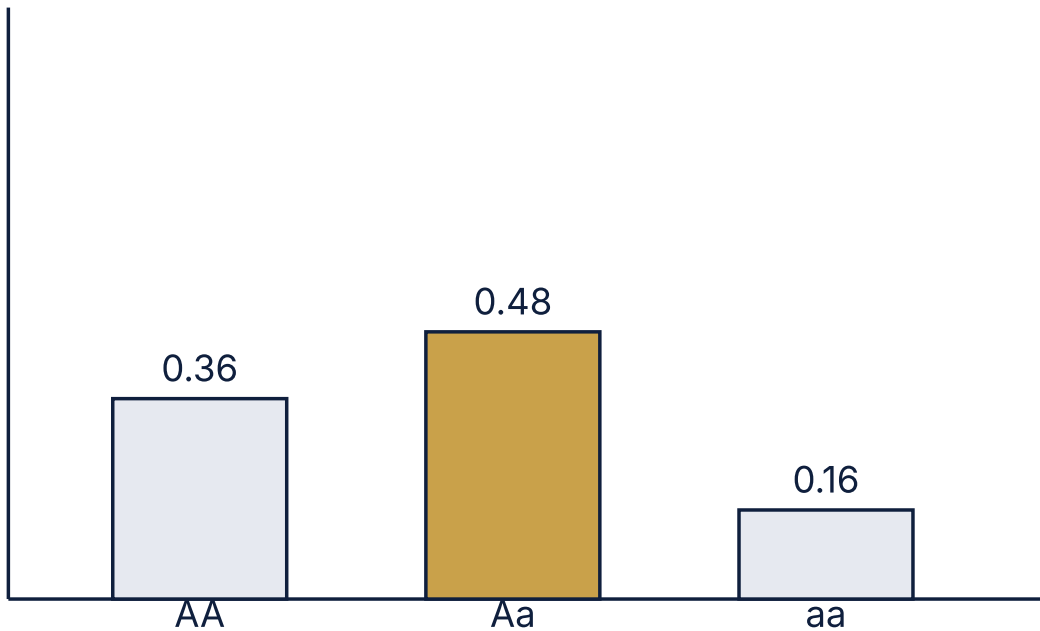
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Worked Examples

EXAMPLE 1: HARDY-WEINBERG

In a population of 1,000 plants, 16% show the recessive trait (aa). Assume equilibrium. Find p , q and the number of heterozygous plants.

Expected genotype frequencies when $p = 0.6$, $q = 0.4$



Hardy-Weinberg expectations. Bar heights are frequencies (sum = 1).

SOLUTION

$q^2 = 0.16$, so $q = 0.40$ and $p = 1 - 0.40 = 0.60$.

Heterozygotes: $2pq = 2(0.60)(0.40) = 0.48$, so 480 plants. For comparison, AA = 0.36 (360) and aa = 160.

Check: $0.36 + 0.48 + 0.16 = 1$.

EXAMPLE 2: SELECTION OVER TIME

Allele a has $q = 0.50$. All aa individuals fail to reproduce each generation. Using $q' = q/(1 + q)$, give q for generations 1 to 4 and explain the pattern.

Generation	0	1	2	3	4
q	0.500	0.333	0.250	0.200	0.167
aa frequency	0.250	0.111	0.063	0.040	0.028

SOLUTION

Gen 1: $0.5/1.5 = 0.333$; Gen 2: $0.333/1.333 = 0.25$; Gen 3: $0.25/1.25 = 0.20$; Gen 4: $0.20/1.20 = 0.167$.

Selection lowers q every generation, but the drop slows because rare a alleles are mostly in heterozygotes (Aa), which are not removed.

So selection against a recessive phenotype is slow to eliminate the allele.

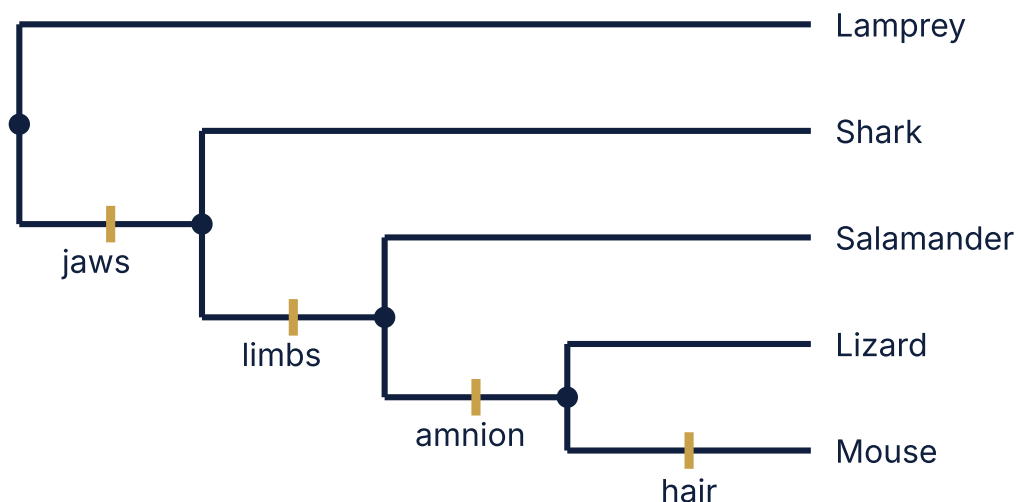
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EXAMPLE 3: READING A CLADOGRAM

In the cladogram above, which trait is shared by the lizard and the mouse but not the salamander, and which taxon is the sister group of the lizard-mouse clade? Justify.



Cladogram. Gold ticks mark where a shared derived trait arises; dots are common ancestors.

SOLUTION

The lizard and mouse share the amnion, a derived trait that arises on the branch leading to their common ancestor. Their sister group is the salamander; the three share limbs, so they are a monophyletic group. Hair is an extra derived trait on the mouse branch.

EXAMPLE 4: FOUNDER EFFECT

A beetle source population has $p = 0.70$ for A. Five beetles (1 AA, 2 Aa, 2 aa) found a new island population. Find p in the founders, compare, and give the aa frequency expected later at random mating.

SOLUTION

Founders carry 10 alleles. A copies = $2(1) + 2(1) = 4$, so $p = 4/10 = 0.40$.

The frequency fell from 0.70 to 0.40 by chance sampling, not selection: a founder effect (genetic drift).

If $p = 0.40$ persists, then $q = 0.60$ and $aa = 0.36$, versus 0.09 in the source population.

EXAMPLE 5: MOLECULAR CLOCK

Species X and Y differ at 24 of 1,200 sites; species Z differs from X at 60 sites. If paired lineages diverge at 0.2% per million years, estimate each divergence time and the likely branching order.

SOLUTION

X-Y: $24/1,200 = 2.0\%$, so $2.0 / 0.2 = 10$ million years.

X-Z: $60/1,200 = 5.0\%$, so $5.0 / 0.2 = 25$ million years.

Z split earlier; X and Y are sister species and Z is the outgroup. Assumes a roughly constant rate.

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Write It Like a 5

Model Response

Prompt: A bacterial population is exposed to an antibiotic and the proportion of resistant cells rises from 0.1% to 90% in a few days. Explain. Response: The population already contained heritable variation, including a few cells with a resistance allele. The antibiotic acted as a selective pressure that killed most susceptible cells, so resistant cells survived and reproduced more, passing the allele on. Allele frequency in the population therefore increased. The drug did not cause the mutation; it selected among existing variants, so this is evolution by natural selection.

What the grader looks for

Existing heritable variation; named selective pressure; differential survival and reproduction; change in allele frequency in the population; no claim that individuals changed or needed to adapt.

Coach's Playbook

- 1 Always state whether you are talking about alleles, genotypes or phenotypes before using a number.
- 2 In Hardy-Weinberg, start from the recessive phenotype, then q , then p , then $2pq$.
- 3 Cause then effect: variation, pressure, differential survival, heritability, allele frequency change.
- 4 For trees, name the shared derived trait and the node, not just 'they look alike'.

Common traps

1) Saying individuals evolve or organisms 'adapt because they need to'. 2) Using 'adaptation' for speciation or any change. 3) Treating a Hardy-Weinberg mismatch or any DNA difference as proof of selection. 4) Swapping phenotype frequency with allele frequency, for example using q^2 as q .

Quick Check

Q: Which force changes allele frequency most in a tiny population? A: Genetic drift. Q: Hardy-Weinberg: if $q = 0.3$, what is $2pq$? A: $2(0.7)(0.3) = 0.42$.

Challenge Corner

A population has $p = 0.80$. After a flood kills 90% of the habitat, 10 survivors by chance carry 3 of 20 alleles as a . Compute the new q and explain the cause. Solution: $q = 3/20 = 0.15$ versus 0.20 before: it dropped by chance from a bottleneck (drift), not by selection. With so few survivors, diversity is lower and drift stays strong.

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Practice

PRACTICE Unit 7 Practice

Show your work. A calculator is allowed. Justify conclusions.

- Which statement about a population of moths turning darker over several generations is correct?
 - Individual moths darkened to match the soot.
 - The frequency of alleles for dark color increased in the population.
 - Moths needed dark color, so mutations for it appeared.
 - Dark color was acquired and passed to offspring.
- In a population at Hardy-Weinberg equilibrium, 9% of individuals have a recessive trait. What percent are heterozygous carriers?
 - 21%
 - 30%
 - 42%
 - 49%
- During a drought finches with larger beaks survive better and later generations have larger average beaks. This is an example of:
 - directional selection
 - stabilizing selection
 - disruptive selection
 - genetic drift
- Use the character table to choose the two taxa most closely related.

Taxon	Char 1	Char 2	Char 3	Char 4
T (outgroup)	0	0	0	0
R	1	0	0	0
Q	1	1	0	0
P	1	1	1	0
S	1	1	1	1

- Q and R
 - R and S
 - Q and T
 - P and S
- Two frog species live in the same pond, but one breeds in early spring and the other in summer. This is:
 - a postzygotic barrier
 - a temporal prezygotic barrier
 - hybrid sterility
 - gametic isolation
 - Which observation best supports the RNA world hypothesis?
 - Proteins fold into specific shapes.
 - DNA is double-stranded.
 - Some RNA molecules store information and also catalyze reactions.
 - Lipids form bilayers in water.
 - A field survey counts 2,000 flowers; 320 are white (recessive, aa) and the rest are purple. Assume Hardy-Weinberg equilibrium.
 - Calculate q and p.
 - Calculate the expected number of heterozygous flowers.
 - A later survey finds $q = 0.50$. Explain what this shows and propose one cause with justification.
 - Researchers place 100 green and 100 brown beetles on green soil and 100 of each on brown soil for 24 hours. Survivors: green on green 82, brown on green 55, green on brown 48, brown on brown 79.
 - Identify the independent and dependent variables.
 - Calculate the percent survival for each group.
 - Make a claim supported by the data and explain the selective agent.
 - Predict allele frequency over generations on green soil.
 - Sequence differences (out of 500 sites) for four species: A-B 10, A-C 40, B-C 40, A-D 60, B-D 60, C-D 60.
 - Identify the two most closely related species and justify.
 - If a pair diverges 0.5% per million years, estimate the time since A and B split and since A and D split.
 - Species A and D both have wings, but wing structure arose separately. Name this pattern and explain why it can mislead a tree.

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10. A river forms and splits a lizard population in two.
- (a) Describe how this could lead to allopatric speciation.
 - (b) Give one prezygotic and one postzygotic barrier that could then keep the lineages separate.
 - (c) State why the origin of life by chemical evolution is a hypothesis, and give one experimental line of support.

Answers**Unit 7: Answers and Explanations**

Read every explanation, including the ones for problems you answered correctly.

7 Natural Selection**PRACTICE · UNIT 7 PRACTICE**

1. B. Selection changes allele frequencies in the population; individuals do not evolve. Choice C is the common 'need' error: mutations arise at random, before the pressure.
2. C. $q^2 = 0.09$, so $q = 0.30$, $p = 0.70$ and $2pq = 0.42$. Choice B (30%) mistakes q for the carrier frequency.
3. A. One extreme is favored and the mean moves in one direction. Stabilizing selection would favor the middle and narrow the range.
4. D. P and S share three derived characters (1, 2, 3), more than any other pair; T is the outgroup. Q and R are tempting because they are listed together, but they share fewer.
5. B. Differences in breeding time prevent mating before fertilization, so it is prezygotic. Postzygotic barriers operate after the zygote forms.
6. C. Ribozymes show that RNA can store information and catalyze, so it could have served both roles early on. Choice D relates to protocells, not an information-and-catalysis system.
7. (a) $q^2 = 320/2000 = 0.16$, so $q = 0.40$ and $p = 0.60$. (b) $2pq = 2(0.60)(0.40) = 0.48$, so $0.48 \times 2000 = 960$ flowers. (c) The allele frequency changed (0.40 to 0.50), so the population is evolving; at least one equilibrium condition is violated. A possible cause: pollinators prefer white flowers (selection), so white alleles leave more offspring. Justify by linking preference to differential reproduction.
8. (a) Independent: beetle color and soil color. Dependent: survival after 24 hours. (b) 82%, 55%, 48% and 79%. (c) Beetles survive better on matching soil, so predators likely select against conspicuous beetles; color-matched beetles have higher fitness. (d) If color is heritable, the green allele frequency increases each generation on green soil as green beetles leave more offspring.
9. (a) A and B: 10 differences, the fewest, so they share the most recent ancestor. (b) A-B: $10/500 = 2\%$, so $2 / 0.5 = 4$ million years. A-D: $60/500 = 12\%$, so $12 / 0.5 = 24$ million years. (c) Convergent evolution gives analogous traits. They resemble each other without recent common ancestry, so many characters and molecular data are needed.
10. (a) The river stops gene flow. Each side experiences different selection, mutation and drift, so allele frequencies diverge over time until members can no longer interbreed. (b) Prezygotic: behavioral isolation (courtship display not recognized). Postzygotic: hybrid sterility. (c) It cannot be directly observed; support: experiments simulating early-Earth conditions that produce amino acids and other small organic molecules (abiotic synthesis).

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Unit 8: Ecology

Exam weighting: about 10-15% of the multiple-choice section. Concept review, worked examples, exam-style writing, and 10 practice items, all with full explanations.

8 Ecology

Follow energy through food webs, model population growth, and predict how species interactions, biodiversity, and disturbance shape communities.

Why This Matters

Ecology is worth 10-15% of the multiple-choice score, and it is the unit where graphs, equations, and cause-and-effect reasoning meet. The exam asks you to read food webs, apply growth models, and predict what happens when one species or one resource changes. Students lose points by mixing up population, community, and ecosystem, by treating a food web as a simple chain, and by naming an effect without tracing how it spreads.

Core Ideas

8.1 Responses to the Environment. Organisms detect cues (light, temperature, chemicals, day length) and respond in ways that improve survival and reproduction. Responses include plant tropisms, flowering controlled by day length, hibernation, migration, pheromone signaling, and cooperative behavior such as group foraging. Behavior with a genetic basis can be shaped by natural selection; learned behavior depends on experience. Either way, the test is the same: does the response raise fitness in that environment?

8.2 Energy Flow Through Ecosystems. Energy enters ecosystems mostly as light captured by autotrophs, passes to heterotrophs through feeding, and leaves as heat. Matter, by contrast, is recycled. At each transfer most energy is used for metabolism, lost as heat, or left in unconsumed or undigested material, so roughly 10% moves up a trophic level. This limits the number of levels and the abundance of top predators.

Productivity

Gross primary productivity (GPP) is the total energy captured by producers. **Net primary productivity (NPP)** is what remains after producers use energy for their own respiration.

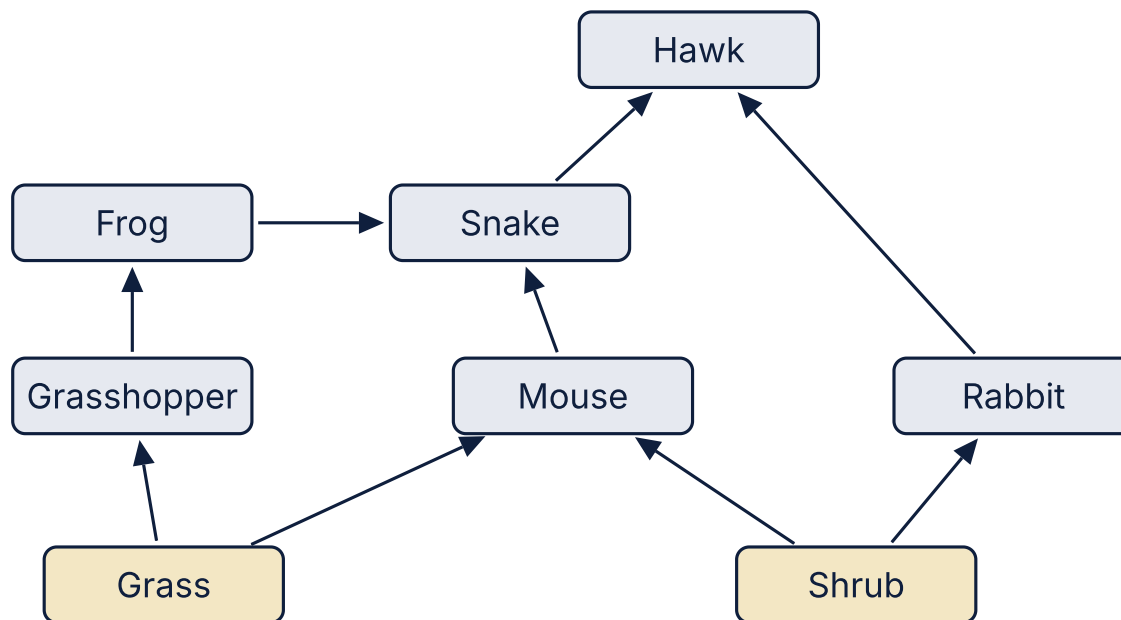
$$NPP = GPP - R$$

Only NPP is available as food for consumers and decomposers.

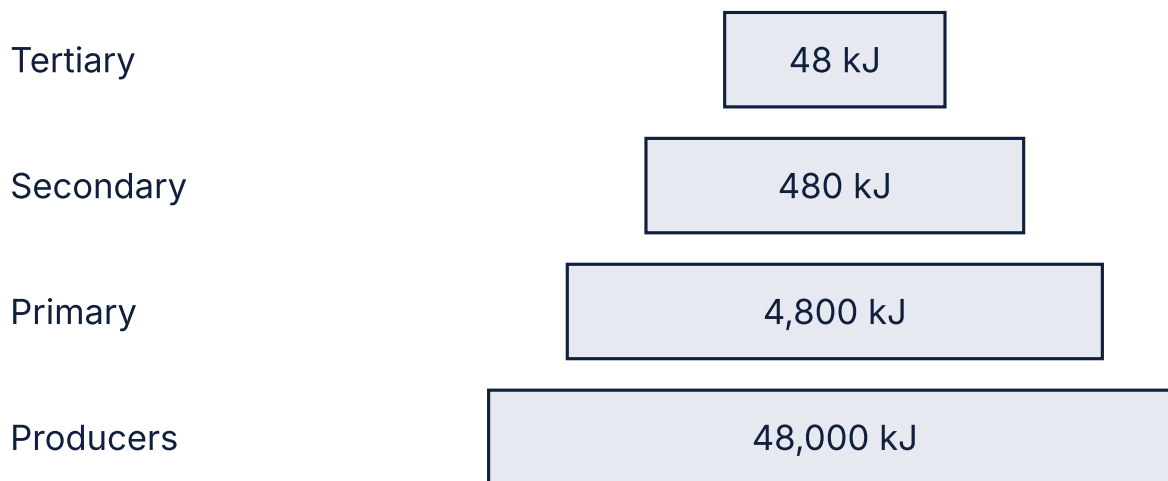
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A food web. Arrows point from the organism that is eaten to the organism that eats it, the direction of energy flow. Grass and Shrub are producers; the snake eats both a mouse and a frog, so it occupies more than one trophic level.



Energy pyramid for a meadow (kJ per square meter per year, about 10 percent passed up each step; bar widths are not to scale).

Energy needs also scale with how an organism regulates temperature. Endotherms spend much of their intake on heat production, so they convert less food into body mass than ectotherms of similar size. Total energy, not just population size, sets how many organisms a level can support.

8.3 Population Ecology. A **population** is a group of the same species living in the same area. Growth is the balance of births, deaths, immigration, and emigration. With unlimited resources, growth is exponential; with limits, it is logistic.

Growth Models

Exponential: $\frac{dN}{dt} = r_{max}N$ (J-shaped curve; growth rate rises as N rises).

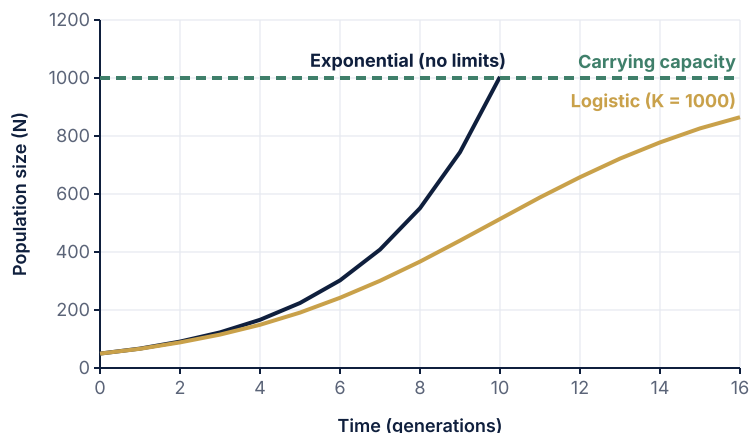
Logistic: $\frac{dN}{dt} = r_{max}N \left(\frac{K - N}{K} \right)$ (S-shaped curve). K is the carrying capacity, the largest population the environment can sustain.

Logistic growth is fastest at $N = K/2$ and falls to zero at $N = K$.

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Both populations start at $N = 50$ with $r(\text{max}) = 0.3$. The logistic curve levels off near K .

8.4 Effect of Density on Populations. Density-dependent factors act more strongly as crowding increases: competition for food or space, disease, predation, waste buildup, and territorial behavior. Density-independent factors act regardless of crowding: fire, flood, hurricane, drought, or a sudden freeze. Density-dependent limits are what create a carrying capacity.

8.5 Community Ecology. A **community** is all the populations interacting in an area. Interactions are classed by their effect on each partner.

Interaction	Effect (A / B)	Example idea
Competition	- / -	Two plants share limited light
Predation, herbivory	+ / -	Hawk eats a mouse; deer browse shrubs
Parasitism	+ / -	Tick feeds on a host and rarely kills it quickly
Mutualism	+ / +	Pollinator gets nectar, plant gets pollen moved
Commensalism	+ / 0	Epiphyte uses a tree for support

Two species cannot indefinitely occupy the same niche; one is excluded (**competitive exclusion**) or they divide resources (**resource partitioning**). A **keystone species** has an effect on community structure far larger than its abundance would suggest. An **invasive species** arrives with few natural controls and can displace natives. After a disturbance, **succession** replaces communities over time: primary succession starts on bare rock or new land with no soil, secondary succession on soil that remains.

8.6 Biodiversity. Biodiversity includes genetic variation, species variety, and ecosystem variety. **Species richness** counts species; **evenness** describes how equally individuals are spread among them. Simpson's index combines both.

Simpson's Diversity Index

$$D = 1 - \sum \left(\frac{n}{N} \right)^2$$

n = individuals of one species, N = all individuals. Values near 1 mean high diversity; values near 0 mean one species dominates. (Check your sheet: some versions leave out the "1 -".)

Diverse communities usually withstand disturbance better, because different species fill similar roles and some survive when others fail. Low genetic diversity leaves a population exposed to a single disease or environmental change.

8.7 Disruptions in Ecosystems. Natural disruptions (fire, flood, eruption) and human ones (habitat loss, pollution, overharvest, invasive species, climate change) alter energy flow and species interactions. Warming can shift ranges and break timing between species, such as flowering and pollinator emergence. Rising atmospheric CO_2 dissolves in the ocean and lowers pH, harming shell builders. Removing a keystone species can set off a trophic cascade through the whole web.

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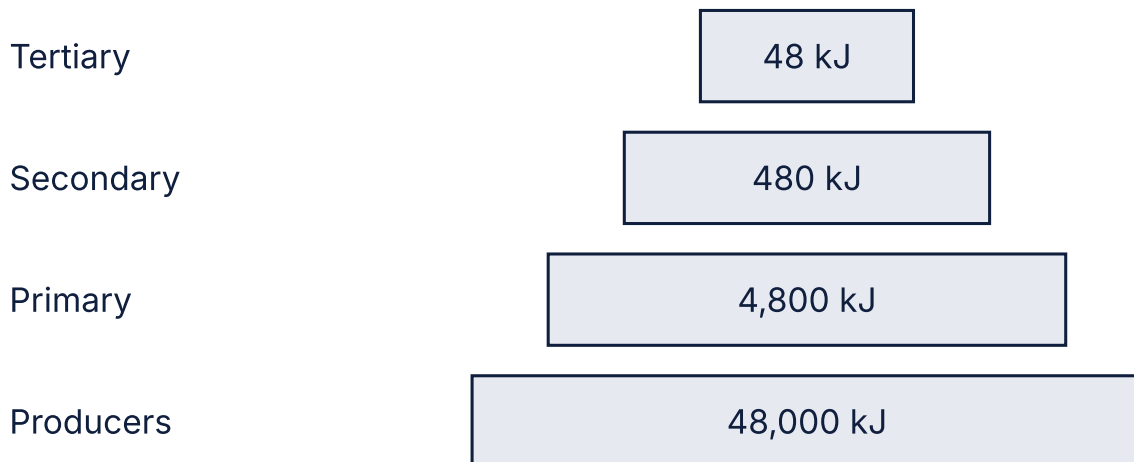
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Worked Examples

EXAMPLE 1: ENERGY TRANSFER

Meadow producers fix 48,000 kJ per square meter per year. Assuming 10% transfer, how much energy reaches secondary consumers? Why are top predators rare?



Energy pyramid for a meadow (kJ per square meter per year, about 10 percent passed up each step; bar widths are not to scale).

SOLUTION

Primary consumers: $48,000 \times 0.10 = 4,800$ kJ.

Secondary consumers: $4,800 \times 0.10 = 480$ kJ.

Each transfer loses about 90% as heat, respiration, and uneaten material, so little energy remains for the top level to support many individuals.

EXAMPLE 2: NET PRIMARY PRODUCTIVITY

A pond's algae capture $1,500 \text{ kJ/m}^2/\text{day}$ (GPP) and use $600 \text{ kJ/m}^2/\text{day}$ in respiration. Find NPP and the percent of GPP respired.

SOLUTION

$\text{NPP} = 1500 - 600 = 900 \text{ kJ/m}^2/\text{day}$.

Respired fraction = $600/1500 = 0.40$, or 40%.

Only the 900 kJ is available to consumers.

EXAMPLE 3: GROWTH RATES

A population has $r_{\max} = 0.25$ per generation and $K = 1000$. Compare dN/dt at $N = 200$ under exponential and logistic models, and find dN/dt at $N = 500$.

SOLUTION

Exponential: $0.25 \times 200 = 50$ individuals per generation.

Logistic at 200: $0.25 \times 200 \times (800/1000) = 40$.

Logistic at 500: $0.25 \times 500 \times (500/1000) = 62.5$, the maximum, because $N = K/2$.

The logistic rate is lower at 200 because crowding already reduces growth.

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EXAMPLE 4: DENSITY DEPENDENCE

Per capita birth and death rates were measured at four densities. Is regulation density dependent? Estimate K.

Density (per ha)	10	20	40	80
Births per individual	0.55	0.50	0.40	0.20
Deaths per individual	0.12	0.14	0.18	0.26

SOLUTION

Births fall and deaths rise as density rises, so both are density dependent.

K is where births equal deaths. At 40/ha births exceed deaths by 0.22; at 80/ha deaths exceed births by 0.06.

The crossing lies between: $40 + 40 \times 0.22/0.28 \approx 71$ per ha.

EXAMPLE 5: COMPARING DIVERSITY

Two plots each hold 4 species and 100 plants. Plot A: 40, 30, 20, 10. Plot B: 85, 5, 5, 5. Compare using Simpson's index and explain.

SOLUTION

A: $1 - (0.16 + 0.09 + 0.04 + 0.01) = 0.70$.

B: $1 - (0.7225 + 3 \times 0.0025) = 0.27$.

Richness is equal (4), but B is uneven. Plot A is more diverse and likely more resilient: losing one species leaves several others filling its role.

Write It Like a 5**Model Response**

Prompt: A predatory fish is introduced into a lake that held three native minnow species, zooplankton, and algae.

Predict and explain two effects on the community. Answer: The fish will reduce minnow populations through predation, and if one minnow is a superior competitor, the survivors may shift in relative abundance. With fewer minnows eating zooplankton, zooplankton will increase, which will increase grazing on algae and lower algal biomass. This is a trophic cascade: a change at the top propagates down because each level controls the one below it. Species richness may fall if a minnow is eliminated, lowering biodiversity and resilience.

What the grader looks for

(1) A specific, directional prediction for a named population. (2) A mechanism that links cause to effect (predation lowers minnows, so zooplankton rise). (3) A second effect further down the web. (4) Correct terms (trophic cascade, biodiversity), not just restated data.

Coach's Playbook

- 1 Identify the level: individual, population, community, or ecosystem.
- 2 On any food web, trace each arrow as energy flow before predicting.
- 3 For growth questions, decide exponential or logistic from whether limits appear.
- 4 For every prediction, write "because" and name the mechanism.

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Common traps

(1) Using population, species, and community as synonyms. (2) Reading a keystone loss as a one-link chain effect rather than a change in biodiversity and resilience. (3) Calling a flood or fire density dependent. (4) Saying ten percent of the energy is "used up"; it is lost as heat and unused material, not destroyed.

Quick Check

Q1: What does an arrow in a food web show? A: Energy moves from the eaten to the eater. Q2: At what N is logistic growth fastest? A: $N = K/2$. Q3: Name one density-independent factor. A: A wildfire (or flood, freeze, or drought).

Challenge Corner

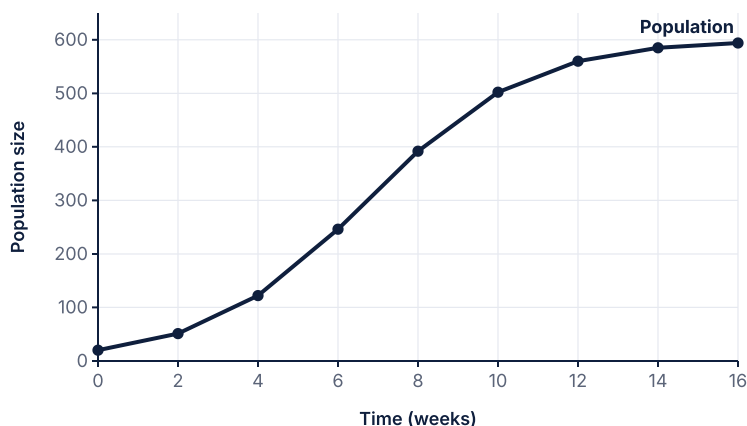
A population with $N_0 = 100$, $r_{max} = 0.4$ per year and $K = 500$ grows by the logistic equation each year. Find N after three years and tell whether growth is faster in year 4 than in year 3. Solution: Year 1: $\Delta N = 0.4 \times 100 \times 0.8 = 32$, so $N = 132$. Year 2: $0.4 \times 132 \times (368/500) = 38.9$, $N = 170.9$. Year 3: $0.4 \times 170.9 \times (329.1/500) = 45.0$, $N = 215.9$, about 216. In year 4 $\Delta N = 0.4 \times 215.9 \times (284.1/500) = 49.1$, which exceeds 45.0, because N is still below $K/2 = 250$, where growth rate peaks.

Practice

PRACTICE Unit 8 Practice

Show your work. A calculator is allowed. Justify conclusions.

- Producers in a lake fix 100,000 kJ of energy. About how much reaches tertiary consumers if 10% is transferred at each step?
(A) 10,000 kJ (B) 1,000 kJ (C) 100 kJ (D) 10 kJ
- Which factor is density independent?
(A) Spread of a respiratory infection in a crowded herd
(B) Competition among seedlings for light
(C) Territorial fighting in a nesting colony
(D) A severe freeze that kills a fixed fraction of insects in a meadow
- Using the graph, during which two-week interval is the population growing fastest?



Growth of a population of yeast-eating mites in a culture.

- (A) 0 to 2 weeks (B) 6 to 8 weeks (C) 4 to 6 weeks
(D) 12 to 14 weeks

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4. Two beetle species eat the same flour in one jar. After several generations only one remains. This outcome is best called
 (A) competitive exclusion (B) mutualism (C) commensalism
 (D) resource partitioning
5. A community has two species, 90 individuals of one and 10 of the other. What is Simpson's index ($D = 1 - \text{sum of squared proportions}$)?
 (A) 0.82 (B) 0.90 (C) 0.50 (D) 0.18
6. Warming causes a shrub to flower two weeks earlier, but its bee pollinator still emerges at the old date. The most likely result is
 (A) increased seed production because flowers last longer
 (B) lower pollination success and seed set
 (C) faster evolution of the bee in one generation
 (D) no effect, because pollination depends only on bee abundance
7. A culture of water fleas gave these counts. Day 0: 10; day 2: 24; day 4: 52; day 6: 95; day 8: 128; day 10: 142; day 12: 145.
 (a) Identify the growth model and estimate the carrying capacity.
 (b) Calculate the average growth rate per day between day 4 and day 6.
 (c) Design an experiment testing whether food supply affects the carrying capacity, naming the independent variable, dependent variable, and one control.
 (d) Predict the effect of doubling food and justify.
8. A bay's phytoplankton have GPP of $15,000 \text{ kJ/m}^2/\text{yr}$ and respire $6,000 \text{ kJ/m}^2/\text{yr}$.
 (a) Calculate NPP.
 (b) Assume 10% transfer. How much energy reaches zooplankton and then small fish?
 (c) Explain why food chains rarely exceed four or five levels.
 (d) A bloom kills half the phytoplankton. Predict the effect on small fish and justify.
9. Species X and Y were raised alone and together on the same food. Mean population after 30 days: X alone 100, X with Y 60; Y alone 80, Y with X 30.
 (a) Calculate the percent change in each species.
 (b) Identify the interaction and justify with the data.
 (c) Explain how resource partitioning could allow coexistence.
10. A forest plot has 4 plant species. Before an invasive vine arrived the counts were 50, 30, 15, 5; two years later they were 90, 6, 4, 0.
 (a) Calculate Simpson's index ($1 - \text{sum}$) for each date.
 (b) Describe how biodiversity changed, separating richness and evenness.
 (c) Explain one way the loss of diversity could reduce ecosystem resilience.

Answers Unit 8: Answers and Explanations

Read every explanation, including the ones for problems you answered correctly.

8 Ecology

PRACTICE · UNIT 8 PRACTICE

1. C. Three transfers from producers (primary, secondary, tertiary consumers) give $100,000 \times 0.1 \times 0.1 \times 0.1 = 100 \text{ kJ}$. Choice B counts only two transfers.
2. D. A freeze kills regardless of how crowded the insects are. The infection, light competition, and territoriality all intensify with crowding, so they are density dependent.
3. B. The population rises from about 246 to 392 (about 146) in weeks 6-8, near $N = K/2 = 300$. Weeks 4-6 add only about 124. Late intervals add little as N nears K.
4. A. Species with the same niche compete and the weaker is eliminated. Resource partitioning would let both persist by using different resources.
5. D. $D = 1 - (0.9^2 + 0.1^2) = 1 - 0.82 = 0.18$. Choice B is the sum of squares left unsubtracted, and 0.50 would require an even split.
6. B. Flowers open before the pollinator is active, so fewer are pollinated. The timing mismatch is the mechanism; abundance alone does not guarantee a visit at the right time.
7. (a) Logistic (S-shaped): growth slows and levels off near 145, so K is about 145. (b) $(95 - 52)/2 = 21.5$ individuals per day. (c) Independent variable: food amount per culture (for example 1, 2, 4 units); dependent variable: population size at the plateau; constants: volume, temperature, light, starting number; control group: the standard food amount used so far (or a replicate set with no change), with several replicate cultures per level. (d) K should increase, because food is a limiting resource and more food supports more individuals before density-dependent factors balance births and deaths.

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8. (a) $NPP = 15,000 - 6,000 = 9,000 \text{ kJ/m}^2/\text{yr}$. (b) Zooplankton: 900 kJ; small fish: 90 kJ. (c) About 90% of energy is lost as heat and unused material at each step, so little remains at higher levels to support populations. (d) Small fish decline, because lower NPP means less energy passed to zooplankton and then to fish (about half as much at each level).
9. (a) X: $(60-100)/100 = -40\%$. Y: $(30-80)/80 = -62.5\%$. (b) Competition (-/-): each does worse with the other present, Y more strongly, showing both use the same limiting resource. (c) If the species used different foods, microhabitats, or feeding times, niche overlap and competition would shrink, so each could keep a stable population.
10. (a) Before: $1 - (0.25 + 0.09 + 0.0225 + 0.0025) = 0.635$. After ($N = 100$): $1 - (0.81 + 0.0036 + 0.0016) = 0.185$. (b) Richness fell from 4 to 3 species and evenness fell because one species now dominates. (c) With fewer species filling roles, a disease, drought, or pest affecting the dominant species would remove most of the community, with few alternatives to maintain the ecosystem.

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Workshop: Experimental Design, Graphs, and Statistics

Skills that earn points on every free-response section.

W Workshop: Experimental Design, Graphs, and Statistics

Learn to name variables and controls, write hypotheses, build graphs with error bars, judge differences between groups, and run a chi-square test, the data skills that appear in every free-response set.

Why This Matters

Every AP Biology free-response question asks you to reason like a scientist, and two of the six are built around experiments and data, one of them with a graph you must draw. This workshop pulls the shared toolkit into one place: designing a test, graphing it, judging whether groups differ, and running a chi-square test. These skills are scored on every exam, whatever the unit.

Reader reports show where points leak. Students define a control as 'matching conditions' instead of the group that lacks the independent variable. They write null hypotheses that predict a direction. They leave off axis labels, choose a bad scale, or omit error bars. They call raw differences meaningful without asking whether error bars overlap. Each of those is fixed below.

Designing the Experiment

Start by naming the variables. The **independent variable** is what the investigator deliberately changes. The **dependent variable** is what is measured in response. **Controlled (constant) variables** are other factors held the same so they cannot explain the result. The **control group** is the group that does not receive the independent variable (or receives the baseline or a placebo), so it shows what happens without the treatment.

Variables and controls

Independent variable: the one factor you change on purpose.

Dependent variable: the measurement that might change because of it.

Control group: lacks the independent variable; it shows the treatment, not something else, caused the change.

Constant variables: temperature, time, volume, light and so on, kept equal across groups.

Next, **replication**. A single plant, tank or tube could differ by chance. Use several independent replicates per group (and repeat the whole trial if possible) so you can calculate a mean and a measure of spread. A larger sample size narrows the uncertainty in the mean. Replicates must be separate units, not repeated measurements of one unit.

Then write a **hypothesis** and a **prediction**. A hypothesis is a testable, explained claim about cause: 'Higher salt concentration lowers hatching because water leaves developing embryos by osmosis.' A prediction is the specific outcome you expect if it is true, in 'if ... then ...' form: 'If salt concentration rises from 0 to 15 g/L, then the percent hatching will fall.' The **null hypothesis** says there is no effect or no difference, and it never predicts a direction: 'Salt concentration has no effect on percent hatching.'

When you design a procedure on paper, say what is changed, what is measured and how often, what is held constant, what the control is and why it is needed, and how many replicates there are. Justify the control by what it rules out ('shows hatching without added salt, so any drop is due to salt'), not by calling it a 'baseline'.

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Choosing and Building Graphs

Graph	Use it when	Notes
Line graph	Independent variable is continuous (time, temperature, concentration) and you want a trend or rate	Connect points; read rate as slope, change in y over change in x
Bar graph	Independent variable is categories or separate treatments	Plot group means; add error bars
Scatter plot	Two measured variables, looking for association	Do not connect points; a trend line is optional; correlation is not causation

Graph checklist (what readers score)

Independent variable on the x-axis, dependent on the y-axis.

Both axes labeled with the quantity and units.

Even, sensible scale that uses most of the grid; start at zero for bars.

Points or bar heights plotted accurately; a title or caption.

Error bars on means when data supply them, and a note of what they show (SEM or 95% CI).

Reading Error Bars

A mean from a sample is an estimate. The **standard error of the mean** is $SEM = s / \sqrt{n}$, where s is the sample standard deviation and n the number of replicates. A **95% confidence interval** is about $\bar{x} \pm 2 SEM$ for reasonably large samples, so a 95% CI bar is roughly twice as long as an SEM bar. Always check which one the figure uses.

Rules of thumb: if 95% CI bars of two means do not overlap, the difference is very likely significant at the 0.05 level. If they overlap by a lot, the data are consistent with no real difference. If they barely overlap, you cannot tell from the picture and need a test. SEM bars are shorter, so SEM bars that overlap tell you the 95% CIs overlap even more; SEM bars with a clear gap suggest a real difference. These are simplifications, not a substitute for a statistical test.

Chi-Square Test

Use chi-square to compare observed counts in categories to the counts expected under a null hypothesis, for example a genetic ratio.

Chi-square steps

State the null hypothesis (observed counts fit the expected ratio; differences are due to chance).

Compute expected counts: total times each expected proportion.

Calculate $\chi^2 = \text{sum of } (o - e)^2 / e \text{ over all categories.}$

Degrees of freedom = number of categories - 1.

Compare with the critical value at $p = 0.05$. If calculated value is greater than critical, reject the null; if not, fail to reject.

Conclude in words about the biology.

Failing to reject does not prove the null true; it means the deviation is small enough to be explained by chance. Rejecting means the data do not fit the expected ratio, which suggests a different inheritance pattern, linkage, selection, or another factor.

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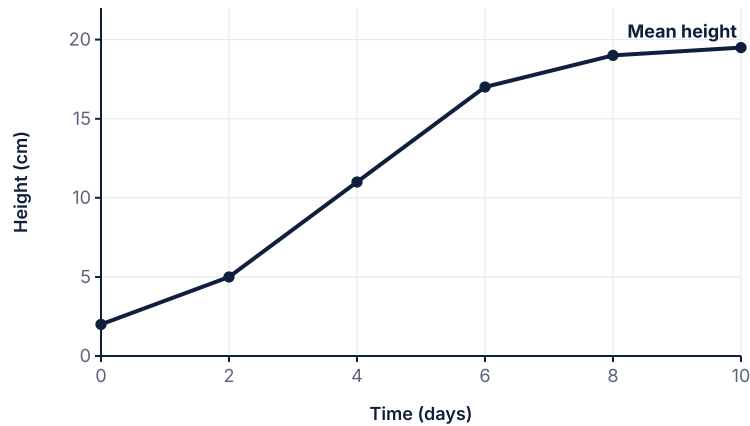
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Worked Examples

EXAMPLE 1: READING A RATE FROM A LINE GRAPH

Seedlings were grown under steady light and their mean height recorded. Describe the trend and calculate the growth rate from day 2 to day 6.



Seedling height over time

SOLUTION

Trend: height rises slowly at first, fastest between days 2 and 6, then levels off near 19 to 20 cm by day 8 to 10.

Rate = change in height / change in time = $(17 - 5) \text{ cm} / (6 - 2) \text{ days} = 3.0 \text{ cm per day}$.

Reasoning: the leveling off suggests growth is limited by something such as space or resources after day 8.

EXAMPLE 2: COMPARING MEANS WITH ERROR BARS

Ten pots per group received 0, 2 or 4 g of fertilizer. The table gives mean dry mass with the standard deviation. Calculate SEM and 95% CI (mean plus or minus 2 SEM) and decide which groups clearly differ.

Group	Mean mass (g)	SD	n	SEM	95% CI
0 g (control)	4.2	0.9	10	0.28	3.6 to 4.8
2 g	5.1	1.0	10	0.32	4.5 to 5.7
4 g	6.6	1.2	10	0.38	5.8 to 7.4

SOLUTION

SEM = SD / $\sqrt{10}$: $0.9/3.16 = 0.28$; $1.0/3.16 = 0.32$; $1.2/3.16 = 0.38$.

CI = mean $\pm$ 2 SEM gives 3.6 to 4.8, 4.5 to 5.7, and 5.8 to 7.4.

The 0 g and 4 g intervals do not overlap, so those means very likely differ. The 4 g interval (5.8 to 7.4) also sits just above the 2 g interval (4.5 to 5.7), so these differ too.

The 0 g and 2 g intervals overlap (4.5 to 4.8), so the data do not clearly show that 2 g changed mass; a test would be needed.

Claim and justification: more fertilizer increased mass, supported by non-overlapping intervals at the highest dose.

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EXAMPLE 3: CHI-SQUARE TEST

A cross is expected to give offspring in a 9:3:3:1 ratio. Among 160 offspring the counts are 80, 38, 28 and 14. Test the null hypothesis at $p = 0.05$ (critical value for 3 degrees of freedom is 7.81).

Phenotype	Observed	Expected	$(o-e)^2/e$
1	80	90	1.11
2	38	30	2.13
3	28	30	0.13
4	14	10	1.60

SOLUTION

Null: the offspring fit a 9:3:3:1 ratio; differences are due to chance. Expected = $160 \times 9/16 = 90$, then 30, 30, 10.

$$\chi^2 = 1.11 + 2.13 + 0.13 + 1.60 = 4.98.$$

df = 4 categories - 1 = 3; critical value 7.81.

$4.98 < 7.81$, so we fail to reject the null. The data are consistent with a 9:3:3:1 ratio; this does not prove the ratio is exactly right.

Write It Like a 5**Model Response**

Prompt: A student claims road salt reduces hatching of brine shrimp. Identify the independent and dependent variables, name the control group and justify it, and state a null hypothesis. Independent variable: salt concentration in the water. Dependent variable: percent of eggs that hatch after 48 hours. Control group: the tanks with 0 g/L added salt, because they lack the independent variable and show the hatching without salt, so any change in other tanks can be attributed to salt. Null hypothesis: salt concentration has no effect on percent hatching. (Constant: temperature, light, volume of water, number of eggs, and four replicate tanks per concentration.)

What the grader looks for

Both variables named correctly and distinguished; control defined as the group lacking the independent variable, with a reason; a null hypothesis with no direction; constants and replication mentioned; and, for graphs, labels, scale, accurate plotting and error bars.

Coach's Playbook

- 1 Underline what is changed and what is measured in the stem.
- 2 Name the control by asking which group lacks the treatment.
- 3 Write the hypothesis with a reason, the prediction with if/then, and the null with no direction.
- 4 On a graph, choose the type, label axes with units, pick a scale, plot, then add error bars.
- 5 State results with direction and size, then justify with a mechanism.

Common traps

1. Defining the control as 'same conditions' or 'a baseline' rather than the group without the independent variable.
2. Null hypothesis that says 'decrease' or 'increase'.
3. Concluding two means differ because the bars have different heights, ignoring error bars.
4. Mixing up SEM and 95% CI, or using df = number of observations instead of categories - 1.

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Quick Check

Q1: What does a control group lack? A: The independent variable. Q2: Give the chi-square df for 5 categories. A: 4. Q3: If 95% CI bars of two means do not overlap, what is likely? A: The means differ significantly.

Practice**PRACTICE Workshop Practice**

Show your work. A calculator is allowed. Justify conclusions.

- Four tanks of brine shrimp eggs contain 0, 5, 10 and 15 g/L salt, and percent hatching is measured after 48 hours. Which is the control group?
(A) The tank with 15 g/L salt
(B) The tank with 0 g/L added salt
(C) All four tanks, since they share the same temperature
(D) The tank with the highest hatching
- Mean enzyme activity is 10.0 units (95% CI 9.0 to 11.0) in group A and 11.2 units (95% CI 10.2 to 12.2) in group B. What is the best conclusion?
(A) Group B is significantly higher because 11.2 is greater than 10.0
(B) Group A is significantly higher because its interval is lower
(C) The intervals overlap substantially, so the data do not show a significant difference
(D) The intervals prove the two groups are identical
- A student expects equal numbers of two phenotypes. Out of 100 offspring, 64 and 36 are seen. Critical value at $df = 1$ and $p = 0.05$ is 3.84. What is the result?
(A) Chi-square = 7.84; reject the null hypothesis
(B) Chi-square = 3.92; reject the null hypothesis
(C) Chi-square = 7.84; fail to reject the null hypothesis
(D) Chi-square = 8.51; fail to reject the null hypothesis
- A researcher asks whether the depth of planting affects bean germination.
(a) Identify the independent and dependent variables.
(b) Name two variables that must be held constant.
(c) Write a null hypothesis and a testable prediction.
(d) Explain why replicates are used.
- Tomato plants were grown in full sun, 50% shade or 80% shade ($n = 16$ each). Mean fruit mass was 82, 70 and 48 g with standard deviations 12, 10 and 14 g.
(a) Calculate the SEM for each group.
(b) Describe how to construct a bar graph of these data, including axes, scale and error bars.
(c) Using mean plus or minus 2 SEM, state whether full sun and 80% shade differ and justify.
- A cross is expected to produce a 1:1:1:1 ratio. Among 120 offspring the counts are 38, 31, 27 and 24.
(a) State the null hypothesis and the expected count for each class.
(b) Calculate chi-square.
(c) Using the critical value 7.81, state your conclusion.

Answers**Workshop: Answers and Explanations****W Workshop: Experimental Design, Graphs, and Statistics**

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1. B. The control lacks the independent variable, which is added salt, so the 0 g/L tank is the control. Choice C describes a constant variable, which is a different idea, and it is the tempting wrong answer.
2. C. The intervals overlap by 0.8 out of a 1.0 arm, which is more than half, so the data are consistent with no difference. Choice A fails because comparing means alone ignores uncertainty.
3. A. Expected is 50 and 50; $\chi^2 = 14^2/50 + 14^2/50 = 7.84$, which exceeds 3.84, so reject. Choice B counts only one category. Choice D divides by the observed counts instead of expected.
4. (a) Independent: planting depth. Dependent: percent of seeds that germinate (or days to emergence).
(b) Any two of: soil type, water amount, temperature, light, seed variety, seed count per pot.
(c) Null: planting depth has no effect on germination. Prediction: if seeds are planted deeper, then fewer will germinate.
(d) Replicates reduce the effect of chance and individual variation, allow a mean and error to be calculated, and make conclusions more reliable.
5. (a) $SEM = SD/4$: $12/4 = 3.0$; $10/4 = 2.5$; $14/4 = 3.5$ g.
(b) Put treatment (full sun, 50% shade, 80% shade) on the x-axis and mean fruit mass (g) on the y-axis; scale 0 to 90 in even steps of 10 starting at zero; label both axes with units; draw bars at 82, 70, 48; add error bars of plus or minus the SEM (or 2 SEM) and say which in the caption.
(c) Full sun: $82 \pm 6 = 76$ to 88 g; 80% shade: $48 \pm 7 = 41$ to 55 g. The intervals do not overlap, so the means very likely differ; heavy shade reduced fruit mass.
6. (a) Null: the offspring fit a 1:1:1:1 ratio and differences are due to chance. Expected = $120/4 = 30$ each.
(b) $(38-30)^2/30 = 2.13$; $(31-30)^2/30 = 0.03$; $(27-30)^2/30 = 0.30$; $(24-30)^2/30 = 1.20$; $\chi^2 = 3.67$.
(c) $df = 3$; $3.67 < 7.81$, so fail to reject the null. The data are consistent with a 1:1:1:1 ratio.

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Mixed Practice Test

A mixed set of multiple-choice and free-response questions across all units, with answers, explanations, and scoring guidance.

T Mixed Practice Test

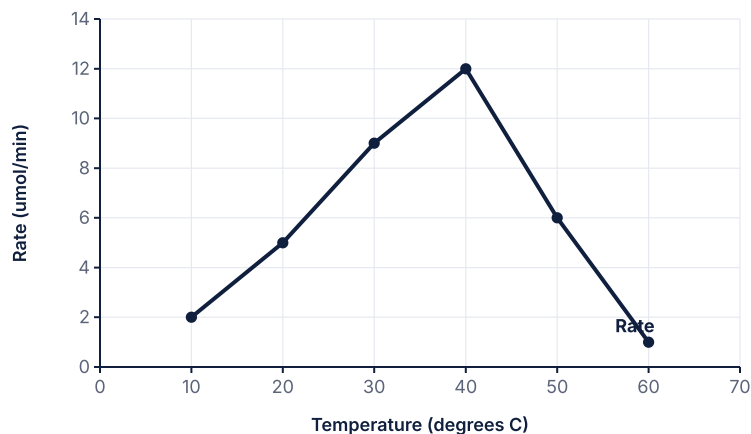
A cumulative test over all eight units, weighted like the exam, with scoring guides.

Instructions and timing (about 50 minutes): Part A is 12 multiple-choice questions (about 15 minutes). Part B is three free-response questions (about 35 minutes). A calculator is allowed. Score with the guide that follows.

PRACTICE TEST Mixed Practice Test

Part A: choose the best answer for items 1 to 12. Part B: items 13 to 15 are free response; write complete, labeled answers.

- Water molecules in a column of xylem sap stay together as water is pulled upward. This cohesion results from
 - ionic bonds between oxygen and hydrogen ions of adjacent molecules
 - hydrogen bonds between the partially positive hydrogen of one molecule and the partially negative oxygen of another
 - covalent bonds that form between hydrogen atoms of neighboring molecules
 - hydrophobic interactions among the nonpolar regions of water
- Cell X is a cube 2 micrometers on a side and cell Y is a cube 6 micrometers on a side. The surface-area-to-volume ratio of X is how many times that of Y?
 - 1/3
 - 9
 - 3
 - 27
- The graph shows the rate of an enzyme-catalyzed reaction at different temperatures. Which best explains the drop in rate from 40 to 60 degrees C?



Rate of an enzyme-catalyzed reaction.

- High temperature disrupts the bonds that maintain tertiary structure, so the active site no longer fits the substrate
- Heat breaks the peptide bonds of the enzyme into free amino acids
- The enzyme is consumed in the reaction and runs out
- All of the substrate has been converted to product

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4. A chemical makes the inner mitochondrial membrane leaky to protons. Which change is expected?
- (A) Glycolysis stops because it depends on the proton gradient
 - (B) ATP production by chemiosmosis increases because protons move faster
 - (C) The electron transport chain halts because electrons need a gradient to move
 - (D) ATP synthase makes less ATP because the proton gradient across the inner membrane is dissipated
5. A mutation disables a protein that normally pauses the cell cycle at the G1 checkpoint when DNA is damaged. The most likely consequence is that
- (A) cells stop in G1 permanently and die
 - (B) mitosis is skipped and cells enter meiosis
 - (C) cells with damaged DNA proceed to S phase and divide, increasing the chance of tumor formation
 - (D) DNA damage is repaired faster because the cycle is shorter
6. Two unlinked genes assort independently. In a cross of AaBb x AaBb (A and B dominant), what fraction of offspring is expected to show the dominant A phenotype and the recessive b phenotype?
- (A) 9/16
 - (B) 3/16
 - (C) 1/16
 - (D) 1/4
7. A base substitution changes an mRNA codon from UCA to UCG, and both codons specify serine. This mutation is
- (A) silent
 - (B) missense
 - (C) nonsense
 - (D) a frameshift
8. DNA fragments of 200, 500, 1,200, and 3,000 base pairs are separated by gel electrophoresis. Which fragment travels farthest from the wells?
- (A) 500 base pairs
 - (B) 1,200 base pairs
 - (C) 3,000 base pairs
 - (D) 200 base pairs
9. In a population in Hardy-Weinberg equilibrium, 16% of individuals show a recessive phenotype. What fraction are heterozygous?
- (A) 0.48
 - (B) 0.24
 - (C) 0.36
 - (D) 0.16
10. Which observation is the strongest evidence that all living organisms share a common ancestor?
- (A) All organisms have a cell wall made of cellulose
 - (B) Nearly all organisms use the same genetic code and have ribosomes
 - (C) All organisms carry out photosynthesis
 - (D) All organisms have mitochondria
11. A producer level fixes 50,000 kJ. If 10% of energy is transferred at each step, how much reaches secondary consumers?
- (A) 5,000 kJ
 - (B) 50 kJ
 - (C) 5 kJ
 - (D) 500 kJ
12. A population has $r(\text{max}) = 0.3$ per year and $K = 800$. Using logistic growth, what is dN/dt when $N = 400$?
- (A) 120 individuals per year
 - (B) 30 individuals per year
 - (C) 60 individuals per year
 - (D) 240 individuals per year
13. [9 points] A student cut potato cores of equal initial mass, placed groups of 10 cores in sucrose solutions at 22 degrees C for 3 hours, and recorded the percent change in mass. Data are mean percent change in mass $\pm$ standard error (SE).
Sucrose (M): 0.0 gave $+18.2 \pm 1.4$; 0.2 gave $+7.9 \pm 1.1$; 0.4 gave -3.1 ± 0.9 ; 0.6 gave -11.8 ± 1.2 ; 0.8 gave -17.5 ± 1.6 .
- (a) Identify the independent variable and the dependent variable. [1 point]
 - (b) Construct a graph of the data, with error bars. [3 points]
 - (c) Estimate the sucrose concentration at which the cores neither gain nor lose mass. [1 point]
 - (d) Using $\Psi_s = -iCRT$ with $i = 1$, $R = 0.0831 \text{ L bar/mol K}$, and $T = 295 \text{ K}$, calculate the water potential of the potato tissue in bars, and explain why the pressure potential can be taken as 0 in the solution. [1 point]
 - (e) Explain, in terms of water potential, why cores in 0.8 M sucrose lost mass. [1 point]
 - (f) State a null hypothesis for this experiment. [1 point]
 - (g) Using the error bars, evaluate whether the mean change in 0.2 M differs from that in 0.4 M. [1 point]
14. [4 points] A stream ecologist removes a predatory trout from 5 of 10 similar stream pools. Mayfly larvae, which graze algae, are counted monthly.
- (a) Identify the control group and justify it. [1 point]
 - (b) State a null hypothesis. [1 point]
 - (c) Predict the change in algae in the pools without trout and explain. [1 point]
 - (d) Explain what evidence would show that trout are a keystone species. [1 point]

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15. [4 points] In a bacterium, the trp operon is controlled by a repressor protein. The repressor is made in an inactive form. When tryptophan is abundant it binds the repressor, which then binds the operator and blocks RNA polymerase.
- (a) Explain why the genes for tryptophan synthesis are transcribed little when tryptophan is abundant. [1 point]
 - (b) A mutation changes the operator so the repressor cannot bind. Predict transcription at high tryptophan and justify. [1 point]
 - (c) A mutation prevents the repressor from binding tryptophan. Predict transcription at high tryptophan and justify. [1 point]
 - (d) Identify the type of regulation and explain its benefit. [1 point]

Key Mixed Practice Test: Answers, Explanations, and Scoring

T Mixed Practice Test

PRACTICE TEST · MIXED PRACTICE TEST

1. B. Unit 1. Water is polar, so molecules attract through hydrogen bonds, which are intermolecular. The covalent O-H bonds are inside each molecule, and water has no nonpolar regions.
2. C. Unit 2. SA/V of a cube is 6/side: $X = 3$, $Y = 1$, so X is 3 times larger. Nine is the ratio of surface areas and 27 the ratio of volumes, not of SA/V.
3. A. Unit 3. Denaturation changes the 3-D shape and the active site. Peptide bonds are covalent and survive these temperatures, and enzymes are not consumed.
4. D. Unit 3. ATP synthase is driven by the H^+ gradient. Glycolysis occurs in the cytosol without it, and electron transport can continue (and even speed up) while the gradient collapses.
5. C. Unit 4. The checkpoint gives time for repair or triggers apoptosis; without it, damage is copied and passed on. Nothing about the mutation causes meiosis.
6. B. Unit 5. $P(A_) = 3/4$ and $P(bb) = 1/4$; multiply to get $3/16$. Nine sixteenths is dominant for both traits and $1/16$ is aabb.
7. A. Unit 6. The amino acid is unchanged because the code is redundant. A missense mutation changes the amino acid; nonsense creates a stop; a frameshift is an insertion or deletion not in multiples of three.
8. D. Unit 6. DNA is negatively charged and moves toward the positive electrode through the gel; smaller fragments move more easily and go farthest. Students often reverse this.
9. A. Unit 7. $q^2 = 0.16$, so $q = 0.4$ and $p = 0.6$; $2pq = 2(0.6)(0.4) = 0.48$. Choice C (0.36) is p^2 and choice D is q^2 .
10. B. Unit 7. Only shared molecular features universal to all life support one ancestor. Cellulose walls, photosynthesis, and mitochondria are absent in many groups.
11. D. Unit 8. Primary consumers get 5,000 kJ, secondary 500 kJ. Choice A stops one step early.
12. C. Unit 8. $dN/dt = 0.3(400)(800-400)/800 = 60$. The value 120 ignores the $(K-N)/K$ term, which is the density-dependent brake.
13. Scoring guide (9 points).
 - (a) 1 point: independent variable = sucrose concentration; dependent variable = percent change in mass of the cores (both needed).
 - (b) 3 points: 1 for correct axes (sucrose concentration on the x axis, percent mass change on the y axis, both labeled with units, even scale that includes negative values); 1 for all five means plotted accurately and joined by a line (quantitative x variable); 1 for error bars of ± 1 SE at every point.
 - (c) 1 point: about 0.34 M (accept 0.32 to 0.36); interpolating between 0.2 M (+7.9) and 0.4 M (-3.1), the zero crossing is $0.2 + 0.2(7.9/11.0) = 0.34$ M.
 - (d) 1 point: $\Psi_{s_s} = -(1)(0.34)(0.0831)(295) = -8.3$ bar; at equilibrium the tissue water potential equals the solution (about -8.3 bar; accept -8 to -8.5). In an open dish the solution is at atmospheric pressure, so $\Psi_{s_p} = 0$ and $\Psi = \Psi_{s_s}$.
 - (e) 1 point: the solution has a lower (more negative) water potential than the cells, so water moves from the cells to the solution by osmosis, decreasing mass.
 - (f) 1 point: there is no difference in mean percent change in mass among the sucrose concentrations (sucrose concentration has no effect). A null with a stated direction does not earn the point.
 - (g) 1 point: 0.2 M spans about 6.8 to 9.0 and 0.4 M about -4.0 to -2.2 (mean $\pm$ SE); the ranges do not overlap, so the means are likely different, supporting rejection of the null for this pair.
14. Scoring guide (4 points).
 - (a) 1 point: the 5 pools where trout remain; they lack the independent variable (trout removal), so any difference in the treated pools can be attributed to the removal. "Same conditions" alone does not earn the point.
 - (b) 1 point: trout removal has no effect on the mean number of mayfly larvae (or algae biomass); no direction stated.
 - (c) 1 point: algae decrease; without the predator, mayflies increase and graze more (trophic cascade).
 - (d) 1 point: removal produces a large change in community structure, such as lower algal biomass and altered species richness, out of proportion to the trout's biomass.

Model: Control pools keep trout, so only trout removal differs. Null: trout removal does not change mayfly numbers. Without trout, mayflies rise and algae fall. If trout loss reshapes the whole community despite their small biomass, they are keystone.
15. Scoring guide (4 points).
 - (a) 1 point: tryptophan activates the repressor; the active repressor binds the operator and blocks RNA polymerase, so transcription is low.
 - (b) 1 point: transcription stays high because the active repressor cannot attach to the operator to block polymerase.
 - (c) 1 point: transcription stays high because without tryptophan binding the repressor stays inactive and does not bind the operator.
 - (d) 1 point: negative feedback (the end product shuts down the genes that make it), saving energy and raw materials when tryptophan is plentiful.

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Free-Response Clinic

Exam-style free-response questions with point-by-point scoring guides and full-credit model responses.



Free-Response Clinic

Practice all six Section II question types with original data, then score yourself against point-by-point guides and full-credit model responses.

How Section II Works

Section II has 6 questions in 90 minutes for 34 points, about 2.6 minutes per point. Aim for roughly 22 minutes per long question, 10 per short question, and a few minutes to check units, labels and graphs.

Question	Type	Points	Task verbs
1	Long: interpret and evaluate experimental results	9	identify, describe, calculate, justify, evaluate
2	Long: interpret and evaluate results with graphing	9	construct, calculate, predict, justify
3	Short: scientific investigation	4	identify, state, explain
4	Short: conceptual analysis	4	explain, identify, evaluate
5	Short: analyze a model or visual representation	4	identify, explain, predict
6	Short: data analysis	4	identify, describe, determine, connect

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PRACTICE Free-Response Clinic

Write full answers, then score each part with the guide. A calculator is allowed. Answer every part in complete sentences.

1. [9 points] Question 1. A microbiologist studies a bacterial protein, GlcT, thought to carry glucose into cells. She grew four groups of cultures (6 cultures per group) and measured glucose uptake after 10 minutes. Values are mean $\pm$ SEM.
Group: Uptake (micromol per min per 10^9 cells)
1. Wild type: 48.0 $\pm$ 2.1
2. glcT gene deleted: 6.0 $\pm$ 0.8
3. glcT deleted, plus plasmid carrying glcT: 44.0 $\pm$ 2.5
4. Wild type, plus transport inhibitor X: 12.0 $\pm$ 1.4
(a) [2 points] Identify the independent variable and the dependent variable.
(b) [2 points] Describe the effect of deleting glcT, and calculate the percent decrease in uptake relative to wild type.
(c) [2 points] Justify the inclusion of group 3 and state what its result shows.
(d) [2 points] A classmate claims that GlcT is the only route by which glucose enters these cells. Evaluate the claim using the data.
(e) [1 point] Explain why glucose needs a membrane protein to enter the cell.
2. [9 points] Question 2. A student placed identical cores cut from one turnip in sucrose solutions of different molarity at 22 degrees C for 90 minutes and measured the percent change in each core's mass.
Sucrose (M): 0.0, 0.2, 0.4, 0.6, 0.8, 1.0
Mass change (%): +18, +10, +2, -6, -14, -22
(a) [3 points] Construct a graph of the data. Describe your graph: which variable goes on each axis with labels and units, the scale you would choose for each axis, and how you would plot and join the points.
(b) [1 point] Use your graph to estimate the sucrose molarity at which there is no net change in mass.
(c) [2 points] Using your estimate from (b), calculate the solute potential of that solution. Use $\Psi_s = -iCRT$ with $i = 1$ for sucrose, $R = 0.0831$ L bar per mol K, and $T = 295$ K. Show your setup.
(d) [2 points] Predict the direction of net water movement for a core in 0.8 M sucrose and justify using water potential.
(e) [1 point] Explain why the student reported percent change in mass instead of the raw change in grams.
3. [4 points] Question 3. An ecologist suspects that phosphate runoff causes algal blooms. She filled two identical tanks with pond water and algae. Tank A received nothing extra; Tank B received phosphate at 0.5 mg per liter. After 10 days, Tank A held 2.1×10^5 algal cells per mL and Tank B held 9.8×10^5 cells per mL.
(a) [1 point] Identify the control group and justify your choice.
(b) [1 point] State a null hypothesis for this experiment.
(c) [2 points] Algal blooms are often followed by fish deaths even though fish do not eat the algae. Explain how the bloom could lower the fishes' oxygen supply.
4. [4 points] Question 4. A lake dried into two ponds. Over many generations, snails in the two ponds came to differ in shell color and, in lab trials, no longer produced offspring when crossed. The allele for dark shells has frequency 0.80 in Pond 1 and 0.30 in Pond 2.
(a) [2 points] Explain how geographic isolation can lead to divergence of the two snail populations.
(b) [1 point] Identify one kind of DNA evidence that would support divergence from a common ancestor.
(c) [1 point] A student says the allele-frequency difference alone proves the snails are now separate species. Evaluate the claim.
5. [4 points] Question 5. A model of a pathway: substrate S is converted to intermediate I by enzyme E1, and I is converted to end product P by enzyme E2. In the model, P binds to a site on E1 away from the active site, shown by a T-shaped bar from P to E1 (a line ending in a flat bar).
(a) [1 point] Identify the type of regulation shown and what the T-bar means.
(b) [1 point] Explain how P can reduce E1 activity without binding the active site.
(c) [2 points] A drug blocks E2. Predict what happens to the amounts of I and P, and justify your prediction using the model.

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6. [4 points] Question 6. Researchers studied a yeast protein, Seg1, needed to separate chromosomes in meiosis. Values are mean $\pm$ 2 SE (error bars, 95% range).
 Genotype: Wild type, Heterozygote, Homozygous mutant
 Seg1 protein (% of wild type): 100 $\pm$ 6, 62 $\pm$ 5, 24 $\pm$ 4
 Cells with mis-separated chromosomes (%): 2, 9, 41
 (a) [1 point] Identify the genotype with the most cells that mis-separate chromosomes.
 (b) [1 point] Describe how protein amount differs between the heterozygote and the wild type, using the data.
 (c) [1 point] Determine whether the protein difference in (b) is likely meaningful, using the error bars.
 (d) [1 point] Connect protein amount to the phenotype, and explain why describing the mutant as 'nonfunctional' is inaccurate.

Key**Free-Response Clinic: Scoring Guides and Model Responses****X Free-Response Clinic****PRACTICE · FREE-RESPONSE CLINIC****1. Scoring guide (9 points).**

- (a) 2 points: 1 for the independent variable (the group/treatment: gene present, deleted, restored, or inhibited); 1 for the dependent variable (glucose uptake rate).
 (b) 2 points: 1 for describing that uptake falls sharply (48.0 to 6.0); 1 for the calculation $(48.0 - 6.0)/48.0 \times 100 = 87.5$ percent, accept 87 or 88.
 (c) 2 points: 1 for explaining that restoring the gene shows the loss of uptake was caused by missing GlcT and not by some other effect of the deletion; 1 for the result: uptake returns to 44.0, close to wild type (SEM ranges 41.5-46.5 and 45.9-50.1 overlap).
 (d) 2 points: 1 for rejecting the claim; 1 for the evidence: the deleted strain still takes up 6.0 (SEM 0.8, clearly above zero), and inhibitor X leaves 12.0, so some glucose enters by another route, or other transporters exist.
 (e) 1 point: glucose is large and polar, so it cannot cross the nonpolar interior of the phospholipid bilayer; a transport protein (facilitated diffusion) provides a path.

Model response: (a) The independent variable is the genotype or treatment of the cultures; the dependent variable is glucose uptake per minute per 10^9 cells. (b) Deleting glcT cut uptake from 48.0 to 6.0, a decrease of $(48.0 - 6.0)/48.0 = 87.5$ percent. (c) Group 3 shows that putting glcT back restores uptake to 44.0, about 92 percent of wild type with overlapping SEM ranges, so the loss in group 2 was caused by the missing gene rather than by damage from the deletion. (d) The claim is not supported. The deleted strain still takes up 6.0, well above zero given the SEM of 0.8, so glucose also enters by some other path. (e) Glucose is polar and cannot cross the nonpolar core of the bilayer, so a transport protein is required.

Common point-losing error: justifying a control only as a 'baseline' instead of saying it shows the treatment affects only the intended target.

2. Scoring guide (9 points).

- (a) 3 points: 1 for sucrose molarity on the x-axis (independent variable) and percent change in mass on the y-axis, both labeled with units; 1 for an even scale, x from 0 to 1.0 by 0.2 and y from -25 to +20 by 5, with the axis crossing at zero change; 1 for all six points plotted accurately and joined with a best-fit line (line graph, because molarity is continuous).
 (b) 1 point: x-intercept of 0.45 M (accept 0.43 to 0.47).
 (c) 2 points: 1 for correct setup: $\Psi_s = -(1)(0.45)(0.0831)(295)$; 1 for the answer, -11 bars (-11.03).
 (d) 2 points: 1 for water leaves the core; 1 for justification: 0.8 M is more concentrated than the tissue (0.45 M), so the solution has lower water potential and water moves from higher to lower water potential. The data agree (-14 percent).
 (e) 1 point: cores differ in starting mass, so percent change allows fair comparison among cores.

Model response: (a) Put sucrose molarity (M) on the x-axis from 0 to 1.0 in steps of 0.2, and percent change in mass (%) on the y-axis from -25 to +20 in steps of 5. Plot the six points and draw a best-fit line, since the independent variable is continuous. (b) The line crosses 0 percent at about 0.45 M. (c) $\Psi_s = -iCRT = -(1)(0.45)(0.0831)(295) = -11$ bars. (d) Water moves out of the core. The 0.8 M solution has a more negative water potential ($\Psi_s = -19.6$ bars) than the tissue (about -11 bars), and water moves toward lower water potential; the core shrinks by 14 percent. (e) Percent change corrects for the differing starting masses of the cores.

Common point-losing error: graphing with mislabeled or unscaled axes, or placing the dependent variable on the x-axis.

3. Scoring guide (4 points).

- (a) 1 point: Tank A is the control because it lacks the independent variable (no added phosphate) while everything else matches; 'same conditions' alone does not earn the point.
 (b) 1 point: Adding phosphate has no effect on algal population density (no direction stated).
 (c) 2 points: 1 for bloom algae dying and being decomposed in large numbers; 1 for decomposers using aerobic respiration, which consumes dissolved oxygen, leaving less for fish.

Model response: (a) Tank A is the control because it is the group without added phosphate, the independent variable. (b) Phosphate addition does not change algal population density. (c) When the abundant algae die, bacteria decompose them using aerobic cellular respiration, which uses up dissolved oxygen, so fish suffocate.

Common point-losing error: writing a null hypothesis that predicts an increase or decrease (that is the alternative hypothesis).

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4. Scoring guide (4 points).

(a) 2 points: 1 for geographic isolation stopping gene flow between the ponds; 1 for independent change in each population: different mutations arise and different selection pressures or genetic drift shift allele frequencies, so differences accumulate over generations.

(b) 1 point: comparing DNA (or protein) sequences and finding more differences between the ponds than within a pond, or a molecular clock/phylogenetic tree placing them on separate branches from a shared ancestor.

(c) 1 point: reject the claim; allele frequencies differ between populations of the same species all the time. Separate species require reproductive isolation, which the failed crosses show, so the frequencies alone are not proof.

Model response: (a) Once the lake split, no snails moved between ponds, so gene flow stopped. Each pond accumulated its own mutations and was acted on by its own selection and drift, so allele frequencies diverged. (b) Sequence comparison showing more differences between ponds than within each pond. (c) The claim is not supported by the allele data alone, because populations of one species can differ in allele frequency; it is the failed crosses (reproductive isolation) that indicate separate species.

Common point-losing error: saying the environment 'created' new traits, or using 'adaptation' to mean speciation.

5. Scoring guide (4 points).

(a) 1 point: negative feedback (end-product inhibition); the T-bar indicates inhibition, not activation.

(b) 1 point: P binds an allosteric site, which changes the shape of E1 so the active site binds S less well, lowering the rate. This is not competitive inhibition, since P does not compete with S for the active site.

(c) 2 points: 1 for the prediction: P decreases and I accumulates; 1 for the justification: E2 is the only step that makes P from I, and with less P the feedback on E1 is released, so E1 stays active and keeps making I.

Model response: (a) Negative feedback: the end product P inhibits an enzyme earlier in the pathway. (b) P binds an allosteric site on E1, which changes its shape so S fits the active site poorly. (c) With E2 blocked, I cannot be converted, so I accumulates and P falls. Because less P means less inhibition of E1, E1 stays active and I builds up even more.

Common point-losing error: confusing an allosteric site with the active site, or reading the T-bar as an activating arrow.

6. Scoring guide (4 points).

(a) 1 point: the homozygous mutant (41 percent).

(b) 1 point: the heterozygote makes 62 percent of the wild-type amount, 38 points lower.

(c) 1 point: yes; the ranges 94-106 and 57-67 do not overlap, so the difference is likely real.

(d) 1 point: less Seg1 goes with more mis-separation (2 to 9 to 41 percent), so too little protein impairs chromosome separation; the mutants still make some protein (62 and 24 percent), so function is reduced, not absent.

Model response: (a) The homozygous mutant, at 41 percent. (b) The heterozygote has 62 percent of the wild-type protein. (c) The 95 percent ranges, 94-106 versus 57-67, do not overlap, so the difference is likely meaningful. (d) As Seg1 falls, more cells mis-separate chromosomes, so less protein impairs meiosis; since the mutants still make 62 and 24 percent, the protein has reduced function rather than none.

Common point-losing error: assuming a heterozygote makes only wild-type protein, or calling a difference meaningful without checking the error bars.

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Reference: Formulas, Skills Checklist, and Glossary

Quick-reference pages to review the night before the exam.

R1 Equations, Statistics, and Math Skills

A quick reference for the equations and statistical reasoning used in AP Biology, with when to use each.

How to Use This Page

Understand when each tool applies, how to set up the calculation, and what the result means. An equation sheet is provided on the exam, but its exact contents change, so check your teacher's current copy. Always keep units, convert Celsius to kelvin by adding 273, and state the biological conclusion.

Core Equations

Topic	Equation	Use
Mean	$\bar{x} = \frac{\sum x}{n}$	Center of a sample
Standard deviation	$s = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}}$	Spread of the data
Standard error of the mean	$SE = \frac{s}{\sqrt{n}}$	Uncertainty of the mean
Rate	$\frac{\Delta y}{\Delta x}$ (slope of a graph)	Change per unit time
Percent change	$\frac{\text{new} - \text{old}}{\text{old}} \times 100$	Compare groups
Q10	$Q_{10} = \left(\frac{R_2}{R_1} \right)^{10/(T_2 - T_1)}$	Effect of 10 degrees C on rate
Hardy-Weinberg	$p + q = 1; p^2 + 2pq + q^2 = 1$	Allele and genotype frequencies
Water potential	$\Psi = \Psi_p + \Psi_s; \Psi_s = -iCRT$	Direction of water movement
Surface area / volume (sphere)	$4\pi r^2; \frac{4}{3}\pi r^3$	Cell size limits
Surface area / volume (cube)	$6s^2; s^3$, so $SA/V = 6/s$	Cell size limits
Population growth	$\frac{dN}{dt} = r_{max}N; r_{max}N \frac{K - N}{K}$	Exponential; logistic
Probability	$P(A \text{ and } B) = P(A)P(B); P(A \text{ or } B) = P(A) + P(B) - P(A \text{ and } B)$	Independent events; mutually exclusive: last term is 0
Gibbs free energy	$\Delta G = \Delta H - T\Delta S$	Spontaneity (negative = favorable)

In Hardy-Weinberg problems, start from the one frequency you can see: the recessive phenotype is q^2 , so take its square root for q . For water potential, $R = 0.0831 \text{ L bar}/(\text{mol K})$, $i = 1$ for sucrose, $i = 2$ for NaCl (ideal), and open dishes have $\Psi_p = 0$.

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Chi-Square Test

$$\chi^2 = \sum \frac{(o - e)^2}{e}$$

Degrees of freedom = number of categories - 1. State a null hypothesis (observed counts fit the expected ratio), compute χ^2 , and compare with the critical value at $p = 0.05$. If χ^2 is greater than the critical value, reject the null; if it is smaller, fail to reject. Never say "accept" and never describe "proving" the null.

Degrees of freedom	p = 0.10	p = 0.05	p = 0.01
1	2.71	3.84	6.63
2	4.61	5.99	9.21
3	6.25	7.81	11.34
4	7.78	9.49	13.28
5	9.24	11.07	15.09
6	10.64	12.59	16.81
7	12.02	14.07	18.48
8	13.36	15.51	20.09

Example: a dihybrid cross gives 98, 27, 25, 10 offspring against 9:3:3:1 expected counts of 90, 30, 30, 10. Then $\chi^2 = 64/90 + 9/30 + 25/30 + 0 \approx 1.84$ with 3 df. The critical value at $p = 0.05$ is 7.81, so we fail to reject the null: the deviations are consistent with chance.

Error Bars and Confidence Intervals

Standard deviation describes spread among the individual measurements; standard error describes how precisely the mean is known. A sample with $s = 2.4$ and $n = 16$ has $SE = 2.4/4 = 0.6$. The 95% confidence interval is roughly the mean $\pm 2SE$, here ± 1.2 (a t value near 2.1 is used for small samples). Always check what the error bars show: SD, SE, or 95% CI.

Reading Error Bars

If the **95% CI bars of two means do not overlap**, the means differ significantly at about $p < 0.05$.

If they overlap, you cannot conclude a real difference. If SE bars overlap, the means are probably not significantly different; non-overlapping SE bars are suggestive but not proof. SE bars are narrower than 95% CI bars, so the same rule is not safe for both.

A significant difference is not necessarily a large or important one. Correlation is not causation.

Worked Q10: a reaction rate is 4 units at 20 degrees C and 12 units at 30 degrees C, so $Q_{10} = 12/4 = 3$. Surface-area example: a cube cell of side 3 micrometers has $SA/V = 6/3 = 2$, while a 6 micrometer cube has 1; doubling size halves SA/V .

R2 Skills Checklist and Glossary

Check your readiness on the six science practices and review key terms.

Skills Checklist

Rate yourself 1 to 3 on each practice, then answer the prompt in writing. Revisit anything below 3 before the exam.

Practice	I can...	Self-check prompt
1. Concept Explanation	I can explain a process or structure and link it to its function.	Explain how a change in one part alters the outcome, using the right terms.
2. Visual Representations	I can interpret and draw models, diagrams, and pathways.	Trace a signal or food web arrow by arrow; predict what a disruption does downstream.
3. Questions and Methods	I can design a test, identify variables, and justify a control.	Name independent variable, dependent variable, constants, and control group; state a null.
4. Representing and Describing Data	I can graph data and describe trends.	Choose axes and scale, label units, add error bars; give direction and size of change.
5. Statistical Tests and Data Analysis	I can calculate and interpret rates, chi-square, SE, and CIs.	Set up the equation, show units, state reject or fail to reject, conclude in context.

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Practice	I can...	Self-check prompt
6. Argumentation	I can make a claim supported by evidence and reasoning.	Write claim, evidence from data, and the biological reasoning that connects them.

Reflect: Which practice cost me the most points on practice tests? What one habit will I change this week?

Glossary

Term	Meaning
ATP	Cell energy currency
Active transport	Movement against gradient, uses energy
Allele	Version of a gene
Allosteric site	Regulatory site away from active site
Autotroph	Makes own food
Biodiversity	Variety of life at all levels
Biomass	Mass of living material
Carrying capacity (K)	Largest sustainable population
Cell cycle	Growth, DNA copying, and division
Chemiosmosis	ATP made by proton flow
Codon	Three mRNA bases for one amino acid
Cohesion	Water molecules sticking together
Competitive inhibitor	Binds the active site
Control group	Lacks the independent variable
Dependent variable	What is measured
Diffusion	Net movement down a gradient
Dominant	Allele expressed when present
Enzyme	Protein that speeds a reaction
Eukaryote	Cell with nucleus
Fitness	Reproductive success
Gene flow	Allele movement between populations
Genetic drift	Random change in allele frequency
Genotype	Alleles an organism carries
Hardy-Weinberg	Model of no allele change
Homeostasis	Stable internal conditions
Hydrogen bond	Weak attraction between polar molecules
Hypertonic	Solution with more solute
Independent variable	What is changed
Keystone species	Large impact beyond abundance
Ligand	Molecule that binds a receptor
Meiosis	Division making haploid gametes
Mitosis	Division making identical cells
Mutation	Change in DNA sequence
Natural selection	Differential survival and reproduction

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Term	Meaning
Negative feedback	Output reduces its own production
Niche	Role and conditions of a species
Null hypothesis	Statement of no effect or difference
Operon	Genes under one promoter
Osmosis	Water diffusion across a membrane
Phenotype	Observable trait
Phylogeny	Tree of evolutionary relationships
Population	Same species in one area
Positive feedback	Output amplifies itself
Primary productivity	Energy captured by producers
Prokaryote	Cell without nucleus
Receptor	Protein that detects a signal
Recessive	Allele masked by a dominant
Replication	Copying DNA
Resilience	Ability to recover from disturbance
Ribosome	Site of translation
Signal transduction	Relay from signal to response
Speciation	Formation of new species
Standard error	Precision of the mean
Succession	Community change over time
Surface area to volume	Limits cell size
Transcription	DNA to RNA
Translation	mRNA to polypeptide
Trophic level	Feeding position in a web
Tropism	Directional growth response
Water potential	Tendency of water to move

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