AP Biology: Study Guide

Key Exam Details

The AP® Biology exam is a 3-hour, end-of-course test comprised of 60 multiple-choice questions, for which you will have 1 hour and 30 minutes (this counts for 50% of your score) and 6 free-response questions, for which you will have 1 hour and 30 minutes (this counts for 50% of your score).

The exam covers the following course content categories:

- Chemistry of Life: 8–11% of test questions
- Cell Structure and Function: 10–13% of test questions
- Cellular Energetics: 12–16% of test questions
- Cell Communication and Cell Cycle: 10–15% of test questions
- Heredity: 8–11% of test questions
- Gene Expression and Regulation: 12–16% of test questions
- Natural Selection: 13–20% of test questions
- Ecology: 10–15% of test questions

This guide will offer an overview of the main tested subjects, along with sample AP multiple-choice questions that look like the questions you will see on test day.

Chemistry of Life

About 8–11% of the questions on your AP Biology exam will cover the topic Chemistry of Life.

Water and the Elements of Life

Water is made of two hydrogen molecules covalently bonded to an oxygen molecule. The oxygen atom pulls most of the electrons in the water molecule toward it, giving it a slightly negative charge and the hydrogen atoms a slightly positive charge. Molecules like water that have distinct regions of charge based on bond structure are called **polar compounds**. The charge structure of water also creates a unique shape, where the hydrogen molecules are concentrated on one side of the oxygen atom.

The polar nature and shape of water molecules make them ideal for forming hydrogen bonds between water molecules. **Hydrogen bonds** are weak bonds that form between a proton in one molecule and an electronegative atom of another molecule. In the case of water, this is between the electronegative oxygen of one molecule and the slightly positive hydrogen of another water molecule. The polar nature of water is important to life for many reasons. For one, it makes water

a solvent to many other molecules. This means that many chemicals that are important to life are readily dissolved in water and can be distributed throughout an organism due to its movement.

Water also has properties of cohesion and adhesion. **Cohesion** occurs when molecules of the same kind tend to stick together. In water, this is due to hydrogen bond cohesion between water molecules. Cohesion causes **surface tension**, which is the tendency of liquid surfaces to shrink to minimize surface area. This is due to water molecules at the water-air surface interfacing and forming stronger hydrogen bonds with water molecules below, causing a shrinking of the space between them. Surface tension causes water droplets to form and allows solid matter to float at the surface of water.

Adhesion, on the other hand, is the tendency of dissimilar molecules to be attracted to each other. Adhesive forces can be strong between water and charged molecules and are responsible for **capillary action**, which is the movement of liquid through spaces on its own, sometimes in opposition to gravity. Capillary action is the result of adhesive forces between water and the surface it is touching, which draws the liquid towards it. Due to cohesive forces, the water also pulls more water molecules behind it. These properties of water are essential to all life on Earth. For example, in plants, capillary action is responsible for moving water from the roots up through the rest of the plant.

Carbon, hydrogen, nitrogen, and oxygen comprise 99% of all living matter. **Organic molecules**, which include most molecules with carbon, are the basis of life on Earth.

Carbon has the unique chemical property of being able to form four bonds with other elements, making it an ideal element to form the backbone of complicated biological molecules. Carbon-based molecules are able to take on many configurations, as carbon can form single, double, or triple bonds with other elements. These molecules can take on many shapes: rings, branches, or long chains. Thus, carbon is the elemental basis of the major biological macromolecules: carbohydrates, proteins, lipids, and nucleic acids. In addition to carbon, nucleic acids and proteins rely on nitrogen and phosphorus to build their structure, which we will discuss in more detail below.

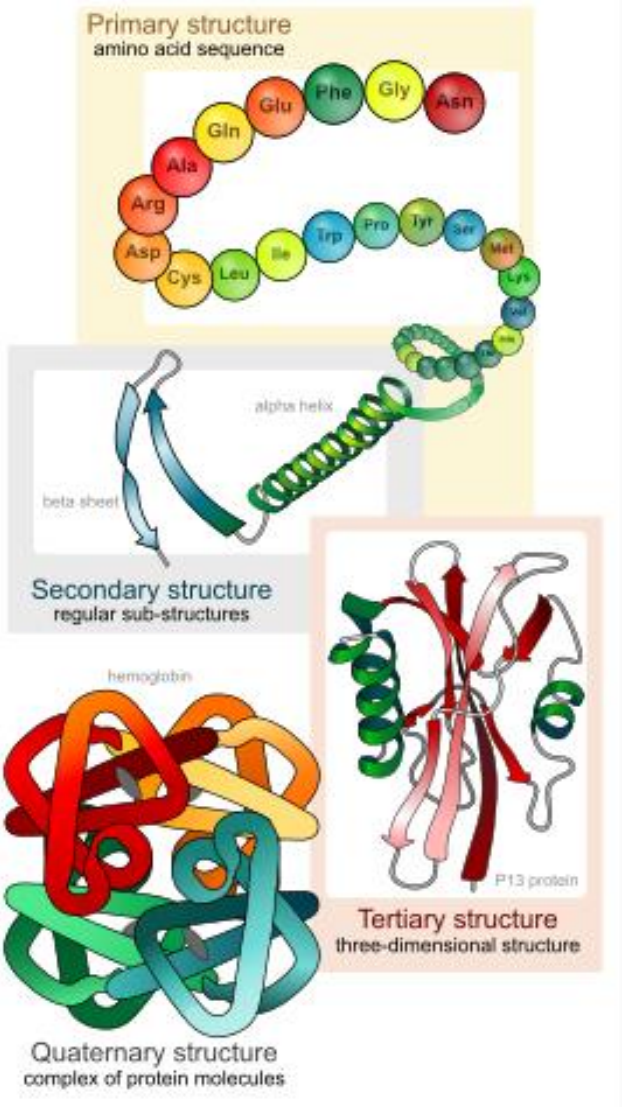
The Makeup and Properties of Macromolecules

Large biological molecules are the building blocks of life. For your AP exam, you should be familiar with carbohydrates, lipids, proteins, and nucleic acids. Carbohydrates, proteins, and nucleic acids are usually types of molecules called **polymers,** which are structures made of repeating smaller units called **monomers**. The monomers that make DNA are nucleotides, amino acids make proteins, and sugars make carbohydrates. The monomer units in each of these cases are not necessarily identical but are of the same kind of molecule. Large polymers are also called **macromolecules.** Lipids, on the other hand, are not generally polymers, thus are not always

considered to be macromolecules. In the formation of biological macromolecules, the composition and order of monomers affect their function.

Macromolecules form through **dehydration synthesis** of monomers. In dehydration synthesis, a covalent bond forms between two monomers, releasing water in the process. The reverse process breaks down polymers into monomers; this is called **hydrolysis**, meaning the bond is lysed by water. Synthesis reactions generally use energy, which is then stored within the covalent bonds of the macromolecule. When hydrolysis occurs, this energy is released for the cell to use.

Proteins comprise the majority of organic molecules in organisms and have huge diversity in structures and function. Proteins are made of strings of amino acids connected by covalent bonds. There are 20 types of amino acids in biological organisms, but they all share similar structural features.



Protein Structure

The basic structure of an amino acid is a central carbon atom with an amino group (NH_2) on one side, a carboxyl group (COOH) on the opposite side, a hydrogen atom, and an R group that determines the identity of the amino acid. Amino acids are linked together by peptide bonds, which are **covalent bonds**, formed by a dehydration synthesis reaction between the **carboxy terminus** of the first amino acid and the **amino terminus** of the second. This organization gives the protein an order where the beginning of the polypeptide chain has an amine group and the end has a carboxyl group. This directionality is set up when proteins are translated from RNA.

The composition and location of amino acids in the polypeptide chain confer their properties to the resulting protein and affect the shape of the protein. Amino acids can be charged, uncharged, hydrophobic, or cause changes in the 3D structure of the protein. The composition and order of amino acids is called the **primary structure**, which accounts for some of the function of proteins, but not all. Proteins take on very complicated shapes in nature.

The **secondary structure** of proteins arise when proteins fold due to interactions between elements in the amino acid backbone (not including R groups). These folds include α **helixes**, which are helical structures formed by hydrogen bonds between carbonyl groups of one amino acid and the amino group of another that is four amino acids down the line. This structure pushes R groups to the outside of the helix, giving them more opportunity to interact. β **sheets** are another secondary structure formed when sections of the polypeptide chain are parallel to each other. This structure also presents R groups outward on top and bottom, so they can interact.

Tertiary structure forms due to interactions between R groups of the same protein. These can include all different types of non-covalent bonds forming between groups or can include strong di-sulfide bonds. Tertiary structures minimize the free energy of a protein by taking the most energetically stable position. Finally, **quaternary structure** forms between amino acids on different polypeptide chains. Protein structures can be **denatured**, meaning they lose their higher order structures due to changes in pH or temperature. However, they generally return to their proper structures when conditions return to normal. This means that most of the information needed to form a structure is retained within the polypeptide sequence of a protein.

Carbohydrates are an immediate source of energy that most life depends on and form important structural elements of organisms. The formula for carbohydrates is $(CH_2O)_n$, where n refers to the number of times this structure repeats. **Monosaccharides** contain 3–7 monomers of CH_2O connected as a chain or a ring. Common monosaccharides include glucose, fructose, and galactose. **Disaccharides** form when two monosaccharides undergo dehydration synthesis to form a covalent bond between them. The covalent bond formed between a carbohydrate and another molecule is called a **glycosidic** bond.

Common disaccharides include sucrose, lactose, and maltose. **Polysaccharides** are long chains of monosaccharides that can be either linear or branched. Common polysaccharides include starch, chitin, cellulose, and glycogen. Disaccharides and polysaccharides can be made of the same or

different monosaccharide monomers, the composition of which determines the properties of the macromolecule.

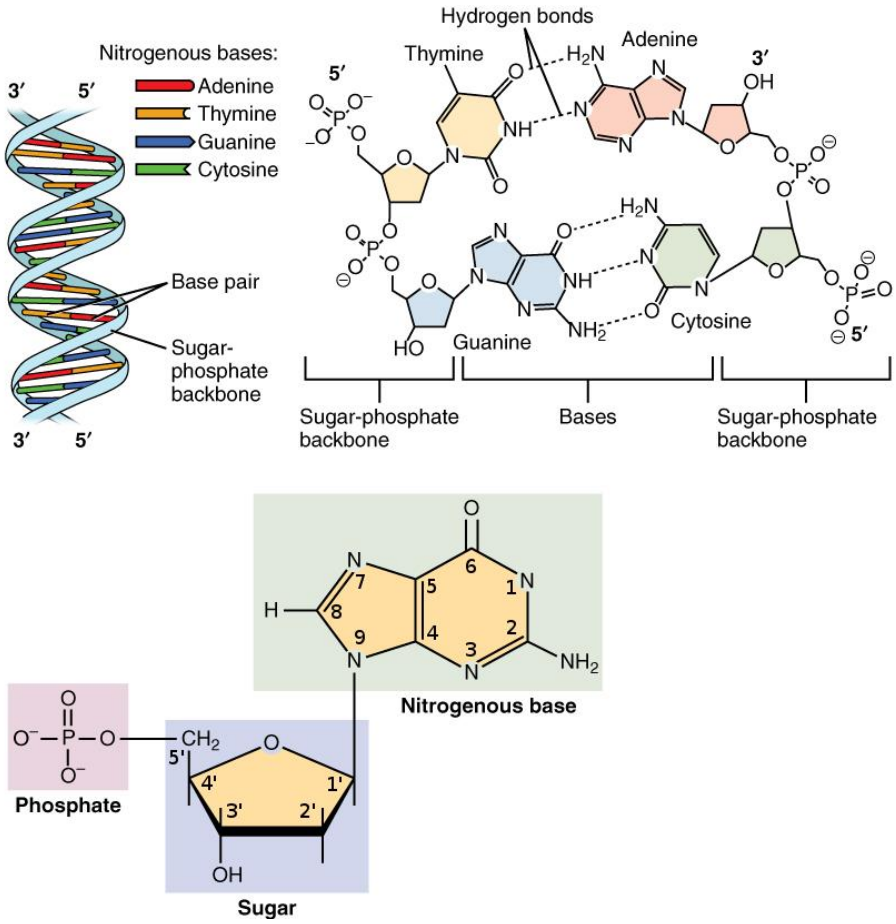
Lipids are nonpolar macromolecules made of hydrocarbon chains that are generally hydrophobic; they include fats, waxes, phospholipids, and steroids. Lipids are a structural unit of membranes and a form of energy storage for organisms. Fats, or triglycerides, are made of a glycerol backbone and three fatty acid chains. The **fatty acid chains** of lipids are made of hydrocarbons bonded to a carboxyl group. The fatty acid chains of triglycerides can be different from each other in both length and saturation.

If all neighboring bonds in the hydrocarbon chain are single bonds, the fatty acid is called **saturated**. Saturated fats have straight fatty acid chains that can pack tightly together and form solids at room temperature. If there are double bonds in the chain, the fatty acid is called **unsaturated**. If the double bond results in hydrogen atoms on the same side of the acid chain, this causes a bend in the chain and results in a *cis* fatty acid. Cis fatty acids tend to form liquid oils at room temperature, as their shape causes spacing between molecules. If the double bond results in hydrogen atoms on opposite sides of the fatty acid chain, the molecule retains the normal shape of the chain, and is called a *trans* fatty acid. Trans fatty acids behave more like saturated fats at room temperature but are also difficult for the body to metabolize.

The Structure of DNA and RNA

DNA, deoxyribonucleic acid, is a polymer made of individual nucleotides that carries genetic information. **Nucleotides** are made of a sugar (deoxyribose), a phosphate group, and a nitrogenous base. The deoxyribose group has a ring structure composed of an oxygen and four carbons. As a convention, carbon atoms of deoxyribose are numbered starting from the connection between the nucleotide and the first carbon, called the 1' carbon. A 5^{th} carbon atom (5') is bonded to the 4' carbon of deoxyribose.

The 5' carbon bonds with the phosphate group. Nucleotides are linked to each other by covalent bonds between the sugar and phosphate groups to make a single strand of DNA. The connection between two nucleotides in a strand of DNA always occurs in the same orientation—this is between the 3′ carbon atom of the first nucleotide and the phosphate group of the second. Since the phosphate atom is connected to the 5' carbon, the orientation of the DNA polymer is referred as 3' to 5'.



DNA Structure

DNA nucleotides come in four varieties, each with a different base: **adenine (A)**, **thymine (T)**, **guanine (G)**, or **cytosine (C)**. In RNA, uracil (U) is used instead of thymine. G and A molecules are called **purines** and consist of double nitrogenous rings. C, T, and U are called **pyrimidines**, and are composed of single nitrogenous rings. Two strands of DNA with complementary base pairs are linked with hydrogen bonds between base pairs to form the double helix pattern we are familiar with. Hydrogen bonds occur only between complementary pairs: C-G or A-T (or A-U, in the case of RNA). You'll notice that purines bond with their complimentary pyrimidine. Cytosine-guanine connections pair via three hydrogen bonds, while adenine-thymine pairs with double hydrogen bonds.

In a DNA polymer, the "backbone" is made of sugar and phosphate groups linked together, with nucleotides in the center. This bond between the phosphate group and two sugars is a **phosphodiester bond**. Two strands of DNA connect together through complementary base pairing to form a double stranded DNA polymer. Note that the connections between two strands of DNA are anti-parallel—one strand will have a 3'-5' directionality, and the second strand will be oriented in the 5'-3' direction.

RNA, ribonucleic acid, is similar to DNA but has ribose as the sugar group and has uracil (U) instead of thymine. Unlike DNA, RNA is usually found in nature as a single strand rather than a double strand.

Outside Reading

- For more on the properties of water: https://www.khanacademy.org/science/biology/water-acids-and-bases
- For more on macromolecules: https://courses.lumenlearning.com/boundless-biology/chapter/synthesis-of-biological-macromolecules/
- To learn more about nucleotide structure: https://www.khanacademy.org/test-prep/mcat/biomolecules/dna/a/dna-structure-and-function

Sample Chemistry of Life Questions

The strongest complementary base pair found in DNA is between

A. adenine and guanine.

B. cytosine and thymine.

C. adenine and thymine.

D. cytosine and guanine.

Explanation:

The correct answer is D. Three hydrogen bonds form between cytosine and guanine, making this a stronger complementary base pair than the adenine/thymine base pair. This is important, for example, during primer construction for PCR in molecular biology because increased GC concentration relative to AT concentration leads to strong primer binding to a DNA template. Adenine and guanine are both purines and do not pair up in the DNA double helix; and cytosine and thymine are both pyrimidines and do not pair up in the DNA double helix. Finally, while adenine and thymine do pair up in the DNA double helix, there are only two hydrogen bonds that form between the two. Three hydrogen bonds form between cytosine and guanine, making the latter base pair stronger.

Water travels up a stem through a process called

A. cohesion-adhesion.

B. cohesion-tension.

C. adhesion-tension.

D. hydrogen bonding.

Explanation:

The correct answer is B. As water evaporates from a leaf, a column of water molecules is pulled upward through cohesion-tension. The water molecules are bound together through hydrogen bonding, and the evaporation at the leaf pulls the chain of molecules upward due to the inherent surface tension of water. Adhesion would mean that the water is sticking to another substance,

which would impede movement upward. Hydrogen bonding joins water molecules together, aiding the pull of water molecules upward.

A carboxylic acid contains which of the following functional groups?

A. –OH

B. –CHO

C. –COOH

D. –O–

Explanation:

The correct answer is C. A carboxylic acid contains the –COOH (carboxyl) functional group. An alcohol contains the –OH (hydroxyl) functional group; an aldehyde contains the –CHO (aldehyde) functional group; and an ether contains the –O– (ether) functional group.

Cell Structure and Function

Around 10–13% of questions on your exam will cover the topic Cell Structure and Function.

Cellular Components and Functions of Those Components

Cells are the smallest functional unit of life. There are two categories of cells: prokaryotes and eukaryotes. **Prokaryotes** are unicellular, and do not have cell walls or membrane-bound organelles, and generally have a single circular chromosome. This group includes bacteria and archaea. **Eukaryotes** have multiple chromosomes organized in a membrane-bound nucleus and also have other organelles. Eukaryotes include single-celled organisms like protozoans and yeast, as well as multicellular organisms like plants and animals.

Animal and plant cells differ in a several features. Animal cells have a thin **plasma membrane** that encloses the cells. The membrane itself is flexible and made of a phospholipid bilayer with various proteins embedded in the membrane. Proteins in the bilayer regulate which molecules enter and exit the cell and are important for communication between the cell and the environment.

Plants, on the other hand, have a **cell wall** in addition to the plasma membrane made of cellulose and lignin, giving strength, rigidity, and protection to plant cells. The cell wall also helps the cell to store water by regulating diffusion and providing the strength to allow high internal pressures without rupture. Plants, fungi, algae, bacteria, and archaea all have cell walls with slightly different compositions.

Plants also have a **central vacuole**, a fluid filled membrane-bound structure that stores water and nutrients for the cell. Animal cells have vacuoles, but these fulfill other purposes. Plant and animal cells also differ in how they produce energy; plant cells contain chloroplasts and mitochondria, while animal cells only have mitochondria. These are described in more detail in the following table of eukaryotic cell organelles.

Organelle	Description
Nucleus	The nucleus contains most of the genetic material of a cell in the form of chromatin. RNA transcription and processing occur within the nucleus. The nucleus also contains the **nucleolus**, the area where ribosomes are made. The nucleus is encased in a plasma membrane with nuclear pores that tightly restrict movement of molecules in and out and to the endoplasmic reticulum.
Mitochondria	Mitochondria are membrane-bound organelles where cellular respiration, the synthesis of ATP from ADP, occurs. ATP is one of the primary molecules the animal cell uses to harness energy. Mitochondria have a double membrane—the outer one is smooth, while the inner one is rough. Mitochondria have their own circular DNA, are able to reproduce within cells, and have some of their own protein synthesis machinery.
Chloroplast	Chloroplasts are membrane-bound organelles that contain chlorophyll and make energy through photosynthesis. Like mitochondria, they also have their own DNA and protein synthesis machinery.
Endoplasmic Reticulum	The endoplasmic reticulum (ER) are folded, membrane-bound organelles that are transport hubs from the nucleus to the Golgi apparatus. There are both rough and smooth ER. The **rough ER** is covered with ribosomes and is the site where membrane-bound proteins and proteins that are packaged in vesicles are made. The **smooth ER** does not have ribosomes on it, hence the smoother appearance, and is the site where many things are synthesized including lipids, fats, and steroids.
Golgi Apparatus	The Golgi apparatus is made of stacks of membrane sacks. This is the site where most protein modification takes place and where proteins are packaged and targeted for export from the cell.
Ribosomes	Ribosomes perform translation of RNA into protein. Ribosomes are made of ribosomal RNA (rRNA) and some associated proteins and can be free in the cell, making proteins in the cytoplasm, or can be found on the rough endoplasmic reticulum where they synthesize proteins that end up on or in cell membranes. Ribosomes are found in every form of life on Earth, providing evidence for a common ancestor.
Lysosomes & Peroxisomes	Lysosomes and peroxisomes are vesicles in the cell where cell waste is destroyed and recycled. Lysosomes contain hydrolytic enzymes that destroy proteins, cell waste, and damaged organelles. Peroxisomes are where lipids and reactive oxygen species are destroyed.
Cytoskeleton	The cytoskeleton is made of microtubules, intermediate filaments, and microfilaments that collectively give structure to the cell, keep organelles in place, help cells move, and provide the framework that proteins move along in a cell.
Centrosome	The centrosome is the main microtubule organizing center of the cell and organizes the mitotic spindle during cell division. A cell has a single centrosome unless it is in the cell cycle.

Vesicles	Vesicles are membrane sacs that transport molecules in a cell. They can carry substances inside for release into the extracellular environment (like neurotransmitters), they can carry membrane-bound proteins that end up on the cell membrane, and they can also remove pieces of membrane for destruction, changing the size and shape of a cell.

Understanding what happens in different organelles as it relates to cell function is a common theme in the Free Response section of the AP exam.

Cell Size

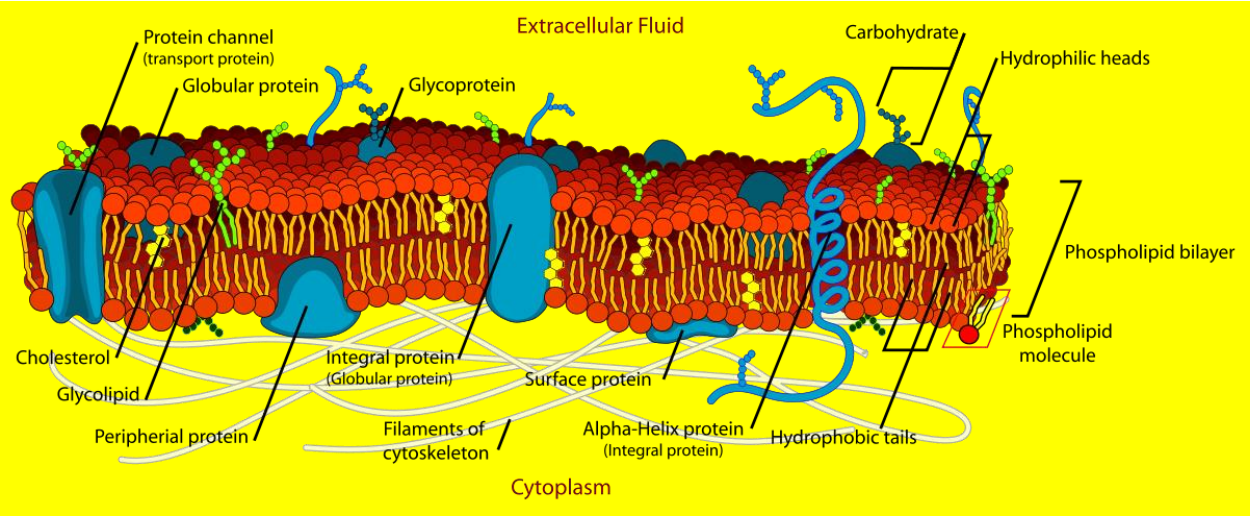
Cells exchange molecules with their environment to sustain the life of the cell or the life of the organism, which includes obtaining things like nutrients, thermal heat, and oxygen, as well as releasing molecules for the organism or waste products. As a cell grows in size, it must maintain a membrane surface area that allows it to sustain its metabolic needs and functions. Thus, the cell can only grow as large as the surface area of the cell can support. Mathematically, the volume of the cell increases faster than the surface area. You can calculate these relationships using the equations in the following table, with radius (*r*), length (*l*), height (*h*), width (*w*), and length of one edge of a cube (*l*).

	Sphere	Cube	Rectangular Solid	Cylinder
Volume	$V = \frac{4}{3}\pi r^3$	$V = s^3$	$V = lwh$	$V = \pi r^2 h$
Surface Area	$SA = 4\pi r^2$	$SA = 6s^2$	$SA = 2lh + 2lw + 2wh$	$SA = 2\pi rh + 2\pi r^2$

In each case, the volume grows much faster than surface area, limiting the amount a cell can grow in these shapes. The result of this is that highly metabolically active cells either remain small in size or take on unique specializations to allow more surface area for exchange. Specializations can include features like membrane folds that increase surface area of the cell.

The Cell Membrane Structure and Function

The **fluid mosaic model** describes the structure of cell membranes. In this model, the plasma membrane is made of a phospholipid bilayer with cholesterol, proteins, glycolipids, and glycoproteins embedded within in it. The components of the membrane are in constant motion.



Cell Membrane

- **Phospholipids** comprise the majority of the plasma membrane; these are lipids made of a hydrophilic head and hydrophobic tails. The hydrophilic heads are made of a glycerol molecule with a phosphate group attached. The hydrophobic tails are made of long, non-polar fatty acids. Phospholipids form a bilayer, where the hydrophilic heads face the aqueous internal and external environments, and the hydrophobic ends stay in the middle.
- **Membrane proteins** can traverse the entire membrane, partially extend on one side of it, or attach loosely to one side of the membrane depending on its hydrophobicity. Proteins that integrate into the membrane are called **integral membrane proteins**. These have a hydrophobic portion that anchors them within the membrane. If they traverse both ends of the membrane, they are called **transmembrane proteins**. **Peripheral membrane proteins** are loosely attached to the membrane either to other integral proteins or to phospholipids.
- **Glycolipids** and **glycoproteins** attach to the outer surface of the cell. These are generally used as signals for the type of cell that they are. For instance, the immune system uses glycoproteins to identify cells that belong to the organism versus invaders.
- **Cholesterol** groups are embedded within the hydrophobic bilayer and affect membrane fluidity. They act to buffer fluidity at both low and high temperatures, making it so the cell can function at a large range of conditions.

The structure of the phospholipid bilayer creates a semipermeable barrier for substances to cross due to the hydrophobic interface. The cell membrane creates **selective permeability**, meaning that only certain molecules can pass through the membrane. Small nonpolar molecules, like N_2, O_2, and CO_2 pass easily across the membrane. Uncharged polar molecules, like water, can pass through in small amounts. Hydrophilic substances like large polar molecules and ions cannot pass freely because the hydrophobic center repels hydrophilic molecules. These require membrane transporters to move across the membrane.

Plants and bacteria have cell walls made of complex carbohydrates in addition to their membranes. Cell walls add an additional layer of support by both providing strength as well as protecting cells from both mechanical and osmotic stress.

Cell Regulatory Mechanisms

The cell has several methods to allow transport across the membrane.

- **Passive transport**, movement across a membrane without energy being used, occurs due to molecule diffusion from areas with high concentration to areas with low concentration by taking advantage of their concentration gradients.
- **Active transport**, movement across a membrane that requires energy, is used to get molecules from areas of low concentration to areas of high concentration.
- **Endocytosis** occurs when a vesicle forms in a plasma membrane, taking in molecules from the external environment into the cell. This is one way that macromolecules enter the cell.
- **Exocytosis** occurs when a vesicle fuses with the membrane and dumps contents into the extracellular space. This is a method used to take macromolecules out of the cell.

There are three forms of passive transport: simple diffusion, facilitated diffusion, and osmosis. During **simple diffusion**, molecules pass across the membrane freely by taking advantage of their concentration gradients. This is what occurs with oxygen and carbon dioxide; they are permeable to the membrane, and thus do not need additional transporters to help them get across.

Molecules that are not able to easily pass through the membrane undergo **facilitated diffusion**. In facilitated diffusion, channels in the membrane surface or carrier molecules assist molecules in crossing the cell membrane. For example, aquaporins are channels in the cell's membrane that allow water to pass through along a concentration gradient. By limiting the number of aquaporins in a cell membrane, the amount of water that can flow in or out is regulated, which keeps the cell from experiencing rapid shifts in water content.

Osmosis is the process by which water moves across a semipermeable membrane from an area of low concentration of solutes to an area of high concentration of solutes, to equalize

concentrations. **Osmolarity** is the total concentration of solutes in a solution. **Osmotic pressure** refers to the pressure that pulls water from one side of a membrane to the other. **Tonicity** refers to the ability of water to move across a membrane by osmosis; this takes into account both the differences in osmolarity as well as the ability of water to move.

Cell environments can be **isotonic**, meaning that the concentration of solutes is the same in the internal and external environments; **hypertonic**, meaning the external environment has more solute than the internal environment; or **hypotonic**, meaning that the external environment has less solute than the internal environment. Cells in a hypotonic solution take on too much water, causing them to swell and potentially burst. On the other hand, cells in a hypertonic solution are at risk of shriveling.

Active transport mechanisms use metabolic energy, often in the form of ATP, to transport molecules. Active transport is used to maintain concentration gradients across cells. For example, neurons take advantage of concentration gradients to signal to each other. The internal environment of a neuron is high potassium and low sodium and external environment is low potassium and high sodium. These concentration differences create a negative membrane potential that positions it to respond to stimulation. The cell uses active mechanisms to maintain this concentration difference and membrane charge using a membrane transporter called the Na^+/K^+ ATPase, which uses ATP to move sodium and potassium across the membrane in an energetically unfavorable direction.

Cellular Compartmentalization

Compartmentalization of processes is an essential feature of cellular environments. Membranes allow cells to compartmentalize processes that need to be kept separated from the rest of the environment. For example, the lytic enzymes in lysosomes would be fatal to the cell if released into the cytosol. Thus, cells developed a way to compartmentalize these enzymes into a membrane-bound organelle. By having membranes, cells and organelles are able to create internal environments that are different than the external environment.

For example, for neurons to fire action potentials, they take advantage of an electrochemical gradient where the internal environment is rich in potassium and the external environment is rich in sodium. Without membranes that actively maintain these different environments, neurons would not function. Internal membranes also facilitate processes by increasing reaction surface areas and keeping molecules in the places that they are needed to function. For example, the internal mitochondrial membrane is an important site of ATP synthesis (discussed later on in this guide). The mitochondria are formed in a way to maximize internal membrane surface area, so they can form more ATP.

Membrane bound organelles evolved from prokaryotic cells through a process called **endosymbiosis**. This is a form of symbiosis where once cell resides inside of another. The theory is that organelles like chloroplasts and mitochondria were once free-living prokaryotes. At some point in history, a eukaryotic cell engulfed a prokaryote—likely a photosynthetic autotroph—but did not digest it. This generated a mutually beneficial relationship where the prokaryote generated energy for the eukaryotic cell, and the eukaryotic cell protected the prokaryotic cell and provided nutrients for it.

Over time, this relationship became permanent as the prokaryotic cell stopped carrying all of the genes needed for its survival and the eukaryotic cell became dependent on the energy the prokaryotic cell provided. This is supported through the fact that both share features of prokaryotic cells, like having their own circular DNA genome. Prokaryotes generally do not have membrane bound organelles—rather, they have regions with specialized structures and functions within them.

Outside Reading

- To learn more about cell organization: https://www.khanacademy.org/test-prep/mcat/cells/eukaryotic-cells/a/organelles-article
- To learn more about cell membrane properties and transport: https://opentextbc.ca/anatomyandphysiology/chapter/the-cell-membrane/
- To learn more about membrane transport: https://courses.lumenlearning.com/nemcc-ap/chapter/3204/

Sample Cell Structure and Function Questions

A cell that produces and secretes a large number of proteins would probably have

A. extensive rough ER.

B. limited rough ER.

C. few mitochondria.

D. a cell wall.

Explanation:

The correct answer is A. The rough ER (endoplasmic reticulum) is responsible for producing proteins (in the bound ribosomes) and transporting them within and outside the cell. Mitochondria are the powerhouses of the cell, responsible for creating energy through respiration. They are not directly involved in protein synthesis or transport, so you would not expect to find a remarkably small (or large) number of mitochondria in such a cell. The cell wall is found in plant cells and is used to protect the cell and provide support. The cell wall is not directly involved in protein synthesis or transport, so you would not necessarily expect to find a cell wall in such a cell. Furthermore, animal cells are capable of producing and secreting large numbers of proteins, so it is not necessary that this type of cell would have a cell wall.

When a solution has a lower solute concentration than the solution on the other side of a membrane, that solution is said to be

A. hypotonic.

B. isotonic.

C. hypertonic.

D. undergoing osmosis.

Explanation:

The correct answer is A. A hypotonic solution has a lower solute concentration than the solution on the other side of a membrane. A hypertonic solution has a higher solute concentration than the solution on the other side of a membrane. Choice B is incorrect because the term *isotonic*

indicates that two solutions have equal concentrations. Choice D is incorrect because *osmosis* is the term for the diffusion of water across a membrane.

What feature of a plant cell prevents it from bursting when in a highly aqueous solution?

A. a large central vacuole

B. a guard cell

C. a cell wall

D. chloroplasts

Explanation:

The correct answer is C. The rigid cell wall of plant cells prevents lysis of the cell when in an aqueous environment. The vacuole of the cell expands, creating turgor pressure, but the cell membrane expands only as much as the cell wall will allow. Choice A is incorrect because the large central vacuole in plant cells swells as water enters the cell in an aqueous environment. The size of the vacuole is limited by space within the cell and by the rigid outer cell wall. Choice B is incorrect because guard cells surround stomata in leaves and regulate transpiration from the leaf. Choice D is incorrect because chloroplasts are the site of photosynthesis in the cell and are located within the cytoplasm.

Cellular Energetics

Around 12–16% of the questions on your AP exam will cover Cellular Energetics.

The Structure and Function of Enzymes

For energy releasing reactions to occur, there is usually an associated energy barrier that must be overcome first. If there were not, then cells would just release energy indefinitely. This energy hurdle is called the **activation energy**. This can be overcome by either inputting energy in the reaction, or through the introduction of a catalyst. **Catalysts** reduce activation energy and increase reaction rate without itself undergoing a chemical change. **Enzymes** are biological catalysts. Enzymes act by changing the conformation of molecules that they interact with to put them into a more optimal state for a reaction to proceed. The **active site** of an enzyme is the portion that interacts with the molecule. The **substrate** is the molecule that the enzyme binds with to facilitate a change.

Enzymes and molecules in a biological reaction are affected by their environment. For example, increases in heat generally cause reactions to take place faster because increased molecule movement increases the frequency of collisions between substrate and enzyme. However, excessive heat can denature proteins, causing their structures to be altered and inhibiting their ability to take part in a reaction. Similarly, pH can alter the efficiency of a reaction by altering hydrogen bonds. These effects can be reversible if the conditions return to baseline. The concentration of substrates in comparison to enzymes will also affect enzyme activity. Generally, the more substrate or more enzyme around, the faster the reaction will proceed, as there are more chances for substrates and enzymes to come into contact.

Other factors that can affect enzyme reaction rates are inhibitors. **Competitive inhibitors** compete for the active site of an enzyme, keeping it from binding the substrate and blocking the reaction. **Noncompetitive inhibitors** bind to other sites on the enzyme, changing the enzyme's conformation and keeping it from efficiently binding the substrate.

The Role of Energy in Living Systems

All living things require energy to sustain life. **Bioenergetics** is the study of energy transformation in living organisms. **Metabolism** is the general term for all energy transformations in living organisms, including processes like photosynthesis, mitochondrial respiration, and movement. In biological systems, energy input constantly exceeds loss to keep the systems going. Energy is then stored in the form of molecules that contain chemical bonds that can be broken down, most often in the form of sugars or fats. **Anabolism** is the process where molecules store energy in the form of chemical bonds. **Catabolism** is the process by which energy is released by breaking these

bonds. Often, energy release mechanisms are linked to processes, so the energy is immediately used by the cell.

As mentioned, cells store energy in the form of fats and sugars. When these are broken down, large amounts of energy are released that may be more than a cell needs to complete a process. This can lead to wasting precious energy for small tasks. Thus, larger energy forms are generally first converted to smaller energy molecules that are then used for cells to carry out normal functions. **Adenosine triphosphate** (**ATP**) is the primary source of energy that cells use to function. ATP can be broken down into ADP (adenosine diphosphate) and AMP (adenosine monophosphate), through process like fermentation and respiration, releasing energy at both steps that can be harnessed to power other cellular processes. ATP breakdown is linked to most cellular processes, providing a streamlined way for cells to harness energy.

The Processes of Photosynthesis

Photosynthesis is the process where light energy is converted to cellular energy in the form of glucose. During photosynthesis, carbon dioxide, water, and light are converted to glucose and oxygen:

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

Photosynthesis initially evolved in cyanobacteria, resulting in oxygenation of the Earth's atmosphere. The pathways that evolved in prokaryotes are the foundations for eukaryotic photosynthesis in plants.

Photosynthesis takes place in two main phases: **photolysis** (the light dependent reaction) and the **Calvin cycle** (the light independent reaction). Photolysis takes place in the thylakoid membranes of chloroplasts. During this step, light energy is absorbed by chlorophylls, which then generate ATP and NADPH. NADPH is an electron carrier used in biological reactions. Water is used in this reaction and oxygen is released.

The Calvin cycle takes place in the stroma of chloroplasts. In this step, carbon dioxide from the environment reacts with ATP and NADPH generated in photolysis to create small 3 carbon sugars, which are then joined to form glucose. Glucose provides the cell with both energy, as it can be used to synthesize ATP, and fixed carbon. **Fixed carbon** refers to organic carbon molecules, like sugars. Fixed carbon is used by cells to build molecules needed in cells for other processes. The Calvin cycle both removes carbon from the atmosphere and fixes the energy generated from photolysis in a form that can be stored in cells for later use.

The light dependent reaction relies on **photosystems** to harvest light energy. During this process, called **non-cyclic phosphorylation**, light is absorbed by two photosystems that harness the

electrons from water to make NADPH and ATP from NADP+ and ADP. There are two photosystems, photosystem I (PSI) and photosystem II (PSII). Photosystem structures are embedded in the thylakoid membrane and are made of a light harvesting complex, composed of proteins and hundreds of chlorophylls and pigments, and a special pair of chlorophyll a at the core.

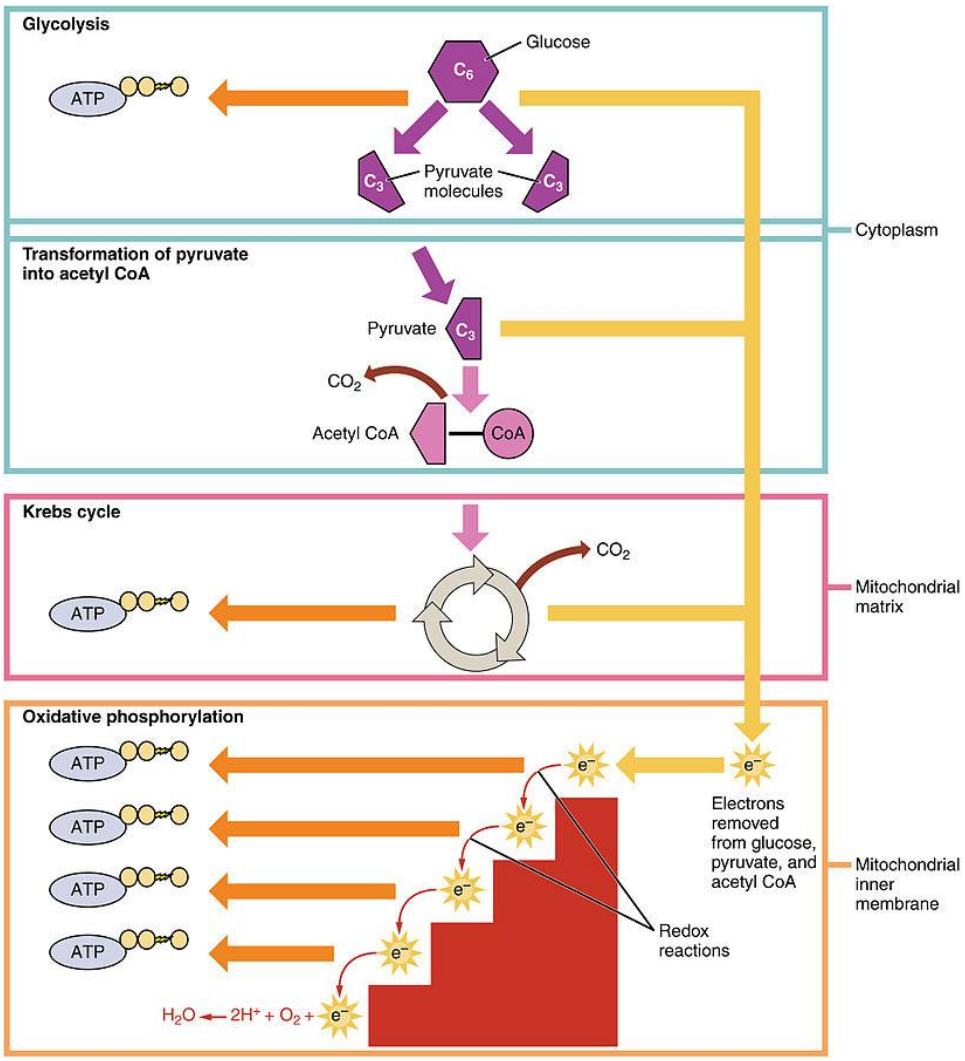
During non-cyclic phosphorylation, light energy is first harnessed by PSII through the light harvesting complex. The energy is passed via PSII's special pair of chlorophyll a (called P680), which in turn boost an electron to a higher energy level. The electron is then passed to an acceptor molecule and replaced with an electron taken from water, releasing oxygen. The high energy electron is then passed along the membrane by a series of transporters, called the **electron transport chain (ETC)**. The electron loses a little energy at each step of the ETC; some of this energy is used to pump H^+ ions from the stroma into the thylakoid membrane—this pumping creates a proton gradient that is linked to formation of ATP from ADP through a process called **chemiosmosis** via an enzyme called **ATP synthase**.

Phosphorylation of ADP to generate ATP in photosynthesis is called **photophosphorylation**. PSI receives the excited electron, which is passed along the ETC. Light energy received by PSI is then used to excite the electron through its special chlorophyll pair (called P700). The electron, now at a very high energy level, is then passed by an acceptor molecule which passes it along another electron transport chain that results in the creation of NADPH from NADP+. ATP and NADPH generated in during the light cycle are then used in the stroma of chloroplasts to generate sugar from carbon dioxide through the Calvin cycle.

The Processes of Cellular Respiration

All forms of life use respiration and fermentation to break down biological macromolecules, like sugars and fats, into ATP.

In eukaryotes, cellular respiration breaks down glucose into carbon dioxide and water to generate ATP. As in photosynthesis, cellular respiration takes place in a series of steps where energy is passed along an electron transport chain.



1. In the first step of respiration, called **glycolysis**, the 6-carbon containing glucose is broken down into two 3-carbon pyruvates, two ATP molecules, and two NADH molecules. During glycolysis, an ADP is converted to ATP and NAD+ is converted to NADH. Glycolysis takes place in the cell's cytosol.

2. After glycolysis, the pyruvate molecules are transported into mitochondria, where they are broken down into two carbon molecules, called acetyl groups, that are bound to coenzyme-A, in a molecule called acetyl CoA. This step, called **pyruvate oxidation**, reduces NAD+ to NADH, but does not generate ATP.

3. Acetyl CoA then moves into the **citric acid cycle**, also called the Krebs cycle. The citric acid cycle is a form of aerobic respiration where acetyl co-A, which is a product of oxidized pyruvate, is metabolized to produce one NADH, one $FADH_2$, two carbon dioxides, and either one ATP or one GTP.

4. In the final step of cellular respiration, called **oxidative phosphorylation**, NADH and $FADH_2$ are then used to make more ATPs through an electron transport chain in the membrane of mitochondria. As in photosynthesis, the electron transport chain uses electrons donated by carrier molecules, in this case, NADH and $FADH_2$, which are then passed along the chain. As electrons are passed along, they lose some energy, which is used to pump H^+ ions from the mitochondrial matrix to the intermembrane space. This creates a chemical gradient, which is used to convert ADP to ATP through chemiosmosis by ATP synthase. The final electron acceptor in oxidative phosphorylation is an O_2 molecule, which generates water. In prokaryotes, the first three steps of respiration take place in the cytosol and oxidative phosphorylation takes place in the cell's membrane. In some anerobic prokaryotes other proton acceptors are used at the end of the electron transport chain in a process called anaerobic cellular respiration.

In some cells, the electron transport chains are decoupled from the generation of ATP. This is used to generate heat to warm the body instead of energy storage.

If oxygen is not available at the end of the electron transport chain to accept electrons, cells take a slightly different approach to respiration. During **fermentation**, glycolysis proceeds, but pyruvates are converted to other organic molecules like lactic acid and alcohol. This regenerates NAD+ from NADH, which allows glycolysis to continue.

Molecular Diversity and Cellular Response to Environmental Changes

Note that there are a variety of somewhat overlapping mechanisms built in for life to generate ATP for immediate energy usage. For instance, in the absence of oxygen, cells can convert to fermentation. Plants have a variety of types of chlorophyll in their cells that can harness energy from different wavelengths of light. The presence of these different types of molecules help organisms adapt to changing environments and optimize species survival. This will be discussed more in later sections on evolution.

Outside Reading

- To learn more about photosynthesis: https://www.khanacademy.org/science/biology/photosynthesis-in-plants
- For more on cellular respiration: https://www.khanacademy.org/science/biology/cellular-respiration-and-fermentation

Sample Cellular Energetics Questions

Enzymes lower the _____ of a reaction.

A. temperature

B. activation energy

C. free energy

D. speed

Explanation:

The correct answer is B. Enzymes lower the activation energy of a reaction, or the energy needed for a reaction to proceed. Enzymes do not affect the temperature or the free energy of a reaction, and they usually enhance the speed of a reaction by reducing the activation energy.

The light-dependent reactions of photosynthesis transform energy from sunlight into chemical energy in the form of

A. photons.

B. pyruvic acid.

C. lactic acid.

D. electrons.

Explanation:

The correct answer is D. Electrons generated in photosynthesis are used to produce energy in the form of ATP or NADPH. Choice A is incorrect because photons are particles of light absorbed by pigments in the first step of photosynthesis. Choice B is incorrect because pyruvic acid is formed as an intermediate product in cellular respiration, not photosynthesis. Choice C is incorrect because lactic acid is formed as an intermediate product in anaerobic respiration, not photosynthesis.

Which of the following is a product of anaerobic respiration?

A. pyruvic acid

B. lactic acid

C. glucose

D. oxygen

Explanation:

The correct answer is B. In anaerobic respiration, pyruvic acid molecules are broken down into end products. In one type of anaerobic respiration, lactic acid is produced. Choice A is incorrect because pyruvic acid is broken down, not produced, in aerobic respiration. Choice C is incorrect because glucose is produced through photosynthesis. Choice D is incorrect because anaerobic respiration produces carbon end products, ATP, and carbon dioxide.

Cell Communication and Cell Cycle

Around 10–15% of the questions on your AP exam will cover the topic Cell Communication and Cell Cycle.

The Mechanisms of Cell Communication

Cells communicate to each other through both long-range and short-range signals. These types of messages often occur through one cell releasing a molecule in the extracellular space, called a **ligand**, that is then received by another cell that has a **receptor** for that ligand. There are four methods of cell communication: paracrine, autocrine, endocrine, and cell-cell contact.

- **Paracrine** signaling occurs when one cell releases ligand into the extracellular space to signal to nearby cells. This type of signaling occurs at neuronal synapses when an axon terminal releases neurotransmitter on a receiving neuron.
- **Autocrine** signaling occurs when a cell releases a signal to itself. This is one way that cells regulate their own growth and intracellular processes.
- **Endocrine** signaling occurs when a cell releases a ligand, typically into the bloodstream, to affect cells a long way away. This is normally how hormones work.
- Signaling through **cell-cell contact** occurs when two cells physically contact each other, and this causes a signal to be passed on. This can occur through gap junctions on cells, which are physical connections between two cells that allow them to exchange small signaling molecules, or through binding of ligands and receptors on the surfaces of two adjacent cells. Cell surface binding is an important way that the immune system uses to recognize pathogens and mount a response against them.

Signal Transduction

When a cell receives a signal, it must have a way to respond to it. **Signal transduction pathways** link the signal to the appropriate response. Signal transduction begins when a ligand is recognized by a receptor. Ligands can be simple molecules like small chemicals, small peptides, or large proteins. Receptors generally recognize one or a few ligands and have several forms.

- **Intracellular receptors** reside within the cell. Hormone receptors are an important example of these; when hormones bind a receptor, the receptor changes shape and enters the nucleus to induce changes in gene expression.
- **Cell surface receptors** reside within the plasma membrane and respond to signals from outside. These include ligand-gated ion channels, G-protein coupled receptors, and enzyme-linked receptors.

- **Ligand-gated ion channels** open or close in response to ligand binding, allowing ions to either flow through the channel or stopping the flow of ions.
- **G-protein coupled receptors** respond to a signal by activating their coupled G-protein. This activated G-protein then interacts with other proteins within the cell, causing other events to occur. The olfactory system relies on G-protein coupled receptors to transduce different odorants into smells that we recognize.
- **Enzyme-linked receptors** are a type of receptor that are coupled to an enzyme. Once activated, the enzyme is able to induce reactions within the cell.

Once a receptor is activated by a ligand, a signaling cascade is initiated that causes changes within the cell. This can include things like inducing gene expression, secreting a molecule, changes in cell growth, or changes in the identity of the cell.

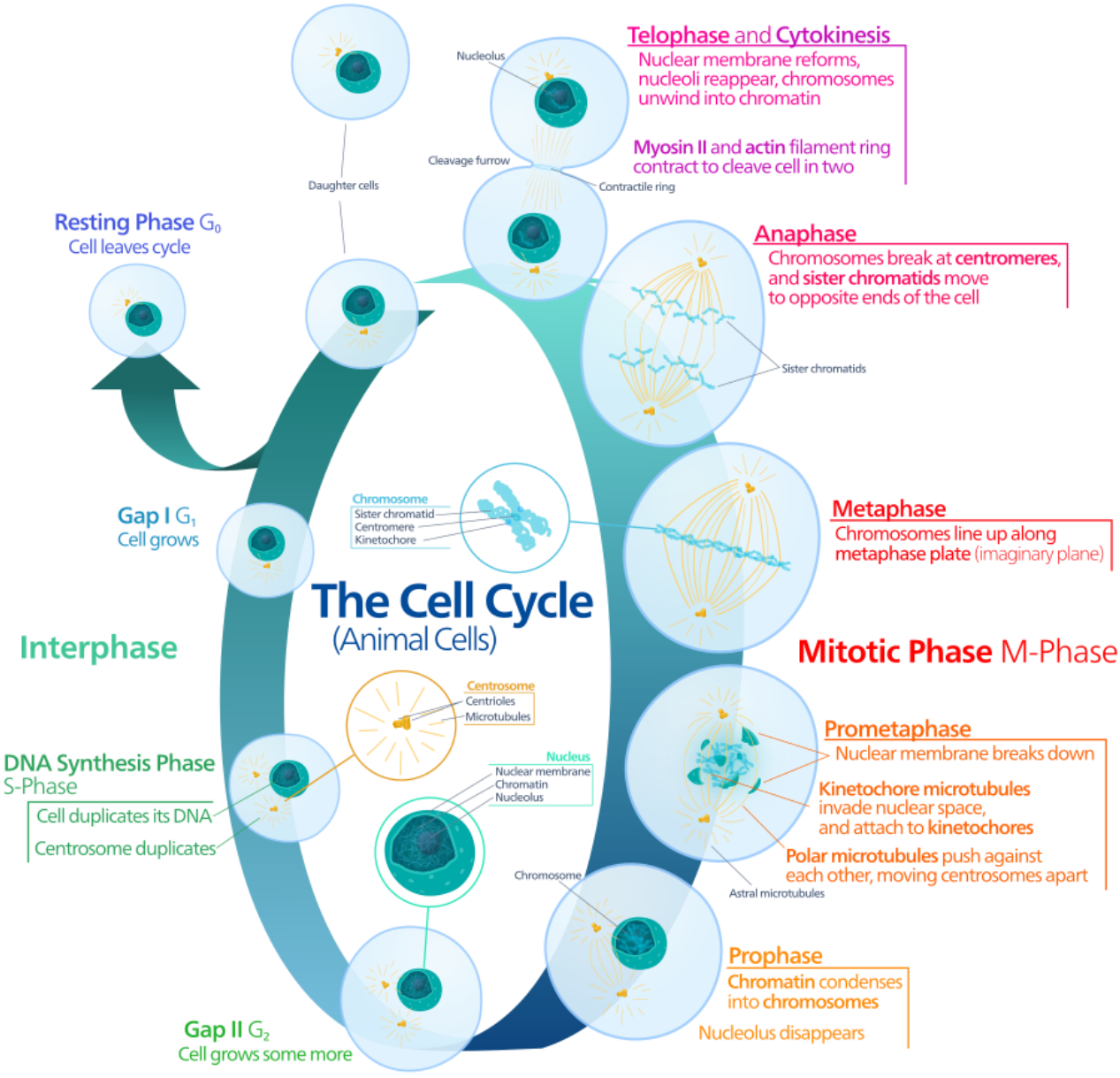
Cellular Responses and Feedback Mechanisms

Feedback mechanisms are used in biological systems to maintain their internal environments and respond quickly to changes. **Negative feedback** mechanisms help to return a system to its set point after a disruption. Negative feedback helps to maintain **homeostasis**, the relatively constant state of the internal environment. For example, when your temperature goes up, several mechanisms occur to bring it back down, like sweating and vasodilation to promote loss of heat. When your body gets too cold, you shiver to generate more heat, and your blood vessels constrict to reduce heat loss.

Positive feedback happens when the response to a signal amplifies that response so that there is a quick change. Positive feedback moves an organism even farther away from equilibrium. This occurs in situations when there needs to be a rapid response to a signal. An important example of this occurs in the process of fruit ripening. Fruits release ethylene as they ripen. Ethylene induces ripening of fruit that it comes into contact with; thus, when one fruit in a bunch begins to ripen, fruit around it will also ripen. This amplifies the signal as more fruit begin to ripen and release ethylene.

The Events in a Cell Cycle

The **cell cycle** is the process that cells undergo to grow, duplicate their DNA, and make two cells with identical DNA. In eukaryotic cells, the cell cycle includes interphase, mitosis, and cytokinesis. **Interphase** is the stage of the cell cycle where cells grow and copy their DNA. During **mitosis**, the cell divides to make two cells with identical DNA.



The stages of interphase are as follows:

1. **Gap I (G_1):** The cell grows in size, copies organelles, and synthesizes the molecules it will need to divide.
2. **S phase:** The cell synthesizes a duplicate copy of its DNA and makes a second centrosome. The two duplicate copies of each strand of DNA are called **sister chromatids**.
3. **Gap II (G_2):** The cell continues to grow and prepare for cell division. At the end of G_2, mitosis begins.

The stages of mitosis are as follows:

1. **Prophase:** The chromatin condenses and the nucleolus disappears. The **mitotic spindle**, a structure made of microtubules and centrosomes that organizes chromosomes during cell division, also begins to form.
2. **Prometaphase:** The nucleus disappears, chromosomes become very compact and begin to attach to the mitotic spindle at their kinetochore. The **kinetochore** is a specialized protein structure that forms at the centromere of chromosomes during mitosis that attaches them to spindle microtubules. The **centromere** is the protein structure that attaches two sister chromatids together. In some texts, prometaphase is termed late prophase and the two steps are not separated.
3. **Metaphase:** Chromosomes line up at the center of the cell at a region called the **metaphase plate**. Each sister chromatid attaches its kinetochore to the microtubules at a different centrosome. This ensures that the daughter cells only get one copy of each chromatid. The cell will not divide until the chromosomes are properly attached.
4. **Anaphase:** Microtubules pull one copy of each chromatid towards their centrosomes.
5. **Telophase:** The mitotic spindle breaks down, a nucleus forms around each set of chromosomes, the nucleolus disappears, and chromosomes unwind again to form chromatin.

Cells split through **cytokinesis**. Cytokinesis begins around anaphase and ends after telophase is over. In animal cells, a **cleavage furrow** forms between the two cells; this actin ring contracts until it separates the two cells. In plant cells, a stiff **cell plate** forms between the two cells to split them. After cell division, daughter cells can either re-enter the cell cycle to form more cells, or they can go into the **resting phase** (**G_0**). A cell can remain in G_0 forever, or until it receives a cue to reenter the cell cycle.

The cell cycle is a tightly regulated process. Remember, this is how a cell passes on genetic information for an organism to grow. If conditions are not ideal, or if mutations in DNA occur, the resulting daughter cells could be too damaged to function, which can cause the cells to undergo regulated cell death (apoptosis) or result in abnormal cell growth (cancer). To keep this from happening, the cell has positive and negative regulators to guide the cell cycle.

Checkpoints are points within the cell cycle where progression can be stopped until conditions are deemed favorable to proceed. There are three checkpoints in the cell cycle.

- The **G_1 checkpoint** occurs during the G_1 phase of the cell cycle. At this point, the cell decides whether to irreversibly commit to replicating. At this point, the cell looks for growth, cell size, and DNA damage before it decides to enter the S phase. If damage is detected or conditions are not favorable, the cell will try to repair or correct problems, or wait in G_0 until conditions are better.
- The **G_2 checkpoint** occurs in the G_2 phase of the cell cycle. At this point, the cell checks for cell size, protein abundance, and integrity of synthesized chromosomes. If problems are found, the cell will try to repair them before advancing.

- The **M checkpoint** occurs at the end of metaphase. In this step, the cell checks if the kinetochores of sister chromatids are attached to the metaphase plate. The cell cycle will not proceed until this occurs.

Molecules called **cyclins** and **cyclin dependent kinases (CDKs)** are positive regulators of the cell cycle; that is, they help the cell cycle proceed. Different cyclins increase expression at different checkpoints in the cell cycle. Without this interaction, the cell cycle will not proceed past a checkpoint. Cyclins bind their partner CDKs and this interaction causes the CDK to phosphorylate other target proteins. These phosphorylation events activate proteins that are needed for the cell cycle to move forward; thus, until a critical level of cyclin/CDKs are present, the cell cycle will not proceed.

On the other hand, **tumor suppressor proteins** are responsible for negative regulation of the cell cycle. These proteins were discovered because mutations in the genes that encode these proteins cause uncontrolled cell growth in the form of cancer. These proteins have roles like checking for DNA damage and halting the cell cycle from progressing in case damage is detected. In some cases, they halt progression through inhibiting cyclin/CDKs.

Understanding the cell cycle and how it contributes to genetic diversity and mutations are common themes in the free response section of the AP exam.

Outside Reading

- To learn more about signaling: https://www.khanacademy.org/science/biology/cell-signaling
- For more information on feedback loops: https://www.albert.io/blog/positive-negative-feedback-loops-biology/
- For more information on cell division: https://www.khanacademy.org/science/biology/cellular-molecular-biology

Sample Cell Communication and Cell Cycle Questions

Interphase includes which of the following phases of the cell cycle?

A. S phase only

B. G_1 and G_2 phases only

C. S, G_1, and G_2 phases only

D. mitosis only

Explanation:

The correct answer is C. Interphase includes the S, G_1, and G_2 phases of the cell cycle. Each of these phases involves growth, protein synthesis, and regular cell function. Mitosis and cytokinesis are other periods of the cell cycle that compose the cell division phase.

Which of the following occurs first in mitosis?

A. chromatin condenses into chromosomes

B. chromatids separate

C. nuclear membranes form around chromosomes

D. two identical cells are formed

Explanation:

The correct answer is A. One of the first steps in mitosis occurs in prophase, when the genetic material contained in chromatin condenses into chromosomes. Chromatids separate during the anaphase stage of mitosis. Before anaphase, chromatin condenses into chromosomes (during prophase), and these chromosomes align in the center of the cell (during metaphase). Telophase is the last step of mitosis and is when nuclear membranes form around the two sets of chromosomes created in the earlier stages of mitosis. Two identical cells are formed during cytokinesis, after mitosis has concluded.

Cell cycles can vary greatly between different cells. Which of the following phases contributes most to these differences?

A. G1

B. G2

C. G3

D. M

Explanation:

The correct answer is A. Differences in the cell cycle are due mostly to variations in the length of the G1 phase. In rapidly dividing cells, G1 is basically nonexistent. In cells that do not divide, G1 persists indefinitely. G2 is the period between DNA synthesis and cell division; it does not vary widely between different cells. There is no G3 phase of the cell cycle. The M phase is the mitosis, or cell division, phase; this lasts roughly the same amount of time in different cells.

Heredity

Around 8–11% of the questions on your AP exam will cover Heredity.

The Process and Function of Meiosis

Meiosis is the form of cell division that creates **gametes** (sperm and eggs). Rather than form two identical daughter cells like mitosis, meiosis forms four daughter cells with half the amount of DNA as a normal cell. Normal cells are **diploid**, meaning that they have two non-identical copies of each chromosome (one from each parent). The non-identical copies of each chromosome are called **homologous chromosomes**. These are distinct from the identical sister chromatids formed in mitosis as homologous chromosomes have unique DNA features. Gametes are **haploid**, meaning that they only have a single copy of each chromosome that can be passed on to a child.

Meiosis has two rounds of cell division, meiosis 1 and meiosis 2, each with their own sets of prophase, metaphase, anaphase, and telophase with distinct features.

The following are the distinct features of meiosis:

- During prophase 1, homologous pairs of chromosomes align and exchange DNA in a process called **crossing over** or **recombination**. Crossing over happens at the homologous parts of chromosome resulting in unique chromosomes being distributed to gametes.
- In metaphase 1, homologous chromosome pairs are passed to daughter cells instead of individual chromosomes. Sister chromatids stay attached during this phase.
- In telophase 1, the nucleus may or may not form depending on the species.
- Meiosis 1 ends with two non-identical cells that each carry sister chromatids from one chromosome of a homologous pair. These chromatids are then split in meiosis 2.
- Meiosis 2 proceeds much like mitosis, but ends in four haploid cells, each carrying a single copy of each chromosome.

The Concepts of Genetic Diversity

Having a diverse genetic pool is important for species survival. Diversity allows populations to adapt to their environments over time, as the more diverse the gene pool is, the more likely individuals will have traits that allow them to adapt to a changing environment. Meiosis is one way that organisms generate diversity.

Diversity is achieved through independent assortment, crossing over, and random fertilization.

- Independent assortment in meiosis I ensures that gametes only receive a haploid set of chromosomes from each parent. This creates diversity in offspring by allowing for an exponential number of combinations of chromosomes to be passed along.
- Crossing over in meiosis I causes recombination between homologous chromosomes, so that gametes receive unique combinations of genetic material from the parent cells. Note that chromosome structure is maintained, so that gametes receive all the necessary genes for life to continue but will have different allele combinations compared to the parental chromosomes. This causes an additional layer of diversity in genetic material that is passed on by creating unique chromosomes in each generation.
- Gametes that undergo fertilization can contain any of the millions of unique combinations of chromosomes produced in meiosis from both parents. This doubles the number of unique combinations that can be produced.

Mendel's Laws and Probability

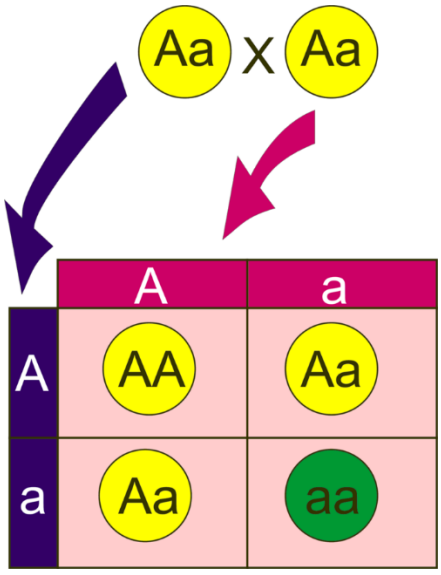
Gregor Mendel developed the principles of inheritance long before the discovery that DNA carries genes. He did this by studying how traits, like seed color and shape, were inherited by pea plants. He found that parents transmit traits (now known to be in the form of genes) to their offspring randomly. Each individual carries two copies of each gene and these can be different, called alleles. Different traits are independent and do not mix, one gene can mask another. Mendel proposed laws for inheritance based on his findings:

- The **Law of Segregation** states that allele pairs separate when gametes are formed. This means that each individual has two copies of each gene and that one copy of a gene is inherited from each parent separately. The biological basis for this law is put forth in meiosis, in which chromosome pairs are split up so that each haploid daughter cell that is formed has only one copy of each chromosome.
- The **Law of Independent Assortment** posits that alleles of genes are inherited independent of each other, meaning that inheriting an allele of one gene does not correlate with inheriting an allele of a different gene. We now know that traits are carried on chromosomes and their distance on the chromosome can affect how often they are transmitted independently. When genes are close together on a chromosome such that they are usually inherited together, they are called linked. Crossing over during meiosis can separate linked alleles; the farther apart they are on a chromosome, the higher the chance of separation.
- The **Law of Dominance** asserts that most genes have either dominant or recessive alleles and that the dominant allele will mask the recessive allele. There are some notable exceptions to this. For example, some traits exhibit **incomplete dominance,** where different alleles result in a blended trait rather than one clear trait. For example, alleles for white and red flowers could blend to form pink flowers. Another variation is the case of **multiple alleles**. In this case, many possible alleles exist, and they all express equally. The most notorious example of this is blood type. In humans, the alleles are A, B, or O. Both alleles are expressed, leading to phenotypes of A, B, AB, or O.

Chromosomes carry genetic information in the form of DNA. Within DNA there are **genes** that encode proteins that carry specific traits. Different variants of genes are called **alleles**, and these account for variability in traits. We inherit one of each chromosome from each parent randomly and have two copies of each chromosome, and thus two alleles for every gene. There is an exception for this in the case of the X and Y chromosomes, which will be discussed later. When an organism has two copies of the same allele, this is called **homozygous**. When an organism has two copies of different alleles, this is called **heterozygous**.

The variants of a gene that an individual has is called the **genotype** and the physical expression of that variant is called the **phenotype**. Phenotypes can be things like eye color, hair type, webbing between toes, etc. Alleles in classical genetics are considered **dominant** or **recessive**. A dominant allele masks the effects of a recessive allele when an individual is heterozygous for that gene. Recessive alleles show their effects only when individuals are homozygous for that allele.

Punnett squares are used to predict the possible genotypes of offspring from two parents. In this notation, dominant genes are notated with capital letters and recessive genes are lowercase. One parent's alleles are notated on the top and the other on the side. Within the boxes are the genotypes of the potential zygotes that can be produced by the parents. By using these, one can deduce the chances that an offspring will have a specific genotype. The following square is an example of a **monohybrid cross**, where only one trait is examined. Multiple traits can be considered by expanding the complexity of the Punnett square.



Punnett Square

Probability rules can be used to predict the passage of single-gene traits to offspring. Using the **product rule**:

$$\mathrm{P(A\ and\ B)} = \mathrm{P(A)} \times \mathrm{P(B)}$$

You can predict the probability of inheritance of two independent alleles. For example, if parents are heterozygous for gene A (Aa) and you would like to predict the probability for an offspring who is homozygous recessive for gene A (aa), you would multiply the probabilities that each gamete would carry allele a. Since the parents are heterozygous, this probability would be 50%. Thus, the chances of a progeny that is aa would be 25% (50% × 50% = 25%).

To predict the chances of multiple independent events occurring, such as the probability that a progeny will inherit a dominant allele of A given two heterozygous parents, then you can use the **sum rule**:

$$\mathrm{P(A\ or\ B)} = \mathrm{P(A)} + \mathrm{P(B)}$$

The sum rule is applicable given mutually exclusive events. In the previous case, there are four mutually exclusive outcomes from this cross (AA, Aa, Aa, and aa). Note the two Aa events can be a result of inheriting an A from the mother and the a from the father, or vice versa. Any of the four outcomes are equally likely and have a 25% chance of happening. Thus, the resulting probability that the offspring will inherit the dominant allele A would be 75% (25% + 25% +25% = 75%).

Note that the use of probability equations provides little benefit over drawing a Punnett square when considering only two alleles of one gene. In the event that you are calculating probabilities for multiple genes, then using probability equations will make calculations much faster.

Non-Mendelian Inheritance

Not all modes of inheritance follow Mendel's laws; these cases are called **non-Mendelian inheritance.** It is important to know the biological basis for such differences and how to identify them on a pedigree for the AP exam.

As mentioned, linked-genes do not follow the Law of Independent Assortment. Experimentally, these genes exhibit inheritance rates that are different from predicted probabilities. You can use the probability that linked genes segregate to estimate the distance between linked genes, called **linkage mapping**.

Genes on the X and Y chromosome display non-Mendelian inheritance traits, as only one copy of each of these chromosomes is expressed at a time. Traits that are carried on these chromosomes are **sex-linked.** Males inherit one copy of the X chromosome and one copy of the Y chromosome.

If there is a disease-causing mutation on the X chromosome that a male inherits, it will be dominant. Females inherit two copies, but only express one in each cell. Early in development, cells randomly turn off one copy of the X chromosome so that only genes from one X chromosome are expressed in each cell. You can see this in calico cats, where some genes for coat color are carried on the X chromosome. The other implication is that if there is a disease-causing mutation on a female's X chromosome, the expression will be variable depending on how many of her cells express that mutated X chromosome.

Some genes will only be passed from the mother. This is due to the fact that some genes are carried outside of nuclear DNA, called **extranuclear genes**, in mitochondria or chloroplasts. Mitochondria are only passed through eggs to progeny; similarly, chloroplasts are only passed from ovules to progeny. To distinguish this pattern of inheritance from X-linked, look for cases where a trait is passed only through mothers to all offspring. X-linked traits passed from mother to daughter should only have a 50% or less expression frequency. X-linked traits will be passed from father to daughter where mitochondrial or chloroplast inherited traits will not.

Some traits exist on a spectrum rather than being present or not. When looking at inheritance patterns, these will also show non-Mendelian inheritance. These traits are generally controlled by multiple genes, rather than just one. For example, things like skin and hair color in humans are due to the expression of many genes. These are called **polygenic traits**. Traits that are controlled by a single gene locus are called **monogenic traits**.

In some cases, like in height, the environment can also affect expression. Although genetics may predispose an individual to being short or tall, factors like nutrition will affect their expressed height. These genes are said to have a **multifactorial basis**.

Note that predicating modes of inheritance (e.g., dominant, recessive, sex-linked) based on phenotypes is a common question on the AP exam. Be sure to be able to identify these based on percentages in a population, through Punnett squares, and through inheritance diagrams.

Outside Reading

- To learn more about Meiosis: https://www.khanacademy.org/science/biology/cellular-molecular-biology/meiosis/a/phases-of-meiosis

- For more information on Mendelian genetics: http://knowgenetics.org/basic-genetics/

  https://www.nature.com/scitable/topicpage/gregor-mendel-and-the-principles-of-inheritance-593

  https://www.khanacademy.org/science/biology/classical-genetics/mendelian--genetics/v/introduction-to-heredity

Sample Heredity Questions

When a heterozygote has a phenotype that is an intermediate of the alleles it possesses, _____ occurs.

A. complete dominance

B. incomplete dominance

C. codominance

D. independent assortment

Explanation:

The correct answer is B. Incomplete dominance refers to the phenomenon wherein the presence of two different alleles causes a phenotype that reflects the blending of both alleles. A classic

example of this is the mating of flowers with white petals and red petals to form a plant with pink-petaled flowers. Choice A is incorrect because complete dominance refers to the classic pattern of inheritance, wherein a character is coded for by two different alleles, with one allele that is completely dominant over the other. An individual will always express the trait of the dominant allele, even in the presence of the recessive allele. Choice C is incorrect because codominance is slightly different from incomplete dominance. While incomplete dominance refers to a phenotype that is a blend of the separate alleles, codominance refers to a phenotype that has the characteristics of *both* alleles. An example of this pattern of inheritance is human ABO blood types. The alleles for A and B are dominant, but when an individual possesses both A and B alleles, the proteins coded by these genes are both expressed. Finally, choice D is incorrect because independent assortment is the concept that genes coding for different traits are passed on independently of the genes for any other trait. This is generally true only for genes that are on separate chromosomes.

Use the Punnett square below to answer the two questions that follow.

	F	F
f	Ff	ff
f	Ff	ff

Assuming F is a completely dominant allele and f is a completely recessive allele, how many different phenotypes are in the F1 generation shown?

A. 0

B. 1

C. 2

D. 3

Explanation:

The correct answer is C. A completely dominant allele will be expressed whenever it appears. In the F1 generation shown above, two offspring are heterozygous for the dominant allele (the Ff individuals), so they will express the dominant phenotype. The remaining two offspring are both

homozygous recessive and will express the recessive phenotype. Thus, there are two different phenotypes in the F1 generation.

In the experiment shown, a researcher crossed a parent with a recessive phenotype with a parent with a dominant phenotype in order to determine the genotype of the dominant parent. What is this technique called?

A. Mendelian cross

B. F1 cross

C. F2 cross

D. test cross

Explanation:

The correct answer is D. A test cross is used to determine genotype when the dominant phenotype is expressed. If the genotype of the dominant parent is heterozygous, the offspring will be a mix of recessive and dominant phenotypes. If the genotype of the dominant parent is homozygous, then the offspring will only show the dominant phenotype. Choice A is incorrect because Mendel was one of the first researchers to discover the dominant and recessive nature of alleles. His crosses involved many different combinations of dominant and recessive parents and were not limited to the specific cross described here. Choice B is incorrect because an F1 cross occurs when offspring of the first cross are interbred. Choice C is incorrect because an F2 cross occurs when offspring of a cross between F1 individuals are interbred.

Gene Expression and Regulation

Around 12–16% of the questions on your exam will cover Gene Expression and Regulation.

The Roles and Functions of DNA and RNA

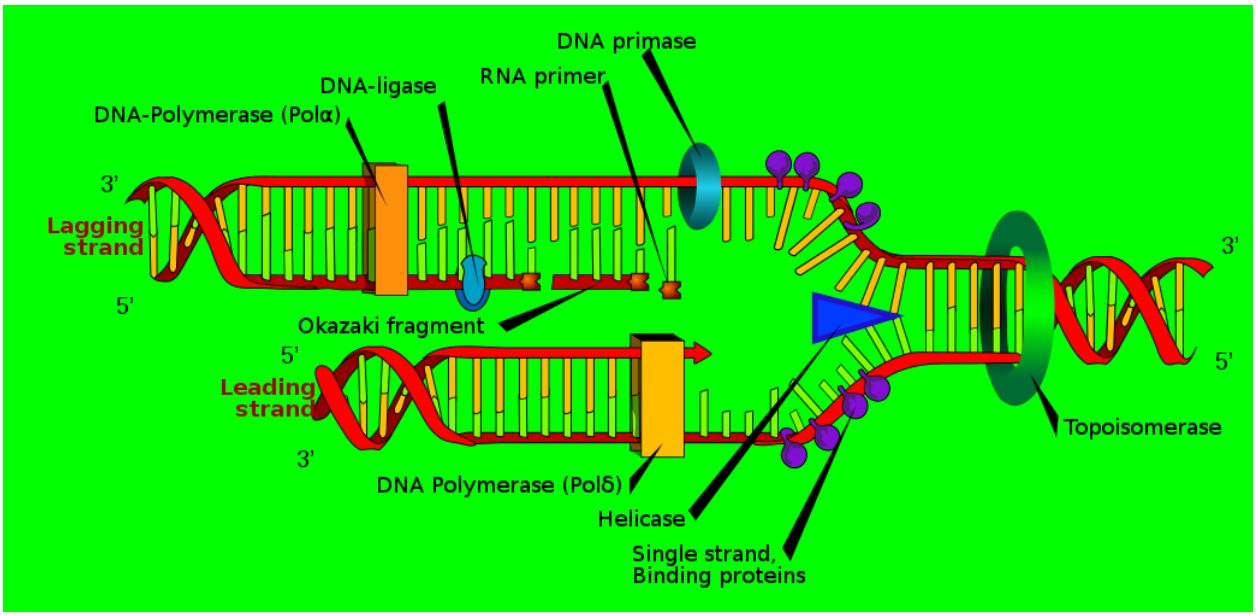
Nucleic acids are the basis for heredity for all life on Earth. In most species, DNA is passed from parent to offspring and contains all the genetic information needed to propagate the species. In some cases, RNA is the basis for heritable genomics instead of DNA.

In eukaryotes, DNA is structured in multiple linear chromosomes contained within the nucleus. Each chromosome contains a unique set of genes that carry information for making RNA and, in turn, proteins. In prokaryotes, DNA is structured in a single circular chromosome. In both prokaryotes and eukaryotes, additional genetic information can be housed outside of chromosomes, called **extra-chromosomal DNA**. For instance, both prokaryotes and eukaryotes can have small, circular, double-stranded DNA molecules called **plasmids**. In addition to these, eukaryotes carry DNA within mitochondria and chloroplasts.

An essential feature of DNA that allows it to pass heritable information is that it is able to replicate with low error rates. All of the information needed to build the machinery for DNA replication is contained within the DNA genome. So how is DNA replicated in the cell cycle? DNA is copied through a process called **semiconservative** replication. This means that one strand of DNA serves as a template for the second strand to from. Several enzymes and RNAs are involved in the process of DNA replication. **Helicase** is the enzyme that separates the double strands into single strands. This allows replication machinery access to single strands of DNA.

The **replication fork** is the point where DNA splits into two strands. **Topoisomerase** works just in front of the replication fork to keep the double stranded DNA from supercoiling. It does this by breaking the phosphate backbone, allowing for unwinding and resealing DNA. **DNA polymerase III** synthesizes new DNA by adding new nucleotides to the 3' end of DNA. Because of this, DNA is always synthesized from the 5' to 3' direction. DNA polymerases are also capable of proofreading their work, so they are able to correct any mistakes made in replication.

DNA polymerases do not initiate synthesis of a single strand of DNA on their own, they require RNA **primers** to attach first. Primers are short strands of nucleotides. DNA polymerase acts by adding new nucleotides at the end of the RNA primers. The RNA primer is eventually replaced by a **DNA polymerase I.**



DNA Replication

This schematic of DNA replication allows DNA to be replicated continuously on one strand of DNA, called the **leading strand**, but does not explain what occurs on the anti-parallel strand. In this strand, called the **lagging strand**, DNA is replicated in short segments called **Okazaki fragments**. RNA primers are attached to sections of the DNA strands and DNA polymerase III adds nucleotides in the 5' to 3' direction between primers. **DNA ligase** then seals the gaps between double stranded fragments on the lagging strand.

There are a few differences in how circular and linear chromosomes replicate. Circular DNA in most prokaryotes have one specific sequence of DNA that signals where replication begins, called the **origin of replication**. When DNA separates, a replication bubble forms with two replication forks at each end. The bubble grows continuously until you have two copies of DNA. In eukaryotes, each chromosome has many origins of replication. Due to the way the lagging strand is formed, some DNA is lost in each round of replication at the ends of linear chromosomes, called **telomeres**.

The Mechanisms of Gene Expression

DNA encodes all of the genetic information needed to make a cell. Within DNA there are **genes**; these are stretches of DNA that encode the blueprints to make RNA and, in turn, proteins. Making proteins from genes is a multi-step process that is carried out by specialized RNA and proteins.

First, mRNA is formed through **transcription**. During transcription, the two DNA strands in the helix unzip to allow RNA polymerase to make a complementary copy of the gene, called **mRNA** (messenger RNA). mRNA is made in the 5' to 3' direction by reading the DNA strand in the 3' to 5' direction. A newly transcribed mRNA is called a pre-mRNA, as it is not yet ready for export from the nucleus and translation to protein. For the mRNA to mature, it needs several modifications, called **posttranslational modifications**.

Posttranslational modifications in eukaryotes include the addition of a **5' GTP cap**, which is important for targeting the mRNA for nuclear export, preventing degradation, and promoting translation. A poly(A) tail is also added to the 3' end of the mRNA; this a string of adenosines that, like the 5' GTP cap, are important for nuclear export, protection from degradation, and translation. Some parts of the sequence that do not translate into proteins, called **introns**, must also be removed through a process called **splicing**. The parts of the gene that encodes mature mRNA are called **exons**. In some cases, exons are selectively included or excluded, resulting in several different sequences of proteins from the same gene in an organism. This process is called **alternative splicing.**

Once the mRNA is mature, it is shuttled out of the nucleus to the cytoplasm for the next step, **translation**. Proteins are made during translation. In this process, the mRNA enters the ribosome where **transfer RNA** (**tRNA**) translates the message to make proteins. tRNA recognizes mRNA sequences and translates them to amino acid sequences. The bulk of ribosomes are also made of specialized RNA, called **rRNA**, and proteins. The function of ribosomes is to bring together mRNA and complementary tRNAs so that proteins form. In eukaryotes, ribosomes are found both in the cytoplasm and on rough endoplasmic reticulum; thus, translation can occur at either of these sites. In prokaryotes, translation occurs in the cytoplasm.

Translation occurs in three steps: initiation, elongation, and termination. During **initiation**, an mRNA sequence, called the **start codon**, signals the start of translation. **Codons** are groups of three base pairs, the sequence of which encodes either a specific amino acid or start or stop sequence. The RNA-amino acid code is universal for all life on Earth; in other words, the same sequence of codons encodes the same amino acids for any form of life, and this provides evidence of a common ancestor. During **elongation**, tRNA read the mRNA codon through RNA interactions, and this in turn signals the attached amino acid to be transferred to the growing protein chain, also called a polypeptide chain. The mRNA continues to elongate until it reaches the stop codon, which signals **termination** of translation. At the end of translation, a newly formed protein is released.

Gene expression in prokaryotes is carried out in a similar manner to eukaryotes, with a few fundamental differences. Prokaryotes do not have a nucleus, so transcription and translation can occur simultaneously. They do have some forms of posttranslational modifications, but they are different than those mentioned for eukaryotes. There are also no introns known in prokaryotes, so alternative splicing does not occur.

Retroviruses also display differences in the flow of gene expression. Retroviruses are viruses made of RNA. Genetic information from retroviruses is first reverse transcribed into DNA through the help of an enzyme called **reverse transcriptase**. Reverse transcriptase takes the single stranded viral RNA molecule and transcribe it into double stranded DNA. The DNA then integrates into the genome of the infected cell through an enzyme called **integrase**. Once integrated into host DNA, the virus takes advantage of the transcription and translation machinery of the cell to replicate new viral progeny.

How Genotype affects Phenotype

In a multicellular organism, not all cells express the same genes and the amounts of proteins made from each gene. The amount of protein made from a gene can affect the cell type as well as the phenotype of the organism. For example, photoreceptors in the retina must express proteins that make it possible to transduce light into neural activity, while cells of the stomach must express a completely different set of proteins to make and secrete digestive enzymes. All of these cells have identical DNA, but the expression of genes within the cells are different. During development of an organism, different **transcription factors**, proteins that regulate transcription of subsets of genes, are expressed and help to determine which subsets of genes are expressed, and what type of cell is ultimately formed.

Expression of genes can be modulated by the **regulatory sequences** within the genome—these are stretches of DNA that control transcription. Transcription factors and other gene regulatory proteins identify specific regulatory sequences and use those as a guide to direct which genes are expressed and how much protein is made. **Promoters** are sequences where RNA polymerase and transcription factors bind to initiate transcription. **Enhancers** are regulatory sequences where proteins bind to increase the likelihood of transcription occurring. Negative regulatory molecules also exist that decrease transcription. For example, **silencers** are DNA sequences that bind proteins, called **repressors**, and block RNA polymerase from binding.

In some cases, groups of genes are regulated together as a group. In prokaryotes, these are called **operons** and are regulated by a single promotor generating a single mRNA. The *lac operon* is an example of this—it contains all of the proteins needed for a cell to metabolize lactose. In eukaryotes, gene expression is coordinated through the expression of transcription factors that regulate many genes in different locations that specify a cell type. For instance, the expression of the transcription factor Pax6 induces the coordinated expression of genes related to the development of eyes.

The amount of gene expression in the cell can also be influenced by **epigenetics**; these are modifications in gene expression through factors other than alterations to the DNA sequence. Examples of epigenetic factors are methylation of DNA or alterations to histones that DNA wraps around in cells. These changes can either enhance or reduce gene expression. In addition to

these, some small non-coding RNA molecules can also regulate gene expression by binding mRNA sequences and blocking translation or mRNA stability.

Mutations, Genetic Diversity, and Natural Selection

The variants of genes expressed, amount of proteins genes make, and the timing of expression can all affect the phenotype of an organism. Alterations in genes or the products that they make can cause new phenotypes to emerge. These changes are often due to mutations in the DNA of the organism. Mutations can be negative, neutral, or positive based on the effect that they have on an organism. The emergence of mutations that affect phenotypes are the basis for genetic diversity of a species.

There are several types of DNA mutations that can occur. Mutations to be familiar with are:

- **Missense mutations** are changes in one single base pair of DNA, causing an amino acid to change from one type to another.
- **Nonsense mutations** are the result of a single base pair change that causes a premature stop codon to appear and shortened protein to be produced.
- **Insertion mutations** are caused by the insertion of a short piece of DNA into a gene.
- **Deletion mutations** occur when one or many base pairs of DNA are deleted. These can affect a single gene or many genes.
- **Duplication mutations** are the result of a bit of DNA being copied one or many times.
- **Frameshift mutations** occur when the insertion or deletion of base pairs causes the codon frame of a gene to shift so that the part of the protein downstream of the mutation translates to different amino acids. This happens whenever there is an insertion or deletion in an exon that is not a multiple of 3 base pairs.

Many different events can induce mutations in DNA including errors in DNA replication or repair as well as external factors like UV radiation or exposure to mutagenic chemicals. Whether the resulting mutation has a negative or positive impact can depend on the environmental context. For instance, the gene mutations that cause sickle-cell anemia can also confer resistance to malaria and are a likely reason why these gene variants are so common in parts of the world where malaria is endemic. The potential benefits of mutations for natural selection are highlighted by the fact that processes that increase genetic variation during reproduction are selected conserved across species, indicating that they have been selected for over time.

In addition to genetic mutations causing changes in single genes, errors in mitosis or meiosis can result in changes in chromosome number, affecting either all or part of a chromosome. In reproduction, chromosomal mutations can cause new phenotypes to emerge, like sterility. These can also result in developmental limitations, as is the case for individuals affected by Down syndrome.

In prokaryotes, many mechanisms exist for sharing of DNA, allowing for the enhanced survival and reproduction of a species. These include horizontal transfer of DNA in the form of plasmids through either uptake of naked DNA or through cell-to-cell transmission. Both prokaryotes and eukaryotes can have their DNA sequence altered by the uptake of viral DNA sequences in their genomes and through transposable elements, short DNA sequences that change positions within and between chromosomes.

Genetic Engineering and Biotechnology

Over the last 30 years, there has been a boom in biotechnology for analyzing and manipulating DNA and RNA. This has changed the scope of how scientists approach understanding diseases and develop new treatments for them, how doctors determine what disease a patient has and what the best approach is to treat it, how we solve crimes, as well as many other aspects of our lives. The use of biotechnology to design experiments often shows up in the free response section of the AP exam.

Some forms of biotechnology to be familiar with are the following:

- **Electrophoresis:** This is a method used to separate molecules by size and charge. Electrophoresis is used to separate DNA, RNA, or protein fragments to help scientists identify what molecules are present.
- **Polymerase Chain Reaction (PCR):** PCR is a method used to amplify a single DNA fragment into many identical fragments. By selectively amplifying a sequence of DNA, scientists are more easily able to identify it through electrophoresis, sequence it, or transfect it into other cells.
- **Bacterial transformation:** This process takes advantage of horizontal gene transfer to introduce new DNA to bacteria. This can be used to produce a protein of interest in large amounts. For example, synthetic insulin has been produced through bacterial transformation. Methods have also been established to allow gene transfer in eukaryotes, including humans. For example, new treatments for some forms of inherited blindness have been developed that introduce healthy copies of genes in the retinas of humans through the use of manufactured viruses.
- **DNA sequencing:** DNA sequencing determines the genetic sequence of nucleotides in DNA. This can be small scale, like sequencing a small stretch of DNA that was amplified through PCR, it can be whole genome sequencing that determines the entire genetic code of an organism, or it can even include sequencing all the RNA of a cell or tissue to understand what genes are expressed. DNA sequencing has many different uses including identification of disease-causing mutations in individuals, finding ancestors, and determining the lineage of species.

Outside Reading

- To learn about the discovery of DNA structure, see: https://www.nature.com/scitable/topicpage/discovery-of-dna-structure-and-function-watson-397/
- For more on DNA replication, see: https://www.khanacademy.org/science/biology/dna-as-the-genetic-material/dna-replication/a/molecular-mechanism-of-dna-replication
- For a more in-depth look at translation, see: https://www.nature.com/scitable/topicpage/translation-dna-to-mrna-to-protein-393/

Sample Gene Expression and Regulation Questions

What has provided the primary variation necessary for natural selection to occur?

A. sexual reproduction

B. punctuated equilibrium

C. mutation

D. independent assortment

Explanation:

The correct answer is C. Mutation produced and continues to produce variety in a gene pool. Choice A is incorrect because although sexual reproduction increases diversity by providing new combinations of genetic material, it is not the primary source of genetic diversity. Choice B is incorrect because punctuated equilibrium refers to the evolutionary trend in which periods of

evolutionary stability are interrupted by short periods of rapid change. Choice D is incorrect because independent assortment refers to the concept that alleles separate independently during the formation of gametes and that in many cases many genes are linked on one chromosome.

Which of the following is an example of a prokaryotic organism?

A. mushroom

B. fern

C. bacterium

D. virus

Explanation:

The correct answer is C. Bacteria are prokaryotic. Prokaryotes lack a nucleus and membrane-bound organelles. Choice A is incorrect because a mushroom is a type of fungi; fungi are eukaryotic. Eukaryotes have membrane-bound organelles, including a nucleus. Fungi differ from other eukaryotes in that they have a cell wall containing chitin. Choice B is incorrect because a fern is a type of plant; plants are eukaryotic. Eukaryotes have membrane-bound organelles, including a nucleus. Plants differ from other eukaryotes in that they have a large central vacuole and a cell wall composed primarily of cellulose. Choice D is incorrect because viruses are typically not considered living organisms and thus are not classified as either prokaryotic or eukaryotic.

Viruses that have RNA as their genetic material are known as

A. lysogenic viruses.

B. lytic viruses.

C. retroviruses.

D. adenoviruses.

Explanation:

The correct answer is C. Retroviruses have RNA as their genetic material. Reverse transcriptase is used to convert RNA into DNA. Choice A is incorrect because *lysogenic* refers to a viral life cycle wherein a virus infects a host and goes through a period of dormancy before bursting forth from the host cell. Choice B is incorrect because *lytic* refers to the process by which a virus infects a host and bursts the host cell open (lysis). Choice D is incorrect because adenoviruses are viruses that infect the respiratory linings.

Natural Selection

Around 13–20% of the questions on your exam will cover Natural Selection.

Evolution and Natural Selection

Evolution refers to the change in heritable traits through changes in genetic information over generations. Natural selection is the major driver of evolution throughout history. Darwin proposed the theory of evolution by natural selection in 1859 in *On the Origin of Species*. The theory asserted that species gradually change over time by passing on heritable traits. Traits that are beneficial for an organism to survive and reproduce in its environment are selected through reproductive success. Given a long enough timeline, these changes can lead to the introduction of new species. Since the inception of the theory of natural selection, it has been repeatedly supported by experiments and historical evidence across a variety of fields including genetics, microbiology, developmental biology, paleontology, and geology.

The basic concept of evolution by natural selection is as follows:

- Many traits are passed down from parent to offspring. This was later substantiated by Gregor Mendel's experiments showing heritability of traits in pea plants decades later. Further along the line, DNA would be found to be the source of heritable traits.
- These traits are variable in a population. Scientists would later find that mutations in DNA are a major source of trait variability.
- Many more organisms are born than will survive to reproduce. This leads to some competition for resources in an environment—whether they be food, shelter, or attractive mates. The traits that are beneficial to survival will help an organism outcompete others for resources and allow them to reproduce. This process is called **differential reproduction**.
- Over time, the traits that are beneficial for reproduction and survival will be more abundant in a population because the organisms that get to reproduce pass on their traits.
- Species adapt to survive in their own environments. As the environment can be ever changing, species evolve over time to adapt.

Humans can also affect speciation through **artificial selection.** This is a process of selective breeding to bring out traits that are considered desirable. Through artificial selection, humans have domesticated dogs and cats and have bred different varieties of each. Similarly, in agriculture, humans have used artificial selection to make crops that yield more edible produce on large scales.

Another mechanism to introduce variation to a population is through gene migration. This occurs when two separated populations of a species breed, thereby potentially introducing new genes to one of the populations.

Population Genetics

As mentioned, differential reproduction is an important factor in increasing the abundance of desirable traits in a population, yet there are also mechanisms for traits that are neutral or even harmful to become abundant. Changes in frequency of a trait in a population can also be through random fluctuation, which is called **genetic drift**. This tends to happen in small and isolated populations, and often for neutral traits. If a population is small and isolated enough, there can be a **bottleneck effect**, wherein the genetic diversity is so small that few traits, including those that are harmful for the species, can take over the population. Reduced variation in two populations of the same species can increase differences between those populations and promote speciation.

New traits are introduced to a population through mutations in DNA. Many of the mutations that arise are recessive but are able to persist in the population despite being neutral or even harmful. How allelic variations remain constant in a population is described by **Hardy-Weinberg equilibrium**. This law uses mathematical modeling of frequencies to show how recessive traits can stay constant in a population over time. For a population to be in Hardy-Weinberg equilibrium, it must have a large population size that is not migrating, doesn't have new mutations, has no selection, and is randomly mating. In Hardy-Weinberg equilibrium, where p is the frequency of allele 1 and q is the frequency of allele 2:

$$p^2 + 2pq + q^2 = 1$$
$$p + q = 1$$

Although this sort of population rarely exists, the equation provides a null-hypotheses for testing. Deviations from Hardy-Weinberg equilibrium provide evidence that the conditions are not being met.

Evidence of Evolution and Common Ancestry

Evidence for evolution exists all around us and crosses biological, physical, geological, geographical, and mathematical disciplines. We are able to chart genetic, molecular, and morphological features of living and extant species to identify how species are related in genetic lineage.

- Fossil evidence, such as the ages of rocks where fossils are found, carbon dating of the fossils, and geographical data from where fossils are found can help to put a timescale on the existence of species. Comparison of homologous structures in the fossil and current anatomical record can help identify lineage. For example, the appearance of vestigial

structures, like the vestigial pelvis on whales and snakes, indicate that these animals derived from quadrupedal species.

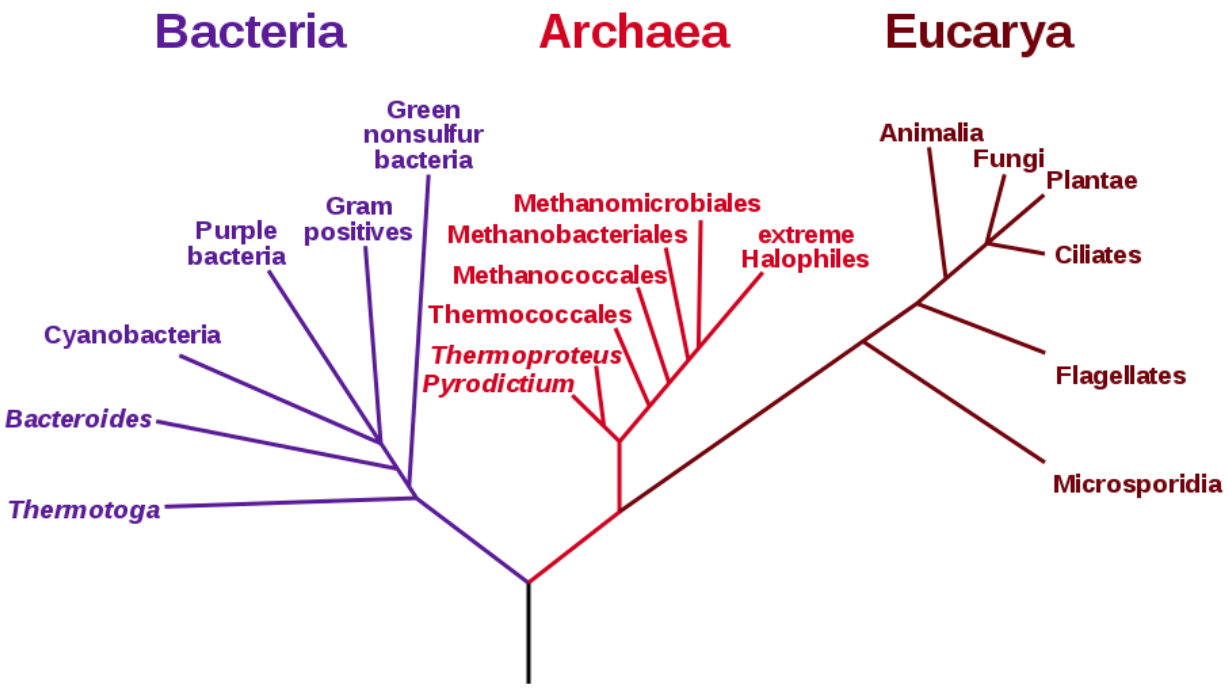
- DNA and molecular evidence can also help to chart the evolution of species. For example, the commonalities in DNA or protein sequences provide evidence for common ancestors that shared those molecules. On the other hand, mutation frequencies in non-conserved regions are used to provide a molecular clock for how long ago two species diverged.
- Molecular and cellular features are conserved across species, providing further evidence for common ancestry. For example, the genes that control eye development are conserved from invertebrates to vertebrates. This means that homologous genes are required to create eye structures in both a fruit fly and a human.
- A common basis for life exists across all species on Earth, indicating a common ancestry. For example, the amino acid code is the same across all species on Earth. In addition to this, all eukaryotes share the same membrane bound organelles, indicating that they arose from a common eukaryotic ancestor.

We can continue to see evolution taking place in front of us. For example, with genomic technology, we are able to track changes in gene frequencies that indicate phenotypes of species around us are also changing. Humans have induced evolution in species around us through the use of chemicals like pesticides, herbicides, and antibiotics that cause resistant species of insects, weeds, and bacteria to evolve.

Charting Species Ancestry through Phylogenetic Trees and Cladograms

The evolution of organisms are often mapped out in terms of **phylogeny**. This is the evolutionary history of organisms. **Phylogenetic trees** and **cladograms** are used to visually map out the ancestral relationships between species. In phylogenetic trees, the length of lines represents the amount of change, or evolutionary timescale between species. **Cladograms** are structurally similar but may not depict the evolutionary timescale. The nodes on phylogenetic trees and cladograms show the most recent common ancestor that existed between two lineages.

Phylogenetic Tree of Life



Phylogenetic Tree

Phylogenetic trees and cladograms can be constructed by comparing traits in different species including morphological differences between living species and fossils or genomic information between species. For instance, shared characteristics present in more than one lineage of species indicate that a common ancestor must have existed between them. When comparing groups, the one that is missing the common trait is generally the most distantly related organism on the phylogenetic tree or cladogram.

Although traits are a historical way of determining relationships, newer forms of molecular data provide more accurate lineage information. Comparing genomic information can help identify lineage by helping to identify the emergence of new gene variants and by comparing the percent conservation of DNA. It is important to note that the study of phylogeny involves making hypotheses about the past through evidence that we have access to today; thus, phylogenetic trees and cladograms are revised as we gather new evidence. Phylogenetic trees and cladograms often appear on the free response section of the exam, so make sure to understand how to interpret these.

Speciation and Extinction

Speciation describes how new species arise. In biology, a species is often defined as a group of individuals that are capable of interbreeding to produce viable and fertile offspring. There are several mechanisms for speciation, but these all require that genetic changes must be so substantial between populations that they no longer allow productive interbreeding.

Allopatric speciation occurs when populations are geographically isolated, thus causing a physical barrier to mating. Geographic isolation can occur through many mechanisms, like through travel to new islands, lava flow forming a land barrier, or tidal changes causing water masses to become isolated.

Sympatric speciation occurs without geographical isolation. This method is very common in plants, where changes in chromosomal structure can cause new species to arise that are not able to mate with the parent species. In the animal kingdom, this method is thought to occur when subgroups of a species gain preferences for different resources or habitats in the same geographical area.

Evidence for speciation happening both gradually or very quickly exists in the historical record. Evidence for **punctuated equilibrium**, a model where species evolve rapidly, exists after large catastrophic events that cause mass extinction or when members of a species migrate to an area with no competition for resources. When these events occur, species undergo **adaptive radiation**, rapid evolution of a wide variety of types, to fill in the ecological niches available.

Extinction events have occurred throughout the history of the Earth. Extinction can happen gradually to a species or it can happen in great numbers due to major ecological events. Extinctions of single species can be due to factors like low genetic variability, habitat destruction, introduction of a predator or parasite, and climate change.

There have been 5 mass extinction events in the history of Earth:

1. **Ordovician-Silurian extinction**. This extinction event occurred around 439 million years ago and wiped out more than 85% of life on Earth. This event is hypothesized to have occurred due to changes in land masses from continental drift, sea levels falling, and a major climate event causing temperatures to fall and glaciers to form. This may have been caused in part by having a high enough biomass of plants on Earth to draw out carbon from the atmosphere and reduce greenhouse gases, causing temperatures to drop.
2. **Late Devonian extinction**. This extinction event occurred around 364 million years ago and resulted in loss of about 75% of life on Earth. This event is thought to have occurred due to large plants releasing too much nutrients into the oceans. This, in turn, caused massive algae blooms that deoxygenated the oceans and caused loss of aquatic species. During this extinction, land creatures also appeared to have died off, possibly due to volcanic ash causing temperatures to drop.

3. **Permian-Triassic extinction**. This occurred around 251 million years ago and destroyed 96% of life on Earth. This was due to a volcanic eruption that released massive amounts of carbon dioxide onto Earth. The carbon dioxide caused bacteria to overgrow and release methane into the atmosphere. The result of this mixture was an increase in the Earth's temperature and ocean acidification.
4. **Triassic-Jurassic extinction**. This occurred around 200 million years ago and was thought to be due to a mixture of asteroid impact, climate change, and volcanic activity. This event caused mammal numbers to drop drastically and allowed dinosaurs to flourish.
5. **Cretaceous-Paleogene extinction**. This occurred around 65 million years ago. Similar to the Triassic-Jurassic extinction, this is thought to have been due to a mixture of asteroid impact, climate change, and volcanic activity. This event essentially wiped out dinosaurs as the major inhabitants of Earth and allowed mammals to flourish.

Human activity also drives extinctions; in fact, some scientist speculate that we are experiencing a sixth mass extinction event due in a large part to human activity. Loss of species due to humans has occurred due to hunting, loss of habitat, climate change, and introduction of invasive species amongst other events.

Genetic diversity in a species helps protect it from extinction. Populations with a high level of genetic diversity are more likely to carry alleles of genes that will make them resistant to perturbations in their environments. Without enough variation, populations become more susceptible to collapsing due to disease or environmental pressures.

An important historical example of this occurred during the Irish Potato Famine. In the 1800s, one single variety of potatoes was grown in Ireland and the crop yields were virtually genetically identical. In the 1840s, a fungus spread in Ireland that caused potato blight. It wiped out potato crops across Ireland, which was a major source of food at the time and resulted in severe famine and deaths. Had the planted crops had more genetic diversity, there would have likely been more blight-resistant plants available so that the results were not as catastrophic.

After a major extinction event, ecological niches open up and allow speciation events. This means that the surviving species rapidly evolve and take over through adaptive radiation. Adaptive radiation can occur either after a mass extinction event, when there are few species inhabiting a niche, or it can occur when a species is introduced to a new environment with few natural predators and good conditions for growth.

Models of the Origin of Life on Earth

Earth formed around 4.6 billion years ago. The atmosphere of Earth at this time consisted of water vapor, methane, ammonia, hydrogen sulfide, carbon dioxide, carbon monoxide, and phosphate with extremely high temperatures and bombardment by asteroids. Conditions on Earth are thought to have been too hostile to support life until around 3.9 billion years ago. The

exact timeframe for when life started is not known, as fossil evidence from that time is absent; rather, the timeline is hypothesized based on observable fossil evidence and the conditions on Earth that were able to sustain life. The oldest identified fossils are 3.5-billion-year-old **stromalites**, which are fossils formed from single-celled microbes. As the bacteria that made these are complicated, it is hypothesized that the first life on Earth appeared much earlier.

The key experiments that address the origins of life have focused on identifying how cells and their essential components could arise in the conditions of the primordial Earth.

You should familiarize yourself with the following important experiments and hypotheses:

- The **Oparin-Haldane Hypothesis**: Life arose step-wise through gradual chemical-evolution. In this hypothesis, an early, oxygen-poor environment was amenable to inorganic molecules forming nucleotides and amino acids forming a primordial soup that could give rise to life. Through a step-wise process, these molecules could become more complicated to the point that they start self-replicating, eventually giving rise to cell-bound life.
- The **Miller-Urey Experiment**: This experiment set up conditions that were meant to mimic the early atmosphere (water, ammonium, methane, nitrogen) of Earth in a closed system. Energy was then provided in the form of heat and sparks. After a week, lipids, amino acids, sugars, and other organic molecules formed. Although our understanding of Earth's early atmosphere has changed, this experiment was the first to show that the building blocks of life could appear quickly in a closed environment if fed the right conditions. This experiment has since been replicated in a variety of different environmental conditions.
- Life on Earth is based on the formation and heritability of polymers (e.g., nucleotides to DNA or amino acids to proteins). Several experiments showed how simple amino acids and nucleic acids could give rise to polymers and RNA. Sidney Fox and colleagues showed that amino acids heated without water could link together to form proteins. Later experiments showed that nucleotides would polymerize on clay surfaces.
- Recent findings suggest that the appearance of life on Earth may have been assisted by meteorites carrying organic molecules. Conditions in space are more amenable to the formation of organic molecules, as in low temperature and high UV. In fact, many of the organic molecules necessary for life have been found on meteorites and other celestial objects, including amino acids, nucleobases, and sugars. Bombardment of early Earth by meteorites could have provided seeds of organic molecules that were needed to generate life on Earth.

Whether genes first arose that could self-replicate and eventually give rise to proteins or self-sustaining metabolic networks arose that gave rise to protein and nucleic acid synthesis is up for debate. **The RNA world hypothesis** proposes that RNA was the first self-replicating information on Earth. RNA has two important features that make this plausible—RNA is a modern source of heritable information and RNA can act as catalysts, called **ribozymes**. Ribozymes could have theoretically catalyzed reactions that caused self-replication. An alternate theory is the **metabolism-first hypothesis**. In this theory, self-replicating metabolic networks may have

existed before nucleic acids. These reactions would have given rise to more complex macromolecules, like proteins.

Reasonable hypothesis and evidence exist for both ideas, as well as a host of other theories. Regardless, these building blocks for life came together to give rise to the first unicellular organism that was capable of replicating its own DNA or RNA and producing proteins according to the universal amino acid code. This then gave rise to all the life that has existed on Earth since.

Outside Reading

- To learn more about Darwin's theories of evolution: https://www.khanacademy.org/science/biology/her/evolution-and-natural-selection/a/darwin-evolution-natural-selection
- For a great review on theories of evolution: https://evolution.berkeley.edu/evolibrary/article/evo_01
- To learn more about Hardy-Weinberg equilibrium: https://www.nature.com/scitable/knowledge/library/the-hardy-weinberg-principle-13235724
- To learn more about phylogenetic tree construction: https://study.com/academy/lesson/cladograms-and-phylogenic-trees-evolution-classifiations.html
- To learn more about theories on the origins of life: https://www.khanacademy.org/science/biology/history-of-life-on-Earth/history-life-on-Earth/a/hypotheses-about-the-origins-of-life

Sample Natural Selection Questions

Which of the following statements about vestigial structures is true?

A. They can predict an organism's lifespan.

B. They are found only in prokaryotes.

C. They may be useless or even detrimental to an organism.

D. They are found only in vertebrates.

Explanation:

The correct answer is C. Vestigial structures are physical features of an organism that are remnants from an evolutionary ancestor and that no longer serve any function. The human appendix is thought to be an example of a vestigial structure. Although it serves no physiological function, the appendix may become inflamed and cause serious health problems.

The Oparin-Haldane Hypothesis theorizes that the early Earth had a reducing atmosphere because there was very little

A. ammonia.

B. oxygen.

C. hydrogen.

D. methane.

Explanation:

The correct answer is B. Oxygen has a propensity to oxidize, or receive electrons, from many different substances. An atmosphere without oxygen would undergo the opposite chemical reaction—reduction, or the donation of electrons. The absence of oxygen prevented developing organic compounds from being oxidized and thus allowed the early atmosphere to help create the organic compounds that support life. Hydrogen can serve as a reducing agent or an oxidizing agent; a lack of oxygen would cause a reducing atmosphere because of oxygen's strong tendency to oxidize. The early atmosphere contained ammonia, methane, and other gases, which contributed to its reducing makeup.

Which of the following describes many diverse species arising from a single species whose members spread into new geographic areas in search of new resources?

A. sympatric speciation

B. allopatric speciation

C. adaptive radiation

D. punctuated equilibrium

Explanation:

The correct answer is C. Adaptive radiation occurs when pioneer species branch out from their environment and inhabit new territory. The new stresses and competition fuel adaptation and natural selection, leading to the evolution of new species. Choice A is incorrect because sympatric species are any species occupying the same geographic region. Choice B is incorrect because allopatric species are species that occupy different geographic regions, but this does not describe the process of speciation described in the question. Choice D is incorrect because punctuated equilibrium is the evolutionary trend in which periods of abrupt speciation events are tempered by long periods of stasis.

Ecology

Around 10–15% of all questions on your AP exam will cover Ecology.

Communication and Responses to Environmental Changes

Ecology is the study of the relationship of organisms with each other and their environments. The factors that affect populations can be **biotic**, related to living organisms, or **abiotic**, related to nonliving things. Biotic factors can include things like food sources, mates, and predators. Abiotic factors include things like water availability, temperature, and soil nutrients. Ecology studies these interactions across different levels, from small to large.

- An **organism** is an individual of a species. Ecologists study adaptations that allow organisms to live in specific environments. These adaptations can be genetic through natural selection, behavioral, physiological, or morphological.
- A **population** refers to a group of organisms from the same species living in the same area at one time. Ecologists study a populations size, density, and structure over time, and the factors that influence those.
- A **community** is all of the populations that live in the same area at the same time. The size of the area depends on the question being asked. It can be small, like the microbiome of an individual's intestines, or huge, like an entire rainforest. Ecologists study how populations interact and how interactions change community structure.
- An **ecosystem** is the community plus the non-living environment. Ecologists study how energy flows in an ecosystem and how nutrients are used.
- The **biosphere** is planet Earth, and includes all living things as well as factors related to the air, water, and ground. On this level, ecologists study global patterns, like climate change, and how they affect ecosystems.

Demography, the statistical study of populations, is an important tool that ecologists use to study how populations change over time. Demography allows biologists to monitor how populations have changed in the past and make predictions about how they will change in the future. Two of the important factors for population biology are **population size**, the number of individuals, and **population density**, the number of individuals per unit of area. **Species dispersion patterns** describe how a population is distributed in an area. Species can have a **uniform distribution** (they are equally spaced), **random distribution** (there is no apparent order), or **clumped distribution** (clusters with high density).

Within a community, organisms respond to changes through both behavioral and physiological changes. For example, some animals respond to changes in the seasons by going into hibernation, which causes drastic changes in their physiology. These responses to the environment can be

used to exchange information about both external and internal factors. For example, some species provide warning about predators in the area by vocalizing or escaping. These signals provide cues for others in the community to escape and avoid predation. Different species have different mechanisms of signaling to each other through visual, tactile, auditory, chemical, and electrical cues. These kinds of behaviors can influence natural selection and the evolution of species. Populations can evolve or learn behaviors that increase fitness by increasing food accessibility and decreasing chances of predation.

Energy Flow Within and Across Ecosystems

Energy is an essential component of establishing an ecosystem. Species use energy to regulate their body temperatures and metabolisms. **Endotherms**, which include mammals and birds, generate thermal energy through metabolism to maintain their body temperatures. **Ectotherms**, including fish, reptiles, amphibians, and invertebrates, are not able to regulate their body temperature through metabolism and rather use external sources like sunlight to regulate temperature.

The metabolic rate of an animal can affect species size; generally, the smaller the animal, the higher their metabolic rate. Some species utilize different reproductive strategies dependent on energy investment—for example, plants that produce energy-expensive seeds, like coconuts, tend to produce very few of them that have a high chance of survival. On the other hand, other plants take advantage of energy availability by producing many energy-poor seeds, each with a low chance of survival. Energy availability can also affect the growth or death of an individual. Gains in energy storage causes growth of an organism, while losses lead to loss of mass, and ultimately death.

Energy availability has direct effects on the viability of a population. Generally, if available energy is reduced the ecosystem will shrink in size and diversity. For example, the community of a backyard garden will include plants and the insects and animals that feed on those plants. If a shade is constructed above that garden, the plants will no longer have enough energy from the sunlight to grow. This, in turn, will cause the insects and animals that depended on those plants to have reductions in available energy for them to consume, reducing the diversity of communities in that ecosystem.

Within an ecosystem, matter is recycled through predation and decomposition. Energy is reused continuously to sustain life within and between ecosystems. **Producers**, also called **autotrophs**, are species that make their own food out of simple molecules. These include **photoautotrophs** that make their own food from light, like plants and algae, and **chemoautotrophs**, which include different species of bacteria, that make their own food from small molecules. Autotrophs are the basis of life in a community as they are the primary energy producers. **Heterotrophs** cannot make their own food—they rely on autotrophs for energy. Organisms that eat autotrophs are **primary**

consumers—these are generally herbivores or animals that eat algae or bacteria. **Secondary consumers** eat primary consumers, and so on. The consumer that is at the top of the food chain is called an **apex consumer**; this species does not have any predators. **Decomposers** are species that feed on dead matter, like fungi, bacteria, insects, and vultures. These break down life back into organic compounds that primary producers can use to grow.

Factors in the Growth, Density, and Success of Populations

Population growth is limited by a population's **natality** (birth rate) and **mortality** (death rate). The birth and death rates are influenced by a number of external factors like food availability, predators, illness, and habitat space. The growth rate of a population is modeled by the following equation:

$$\frac{dN}{dt} = B - D$$

dN = change in population

dt = change in time

B = Birth rate

D = Death rate

If the *B* is positive and not constrained as the population grows, the population would experience **exponential growth**. If *B* is not constrained, the larger the population grows (*N*) the faster it would grow (*dN/dt*). Theoretically, this population would grow fast enough to overtake the Earth. The equation for exponential growth is as follows:

$$\frac{dN}{dt} = r_{max}N$$

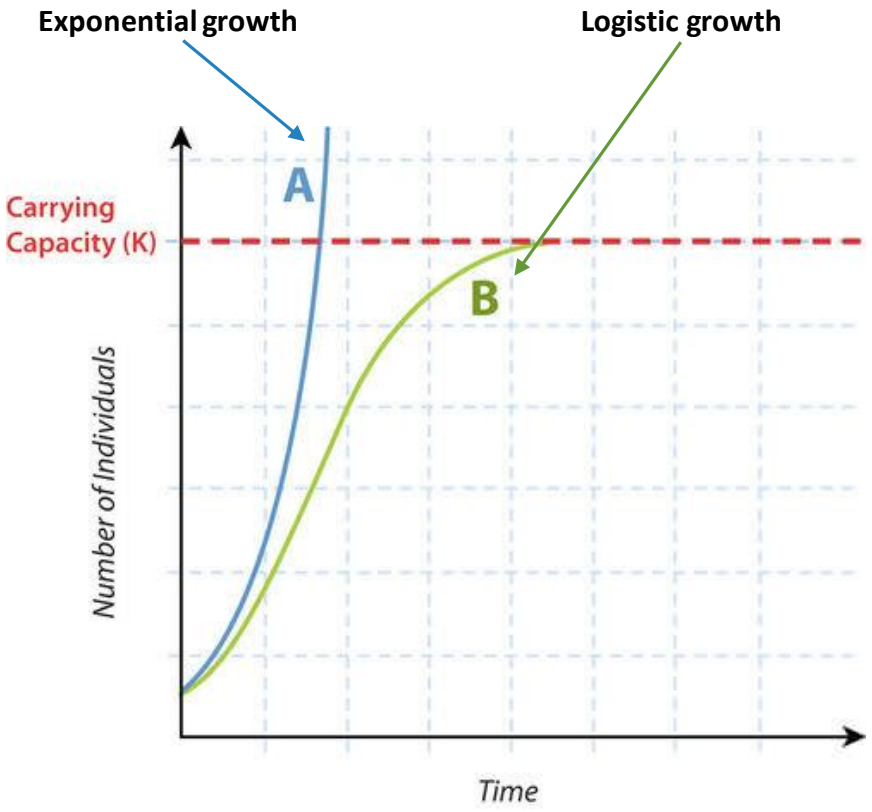
N = Population size

r_{max} = maximum per capita growth rate of populations

Luckily, environmental constraints limit how fast a population can grow. In most populations, as they grow, resources get used up and limit future growth. This causes the growth to level off and take an S-shaped form. This is called **logistic growth**. The maximum population size in an environment is called the **carrying capacity** (***K***). The growth equation then becomes as follows:

$$\frac{dN}{dt} = r_{max} N \frac{(K - N)}{N}$$

In general, when introduced to a new environment, most populations will take on an initial exponential growth phase that will level off as resources get used up.



Populations are limited by density-dependent and density-independent factors. **Density-dependent factors** cause *r* to change as the population increases. These include things like competition between members of the population for food resources, predation that increases upon the population as the population increases, communicable diseases and parasites, and accumulation of harmful waste that inhibits natality or promotes mortality.

These factors tend to contribute to the carrying capacity of the environment and lead to logistic growth curves. **Density-independent factors** are not dependent on the size of the population; thus, they do not tend to affect the population curve in the same way. Rather, these events tend to lead to sudden changes in population growth. These are often things like natural disasters or changes in the environment, like pollution levels.

Factors in Community and Ecosystem Dynamics

Community structure describes the number of different species, populations of each, and the way that they interact. **Species richness** describes the number of species within a community. Some communities are very species-rich, like rainforests, or species-poor, like the Antarctic. Areas near the equator tend to be more species-rich, as they have more light, more rainfall, and experience fewer seasonal shifts, thereby allowing more plant life to thrive. **Species diversity** is a measure of both the species richness and the relative abundance of each. More diverse communities are healthier and better able to rebound after a disturbance.

Species diversity is measured by **Simpson's Diversity Index**:

$$\text{Diversity Index} = 1 - \Sigma\left(\frac{n}{N}\right)^2$$

n = total number of organisms of a particular species

N = total number of organisms of all species

Community ecology studies how different species in an environment interact with each other. **Interspecific interactions** describe interactions between species. These can take on several forms:

- **Competition**: species compete for the same limited resources, like food or shelter, and both species are negatively affected.
- **Predation**: one species feeds on another.
- **Mutualism**: long-term interaction where both species have a beneficial relationship.
- **Commensalism**: long-term interaction where one species benefits and the other is unaffected.
- **Parasitism**: long-term interaction where one species benefits and the other is harmed.
- **Amensalism**: long-term interaction where one species is neither helped nor harmed but the other is harmed.

Interspecific interactions between species in a community can have both positive and negative effects that can be modelled. For example, **trophic cascades** can affect entire ecosystems. These occur when a predator is present in a population. By consuming the trophic level below them (say a shark consuming fish near a reef), they both limit the growth of their direct prey through predation and influence their behavior by causing them to avoid certain places. The effect of this is not just on their prey, but on lower trophic levels. By limiting the population size of their prey, the predator allows more growth of the prey's prey. If the predator's population is decimated, then this will trickle down through and allow overgrowth of the next trophic level—and possible destruction of lower levels.

Community structure is affected by the species that live within them and by abiotic factors like climate, geography, and catastrophic events. Some species within communities have larger effects than others. **Keystone species** have an effect on the community that is not proportional to their abundance. These are things like predators that feed on other species or that take up a disproportionate amount of resources. If a keystone species is removed from an ecosystem, the ecosystem generally collapses. **Foundation species** create and define the community, often by making an environment able to sustain life. **Invasive species** are species that are not native to an environment and their introduction causes harm to the community. In some cases, invasive species overtake and decimate communities through exponential growth.

> Note that relationships between populations in an environment and how they affect evolution of traits are a common topic of the free response section on the AP exam.

Invasive Species, Human Interaction, and Environmental Changes

Changes to the environment that a species resides in is a source of selective pressure. **Adaptations** are genetic variations that are favored by selection, as they provide advantages to that organism in their environment. These are the basis for species evolving within their environments. Genetic variations caused by mutations cannot predict how the environment will change in the future; rather, they are due to random events in the production of gametes. Thus, preexisting genetic variation in a population drives how a species will adapt to a changing environment. This is one of the main reasons that population diversity is essential for species survival. Changes in ecosystems that drive adaptation are:

- **The introduction of an invasive species**: Invasive species do not have natural predators in a new ecosystem, and thus are able to outcompete native species for resources. This can lead to exponential growth, as invasive species have virtually no cap on population growth besides lifespan and availability of food and space. This causes adaptive pressure on other species living within that ecosystem.
- **Human activity**: Human activity can lead to introduction of invasive species, introduction of new diseases, or destruction of native habitats. All of these changes can disrupt local ecosystems.
- **Geological and meteorological events**: These can cause changes in the environment of an ecosystem and provide adaptive pressure. Examples include events like the formation

of mountain ranges or rivers that provide physical barriers and changes in climate that alter the habitability of an ecosystem.

Outside Reading

- For more information on population biology and ecology, see: https://www.khanacademy.org/science/biology/ecology
- For more information on trophic cascades: https://www.nature.com/scitable/knowledge/library/trophic-cascades-across-diverse-plant-ecosystems-80060347/

Sample Ecology Questions

Which of the following is an example of a density-dependent factor that affects a community?

A. temperature

B. fire

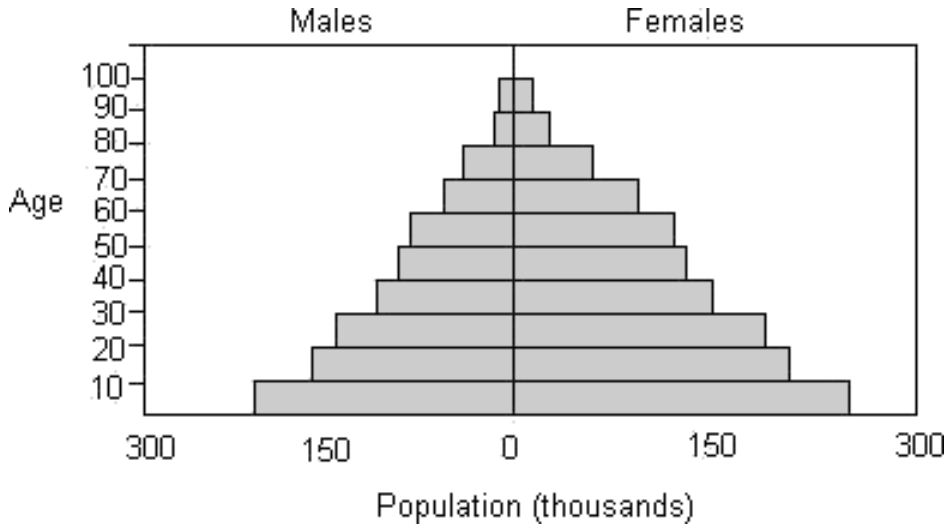
C. scarcity of food

D. pollution

Explanation:

The correct answer is C. Food supply is a density-dependent factor; the more individuals there are in a community, the greater the impact this factor has on a community. Temperature is a density-independent factor because it affects a community regardless of the number of organisms living in it. Fire would generally devastate a community, regardless of the number of

organisms living there; therefore, it is also a density-independent factor. Finally, pollution has a detrimental effect on both high-density and low-density communities.



Answers in biomedical science would cause the age distribution curve above to change toward which of the following?

A. The bottom rows would become even wider.

B. The middle rows would become narrower.

C. All rows would become narrower.

D. The upper rows would become wider.

Explanation:

The correct answer is D. Advances in biomedical science generally allow people to live longer, so the upper rows, which represent older members of the population, would widen.

All of the following are examples of biotic factors in an ecosystem EXCEPT

A. competition.

B. symbiosis.

C. predation.

D. sunlight.

Explanation:

The correct answer is D. Sunlight is the only choice that does not describe a species-species interaction. Because it is not a living thing, sunlight is an abiotic factor in an ecosystem.