TMAS Academy

ACE AP Biology 2025

- 100+ Problems
- All Topics
- Detailed Solutions

Aditya Baisakh, Amaan Shafi, Abby Trinh

Contents

§0.1 Credits/Acknowledgements

- We thank **Ritvik Rustagi**, founder and CEO of TMAS Academy, for providing us the opportunity to give back by writing this AP Biology book for the public.
- We would also like to thank **Evan Chen**, U.S. Math Olympiad team coach and current Ph.D. student at MIT, for providing the LaTeX template used to write and format this book.
- We would also like to thank **College Board** for providing us with practice problems that were used in this book.
- I (Aditya Baisakh) would like to **Sal Khan**, the founder of Khan Academy, for creating the AP Biology course whose materials has helped me understand the content well enough to educate others.
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§0.2 About the Author: Aditya Baisakh

My name is Aditya Baisakh. I am a senior at Baton Rouge Magnet High School with an avid interest in STEM. I authored Units 1, 3, and 8 in this book, and also wrote solutions to the multiple choice and some free response questions. I hope our efforts inspire your passion in biology and help you on your quest for college credit!

§0.3 About the Author: Amaan Shafi

My name is Amaan Shafi. I am a senior at Baton Rouge Magnet High School with a passion for biomedical science. I authored Units 2, 4, and parts of 7 in this book, and also wrote solutions to some free response questions. I hope this book comes in handy during the inevitable late-night study sessions that I experienced myself! :)

§0.4 About the Author: Abby Trinh

My name is Abby Trinh. I am a freshman at San Gabriel High School with an interest in biochemical engineering and mathematics. I authored Units 5, 6, and parts of 7 in this book, and also wrote solutions to some free response questions. I hope that this book helps everyone achieve their academic goals!

§0.5 About TMAS Academy

TMAS Academy, previously known as Explore Math, was started by Ritvik Rustagi in 2020 to spread competition math. In its entirety, it is **The Math and Science Academy**. TMAS Academy has previously published eight books: *ACE The AMC 10/12, ACE AP Physics 1, ACE AP Calculus AB, ACE AP Calculus BC, ACE AP Physics C: Mechanics, ACE AP Chemistry, ACE AP Computer Science Principles, ACE AP Statistics*, and now the ninth, brought to you by Aditya, Amaan, and Abby: *ACE AP Biology*. The team has evolved into a large network of hard-working, passionate, and dedicated students who enjoy STEM and helping others. We believe that everyone should be able to achieve their full potential with learning, so we have dedicated our efforts to making educational resources accessible to all.

For more information on TMAS Academy, check out the official website.
Website: https://www.tmasacademy.com/
If you have any questions on TMAS Academy and its programs, please feel free to email **ritvikrustagi7@gmail.com**.

§0.6 Opportunities For You To Contribute To TMAS Academy

TMAS Academy is very inclusive and you can help support its cause in several ways. You can **join the team** by filling out the form below, which can also be found on the website: https://forms.gle/VXGvj27UvcZPGhiJ8

Donations: If you want to assist us in our monthly payments to run this organization, which includes website costs, Overleaf costs (the platform used to write these books), and filming/editing costs, then please consider donating! For those who are willing to contribute, we have listed some ways below. **Don't forget to write a message so we know who you are and send you a thank you note!**

- You can donate through PayPal to the email: ritvikrustagi7@gmail.com
- If you want to donate and the above method doesn't work for you, then you can send an email to ritvikrustagi7@gmail.com

You can also contribute by **subscribing** to the YouTube channel:
https://www.youtube.com/@tmasacademy
Also, don't forget to join the Discord server to connect with other hardworking students preparing for AP exams and math competitions such as AMC 10/12 and AIME.
https://discord.gg/tmas-academy-1019082642794229870

There are occasional group study sessions and other review sessions led by Ritvik Rustagi and others in the server!

You can also follow all of our social media such as the LinkedIn page and the Instagram account that is run by the media team. Also, please join the mailing list to learn about all updates and our upcoming books and videos. All of that can be found at the bottom of the site: https://www.tmasacademy.com/

Finally, you can spread our efforts and initiative to anyone you know who may benefit from or support us, be it your classmates, teachers, or other nonprofit organizations focused on education.

§0.7 Benefits of Doing This Course

Taking AP Biology comes with several benefits. For example, you can earn credit hours and potentially test out of several college courses, saving you both time and money in the long run. Additionally, this course emphasizes analyzing data, interpreting results, and applying principles of the scientific method to approach complex problems, which enhances your problem-solving and critical-thinking skills. Finally, you get to experience hands-on learning, as many AP Biology classrooms include extensive laboratory work, allowing students to gain more practical experience.

§0.8 Exam Format (Effective 2025)

The AP Biology exam is three hours long and has two sections: multiple choice and free response. Both sections are worth 50% of your total score.

Multiple Choice Section

- 60 questions to be answered in 90 minutes.
- The questions test your understanding of biology fundamentals and applying several concepts to solve problems.

Free-Response Section

- 6 questions to be answered in 90 minutes.
- Includes 2 long-answer questions and 4 short-answer questions.
- The questions test your ability to analyze data and apply the scientific method.

Exam Materials

- You can use a four-function calculator (with square root), scientific functions, and the AP Biology Equations and Formulas Sheet.
- You will complete the multiple choice section and view the free response questions in the Bluebook testing app.
- You will handwrite your free-response answers in paper exam booklets.

Scoring

- The College Board curves the AP exam scores each year to standardize student performance over several cohorts of data.
- Your score is only determined by the number of questions that you answer correct. Points are not deducted for incorrect answers. *It is to your advantage to answer every question on the exam.*

Best Practices

- Know the key terms and concepts well.
- Think about how concepts relate to each other, rather than just memorizing facts.
- Use AP-style practice questions to build your skills and confidence.
- Set aside time to study and break up your study into manageable chunks.
- Develop strategies to deal with anxiety and test-related stress.
- Begin preparing well in advance, ideally at least two months before the exam. In other words, don't cram!
- When solving FRQs, do **NOT** label the specific FRQ action (Describe, Explain, Justify, Predict, etc.) that you are solving.

Here is the breakdown of topics tested on the exam, effective for the 2025 administration. From College Board: The course content outlined below is organized into commonly taught units of study that provide one possible sequence for the course. Your teacher may choose to organize the course content differently based on local priorities and preferences.

- **Unit 1: Chemistry of Life**, 8% – 11% of total score.
- **Unit 2: Cell Structure and Function**, 10% – 13% of total score.
- **Unit 3: Cellular Energetics**, 12% – 16% of total score.
- **Unit 4: Cell Communication and Cell Cycle**, 10% – 15% of total score.
- **Unit 5: Heredity**, 8% – 11% of total score.
- **Unit 6: Gene Expression and Regulation**, 12% – 16% of total score.
- **Unit 7: Natural Selection**, 13% – 20% of total score.
- **Unit 8: Ecology**, 10% – 15% of total score.

§0.9 What if there is an error in the book?

There are possibilities for minor errors, such as typos or in solving problems.
If that is the case, please click on this link to report the mistake:
Error Form

1 Chemistry of Life

We begin our journey into biology, the study of life. This unit is the foundation of the chemical and biological bases of life, including the properties of water and the structure and function of biological macromolecules. By developing an understanding of these concepts, we can learn how and why biological interactions occur, an invaluable skill for the entirety of this course.

§1.1 Structure of Water and Hydrogen Bonding

As we all know, water is essential for all life on Earth. In this section, we will unpack all the properties of water and how its associated chemical properties make it such a unique molecule.

What is Water? Water is a **polar** molecule, so its ends have opposite partial charges, and the molecule has an overall uneven charge distribution. It has a **chemical formula** of H_2O, telling us that a water molecule consists of two hydrogen atoms and one oxygen atom. Water is polar because the hydrogen atoms each carry a partial positive charge and the oxygen atom carries a partial negative charge. We can examine partial charges further when we talk about hydrogen bonding.

Hydrogen Bonding Hydrogen bonding is a type of intermolecular bond that occurs when a hydrogen atom bonds to a highly electronegative atom, such as fluorine, oxygen, and nitrogen (FON).

Hydrogen bonding leads to a molecular **dipole moment**, which results in the partial positive and negative charges on the hydrogen and oxygen atoms, respectively. This structure explains the polarity of water. Most importantly, note that water molecules interact through hydrogen bonding. The hydrogen atoms of one water molecule are strongly attracted to the adjacent oxygen atoms of another water molecule, and vice versa. The image below represents this phenomenon.

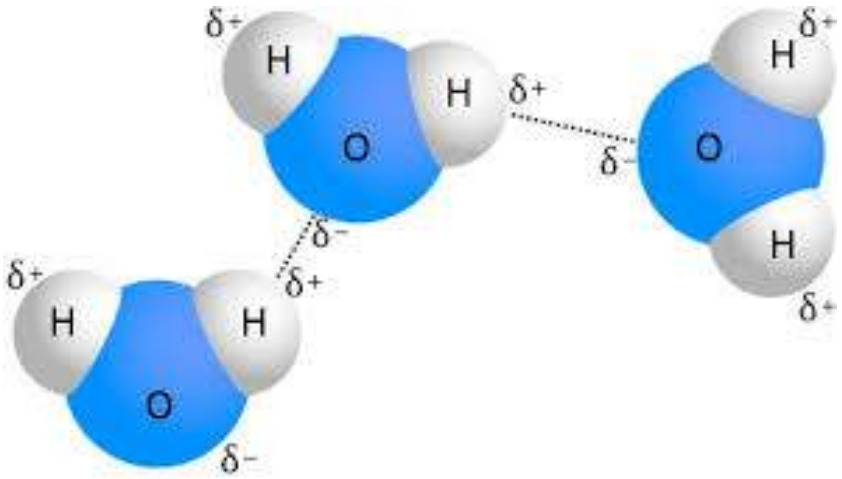


Image Credit: Chemicool

While hydrogen bonds are generally weaker than other forms of covalent bonds, where electrons are shared between atoms in a compound, they are still relatively strong and critical to various chemical processes.

In biology, hydrogen bonding occurs in many different kinds of molecules, including water, DNA, and nucleic acids. It is also responsible for other properties, e.g. the shape and function of macromolecules, compound stability, and the formation of more intermolecular bonds. Finally, they give rise to the properties of water which will conclude this section.

Properties of Water The properties of cohesion, adhesion, surface tension, specific heat, and evaporative cooling are extremely important and explain how water supports biological processes.

1. **Cohesion** is the attraction of water molecules. These attractive forces are referred to as cohesive, and they are present because water molecules form hydrogen bonds with each other. For example, water (in droplet form) is "pulled" by other water molecules up the stem of a plant by sticking to one another. Cohesion due to hydrogen bonding contributes to the movement of water and nutrients against gravity in plants. **Transpiration** is the loss of water from a plant in the form of water vapor.

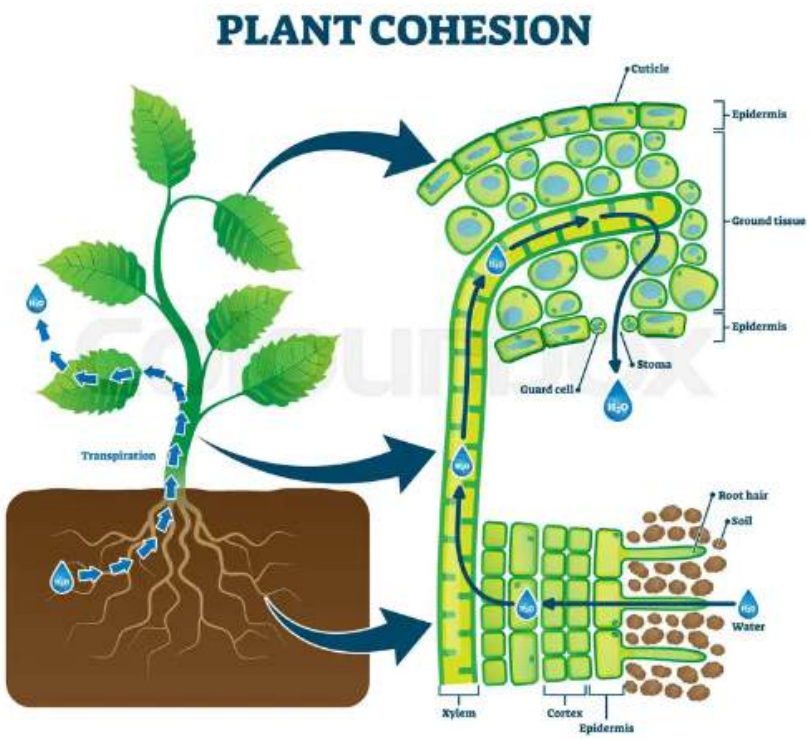


Image Credit: Eduards Kantans

2. **Adhesion** occurs when one substance is attracted to another. Water tends to adhere to other molecules and surfaces that have polar components.
   - EX: Water sticks to glass surfaces, such as windows and drinking glasses.
3. **Surface tension** refers to the difficulty to break the surface of the water due to the cohesive forces between molecules.

- EX: When insects stride on water, the high surface tension allows them to stay afloat and walk on the surface of lakes, rivers, and other freshwater bodies.

4. **Specific heat** is defined as the amount of heat energy that is required to raise or lower the temperature of one gram of a substance by one degree Celsius. Water has a very high specific heat, so it can absorb a lot of heat without a significant change in temperature. This is why it takes so long to evaporate large quantities of water!

5. **Evaporative cooling** is based on the idea that water has a high heat of vaporization, so it can absorb a lot of heat and leave the surface cooler. For example, excess body heat can convert sweat into water vapor, which causes the cooling effect that we feel in our body.

6. Finally, the **dissociation of water** represents the shift of hydrogen from one water molecule to another.
   - When a molecule is increasing **hydronium concentration** by releasing hydrogen ions into solutions, it is an **acid**; $HCl \rightarrow H^+ + Cl^-$
   - When a molecule is increasing **hydroxide concentration** by releasing hydroxide ions to solutions, it is a base; $NaOH \rightarrow Na^+ + OH^-$
   - The counterbalance of hydronium and hydroxide results in water having a **neutral pH** of 7.0, meaning it is neither acidic nor basic. pH is a metric of how acidic or basic a solution is, determined by the concentration of H^+ ions present in that solution. It is measured on a **scale** of 0 to 14 and essentially, each level on the pH scale corresponds to a ten-fold change because the pH scale is **logarithmic**. Most biological fluids are in the pH range of $6 - 8$. Finally, the pH of a solution can be calculated by taking the negative logarithm of its H^+ concentration:
   $$\text{pH} = -\log[H^+]$$

Let's end this section with some conceptual AP-style problems.

Problem 1.1.1 — Multiple Choice Question

What role does cohesion play in the process of transpiration in plants?

(A) Cohesion prevents water from entering the plant's vascular system.
(B) Cohesion allows water molecules to form a continuous column in xylem vessels, facilitating upward movement.
(C) Cohesion breaks down cell walls to allow water movement.
(D) Cohesion increases the rate of evaporation from leaf surfaces.

Solution: Cohesion is the tendency of water molecules to stick together due to hydrogen bonding. Because these molecules are cohesive, xylem vessels act as tubes which transport water from the plant's roots to the leaves. As the water evaporates from the leaves through the stomata, the cohesive force pulls the next "set" of water molecules to replace the lost water, in a process known as transpiration. The correct answer is $\boxed{\textbf{(B)}}$.

Problem 1.1.2 — Multiple Choice Question

What characteristic of water molecules allows them to be both hydrogen bond donors and acceptors?

(A) The presence of both partially positive hydrogen atoms and partially negative oxygen atoms.
(B) The high electronegativity of hydrogen atoms in water molecules.
(C) The symmetric arrangement of hydrogen atoms around the oxygen atom.
(D) The ability to form covalent bonds with water molecules.

Solution: We first eliminate (B). Although oxygen has a high electronegativity, the relatively low electronegativity of hydrogen also impacts water polarity, but to a smaller effect. Next, eliminate (C). The symmetry of the hydrogen atoms around the oxygen atom is not the key reason for water's ability to be both a donor and acceptor. Lastly, covalent bonds are chemical bonds within a water molecule that hold the oxygen and hydrogen atoms together. However, hydrogen bonding is an interaction that occurs between multiple water molecules, so we eliminate (D). A hydrogen bond forms between a partially positive hydrogen atom on one water molecule and a partially negative oxygen atom on another molecule. This is consistent with $\boxed{\textbf{(A)}}$.

Problem 1.1.3 — Multiple Choice Question

Which property of water allows insects like water striders to walk on its surface, and how is this property related to hydrogen bonding?

(A) Polarity, which causes water molecules to orient themselves perpendicular to the surface, creating a repulsive force against the hydrophobic legs of water striders.
(B) Surface tension, which is enhanced by hydrogen bonding between water molecules at the air-water interface, creating a resistant 'skin' on the water's surface.
(C) Specific heat capacity, which is elevated due to hydrogen bonding, allowing the water's surface to absorb the kinetic energy of the insect's movement without breaking.
(D) Viscosity, which is increased by hydrogen bonding, making the water's surface more resistant to deformation by the insect's weight.

Solution: We know that surface tension is the ability of a liquid to resist external forces caused by cohesion between its molecules. We can eliminate (D) immediately; viscosity is the resistance of a fluid to flow. Also, water molecules are polar, but this is not the direct reason for surface tension. Polarity is the reason for hydrogen bonding, which in turn leads to surface tension, so we eliminate (A). Specific heat capacity is defined as the amount of heat energy that must be supplied in order to raise the temperature of a substance by one degree. This is not relevant to the the ability of insects to walk on water's surface, therefore, we eliminate (C). THe only answer choice left is (D), which makes sense because the strong hydrogen bonds between water molecules lead to a network of tight interactions, which forms a "skin," or layer, on the water's surface. Thus, $\boxed{\textbf{(D)}}$ is correct.

§1.2 Elements of Life

In this section, we will learn about the elements that make up all living things and some of the rules that all living things must follow in order to survive.

The Chemical Organization of Organisms All living organisms are made up of **matter**, which represents everything in the universe that occupies space and has mass. The smallest unit of matter that can identify it is the **atom**. Atoms are made up of even smaller, *subatomic* particles, which are called protons, neutrons, and electrons. There are various combinations in which atoms can form different types of matter, such as solids, liquids, and gases, and to make up elements that cannot be broken down any further by chemical reactions. Although the periodic table of elements exists, for this course, the essential elements are oxygen (O), carbon (C), hydrogen (H), nitrogen (N), calcium (Ca), phosphorus (P), potassium (K), sulfur (S), sodium (Na), chlorine (Cl), and magnesium (Mg).

Compounds are substances that can be broken down further by chemical reactions because they are composed of two or more elements in a fixed ratio to each other. For example, water, H_2O, consists of two hydrogen atoms and one oxygen atom. Because there is a fixed ratio for any number of water molecules, H_2O is, by definition, a compound.

Living systems and the organisms within them require constant energy changes and **macromolecules**. This exchange of matter is what allows organisms to grow and reproduce. By understanding the chemistry behind atoms and molecules, we can understand how elements shape life!

Atoms: A Closer Look We know that the smallest unit of mass that retains all properties of an element is the atom. The subatomic particles that make up the atom are positively charged protons, neutrally charged neutrons, and negatively charged electrons.

The number of protons within the nucleus of an atom determines its **atomic number**. In the picture below, the number 6 is the atomic number of carbon. The **atomic mass number** is the sum of the protons and neutrons in the nucleus. The atomic mass number of carbon is 12.01, rounded to four significant figures.

Isotopes are two atoms of the same element that have a different number of neutrons. This implies that isotopes have different atomic masses. Radioactive isotopes are commonly used for fossil dating and medical imaging. These species spontaneously decay, releasing energy. For example, **Carbon-14**, or radiocarbon, contains six protons and

eight neutrons, and is used for fossil dating, archaeologic sites, and artifacts.

There is a special property of electrons in an atom. Located outside of the nucleus in a region called the **electron cloud**, these subatomic particles are located at different **energy levels** or electron shells. As electrons absorb energy, they move up or jump an energy level farther away from the nucleus, and vice versa. The transfer of energy in electrons is important for AP Biology because it directly relates to several energy processes that take place in organisms' cells, e.g. cellular respiration, oxidative phosphorylation, and more.

The Elemental Building Blocks of Life We begin with **carbon**. This element is the building block of all of the major macromolecules that we will study in this course: carbohydrates, lipids, proteins, and nucleic acids. It is a major component of virtually all chemical compounds and helps form cells in organisms. Carbon is so special because it has a property known as **tetra-valence**, i.e. the ability to form four covalent bonds. In chemistry, all atoms strive to be *stable*, i.e. fill their outermost electron shell with eight electrons and satisfy the **octet rule**. This rule states that atoms will lose, gain, or share electrons in order to achieve a stable configuration of eight valence electrons. For example, carbon is stable when it bonds covalently with four hydrogen atoms, forming methane (CH_4).

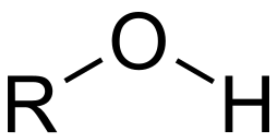
The next element we will discuss is **nitrogen**. It is a building block of proteins, nucleic acids, and enzymes (special type of protein). These molecules are important in biological processes such as metabolism, cell division, and DNA replication. Nitrogen also occurs in significant amounts in hormones, e.g. adrenaline and insulin. Nitrogen serves a key role in the environment, being a part of the **nitrogen cycle**, which balances nutrients in an ecosystem. While nitrogen primarily exists as an atmospheric gas, plants and other microorganisms can convert it into a usable form for other organisms in a process known as **nitrogen fixation**, keeping ecosystems abundant and healthy.

Lastly, we will discuss **phosphorus**, a key element in biology due to its role in nucleic acids, certain proteins, and lipids. Beyond DNA and RNA, phosphorus is also important for many biological processes, especially those involving energy production. Finally, like nitrogen, it helps balance nutrients in an ecosystem.

Functional Groups In AP Biology, a **functional group** refers to a specific cluster of atoms within a molecule that provides the molecule with its unique structure, and therefore, a unique function. To keep things simple, we classify them as either hydrophilic or hydrophobic depending on polarity (and sometimes charge) properties.

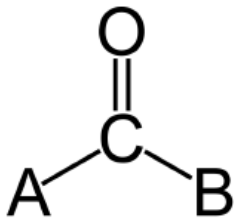
Let's unpack the important functional groups one by one!

- **Hydroxyl group**: Consists of hydrogen bonded to oxygen (OH) attached to a carbon skeleton.

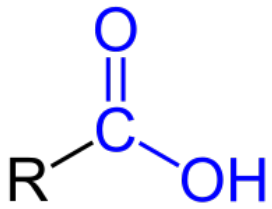


- **Carbonyl group**: Involves a double bond (two shared pairs of valence electrons)

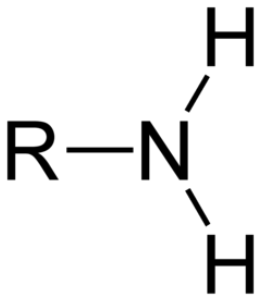
between carbon and oxygen atoms. If the carbonyl group is on the end of the carbon skeleton, it is called an *aldehyde*. If not, then it is a *ketone* (polar).



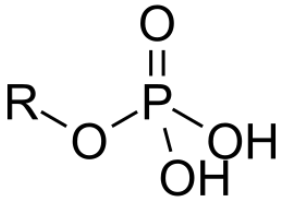
- **Carboxyl group**: A hybrid of carbonyl and hydroxyl functional groups where carbon is double-bonded to oxygen as well as a hydroxyl group. Molecules containing a carboxyl group are considered *acidic* because they release H^+ ions in aqueous solutions.



- **Amino group**: Consists of nitrogen bonded to two hydrogen atoms and one carbon atom. Organic molecules which contain an amino group are called *amines*. They are *basic* in nature, because they remove H^+ ions from aqueous solutions.

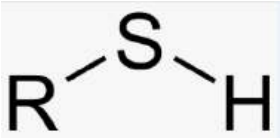


- **Phosphate group**: shown as a phosphate ion (PO_4^{3-}) covalently bonded with the carbon skeleton. Lots of energy is used to make nucleic acids and phospholipids, and a phosphate group makes this process possible. Additionally, these species are *acidic* because they release H^+ ions into aqueous solutions.



- **Sulfhydryl group**: This group consists of a sulfur atom bonded to a hydrogen atom (covalent). Molecules containing this functional group are considered slightly

polar, although they are much less polar than molecules with hydroxyl groups, because of the lower electronegativity difference between sulfur and hydrogen as opposed to oxygen and hydrogen.



Note: In the above images, R represents an unknown part of the molecule to which the functional group is attached.

Problem 1.2.1 — Multiple Choice Question

The following table shows the relative percentages of elements in a certain biological molecule.

Element	% of Total
Carbon (C)	38%
Nitrogen (N)	17%
Phosphorus (P)	10%
Oxygen (O)	31%
Sulfur (S)	0%
Hydrogen (H)	4%

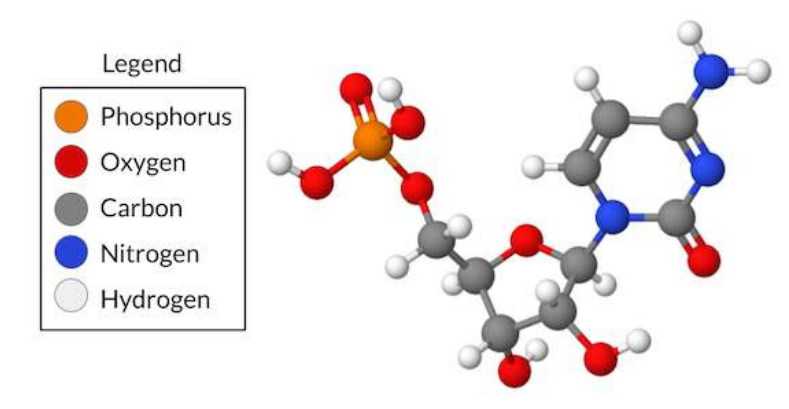
Which of the following best describes the biological molecule?

(A) The molecule is a protein.
(B) The molecule is a nucleic acid.
(C) The molecule is a complex carbohydrate.
(D) The molecule is a simple carbohydrate.

Solution: All carbohydrates, simple and complex, do not contain nitrogen or phosphorus. However, the molecule described in this table contains both of these elements. Therefore, we eliminate (C) and (D). Additionally, proteins do not contain phosphorus, so we eliminate (A). Nucleic acids, on the other hand, contain carbon, oxygen, hydrogen, nitrogen, and phosphorus, but not sulfur. This is consistent with the data in the table, therefore, $\boxed{\textbf{(A)}}$ is correct.

Problem 1.2.2 — Multiple Choice Question

Consider the following molecular model.



Based on its elemental composition, which of the following molecules is most likely to represent the model?

(A) Phenylalanine, a building block of proteins
(B) Glucose, a simple carbohydrate
(C) Cellulose, a complex carbohydrate
(D) Cytidine, a building block of the nucleic acid DNA

Source: Khan Academy

Solution: The phenylalanine molecule cannot be represented by the model because proteins do not contain phosphorus. Glucose and cellulose are carbohydrates that do not contain nitrogen or phosphorus. Therefore, they also cannot be represented by the molecule. This eliminates options (A), (B), and (C). However, nucleic acids contain both nitrogen and phosphorus. This is consistent with what is shown in the model, so the correct answer is $\boxed{\textbf{(D)}}$.

§1.3 Introduction to Biological Macromolecules

Think back to when you went grocery shopping. If you look at the "Nutrition Facts" label on the back of some of your items, you may already be familiar with large biological molecules such as proteins, carbohydrates, and fats that we will discuss in this section. In addition, the fundamental chemistry behind these large molecules will be covered. We will unpack the types of chemical bonding and why it is so essential to understanding the nature of these biological molecules.

Chemical Bonds We know that atoms are the smallest units possible of all matter. Everything in the universe is made up of atoms. However, atoms on their own are not of much help to us. We want to understand what causes atoms to interact with each other and form the macromolecules that are so significant for this course.

Chemical bonding represents any of the interactions that account for atoms associating

into ions, molecules, crystals, and other chemical species. There are two types of chemical bonding: **covalent bonding** and **ionic bonding**.

Covalent bonding involves sharing of electrons between two or more atoms in a molecule. A single bond is a structural formula that describes one shared pair of electrons and is represented by one line (−). The structural formula of chemical bonds in general involve two lines connecting two atoms together. Finally, an atom's tendency to attract electron density to itself is referred to as **electronegativity**.

Note 1.3.1

Examples of molecules that display covalent bonding among its atoms include methane (CH_4), carbon monoxide (CO), and iodine pentafluoride (IF_5).

Ionic bonding involves a transfer of electrons (electrostatic attraction) between a positive and negative ion. After the transfer, both atoms have complete valence shells, and ionic compounds, or salts, are formed.

Note 1.3.2

Examples of ionic compounds include sodium fluoride (NaF), potassium nitrate (KNO_3), and calcium chloride ($CaCl_2$).

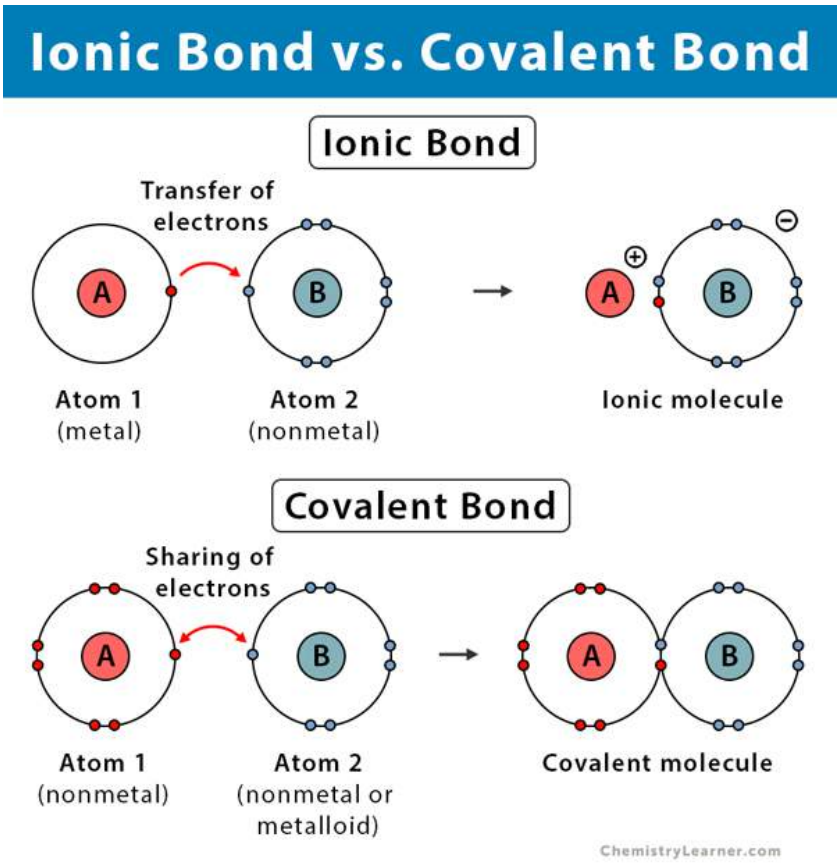


Image Credit: Chemistry Learner

We can further divide covalent bonds into two classes: **nonpolar covalent** and **covalent**

bonds. In nonpolar covalent bonds, there is an equal sharing of electrons and charge distribution, so the electronegativity difference between the bonded atoms is pretty small. In polar covalent bonds, the opposite is seen. The charge distribution is uneven and electrons are unequally shared. The electronegativity difference between bonded atoms is significant, with the more electronegative atom having more electron density. Finally, make sure you don't forget this:

- **InTRAmolecular bonds** occur within a molecule. (e.g. covalent bonds).
- **InTERmolecular bonds** take place between different molecules. For example, a hydrogen atom bonded with an electronegative atom is attracted to another electronegative atom displays the concept of hydrogen bonding.

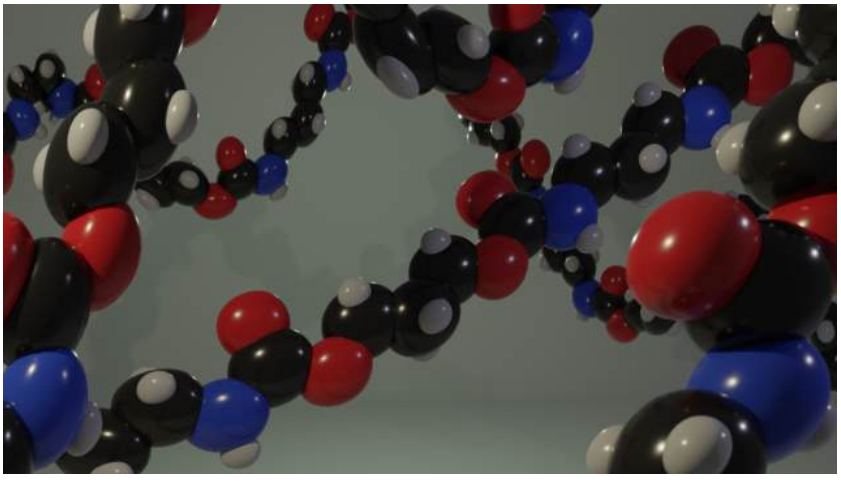
Note 1.3.3

Please note that hydrogen bonds are **not** covalent bonds!

Introduction to Macromolecules As humans, we can be thought of as a package of four major types of large biological molecules, or macromolecules: carbohydrates (including sugars), lipids (such as fats), proteins, and nucleic acids (such as DNA and RNA). While these are not the only molecules existing in our bodies, the most prominent molecules can be divided into these groups. Together, these four macromolecules comprise the majority of the dry weight of a cell. (Water comprises the majority of the wet weight.)

Monomers and Polymers Most large biological molecules are **polymers**, long chains made up of repeating molecular subunits (building blocks) called **monomers**. An easy way to relate the two is by using the following device: "polymers are the pod that holds the peas (monomers)."

Carbohydrates, proteins, and nucleic acids are found as polymers due to their large size. Lipids are generally not considered polymers because they are much smaller than the other three. However, this course uses the term "macromolecule" more loosely, to describe the four large biological molecules. This is just a naming convention, so don't get confused. For the purposes of AP Biology, just treat lipids as a macromolecule, but also know that they don't generally form polymers. The image below displays polymeric structure.



As we can see, polymers can be thought of as long molecules made of many building blocks, known as monomers, that are linked by covalent bonds.

Dehydration Synthesis We know that polymers are formed by monomers. But how does this process happen? Macromolecules are generally assembled through **dehydration synthesis** reactions, where covalent bonds are formed between adjacent monomers until there exists a series of monomers covalently bonded to one another. In the process, water molecules are released. This should make sense as to why the reaction is referred to as "dehydration synthesis"; water is lost, and a new covalent bond is formed! Finally, this is a condensation reaction, which requires energy (making it endergonic) and enzymes (proteins that speed up chemical reactions), and results in small molecules binding together to form larger molecules (*anabolic* process).

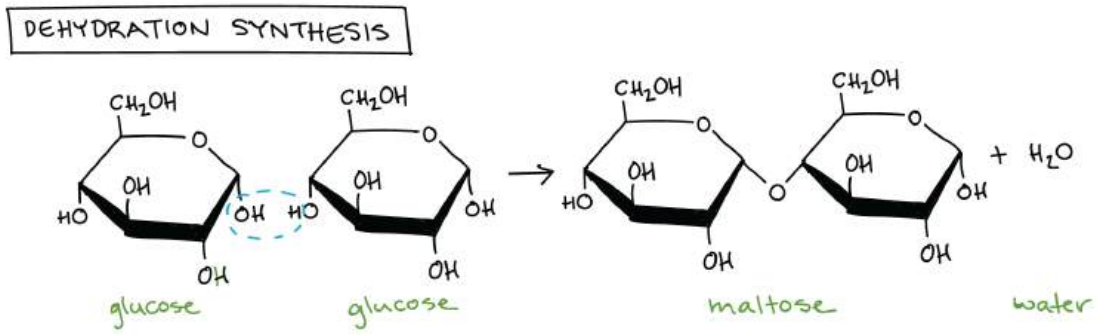
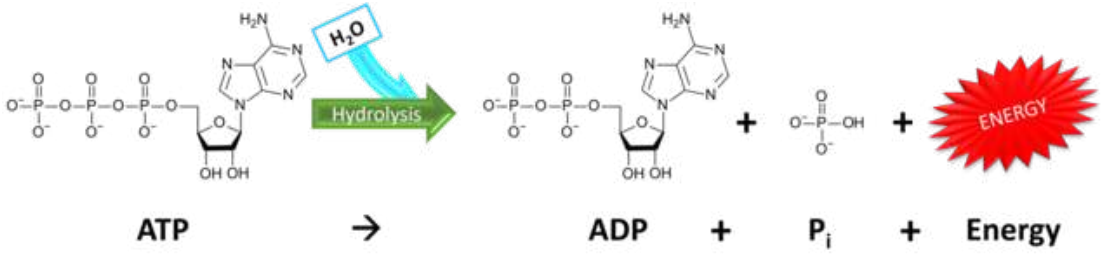


Image Credit: Khan Academy

In the above dehydration synthesis reaction, two molecules (monomers) of glucose combine to form a single molecule of maltose sugar. In the process, one of the glucose loses a hydrogen atom, the other loses an OH group, and a water molecule is released as a new covalent bond is generated between the glucose molecules. As this repeats, this chain of monomers grows in length and eventually forms a polymer.

Polymer Structure Even though all polymers are composed of repeating monomer units, there is a lot of variety in their shape and structure. The three largest biological molecules (carbohydrates, nucleic acids, and proteins) all contain different types of monomers, with their unique compositions corresponding to their unique functions in various living organisms. Additionally, single types of monomers may form polymers with very different properties. For example, starch, glycogen, and cellulose are all of the carbohydrates group, but they exhibit different bonding and branching patterns.

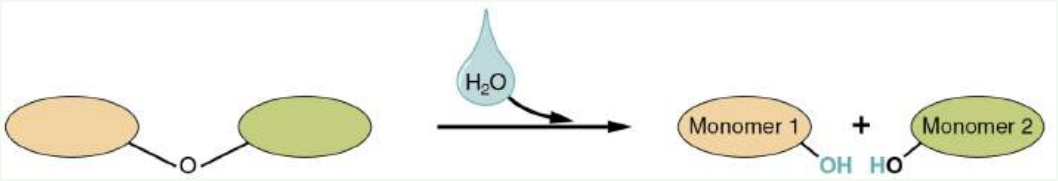
Hydrolysis We can also work backwards, i.e. go from polymers to monomers by adding water. This should make sense because *hydro* - *water*, *lysis* - *break*. Hydrolysis uses H_2O to break down the molecules splitting into H^+ and OH^- ions. Unlike dehydration synthesis, this process is exergonic (involves release of energy) but it also requires enzymes. Finally, it is *catabolic*, so the complexity of molecules is reduced.



The hydrolysis of ATP produces ADP, inorganic phosphates, and free energy. We will learn more about these molecules when we study photosynthesis and cellular respiration in Unit 3: Cellular Energetics.

Problem 1.3.4 — Multiple Choice Question

Which of the following best describes the role that water plays in the reaction depicted below?



(A) In the reverse of this reaction, water is used to promote hydrolysis.
(B) Water is a product of this dehydration synthesis reaction.
(C) When water is added, the two monomers form a covalent bond that holds the dimer together.
(D) As a reactant, water cleaves the covalent bond that holds the dimer together.

Source: *OpenStax College Biology*

Solution: In this reaction, water acts as a reactant that breaks covalent bonds within one molecule to form two subunits of that molecule. Such reactions are called hydrolysis reactions, therefore, we can eliminate options (A), (B), and (C). Finally, answer choice **(D)** best describes a hydrolysis reaction, and we find it is the correct answer.

Problem 1.3.5 — Multiple Choice Question

Which of the following questions would a researcher most likely ask if they wanted to know whether a hydrolysis reaction or a dehydration synthesis reaction is occurring?

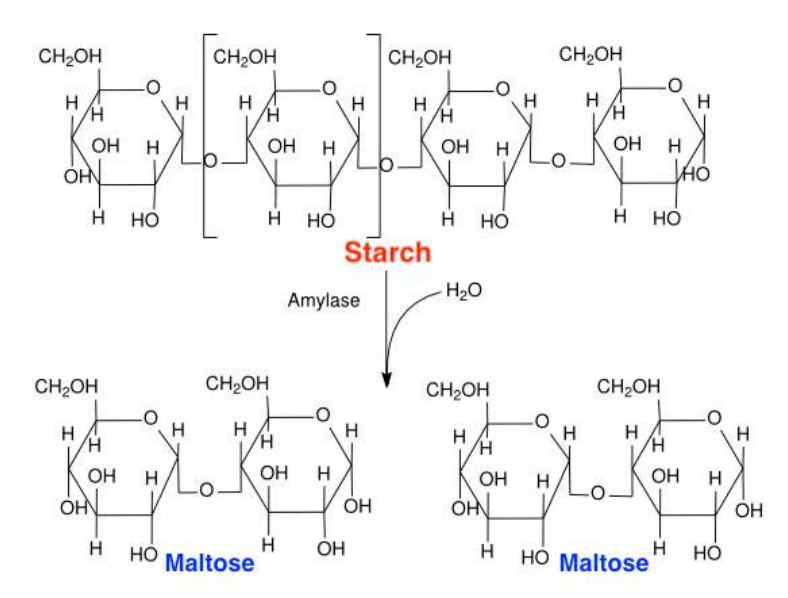
(A) Is water a reactant or product of the reaction?
(B) Is an enzyme involved in the reaction?
(C) Are the monomers identical to one another?
(D) Which polymer is involved in the reaction?

Solution: Immediately, options (C) and (D) can be eliminated. Monomers do not have to be identical to each other to participate in a hydrolysis or dehydration synthesis

reaction. Additionally, polymers can participate in both hydrolysis and dehydration synthesis reactions, so simply knowing the polymer type would not help the researcher identify the reaction that is occurring. For that matter, enzymes are often involved in both hydrolysis and dehydration synthesis reactions, so this would also be of no use to the researcher. Eliminate (B). However, water acts as a reactant in hydrolysis reactions and is a product in dehydration synthesis. The answer to this question would most likely help the researcher determine the type of reaction that is occurring, so we select $\boxed{\textbf{(A)}}$.

Problem 1.3.6 — Multiple Choice Question

The human body is capable of digesting the complex polymer starch into simpler subunits. This digestive process requires the presence of water and the enzyme amylase in order to break down starch into maltose. This is depicted below.



Which of the following statements best describes the digestion of starch into maltose?

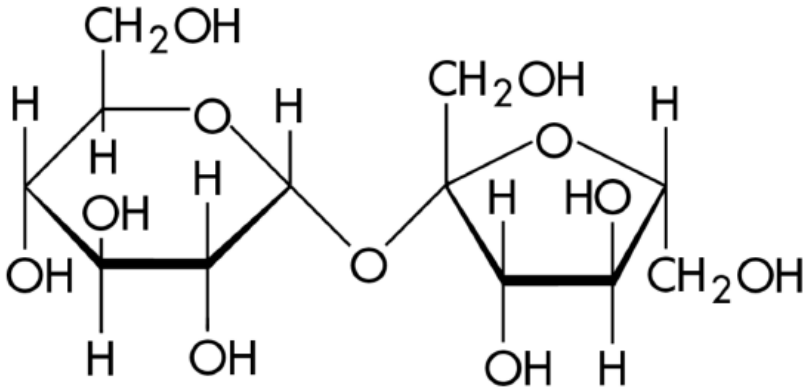
(A) This is a dehydration synthesis reaction that requires water to form a complex polymer from simpler subunits.
(B) This is a hydrolysis reaction that forms water by breaking down a complex polymer into simpler subunits.
(C) This is a hydrolysis reaction that requires water to break down a complex polymer into simple subunits.
(D) This is a dehydration synthesis reaction that produces water when forming a complex polymer from simpler subunits.

Solution: The reaction depicted in the figure shows a starch polymer breaking down into two maltose monomers. Because this happens in the presence of water, dehydration synthesis cannot describe the process, so we eliminate options (A) and (D). Since the products of this reaction are only the two maltose subunits, we can also eliminate (B). Water is required to start this process, so it cannot be produced in the end. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

§1.4 Properties of Biological Macromolecules

In this section, we will learn about the structural properties of carbohydrates, lipids, proteins, and nucleic acids. Additionally, we will discuss how their structures affect the variety of functions that they perform in living organisms.

Structure of Carbohydrates Carbohydrates are simple and complex sugars as well as sugar polymers (usually ending in the suffix *-ose*). In the molecular structure of carbohydrates, there are several hydroxyl groups ($-$OH) and a carbonyl group (C $=$ O). There are two cases for naming the sugar depending on the location of the carbonyl group in the carbohydrate. If the carbonyl group is at one end, the sugar has an *aldehyde* and is known as an *aldose sugar*. On the other hand, if the carbonyl group is in the middle, the sugar contains a ketone and is a *ketose sugar*.



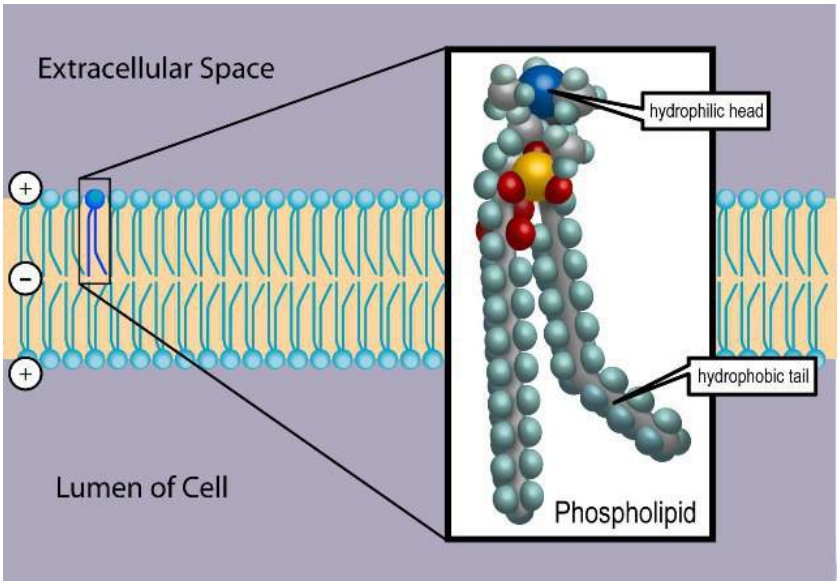
Monosaccharides, or simple sugars, generally have a chemical formula that is some factor of the formula unit CH_2O, where the carbon, hydrogen, and oxygen atoms are in a $1:2:1$ ratio. Glucose, $C_6H_{12}O_6$, is the most common monosaccharide. Another example is fructose, the sugar that naturally exists in many fruits.

Structure of Lipids We know that lipids are the only type of macromolecule that do not form polymers. They tend to be nonpolar molecules and *hydrophobic* - water fearing (no affinity for water). Most lipids are hydrocarbons, containing only carbon and hydrogen atoms. They are important for energy storage, and they also have the most energy (about 9 calories per gram). Animal organisms usually depend on fat for insulation, e.g. bears use their fat to stay warm during hibernation, penguins being able to survive the subzero temperatures in Antarctica, etc. Finally, fats are composed of **glycerol** and three **fatty acids** which are joined by an ester bond which forms a **triglyceride**.

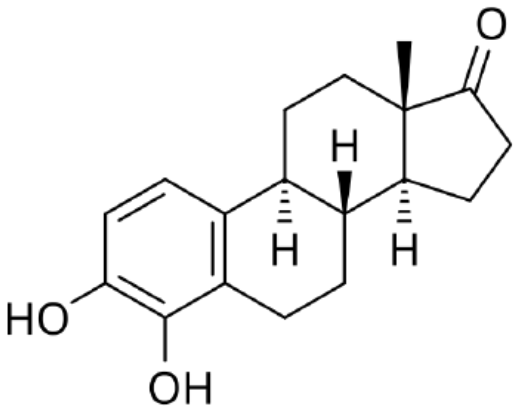
Saturated and Unsaturated Fatty Acids Let's analyze the chemistry of glycerol and the three fatty acids. Glycerol is a three-carbon alcohol, $CH_2OH - CHOH - CH_2OH$, with a hydroxyl group attached to each C atom. Fatty acids consist of long carbon chains attached to a carboxyl ($-$COOH) group and can be either saturated or unsaturated. **Saturated** fatty acids have no double bonds ($=$) between C atoms, contain the most hydrogen atoms as possible, are usually found in animals, and are solid at room temperature. On the other hand, **unsaturated** fatty acids contain one or more double

and/or triple (≡) bonds between C atoms and are liquid at room temperature. The most common source of unsaturated fatty acids are plants, fish, and vegetable oil.

Phospholipids Phospholipids are one of the fatty acids in triglyceride, except it's replaced by a phosphate group. Therefore, this lipid contains 1 glycerol molecule, 2 fatty acids, and 1 phosphate group. When we get to cells, we will discuss the *phospholipid bilayer*, a major component of the cell membrane which contains a hydrophilic (water-loving) head with glycerol and the phosphate group and a hydrophobic tail with two fatty acids (one saturated and the other unsaturated). Phospholipid assembles into this bilayer found in cell membranes when placed in contact with water.



Steroids A steroid is a skeleton of carbon atoms that contains 4 fused rings. While steroids are structurally different from most lipids, they are hydrophobic and insoluble in water, so they are still considered lipids. Steroids make up most animal cell membranes, effectively filtering in and out certain substances from the cell. Most steroids contain short tails, e.g. cholesterol. Cholesterol also has a hydroxyl functional group attached to it. Any steroid with a $-$OH functional group is also an alcohol, and such molecules are called *sterols*.



The above image shows the steroid molecule 4-hydroxyestrone, which is considered a sterol due to the presence of its hydroxyl function group.

Structure of Proteins Proteins are made up of carbon, hydrogen, oxygen, nitrogen, and sulfur. They contain 20 unique **amino acid** monomers that are joined by peptide bonds (also known as **polypeptides**). Note that these bonds are covalent! The structures of amino acids have specified chemical and physical properties which determine their function in the cells of various organisms. Therefore, *a slight change in structure at the primary stage can dramatically change both a protein's structure and function.*

When two amino acids are joined by dehydration synthesis, they form a *dipeptide*. When several amino acids join through the same process, their polymers (polypeptides) are formed. When one or more polypeptides fold, the result is a protein.

The physical and chemical properties that are unique for different amino acids have a huge impact on its shape, and thus its function. For example, some amino acids are acid and some are basic, some are polar and some are nonpolar, etc. Therefore, the folding between polypeptides will vary, and one small change in the peptide change can significantly alter the nature of the protein.

Finally, each amino acid consists of an amino group, carboxyl group, and R group (arbitrary group with hydrophilic, hydrophobic, and ionic properties). Interestingly enough, the R groups actually determine the properties of amino acids and, ultimately, the folding. If College Board asks about the polarity of an amino acid, the R group should typically give a clue as to what the answer is.

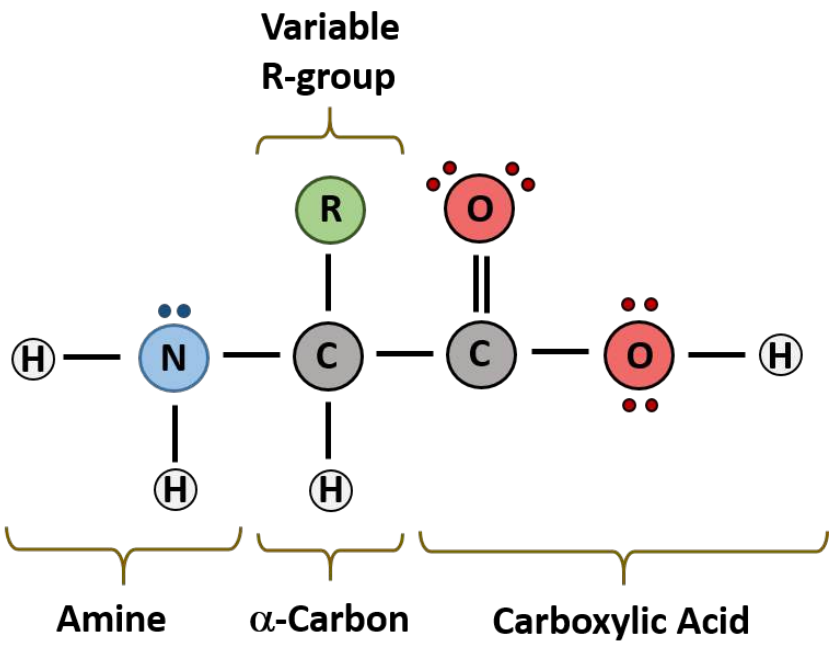


Image Credit: Western Oregon University

Structure of Nucleic Acids Nucleic acids contain carbon, hydrogen, oxygen, and nitrogen, but they also contain some phosphorus. Their polymers are composed of **nucleotide** monomers, and nucleic acids compose the genetic information, or DNA, of living cells.

Nucleotides contain a five-carbon sugar, phosphate group, and a nitrogenous base (adenine, thymine, guanine, cytosine, uracil).

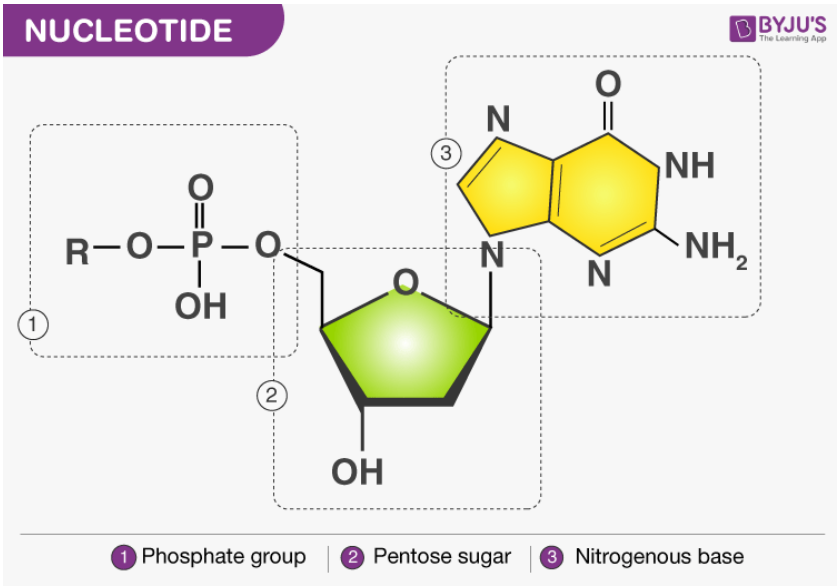


Image Credit: BYJU'S

Nucleic acids also compose our **RNA**, which works a bit differently from DNA. We will learn more about these two molecules in later units.

Let's practice with the following multiple-choice questions.

Problem 1.4.1 — Multiple Choice Question

What is the difference between aldose sugar and a ketose sugar?

(A) Aldose sugars don't have hydroxyl groups, but ketose sugars do.
(B) Aldoses and ketoses refer to lipids, not sugars.
(C) Aldose sugars are monosaccharides, while ketose sugars are disaccharides.
(D) The carbonyl group is at an end in an aldose sugar, while it's in the middle in a ketose sugar.

Solution: Both aldose and ketose sugars contain hydroxyl groups (-OH) attached to their carbon atoms. Their difference lies in the position of the carbonyl group, not the presence of hydroxyl groups, so option (A) is wrong. Aldoses and ketoses are types of sugars (monosaccharides). Lipids are a different class of organic molecules altogether, so eliminate (B). Moreover, both aldose and ketose sugars are monosaccharides; their difference is attributed to the structure of their carbonyl groups, so we eliminate (C). However, we do know that aldose sugars contain the carbonyl group at the end of their molecular structure, while ketose sugars have the carbonyl group in the middle. This is consistent with option $\boxed{\textbf{(B)}}$.

Problem 1.4.2 — Multiple Choice Question

How does the structure of phospholipids contribute to their function in cell membranes?

(A) Their uniform polarity creates a rigid barrier that prevents any molecular movement across the membrane.
(B) Their amphiprotic nature allows them to form a bilayer with hydrophilic heads facing the aqueous environment and hydrophobic tails facing inward.
(C) Their hydrophilic tails interact with water molecules, creating a fluid mosaic structure throughout the entire membrane.
(D) Their covalent bonds between phosphate groups allow for selective permeability of only charged molecules.

Solution: While phospholipids do create a barrier, it is not completely rigid. The fluidity of the membrane is due to the movement of the fatty acid tails, and the flexibility of the phospholipid bilayer allows for dynamic interactions with other molecules, so option (A) is incorrect. Moreover, the heads of phospholipids are hydrophilic, not the tails, so option (C) is also incorrect. Phospholipid bilayers are selectively permeable, but this selectivity is primarily due to the hydrophobic nature of the fatty acid tails, not the covalent bonds between phosphate groups, so we eliminate option (D). The correct answer is $\boxed{\textbf{(B)}}$, as the hydrophilic heads interact with the aqueous (water) environment and the hydrophobic tails face the interior of the membrane.

§1.5 Structure and Function of Biological Macromolecules

In the previous two sections, we talked about the four types of macromolecules: nucleic acids, carbohydrates, proteins, and lipids. These macromolecules compose all cells and perform many tasks. In this section, we will talk about the structure of these macromolecules and what purposes they serve in living organisms.

- Nucleic acids contain nitrogenous bases, sugars, and phosphate groups, and they carry the genetic information of an organism. The two types of nucleic acids are **DNA** and **RNA**. As we now know, DNA stores and transmits genetic information, while RNA carries out DNA's instructions and aids in protein synthesis.
- Carbohydrates contain only carbon, hydrogen, and oxygen atoms. They provide both short-term and long-term energy and structural support in cells. Most food items, such as bread, pasta, and white sugar, are examples of carbohydrates.
- Proteins are large molecules that are composed of amino acids, and they are important for several cellular processes, such as transporting molecules, speeding up chemical reactions, and providing structural support to the cell. Finally, proteins are found in all cells and tissues of organisms.
- Lipids generally consist of long hydrocarbon (only carbon and hydrogen atoms) chains, and they are important for energy storage and cell membrane structure. Cooking oils, fats, and phospholipids are some great examples of lipids.

Understanding How Structure Affects Function The monomer subunits of polymers play a key role in determining the structure and function of their macromolecules. The directionality (orientation) of the monomers can affect the overall configuration of the polymer's structure. For example, in a protein, the **primary structure** refers to the specific amino acid sequence that identifies the protein. In turn, this sequence determines the three-dimensional, or **tertiary structure** of the protein. Finally, the tertiary structure dictates the protein's function. Not just proteins, but nucleic acid and carbohydrate polymers' structure and function are affected by the arrangement of monomers.

Nucleic Acids Nucleic acids, e.g. DNA and RNA, are long, linearly shaped polymers that are made up of nucleotide monomers. The sugar and phosphate groups of adjacent nucleotides covalently bond to form the monomers. This sequence of nucleotides in a nucleic acid molecule carries the genetic information needed to build and maintain cells.

Proteins Similar to nucleic acids, proteins are also linear monomers. They are made up of amino acids linked together by peptide bonds. The *carboxyl* group of one amino acid is paired with the *amino* group of an adjacent amino acid to form the peptide bond. For each iteration of this process, one water molecule is released. This sequence of amino acids is important for a protein because it refers to its primary structure, which determines the tertiary structure, which in turn determines the protein's function. Some functions of proteins include, but are not limited to, structural, catalytic, cell signaling, defense, and cell membrane transport.

There are four levels of protein structure that we should be familiar with.

- **Primary structure** - a sequence of amino acids joined by peptide bonds.
- **Secondary structure** - the result of hydrogen bonding between components of the polypeptide backbone, with the carboxyl and amino groups along the peptide chain forming alpha helix or beta-pleated sheet, respectively.
- **Tertiary structure** - refers to a protein's 3D spatial configuration, the way its secondary structure folds itself up in the interior. These unique folded shapes determine the specificity of proteins' functions.
- **Quaternary structure** - connects the subunits (amino acids) of proteins with multiple polypeptide chains, e.g. DNA polymerase (protein which copies DNA and helps maintain and repair it), hemoglobin (a protein in red blood cells that carries oxygen from the lungs to the body's tissues and returns carbon dioxide from the tissues back to the lungs), etc.

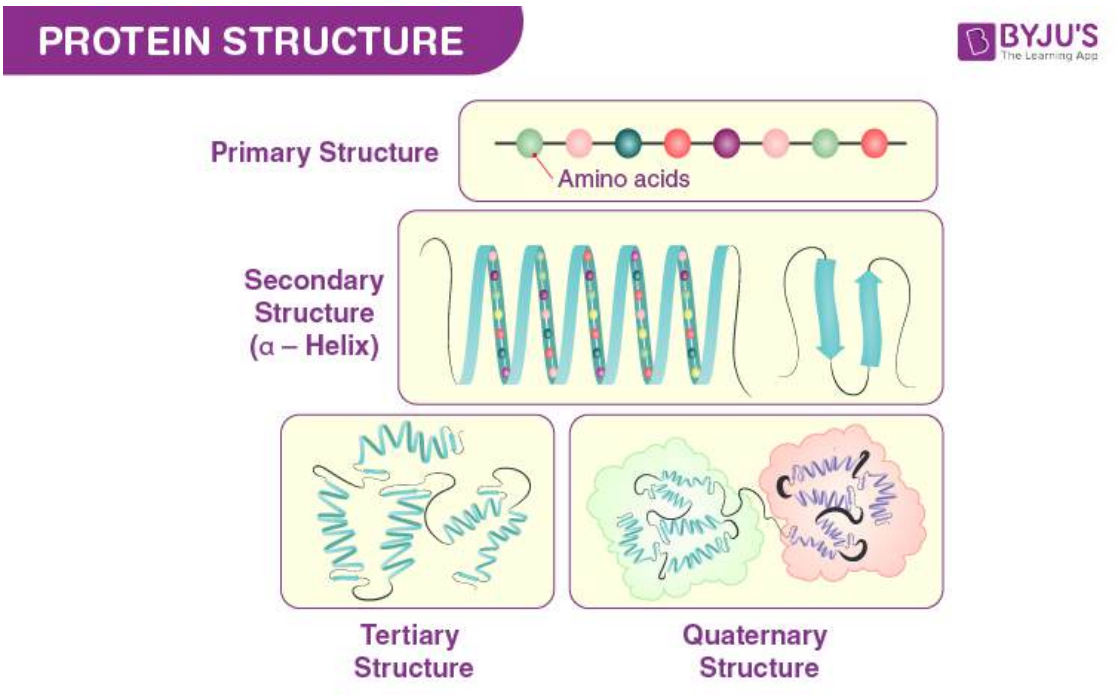


Image Credit: BYJU'S

Another important thing to consider when studying the levels of protein structure is **denaturation**. This is the process that occurs when proteins lose their tertiary structure due to disturbances within the non-covalent interactions that hold the protein in its original conformation. This can happen due to several factors, e.g. heat, pH changes, presence or absence of certain chemicals, etc. Denaturation can result in decreased or absent biological activity within a protein, so it is also known as the protein's "inactive form." Don't confuse this process with hydrolysis! In denaturation, proteins are not broken down into smaller peptides or amino acids by the action of water or enzymes.

Fun fact: Species that share a common ancestor have similar structured proteins and their amino acids correspond to each other. We will take a closer look at the concept of evolution in Unit 7: Natural Selection.

Carbohydrates **Monosaccharides**, commonly known as *simple* carbohydrates, contain one sugar. On the other hand, *complex* carbohydrates, or **polysaccharides**, contain several sugar units linked together. Regardless of monosaccharide or polysaccharide, all carbohydrates can be classified as either *linear* or *branched*.

Linear carbohydrates have a straight chain of sugar units, while **branched** carbohydrates have sugar components that deviate from the main chain. This variation in carbohydrates' structure can affect their physical and chemical properties, and how they are used by organisms.

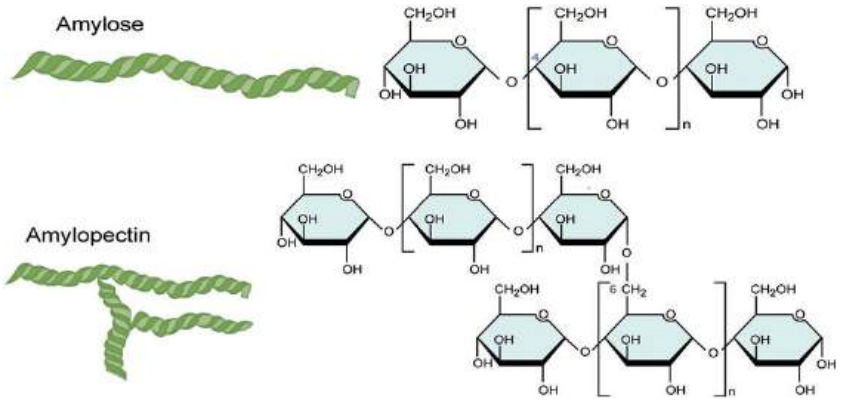


Image Credit: ResearchGate

Notice how amylose contains each of its sugar units in a straight line, while amylopectin contains some sugar units that are not part of the primary chain. Thus, amylose is a linear carbohydrate, while amylopectin is branched.

More Information on Carbohydrates Carbohydrates play significant roles in many biological processes, such as metabolism, cell communication, and tissue structure and function. They are also an important source of energy for organisms, providing fuel for the muscles, brain, and other vital organs. Let's talk about some more notable carbohydrates, specifically disaccharides and polysaccharides.

Disaccharides are made up of two monosaccharides joined together by a covalent bond and formed by dehydration synthesis. (the prefix *di* means two)

Note 1.5.1

Here are some examples of common disaccharides:

- Maltose - contains two glucose monosaccharides combined through dehydration synthesis.
- Sucrose - contains one glucose monosaccharide and one fructose monosaccharide combined through dehydration synthesis.
- Lactose - contains one glucose monosaccharide and a galactose monosaccharide combined by dehydration synthesis, this covalent bond that joins the monosaccharides together is called a **glycosidic bond**.

Polysaccharides are sugar polymers that serve in storage and structure within organisms. These functions are determined by the positions of glycosidic bonds and the unique monomers in the sugar polymer.

Note 1.5.2

Here are some examples of common polysaccharides:

- **Starch** - stores energy in plants
- **Glycogen** - stores energy in animals (includes humans!), usually in their muscle and liver cells.
- Cellulose - a structural polysaccharide which composes the cell wall (unique to plant cells).
- **Chitin** - another structural polysaccharide, which is found in exoskeletons of arthropods and cell walls of fungi (e.g. wild mushrooms, yeasts, and molds).

Problem 1.5.3 — Multiple Choice Question

How does the antiparallel orientation of DNA strands contribute to the molecule's stability and function in genetic information storage?

(A) It facilitates the binding of histone proteins to the DNA molecule.
(B) It allows for complementary base pairing and hydrogen bonding between the strands.
(C) It enables the DNA to form a triple-helix structure.
(D) It prevents the formation of secondary structures like hairpins.

Solution: While histone proteins do bind to DNA, the binding helps compact the molecule into chromatin, not directly responsible for the antiparallel orientation. Therefore, (A) is incorrect. In addition, the antiparallel orientation is essential for the double helix structure, but it does not directly enable the formation of a triple helix, so eliminate (C). Choice (D) is not really relevant to the antiparallel orientation of DNA strands, so it makes sense to eliminate it. The antiparallel orientation of DNA strands means that one strand runs 5' to 3' and the other runs 3' to 5'. This allows for the specific pairing of complementary bases (A with T and C with G) between the two strands, forming the double helix structure. This mechanism is consistent with option $\boxed{\textbf{(B)}}$.

Problem 1.5.4 — Multiple Choice Question

Which level of protein structure is most directly affected by the process of denaturation, and how does this impact the protein's biological activity?

(A) Secondary structure, resulting in the formation of new alpha helices and beta sheets.
(B) Primary structure, causing the peptide bonds between amino acids to break.
(C) Tertiary structure, leading to loss of specific three-dimensional conformation and biological function.
(D) Quaternary structure, inducing the dissociation of subunits in multimeric proteins.

Solution: We can immediately eliminate (B), because the primary structure of a protein is the sequence of amino acids, which remains unchanged by denaturation. Denaturation can affect the quaternary structure if the protein is composed of multiple subunits. However, this is relatively unlikely, so we eliminate (D). While denaturation can affect secondary structure by disrupting the alpha helices and beta sheets, the primary impact is on the tertiary structure. A protein's structure is a component of the tertiary structure. Therefore, we eliminate (A) and choose $\boxed{\textbf{(C)}}$.

§1.6 Nucleic Acids

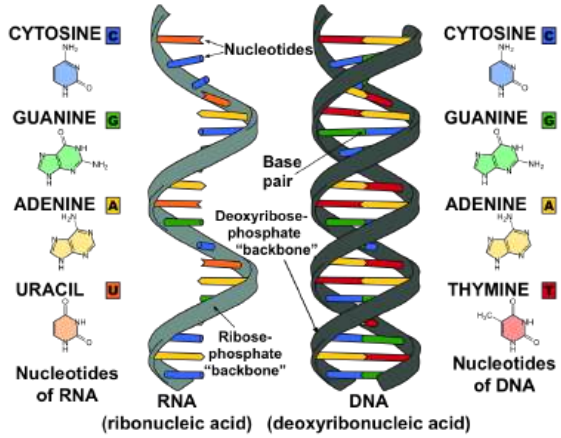
This section is all about DNA and RNA, their importance within cells, and their structures that can be examined to determine why they have different functions. We will learn about their production as well as explore the many roles they serve within cells.

DNA and RNA Nucleic acids are large complex molecules that serve in storing, transmitting, and expressing hereditary information. More information on heredity can be found in Unit 5. But for now, we should know that these macromolecules are composed of monomers that are called **nucleotides**, which consist of a 5-*carbon* sugar, a *nitrogenous base*, and a *phosphate group*.

For AP Biology, the two important nucleic acids are **deoxyribonucleic acid (DNA)** and **ribonucleic acid (RNA)**. The former stores the instructions for building the proteins in cells, while the latter assists in actually creating the proteins from the instructions stored. **Genes** are a specific unit of hereditary information that contain the instructions for protein synthesis. They are made of (you guessed it!) DNA, and are located at chromosomes. The nucleotide sequence of a gene determines the amino acid sequence for a particular protein, thus assigning it a unique purpose within an organism.

A Study of DNA In simple terms, deoxyribonucleic acid (DNA) is a molecule that stores and transmits genetic information. It can replicate, or make an exact copy of, itself. This process results in the synthesis of **messenger RNA (mRNA)** which then controls protein synthesis. Finally, the 5-carbon sugar component in DNA is *deoxyribose*.

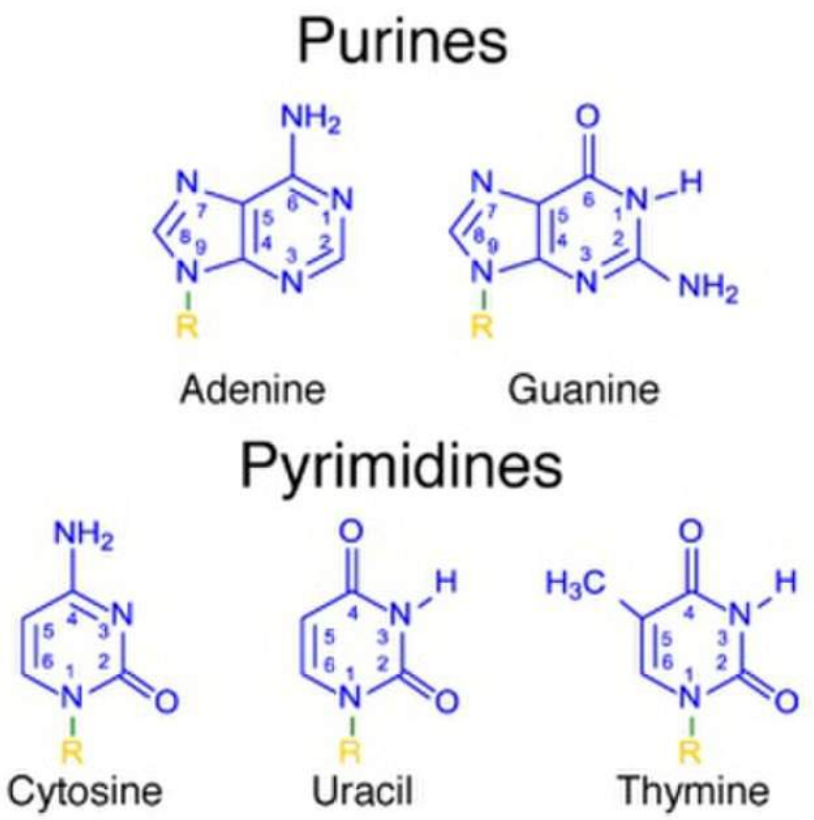
The linkage of covalent bonds allow for a straight-line sequence of nucleotides in nucleic acids in general. It is defined by a hydroxyl group (-OH) present on the 3' carbon of one nucleotide and a phosphate group on the 5' carbon of the next nucleotide. As DNA and RNA are formed, nucleotides are added to the 3' end of the strand (which continues to grow in length), resulting in covalent bonds between adjacent nucleotides. Without this process, replicating and expressing genetic information would be impossible.



A prime (') identifies the carbon atoms in the ribose, e.g. 2' carbon or 5' carbon. DNA is structured as an antiparallel double helix, with each strand in a pair running in opposite 5' to 3' orientation, and the 5' end of one DNA molecule is paired with the 3' end of the other molecule, and vice versa.

Purines and Pyrimidines It is extremely important for nucleic acids to contain properly functioning nitrogenous bases because they are responsible for the genetic code. In total, there are five nitrogenous bases: **cytosine (C)**, **thymine (T)**, **uracil (U)**, **adenine (A)**, and **guanine (G)**. Additionally, note that uracil is only found in RNA and thymine is only found in DNA. Finally, nitrogenous bases can be divided into two classes: **purines** and **pyrimidines**.

- Purines include adenine and guanine and are composed of a *double-ring* structure.
- Pyrimidines include thymine, cytosine, and uracil, and are composed of a *single-ring* structure.
- Each purine bonds with a pyrimidine through **hydrogen bonding**, and this form of base-pairing allows the process of DNA replication to be stable and accurate. Thus, genetic information can be transferred through successive generations.



Chargaff's Rule Chargaff's rule states that in any DNA sample, there are always equal quantities between the adenine and thymine bases and the guanine and cytosine bases. This is due to the nature of hydrogen bonding, i.e. when adenine pairs with thymine (A-T), two hydrogen bonds are involved when forming this pair, and three hydrogen bonds are involved when guanine pairs with cytosine. DNA is composed of two nucleotide strands held together by strong hydrogen bonds, resulting in a **double helix** structure. While RNA is single-stranded, it also has a sugar-phosphate backbone. For this course, you should know the three types of RNA: **mRNA (messenger RNA)**, **tRNA (transfer RNA)**, and **rRNA (ribosomal RNA)**.

Problem 1.6.1 — Chargaff's Rule

A researcher isolates a sample of DNA from an animal species and finds that it contains the following amounts of the four nitrogenous bases: adenine (A) = 43%, thymine (T) = 43%, and cytosine (C) = 7%. Using Chargaff's rule, what is the percentage of guanine in the sample?

Solution: Chargaff's rule states that in a double-stranded DNA molecule, the percentage of A is equal to the percentage of T, and the percentage of G is equal to the percentage of C. Since the percentage of A in the sample is 43% and the percentage of T in the sample is 43%, we know that the percentage of G must be equal to the percentage of C. Since the percentage of C in the DNA molecule is 7%, the percentage of guanine in the sample must be $\boxed{7\%}$.

Differentiating DNA from RNA While it is unlikely for MCQs or FRQs on the AP Biology exam to directly ask for similarities and differences between DNA and RNA, it's important to possess this foundational knowledge to answer more complex, application-based questions that you may encounter.

Similarities:

- DNA and RNA are both nucleic acids that are composed of nucleotides.
- Each of their nucleotides contain a 5-carbon sugar molecule, a phosphate group, and a nitrogenous base (A, T, G, C, U).
- Both nucleic acids share three nitrogenous bases: adenine, guanine, and cytosine.
- Both transmit genetic information and are active in the synthesis and control of proteins in virtually all living organisms.

Differences:

- DNA contains the 5-carbon sugar deoxyribose, while RNA contains the sugar ribose. The former sugar contains one less oxygen atom than the latter.
- DNA and RNA contain different nitrogenous bases; the former contains thymine while the latter contains uracil.
- DNA is double-stranded and has two complementary strands that are held together by hydrogen bonds. In contrast, RNA is usually single-stranded.
- Finally, DNA and RNA molecules have different orientation and cardinality. In simple terms, the two strands in DNA are uniquely oriented in opposite directions, with one strand running from the 5' to 3' carbons and another strand running from 3' to 5'. This is known as **antiparallel orientation**. DNA is responsible for transmitting genetic information through successive generations, while RNA is primarily involved in the synthesis of proteins and other cellular processes.

Problem 1.6.2 — Multiple Choice Question

Human immunodeficiency virus (HIV) is classified as an RNA virus because its genome, or genetic material, consists of a single strand of RNA.

Which of the following claims is best supported by the information above?

(A) The structure of HIV forms a double-stranded nucleic acid.
(B) Uracil nucleotides are present in the HIV genome.
(C) The nucleotides of HIV form an antiparallel nucleic acid structure.
(D) Deoxyribose is a five-carbon sugar with the nucleic acid structure of HIV.

Solution: Eliminate (D), as the five-carbon sugar in the RNA structure is ribose, not deoxyribose. Options (A) and (C) are not possible because only double-stranded nucleic acids can have an antiparallel structure of nucleotides, not in the case of single-stranded RNA in the HIV virus. Finally, since HIV is an RNA virus, the uracil nucleotides take the place of thymine nucleotides, which would have been the case for a DNA virus. The correct answer is $\boxed{\textbf{(B)}}$.

§1.7 Unit 1 Practice Questions

Problem 1.7.1 — 2008 AP Biology FRQ (Excerpt)

The physical structure of a protein often reflects and affects its function.

(a) Describe THREE types of chemical bonds/interactions found in proteins. For each type, describe its role in determining protein structure.

Solution: One major chemical bond in proteins is hydrogen bonding, particularly $H-O$ and $H-N$ interactions. Hydrogen bonds are primarily associated with the secondary structure of a protein, specifically in the formation of alpha helices and beta pleated sheets, where they form between the backbone amino and carbonyl groups of amino acids, holding these structures in place.

In addition, van der Waals forces, or interactions between molecules, can lead to unequal electron clouds in the R group of a protein, inducing a dipole moment in the molecule, which affects the tertiary and quaternary structures. Finally, ionic bonds can lead to the R groups of proteins being charged. This plays a significant role in determining the tertiary structure of a protein, as ionic bonds create electrostatic attractions between oppositely charged side chains, helping to fold the protein into its three-dimensional shape.

Problem 1.7.2 — 2009 AP Biology FRQ (Form B)

Water is essential to all living things.

(a) Discuss THREE properties of water.

(b) Explain each of the following in terms of the properties of water. You are not limited to the three properties discussed in part (a):

- the role of water as a medium for the metabolic processes of cells
- the ability of water to moderate temperature within living organisms and in organisms' environments
- the movement of water from the roots to the leaves of plants

Solution to part a: An important property of water is that it is a polar molecule, consisting of polar covalent bonds created by unequal sharing of electrons between O and H atoms within a single H_2O molecule.

Another property of water is its high specific heat capacity, which is crucial to life on Earth because it allows the absorption and releasing of large amounts of heat without experiencing significant temperature changes.

Finally, water molecules display cohesion, or attraction, to each other due to water's polarity and surface tension. Cohesion between water molecules is crucial for plants because it allows water to be efficiently transported from the roots to the leaves through

the xylem, forming a continuous column of water, delivering necessary nutrients and maintaining plant structure.

Solution to part b: For the role of water as a medium for cellular and metabolic processes, we can consider osmosis−movement of water across membranes due to differences in the potential of water down a concentration gradient.

The ability of water to moderate the temperature within living organisms and their environments is highly correlated with its specific heat−which moderates the climates, maintains stable cellular temperatures and induces a stable internal environment in the organisms.

Finally, water moving from the roots to the leaves of plants best describes the process of transpiration, when water potential differences or evaporation through the stomata causes water molecules to move away from the leaves.

2 Cell Structure and Function

This unit is all about cells, the fundamental building block of all life, including the different components of a cell (cell membrane, cytoplasm, mitochondria, and nucleus), their respective functions, and how they all work together to maintain life processes within organisms. We will explore the cell membrane, organelles, important cellular processes, prokaryotic vs. eukaryotic cells, and the cell cycle.

§2.1 Cell Structure: Subcellular Components

The Nucleus The first subcellular cell structure that we will discuss is the nucleus. The nucleus is basically the brain of the cell because it functions as the control center, ensuring that the rest of the cell is functioning properly. In addition to leading the rest of the cell, the nucleus contains genetic information in the form of deoxyribonucleic acid (DNA).

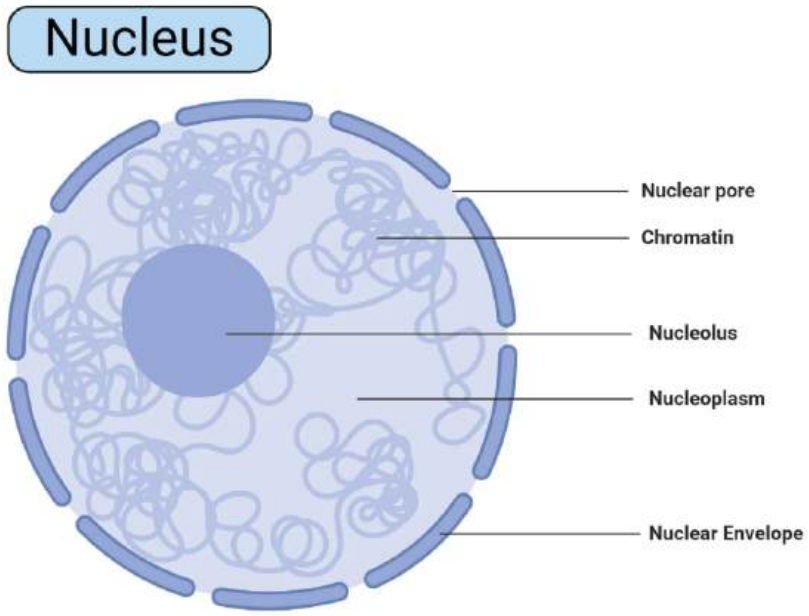


Figure: Nucleus, Image Copyright © Sagar Aryal, www.microbenotes.com

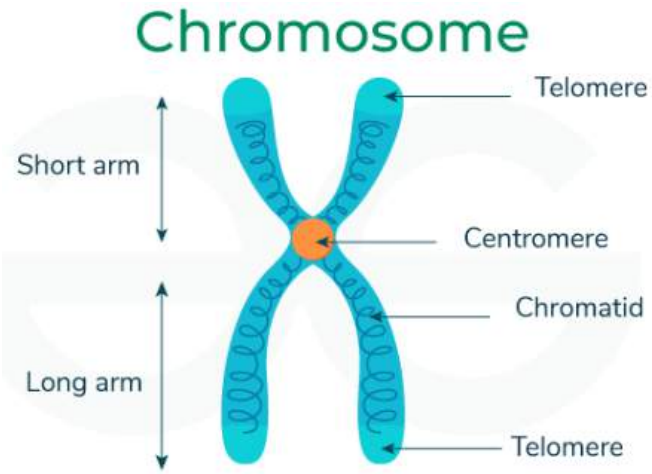
Image Credits: Sagar Aryal, Microbe Notes

Nuclear Envelope The nuclear envelope is a **double-layered membrane** that separates the interior of the nucleus from the surrounding cytoplasm. The nuclear envelope is porous, which means that it contains many holes called nuclear pores. These nuclear pores are selective pathways, meaning that they only let certain molecules and materials pass through. In the case of the nuclear envelope, only small, ionic molecules are allowed to pass through to the nucleus.

Definition 2.1.1

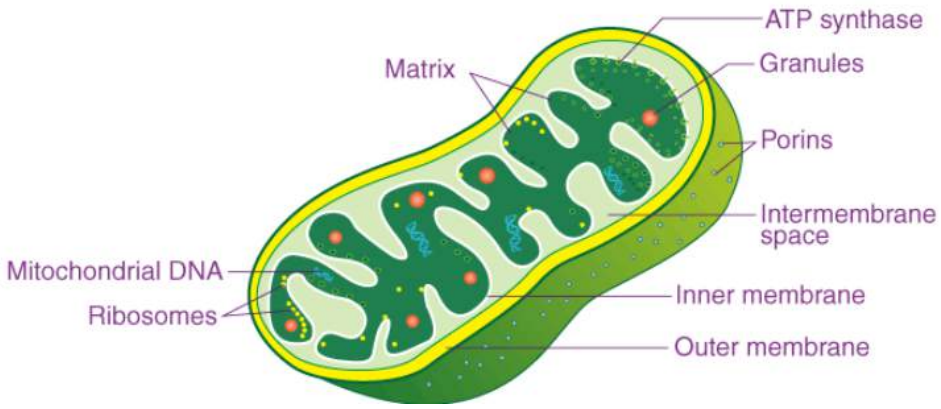
The **cytoplasm** is the liquid in which the subcellular components of the cell float around. It is responsible for maintaining the shape of the cell, expediting the movement of cell materials, containing chemical reactions, and preventing cell components from moving around too much.

Chromosomes At this point in your life, you might know that chromosomes are those X-shaped things that carry important genetic info. But what makes up each chromosome? Chromatids! Chromatids are long segments of DNA that join together at the middle to form the X-shaped chromosome that we are familiar with.



Nuclear Lamina The nuclear lamina is a network of protein filaments that functions as the infrastructure of the nucleus by supporting the nuclear envelope. The nuclear lamina can be compared to the metal beams that keep buildings from simply falling down.

Mitochondria The mitochondria is the site of ATP production in most cells. By producing ATP, the mitochondria allows for the cell to function by performing important processes such as muscle movement and active transport of molecules.



Mitochondrial DNA Mitochondria, along with chloroplasts in plant cells, are unique because they contain their own DNA. Instead of having a linear structure like regular

DNA, mitochondrial DNA is actually circular. The circular structure of mitochondrial DNA supports the endosymbiotic theory.

The **endosymbiotic theory** states that mitochondria exist because a prokaryotic organism was engulfed, or eaten, by a eukaryotic cell. Once inside the eukaryotic cell, the prokaryotic organisms actually formed a symbiotic relationship with their host cell. As a result, prokaryotic organisms evolved into what we know as mitochondria while keeping their circular DNA, which we now call mitochondrial DNA.

Note 2.1.2

Specifically, the relationship between the eukaryotic cells and the prokaryotic organisms they engulfed was mutualistic because the prokaryotic organism gained a safe home, while the eukaryotic cell became more efficient in producing energy.

Component	Evidence
Membranes	Some organelles have double membranes (outer membrane may be vesicular in origin)
Antibiotics	Susceptible to antibiotics (e.g. chloramphenicol) (indicates organelles may have bacterial origins)
Division	Reproduction occurs via a fission-like process
DNA	Has own DNA which is naked and circular (like prokaryotic DNA structure)
Ribosomes	Have ribosomes which are 70S in size (identical to prokaryotic ribosomes)

This table has a nice mnemonic (MAD DR) that you can use to remember evidence that mitochondria and chloroplast have emerged as a result of endosymbiosis.

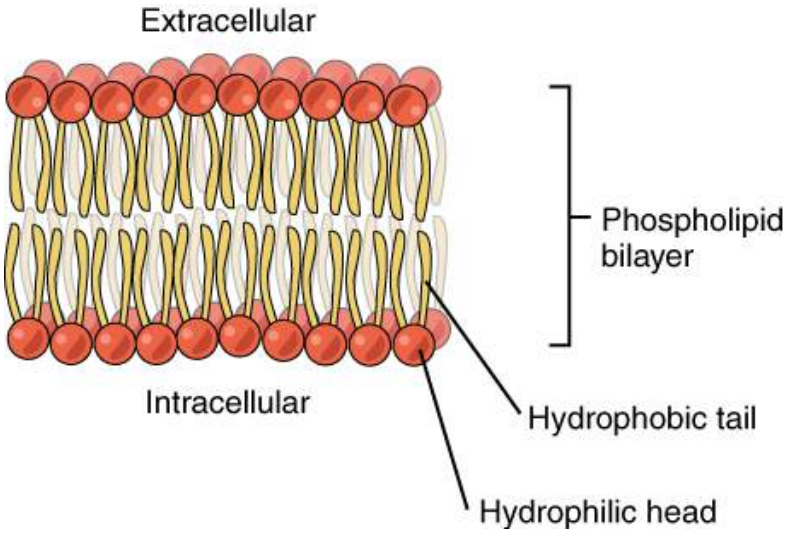
Image Credits: BioNinja

Double Membrane Unlike most other organelles, the mitochondria has a double membrane consisting of a smooth outer layer and highly-folded inner layer. The smooth outer layer is a *phospholipid bilayer*. On the other hand, the inner layer contains folds called cristae. The folded shape of the inner membrane allows for a greater surface area to occupy the same space that an unfolded membrane would, resulting in increased production of ATP.

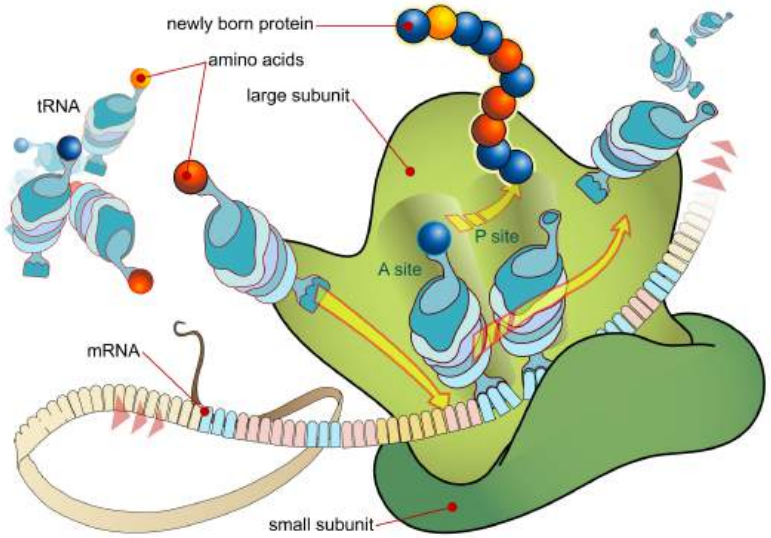
By adopting this orientation, the bilayer actually gains the advantage of being selectively permeable to substances intending to pass through. As you can see from the diagram (next page!), the lipids are placed with tails pointed inwards and heads pointed outwards. In order to pass through, molecules must be small, nonpolar molecules because they can squeeze through the gaps between each lipid head. On the other hand, larger, polar molecules must depend on dedicated proteins to enter cells and organelles with a bilayer.

Definition 2.1.3

The **phospholipid bilayer** is a double membrane consisting of two layers of lipids arranged in such a way that their hydrophobic tails face inward and hydrophilic heads face outward towards the surrounding environment.



Ribosomes Ribosomes are organelles composed of ribosomal RNA and proteins, and use mitochondrial RNA (mRNA) as a blueprint to synthesize proteins. Specifically, the process is called protein synthesis, but that's covered a little later on in unit 6. Each ribosome has two parts: a large subunit and a small subunit. Ribosomes are produced in a region of the nucleus called the nucleolus, and then get transported to the cytoplasm via nuclear pores. Generally, ribosomes can be found as either unbound, meaning they float around in the cytoplasm, or bound to the ER and Golgi apparatus.



The diagram shows a ribosome in the process of producing a protein. This process is called mRNA Translation, but we will cover it in Unit 6. As you can see, the ribosome has a large and small subunit that works together to make proteins from mRNA strands.

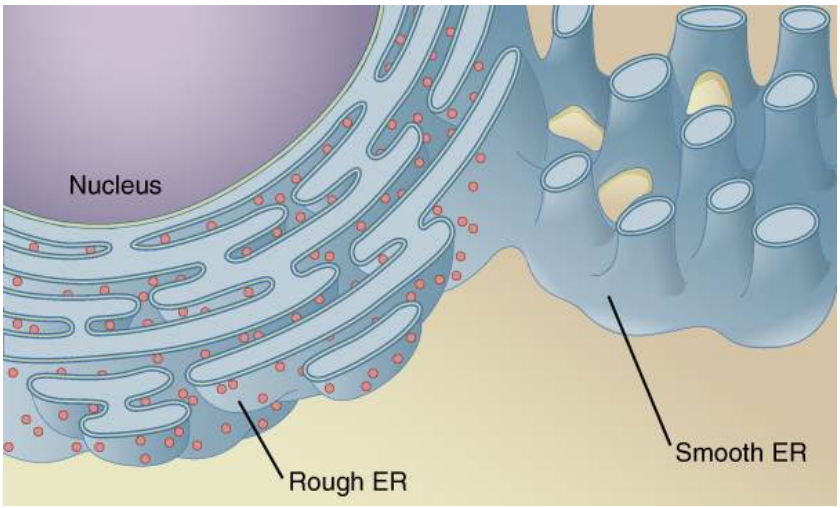
Endoplasmic Reticulum The endoplasmic reticulum (ER) is responsible for producing, modifying, and transporting proteins and lipids that will be used in all parts of the cell. There are two types of ER: smooth ER and rough ER.

Smooth ER The smooth ER is highly involved in the production of lipids such as phospholipids and steroids and detoxification of toxic substances. After being transported to their destination by vesicles, lipids produced by the smooth ER are used as material for both the smooth ER's membrane and cell membranes.

The smooth ER detoxifies toxic substances by adding a hydroxyl group to harmful chemicals, making the substance easier to flush out because it is dissolved in water. Forcing the smooth ER to detoxify larger and larger amounts of toxic substances results in an increase in the size of the smooth ER and consequently in a larger amount of enzymes involved in detoxification. As a result, a tolerance for toxic substances (often drugs) is built up.

Rough ER Unlike its smooth counterpart, the rough ER is covered in many ribosomes that produce proteins. After being produced by ribosomes, proteins are secreted, transported to the cell membrane, or taken by lysosomes. The ER expands itself by producing membrane proteins, or proteins that are destined to become part of a cellular membrane.

The rough ER also ensures proper protein quality by getting rid of improperly folded proteins through a process called ER-associated degradation (ERAD), but this concept is beyond the scope of AP Biology, so we will not cover it.



The endoplasmic reticulum is shown in the image above. As you can see, the portion labeled Rough ER is covered in small dots that represent ribosomes, while the portion labeled as Smooth ER lacks these ribosomes.

Golgi Apparatus The Golgi functions as the "post office" of the cell by modifying, packaging, and shipping out the proteins and lipids produced by the ER. The golgi is composed of many flattened membranous sacs called cristae that look like circles that you have smashed together. Take a look at the cristae (blue ellipses) in the diagram of

the Golgi apparatus below.

The main function of the Golgi apparatus is to receive, modify, and send the proteins and lipids that were just produced by the ER. First, newly produced proteins/lipids enter the golgi when their carrier vesicle merges with the golgi's cis face. After entering the golgi through the cis face, the ER products are modified through chemical reactions such as phosphorylation. Once modified, ER products make their way through the Golgi to the trans face, where they are packaged into specific transport vesicles based on their target destination. Finally, the transport vesicles pinch off of the Golgi apparatus and travel to the destination to deliver the modified ER products.

Lysosomes Some people like to think of lysosomes as "garbage trucks" of the cell because they basically cruise around and "eat" cellular trash. Lysosomes are membrane-bound organelles, which means that their interior contents are separated from the surrounding cellular environment by a membrane. Inside its membrane, a lysosome contains hydrolytic enzymes used to break down large molecules into smaller molecules. Lysosomes can also trigger apoptosis, which means cell death, by releasing digestive enzymes into the surrounding cytoplasm.

Definition 2.1.4

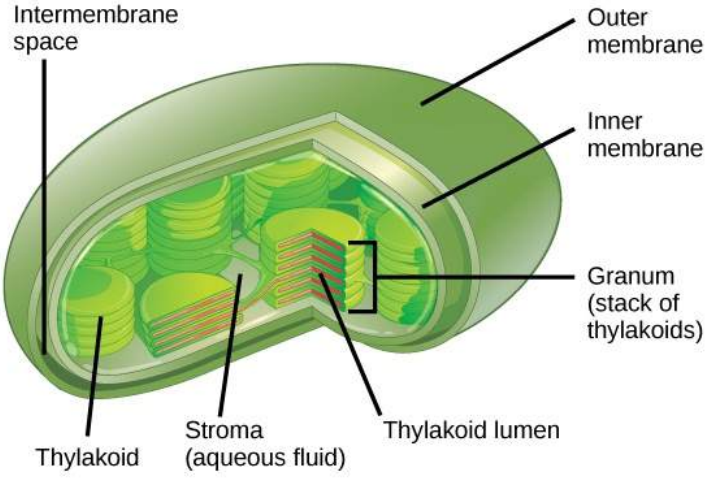
A **hydrolytic enzyme** is an enzyme that breaks larger molecules into small molecules by adding water molecules to the bonds between molecules. Another term for this process of strategically adding water to break down molecules is hydrolysis.

Vacuoles Vacuoles are membrane-bound organelles that contribute to maintaining structural integrity, food and water storage, and waste disposal. There are different types of vacuoles that are individually differentiable based on the function they serve. For example, a contractile vacuole pumps excess water outside the cell to maintain proper water levels. The structure of the vacuole depends on whether the vacuole is in an animal cell or a plant cell. In plant cells, the vacuoles are much larger because the ability to store large amounts of water in order to maintain turgor pressure. In animal cells, vacuoles are smaller because their main function is not just water storage.

Definition 2.1.5

Turgor pressure is the pressure from the contents (mostly water) of a plant cell pushing outwards against the plasma membrane. When turgor pressure is too low, the cell cannot keep its shape, and when turgor pressure is too high, the cell is in danger of bursting.

Chloroplast A chloroplast is where photosynthesis occurs, which means that most animal cells do not contain chloroplasts (an exception is some sea slugs that can photosynthesize in a limited capacity). Chloroplasts are double-membrane structures, allowing for selective permeability. Inside the chloroplast, there are flattened membranous sacs called thylakoids that contain chlorophyll, a green pigment that is responsible capturing light energy from the Sun. An easy way to remember the shape of thylakoids is to remember them as looking like pancakes stacked on top of each other.



If you take a look at the image above, you'll notice that the chloroplast has a double membrane. Also, this is a good visualization of what thylakoids look like. If the flattened pancake route does not work, come up with your own way of remembering the shape!

Problem 2.1.6 — Multiple Choice Question

Which of the following organelles are exclusive to plant cells?

(A) Mitochondria
(B) Nucleus
(C) Chloroplast
(D) Golgi apparatus

Solution: Chloroplasts are unique organelles found only in plant cells and are crucial for photosynthesis. The correct answer is $\boxed{\textbf{(C)}}$.

Problem 2.1.7 — Multiple Choice Question

Which of the following is not the function of the Golgi apparatus?

(A) Processing and shorting of glycoprotein
(B) Lipid metabolism
(C) Carbohydrate metabolism
(D) Amino acid metabolism

Solution: Golgi apparatus involves the metabolism of carbohydrates, and lipids, but not of amino acid, so, amino acid metabolism is incorrect. Synthesis of glycolipids and sorting of glycoprotein also takes place in Golgi apparatus. The answer is $\boxed{\textbf{(D)}}$.

§2.2 Cell Structure and Function

Cell structures are designed to support their specific functions, helping cells perform vital tasks efficiently. The plasma membrane controls what enters and exits, maintaining balance inside the cell. Organelles such as mitochondria and chloroplasts have specialized internal structures that maximize energy production, while others, such as lysosomes, safely handle digestion. Understanding how each structure contributes to cellular processes reveals why cells are organized the way they are—and how they work together to keep organisms alive.

A few examples, most of which we have already discussed, are below.

Mitochondria The mitochondria membrane consists of inner foldings, referred to as **cristae**, that are essential to the increased surface area of the membrane. This increase allows more space for the Electron Transport Chain, an essential part of cellular respiration (more information on this in Unit 3). The matrix, used as the site of the Krebs cycle, is right next door and can therefore transfer its products easily to the ETC. With the ETC, ATP synthesis happens. As you might already know, the mitochondria is called the "powerhouse of the cell," meaning the synthesis of ATP is crucial to cell survival, hence increased surface area would prove to be beneficial to the cell.

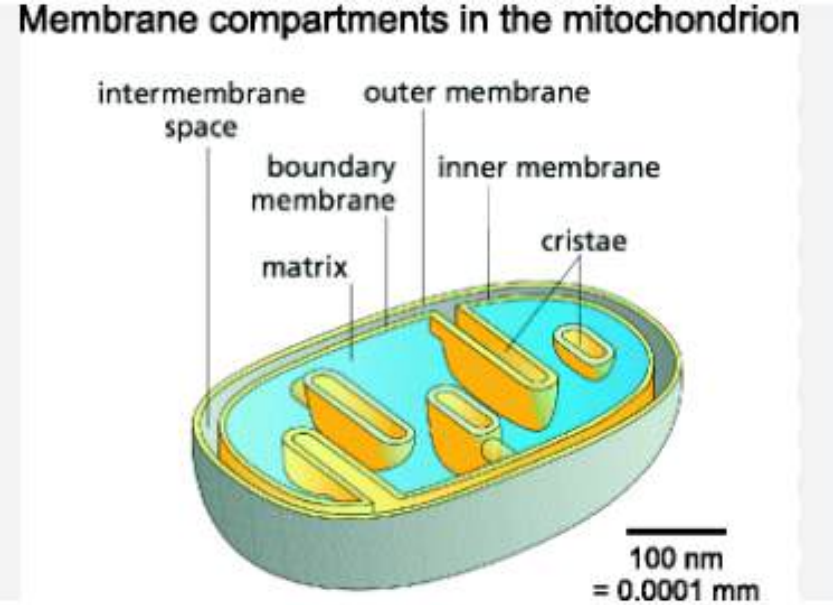
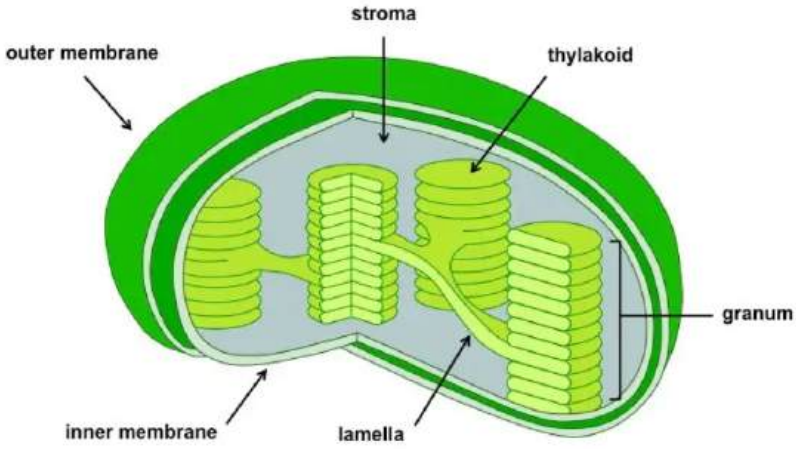


Image Credit: BMC Biology - BioMed Central

Chloroplast Like the mitochondria, the stacked thylakoid membranes of the chloroplast allow for an increase in surface area necessary for the ETC of the light-dependent reactions of photosynthesis. These membranes are equipped with **photosystems** and **chlorophyll**, maximizing the plant's energy output from light. The thylakoids are stacked in an arrangement called **grana**, where ATP synthesis occurs. Within the inner membrane and outside the thylakoid is the **stroma** fluid. The proximity of the stroma to the thylakoids allows for the sharing of products between the Calvin Cycle (which happens in the stroma) and the light-dependent reactions (more on this in Unit 3). As seen below, the structure of the chloroplast lends to its function.



Plasma Membrane Also known as the cell membrane, this structure has been specifically designed to be semi-permeable. This means that only certain molecules are allowed to travel freely throughout the cell, while others need specific proteins in order to facilitate their movement. The selective nature of the plasma membrane results in a **concentration gradient**, which serves as an essential part of many biological processes.

Lysosome In a cell, lysosomes within the plasma membrane are critical to survival. If the enclosed hydrolytic enzymes were to burst, other organelles could also burst, leading to cell death. In order to prevent this, the membrane is designed to hold the enzymes within. The lysosome will bind with other vesicles that contain contents necessary for digestion when needed.

Endoplasmic Reticulum Later, we will discuss protein synthesis, but understand that the endoplasmic reticulum specializes in this process! On the membrane there are ribosomes, which use RNA to produce the proteins. Then, proteins are packaged and sent off to the Golgi body, which can be thought of as the "USPS delivery point" of the cell.

Problem 2.2.1 — Multiple Choice Question

Phenytoin is a prescription drug that is used to treat patients with epilepsy. A side effect of phenytoin is that it can be toxic to mitochondria.

Which of the following processes will be most immediately disrupted by this side effect?

(A) ATP synthesis
(B) Lysosome synthesis
(C) Lipid synthesis
(D) Protein synthesis

Solution: Phenytoin can be toxic to mitochondria, whose main function is to produce ATP. Therefore, the drug will most immediately disrupt ATP synthesis. Lysosome, lipid, and protein synthesis are related to the Golgi complex, endoplasmic reticulum, and ribosome organelles, respectively, and will not be most disrupted by the drug. The correct answer is $\boxed{\textbf{(A)}}$.

Problem 2.2.2 — Multiple Choice Question

Wolman disease affects lysosomal function and results in the accumulation of lipids in the liver, spleen, intestines, adrenal glands, and lymph nodes.

Which of the following best explains why excess lipids accumulate in individuals with Wolman disease?

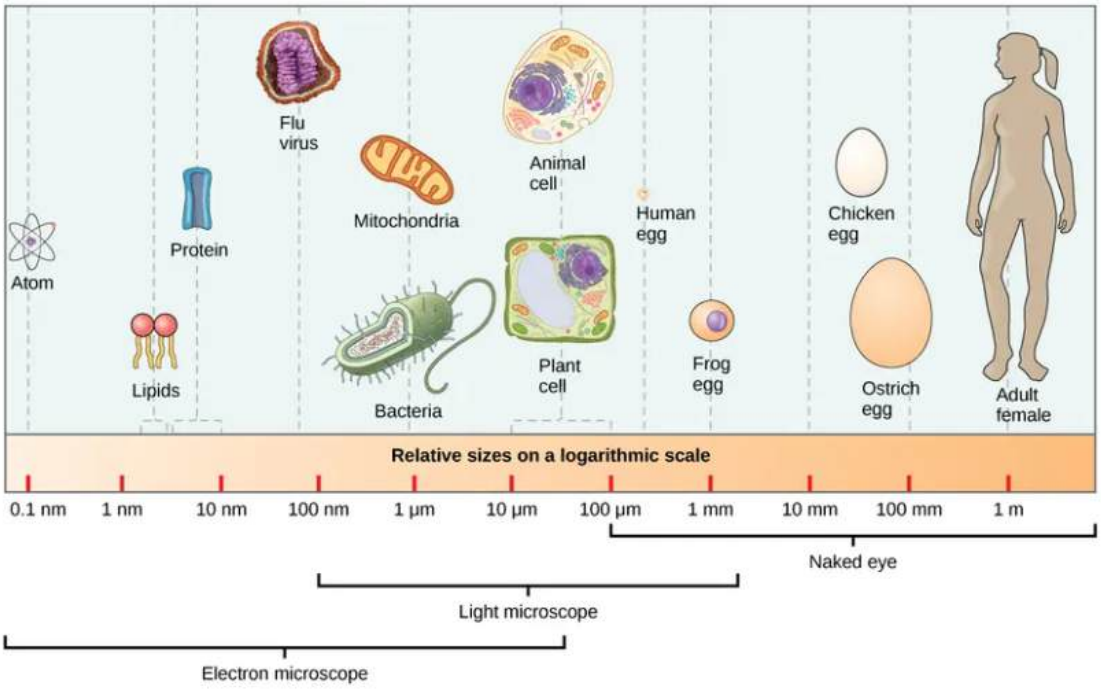
(A) The lysosomes prevent lipids from entering the cell through endocytosis.
(B) The lysosomes allow excess lipids to enter the cell through endocytosis.
(C) The lysosomes contain an insufficient amount of lipid-digesting enzymes.
(D) The lysosomes accumulate extra lipid-digesting enzymes.

Solution: It might be tempting to select (B), however, lysosomes break down excess waste and materials. They do not control how lipids enter the cell, which also eliminates (A). Moreover, an excess accumulation of lipid-digesting enzymes would result in the breakdown of more lipids, not a build-up of them. Therefore, (D) is incorrect. However,

a shortage of digest enzymes would lead to a build-up of lipids in the cell, which is consistent with option $\boxed{\text{(C)}}$.

§2.3 Cell Size

We know that cells are incredibly small. They need to maintain this small size in order to maximize the amount of space for the transfer of nutrients and waste (surface area) with the smallest cell volume. As the volume increases, the cell will need more and more nutrients to enter, and the higher the surface area, the more nutrients can enter, which maximizes its efficiency.



Surface Area to Volume Ratio The greater the **surface area to volume (SA/V)** ratio is, the **more efficient** the cell becomes. When the cell reaches a point where the surface area doesn't allow enough nutrients to pass that the cell needs, it divides. We will explore this topic in-depth in Unit 5.

Tissues and membranes that have folds have them to increase the surface area. This concept of the surface area to volume ratio is extremely important to College Board, as it is very necessary for our biological systems to function at an efficient rate.

Important Geometric Formulas The following surface area and volume formulas are given in your AP Biology Equation Sheet:

Surface Area and Volume

Surface Area of a Sphere
$SA = 4\pi r^2$

Volume of a Sphere
$V = \frac{4}{3}\pi r^3$

Surface Area of a Rectangular Solid
$SA = 2lh + 2lw + 2wh$

Volume of a Rectangular Solid
$V = lwh$

Surface Area of a Cylinder
$SA = 2\pi rh + 2\pi r^2$

Volume of a Cylinder
$V = \pi r^2 h$

Surface Area of a Cube
$SA = 6s^2$

Volume of a Cube
$V = s^3$

r = radius
l = length
h = height
w = width
s = length of one side of a cube
SA = surface area
V = volume

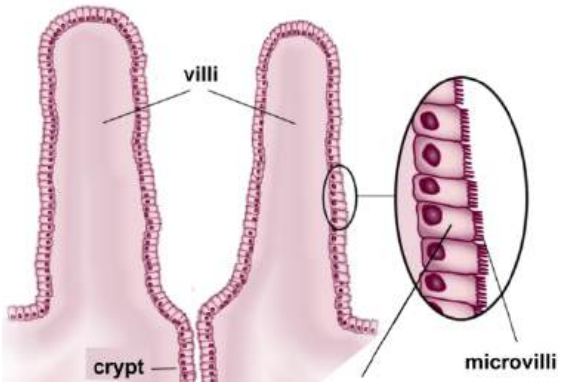
Significance of Cell Size A recurring concept in AP Biology is membrane surface area to volume ratio. This is because virtually all important processes take place within the membrane. For example, ATP synthesis takes place on the membrane of mitochondria and chloroplasts and transport takes place on the plasma membrane. This limitation can make cell size small. Smaller cells usually have a better surface area to volume ratio and as the cell gets bigger, this ratio decreases. This can affect the rate of anything, from heat exchange to ATP synthesis.

Discussion on Relative Surface Area and Volume If you were to take two perfectly round spheres, one large and one small, and compare the surface areas, the larger sphere would win. However, not every part of the cell has the luxury of choosing the large sphere. Thankfully, nature has a unique way of optimizing whatever little space it has: **folding**! By folding their membranes, organelles can increase surface area without expanding the region they take occupy. One way of measuring a cell's ability to obtain necessary nutrients is its surface area-to-volume ratio. It is pretty self-explanatory: calculate the surface area and then divide it by volume to get the ratio.

Connecting Plasma Membrane with Cell Size The plasma membrane is a very important organelle in the transport of nutrients and vital cell materials within and outside the cell. Therefore, the plasma membrane must be large enough so that there is an appropriate amount of material exchange without taking up too much precious cell space.

Relationship Between Volume and Surface Area As the volume of a cell increases, its relative surface area decreases. As a result, the demand for important materials increases, but the cell cannot match it because of its decreasing surface area. When the surface area decreases relative to the volume, the volume-to-surface area ratio is also decreasing. When the volume-to-surface area ratio decreases, the efficiency of the cell's exchanges with the surrounding environment dramatically decreases.

Cellular Structures That Increase Surface Area Besides folding membranes, cells use villi and mitochondrial cristae to increase their surface areas. Villi are tiny finger-shaped protrusions that are usually found in cells from the intestines. Mitochondrial cristae are folds in the inner membrane of the mitochondria.



This figure shows a diagram of villi from cells in the small intestine. These villi have completely maximized their surface areas by even growing microvilli on top of themselves!

Problem 2.3.1 — Short Answer Question

The physical characteristics of a cell influence how it functions. For example, the surface area and volume of a cell affect how efficiently waste is removed from the cell via diffusion.

The table below shows data for four different spherical cells.

Spherical cell	Radius (μm)
Cell A	1
Cell B	2
Cell C	3
Cell D	4

Using the information from the table, what is the surface-area-to-volume ratio for the spherical cell that removes waste via diffusion most efficiently?

Solution: A cell removes waste via diffusion more efficiently when it has a *higher* surface-area-to-volume ratio. To calculate the surface-area-to-volume ratio for each of the spherical cells, we need to divide each cell's surface area by its volume:

$$\frac{\text{Surface Area}}{\text{Volume}} = \frac{4\pi r^2}{\left(\frac{4}{3}\pi r^3\right)} = \frac{3}{r}$$

For each cell, we plug in r to get

$$\text{Cell A: } \frac{3}{r} = \frac{3}{1} = 3\ \mu\text{m}^{-1}$$

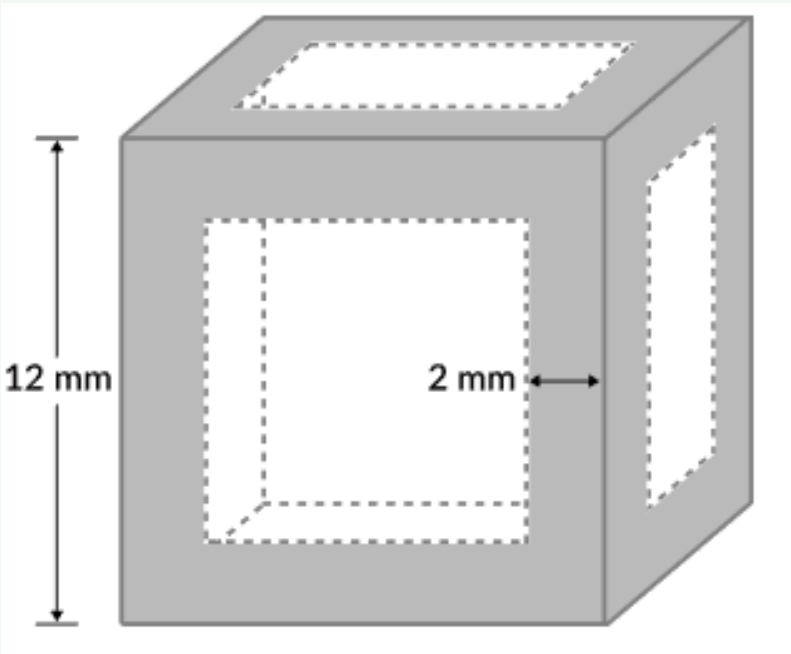
$$\text{Cell B: } \frac{3}{r} = \frac{3}{2}\ \mu\text{m}^{-1}$$

$$\text{Cell C: } \frac{3}{r} = \frac{3}{3} = 1\ \mu\text{m}^{-1}$$

$$\text{Cell D: } \frac{3}{r} = \frac{3}{4}\ \mu\text{m}^{-1}$$

Cell A has the highest surface-area-to-volume ratio, so it must remove waste via diffusion most efficiently, therefore, the answer is $\boxed{3\ \mu\text{m}^{-1}}$.

Problem 2.3.2 — Short Answer Question



The figure above depicts an agar cube with a side length of 12 mm. In an experiment, students submerged the cube in blue dye for 12 hours. The blue dye permeated 2 mm on each side, as indicated by the shading in the figure.

Calculate the volume of the agar cube that remained unpenetrated by the blue dye.

Source: Khan Academy

Solution: Because the blue dye permeated the agar cube equally on all sides, the inner, unpenetrated portion of the agar cube is *also* cube-shaped. To find the volume of this inner cube, we first need to calculate its side length. To do so, let's subtract the

permeation distance of the blue dye (2 mm on *each* side) from the total length of the agar cube (12 mm):

$$12 - 2 - 2 = 8\,\text{mm}$$

Next, using the side length we calculated, we can find the volume of the inner cube. Because all sides of a cube have the same length, we know that the length, width, and height of the inner cube are all 8 mm. Finally, the unpenetrated region is a box with volume given by $V = lwh$, so our answer is $8 \cdot 8 \cdot 8 = \boxed{512\,\text{mm}^3}$.

§2.4 Plasma Membranes

The plasma membrane provides protection for a cell. It also provides a fixed environment inside the cell, and that membrane has several different functions.

Note 2.4.1

To clarify, the terms plasma membrane and cell membrane mean the same thing, which means that they can be used interchangeably

Components Plasma membranes consist a phospholipid bilayer that acts as a selective barrier for the cell. The phospholipid bilayer consists of many phospholipids that have a polar, hydrophobic head and two nonpolar, hydrophilic tails. To create a phospholipid bilayer, the phospholipids create two rows by lining up side by side with their polar heads facing outward and nonpolar tails facing inward. The bilayer stays connected as a result of hydrophobic interactions between the tails of the phospholipids. Because of this orientation, the plasma membrane is selectively permeable to everything that tries to pass through, resulting in a layer of protection between the cell interior and foreign environment.

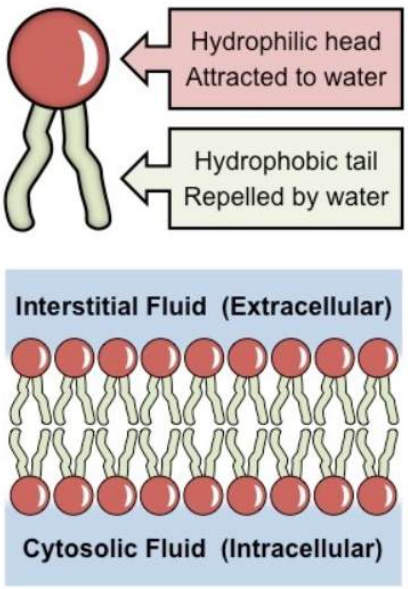


Image Credit: BioNinja

Proteins Attached to the surface of the plasma membrane are three types of proteins: integral, peripheral, and glycoproteins. **Integral proteins** are embedded within the plasma membrane and often allow for easier transport by acting as channels. These proteins are permanently attached to the plasma membrane and cannot move from their spot. **Peripheral proteins** are usually attached to an integral protein or the hydrophobic head of a phospholipid. Unlike integral proteins, peripheral proteins do not offer a channel through the plasma membrane because they do not penetrate through and are only found on the outer layer of the plasma membrane. In the image below, there is a third type of protein called the glycoprotein. **Glycoproteins**, unlike integral and peripheral proteins, can be attached to the outer layer of the plasma membrane or freely float around the cell. They have sugar molecules called glycans (aka polysaccharides) attached to them which assist in protein folding and interactions with other cells.

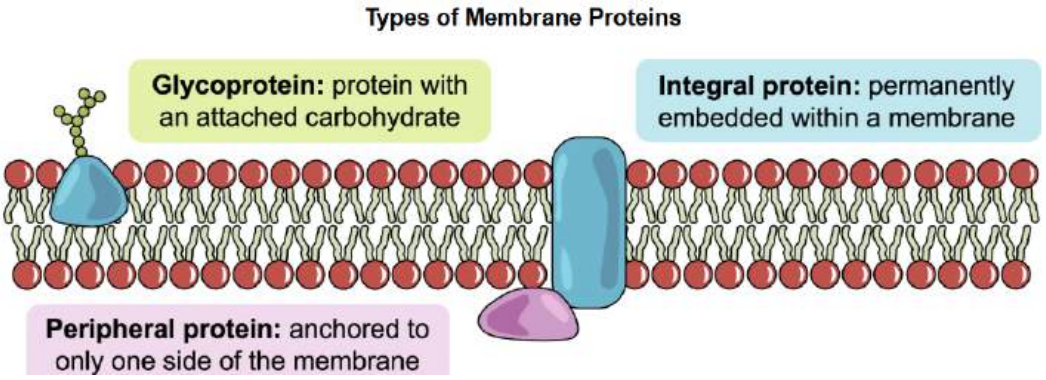


Image Credit: BioNinja

Fluid Mosaic Model The fluid mosaic model is often used to describe the structure of cell membranes because it accurately details the membrane as a flexible structure made up of several components. The fluid mosaic model describes the cell membrane as a flexible lipid bilayer that contains floating proteins. The movement of proteins is lateral, meaning that they can only move in a side-to-side motion. The fluidity of the membrane is caused by the weak hydrophobic interactions that occur between the hydrophobic heads of the phospholipids.

The fluidity of the membrane depends heavily on the temperature: low temperatures result in less fluidity, while high temperatures result in more fluidity. At low temperatures, the membrane solidifies just as butter hardens when placed in the freezer. Cholesterol, a steroid, is interesting because it actually counteracts the effects that extreme temperatures have on the fluidity of the cell membrane. In order to accomplish this, cholesterol prevents the phospholipids from clumping tightly and also limits the speed of their movement.

This is an effective approach because at high temperatures, when molecules want to move around rapidly, cholesterol forces them to move slower. At low temperatures, cholesterol is effective because it prevents phospholipids from clumping together and solidifying.

Problem 2.4.2 — Multiple Choice Question

The images below show the 3D space-filling models of two fatty acids. One fatty acid has a straight structure and the other fatty acid has a kinked, or bent structure.

Which of the following correctly describes how high levels of fatty acid structures contribute to the rigidity of the cell membrane?

(A) The cell membrane becomes more rigid as the amount of saturated fatty acids with a straight structure increases.
(B) The cell membrane becomes less rigid as the amount of unsaturated fatty acids with a straight structure increases.
(C) The cell membrane becomes less rigid as the amount of saturated fatty acids with a straight structure increases.
(D) The cell membrane becomes more rigid as the amount of unsaturated fatty acids with a kinked structure increases.

Solution: Recall that saturated fatty acids have hydrocarbon tails with a straight structure. A straight structure allows many saturated fatty acids to be densely packed together, which makes the cell membrane more rigid. A kinked structure will therefore be ineffective. Unsaturated fatty acids have hydrocarbon tails with a kinked structure, which reduces the rigidity of the plasma membrane. Thus, (B) and (D) are eliminated. (C) is also eliminated because we established that a straight structure increases the rigidity of the membrane, not the other way around. The correct answer is $\boxed{\textbf{(A)}}$.

Problem 2.4.3 — Multiple Choice Question

Which of the following best describes how high levels of cholesterol affect the cell membrane at certain temperatures?

(A) At low temperatures, high amounts of cholesterol increase the rigidity of the cell membrane.
(B) At high temperatures, high amounts of cholesterol increase the fluidity of the cell membrane.
(C) At low temperatures, high amounts of cholesterol increase the fluidity of the cell membrane.
(D) At high temperatures, high amounts of cholesterol decrease the rigidity of the cell membrane.

Solution: At low temperatures, high amounts of cholesterol cause phospholipids to spread apart, which *decreases* the rigidity of the cell membrane, so eliminate (A). At high temperatures, high amounts of cholesterol cause the opposite effect: as phospholipids pack close together, the fluidity of the membrane decreases, so eliminate (B). Moreover,

this increases the rigidity of the cell membrane, so eliminate (D). However, cholesterol can prevent cell membranes from being non-functional due to low temperatures. Specifically, it packs between the phospholipids in the membrane, increasing their *spacing*, and *increasing* the fluidity of the membrane. Thus, the correct answer is **(C)**.

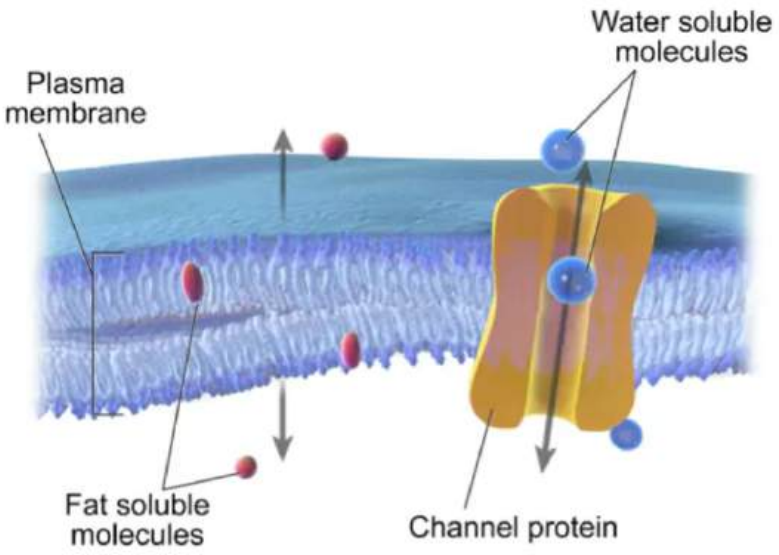
§2.5 Membrane Permeability

The cell membrane is selectively permeable, or very picky, when it comes to what it allows to pass through and enter the cell. Having a cell membrane that is selectively permeable benefits the cell because it prevents harmful, foreign substances from entering and causing problems within. The cell membrane is basically a large gate that separates the interior of the cell from the surrounding, possibly dangerous, exterior environment.

Selective Permeability Due to the phospholipid bilayer structure of the cell membrane, it is equipped with selective permeability. This allows some substances to easily cross, while others are not allowed or may require a special transport protein in order to do so. Small, non-polar molecules are able to freely cross the cell membrane, while polar or charged molecules require transport proteins to cross. If a molecule, e.g. water, is small, polar, and uncharged, it can still pass through the membrane but in small quantities and with the help of a transport protein to move across in larger quantities. Transport proteins specifically designed to aid the movement of water molecules across the cell membrane are called **aquaporins**.

Meanwhile, small non-polar molecules, e.g. N_2, O_2, and CO_2, can freely cross the membrane without the assistance of any transport protein. Hydrophilic substances don't have that luxury because the hydrophobic tails of the membrane will not interact with them. Therefore, only hydrophobic substances can freely cross the membrane, as they interact with the membrane's fatty tails. These tails repel charged and polar molecules, hindering their movement.

Diffusion Across Cell Membrane: A Visual



Extracellular Matrix in Animal Cells Naturally, most animal cells release materials into the extracellular space, which creates a complex mesh of proteins and carbohydrates referred to as the **extracellular matrix (ECM)**. The protein **collagen** is an integral component of this structure, and they are modified with carbohydrates, and when released from the cell they assemble into long fibers called collagen fibrils.

In the extracellular matrix, **proteoglycans**, interweave the collagen fibers, which are usually attached to a long polysaccharide backbone.

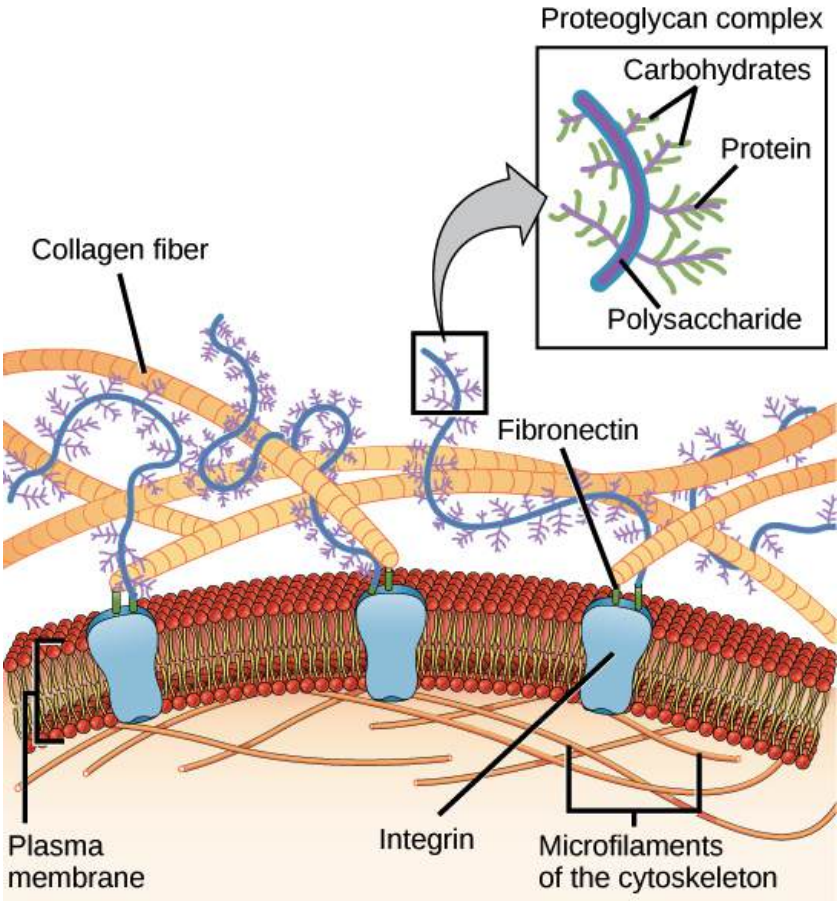


Image Credit: *OpenStax Biology*

The cells that the extracellular matrix envelops are directly linked to it. **Integrins**, which are proteins embedded in the plasma membrane, are some of the important connections. Extracellular matrix proteins, such as the green **fibronectin** molecules in the accompanying picture, can serve as linkages between integrins and other extracellular matrix proteins, such collagen. The integrins are connected to the cytoskeleton on the inner side of the membrane.

Note 2.5.1

Integrins act as anchors between the cell and the extracellular matrix. They also enable a cell's sensing of the environment, detecting both chemical and mechanical indicators from the matrix and triggering signaling pathways in response.

Example 2.5.2

Blood clotting also emphasizes the communication between cells and the extracellular matrix. When the cells lining a blood vessel are damaged, they display a protein receptor called tissue factor. As this receptor binds to a molecule within the matrix, it triggers a range of responses that reduce blood loss, such as platelets sticking to the wall of the damaged blood vessel and inducing the production of clotting factors.

Cell Wall in Plant Cells Unlike animals, plants do not make collagen, but they have their own supportive extracellular structure: the **cell wall**. It acts as a rigid structural boundary for the cell. Have you ever noticed that when you bite into a raw vegetable, like cucumber, it crunches? This is attributed to the rigidity of cucumber's cell walls. Fungi also have cell walls, and so do some protists (a group of primarily unicellular eukaryotes) and most prokaryotes, but we will focus mostly on plants.

The major organic molecule that composes a cell wall's structure is **cellulose**, a polysaccharide that contains several glucose units. When cellulose assembles, it forms fibers called microfibrils, as shown below.

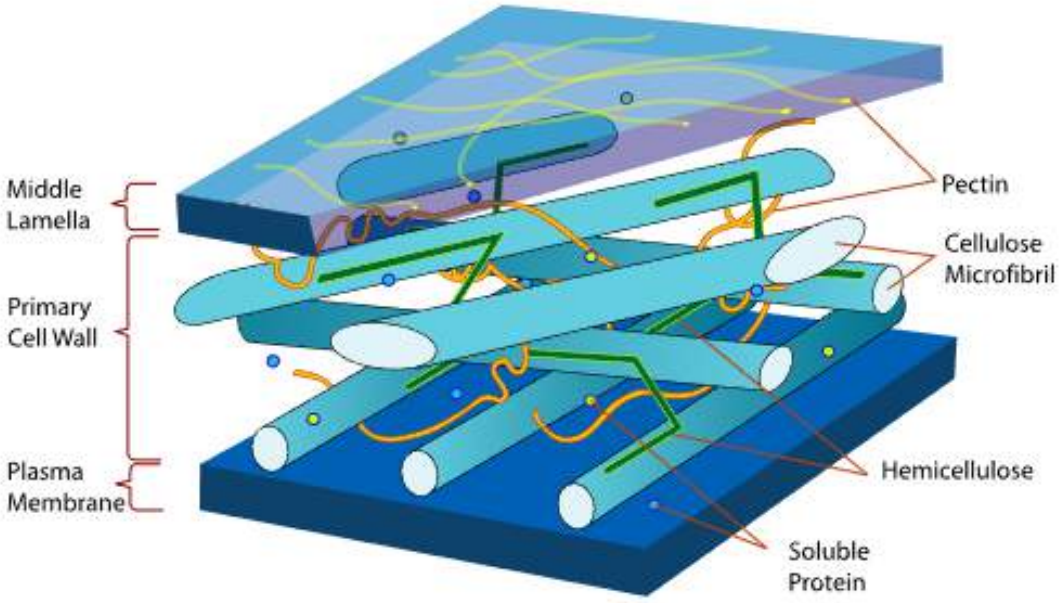


Image Credit: "" by Mariana Ruiz Villareal, public domain

In addition to cellulose, plant cell walls also contain other polysaccharides, e.g. hemicellulose and pectin, also shown in the diagram. The **middle lamella**, shown along the top of the diagram, is a sticky layer that helps hold the cell walls of adjacent plant cells together.

Problem 2.5.3 — Multiple Choice Question

Which of the following best describes how substances move across the cell membrane?

(A) Hydrophilic amino acids freely move across the cell membrane.
(B) Nucleic acids freely move across the cell membrane.
(C) Polar amino acids freely move across the cell membrane.
(D) Ions move across the cell membrane through embedded channel proteins.

Solution: In this case, both hydrophilic and large amino acids cannot freely move across the membrane because of the latter's hydrophobic lipid tails. There are special embedded proteins that transport them across the membrane, eliminating options (A) and (C). Nucleic acids are large and hydrophilic, so they also cannot move across the cell membrane without the help of transport proteins, which eliminates (B). Ions are charged and hydrophilic, so they are transported across the cell membrane by embedded channel proteins, which is consistent with $\boxed{\textbf{(D)}}$.

Problem 2.5.4 — Multiple Choice Question

Which of the following statements best describes the selective permeability of the cell membrane?

(A) The cell membrane regulates the transport of intracellular substances out of, but not into the cell.
(B) The cell membrane regulates the transport of specific substances into and out of the cell.
(C) The cell membrane regulates the transport of extracellular substances into, but not out of the cell.
(D) The cell membrane regulates the transport of all substances into and out of the cell.

Solution: The cell membrane is permeable, so it allows for the passage of substances both into and out of the cell. It is also selective, so only specific substances can enter and exit the cell. It regulates *both* the entry of extracellular substances into the cell *and* the exit of intracellular substances out of the cell. Moreover, it *only* regulates the transport of specific substances that cannot freely pass across it. This eliminates options (A), (C), and (D), leaving us with $\boxed{\textbf{(B)}}$.

§2.6 Membrane Transport

There are several processes by which ions and molecules can cross cell membranes; the mechanism required will depend on factors such as whether or not the substance to be transported is small, large, or polar, and if the concentration gradient across the membrane is opposed or not. Mechanisms of transport include passive transport, e.g. diffusion and osmosis, and active/bulk transport, e.g. endocytosis and exocytosis.

Passive Transport **Passive transport** is a type of membrane transport that does not require energy to occur. In this section, we will discuss two important classes of passive transport: diffusion and facilitated diffusion.

During **diffusion**, substances move from an area of higher concentration to an area of lower concentration, until the concentrations across a space are equalized.

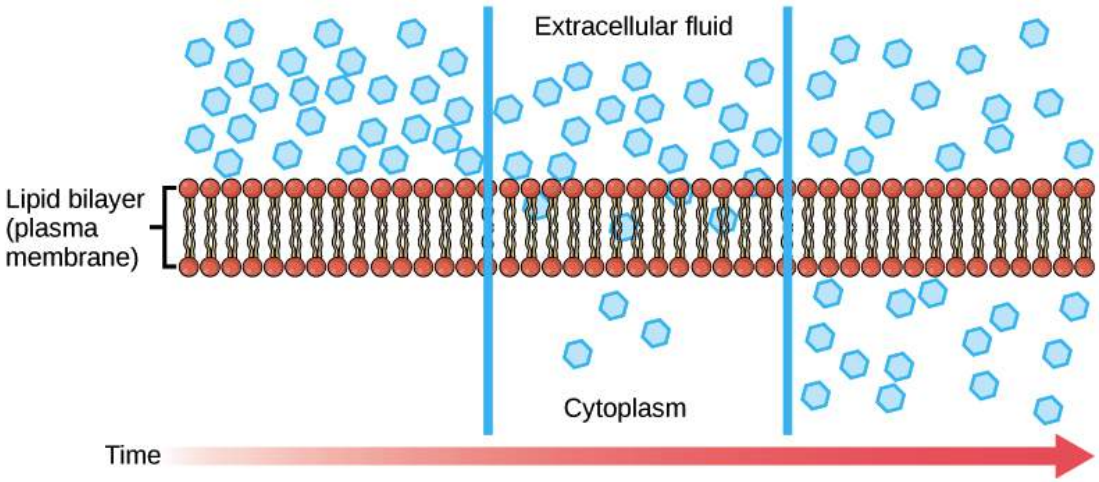


Image Credit: *OpenStax Biology*

This also applies for some substances moving into and out of cells. Because the cell membrane is semipermeable, only small, uncharged substances like carbon dioxide and oxygen can easily diffuse across it. Charged ions or large molecules require different kinds of transport: facilitated diffusion!

Facilitated diffusion involves membrane proteins assisting polar or charged substances in crossing the plasma membrane. These proteins can be classified as **carrier proteins** or **channel proteins**.

Although a concentration gradient—a region of space over which the concentration of a substance changes—may exist for these substances, their chemical properties prevent them from crossing the hydrophobic tails of the cell membrane. Substances transported through facilitated diffusion still move with the concentration gradient, but the transport proteins protect them from the hydrophobic region as they pass through.

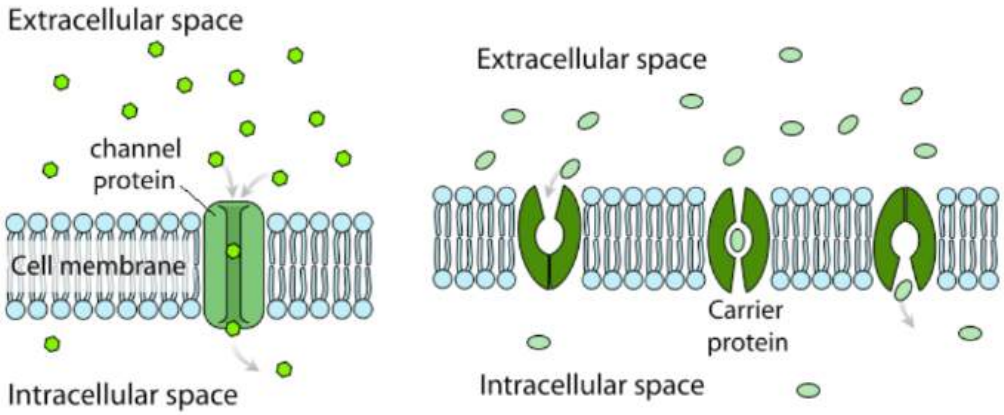


Image Credit: Modified from "Scheme facilitated diffusion in cell membrane," by Mariana Ruiz Villareal (public domain)

There are a couple of misconceptions we need to address here.

- **Not everything** enters the cell through passive transport. Only the smallest molecules like water, carbon dioxide, and oxygen can freely diffuse across cell membranes. Larger or charged molecules often require an input of energy to be transported into the cell. This is the concept of active transport, which we'll explore later.
- Even when equilibrium is reached, particles do **not** stop moving across the cell membrane. Although it may seem as if the concentrations are not changing, nearly equal numbers of particles cross the membrane in both directions, indicating no *net* movement.

Active Transport **Active transport** is a type of transport that requires an input of energy to occur. This involves substances moving against the concentration gradient (from an area of lower concentration to an area of higher concentration). This process is "active" because it requires the use of energy (usually in the form of ATP, the primary energy carrier in living organisms). It is the opposite of passive transport.

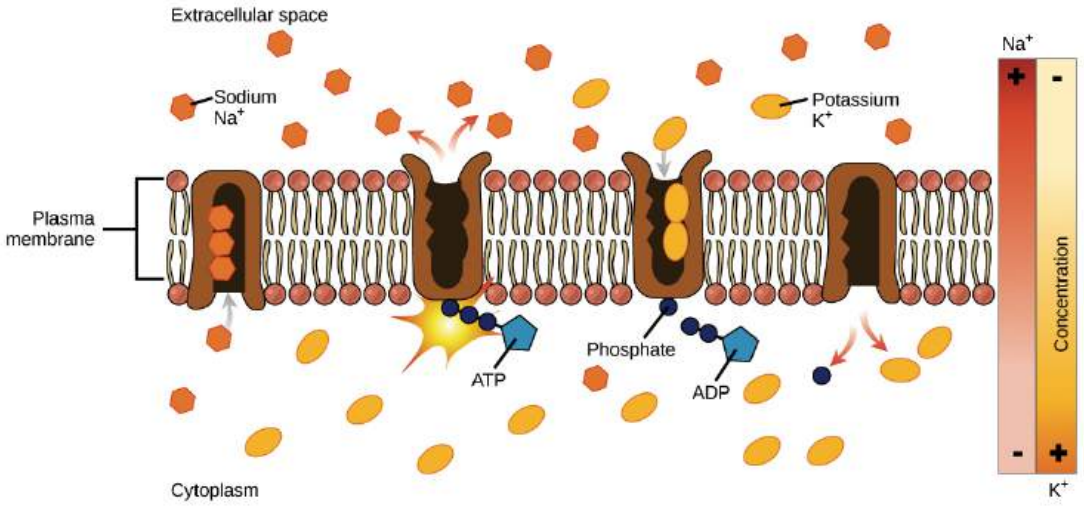


Image Credit: *OpenStax Biology*

Active transport requires assistance from carrier proteins, which change conformation when ATP is hydrolyzed.

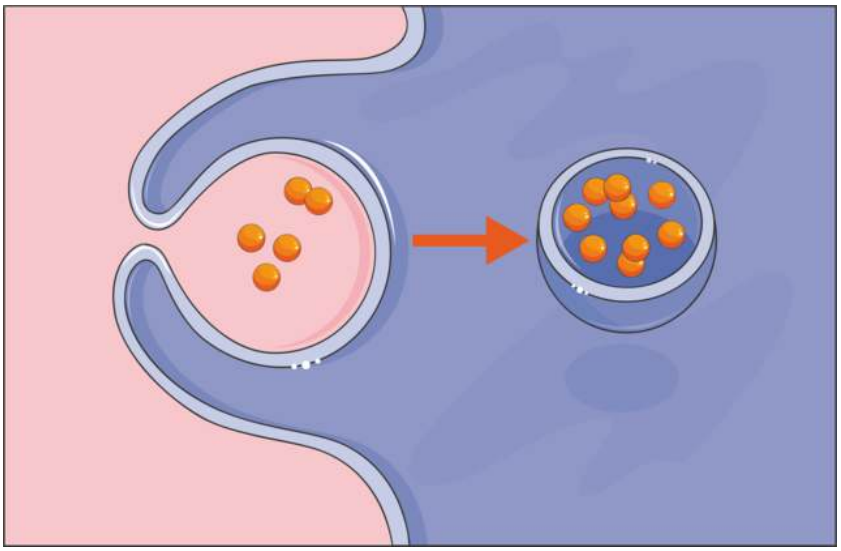
Let's tackle the common misconceptions regarding this form of membrane transport.

- Active transport is **not** the same as facilitated diffusion. Both active transport and facilitated diffusion do use proteins to assist in transport. However, active transport works against the concentration gradient, moving substances from areas of low concentration to areas of high concentration.
- Additionally, active transport uses **carrier proteins**, while facilitated diffusion uses channel proteins. This is because carrier proteins require ATP in order to achieve conformational changes. Channel proteins are not used in active transport because substances can only move through them along the concentration gradient.

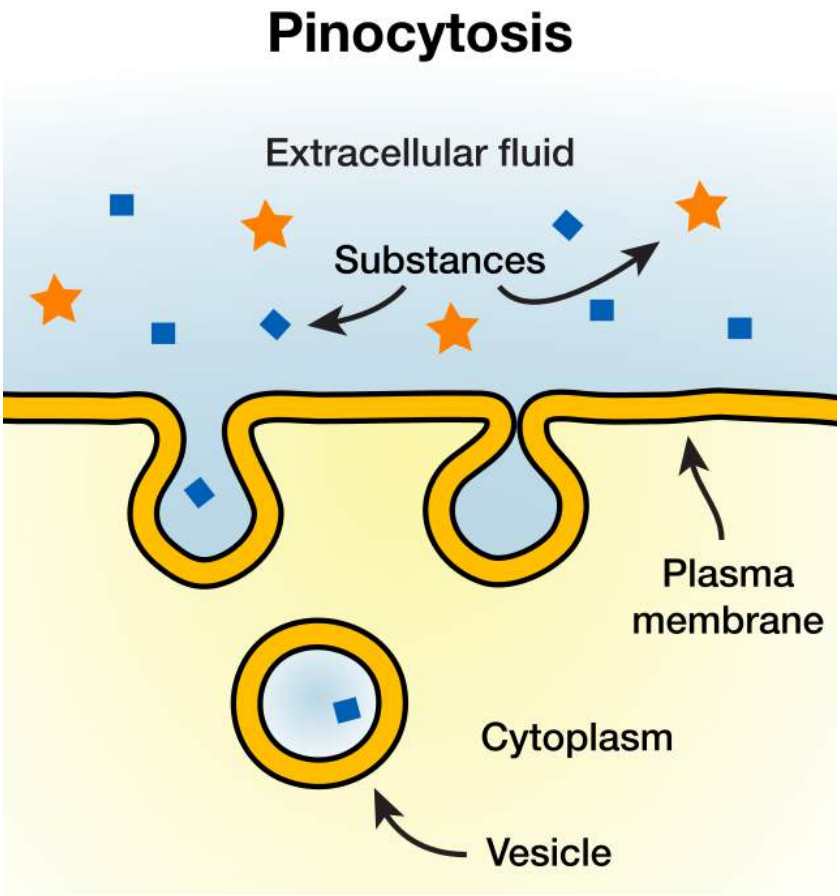
Bulk Transport Large molecules, or large quantities of molecules in general, can be moved across the membrane using **bulk transport**, which requires energy and involves a membrane-bound vesicle.

Endocytosis is a type of active transport that moves particles, such as large molecules, parts of cells, and even whole cells, into a cell. We will discuss the different types, but endocytosis in general involves the invagination of the cell membrane, the formation of a pocket around the particle. The pocket pinches off, resulting in the particle containing itself in a newly created intracellular vesicle formed from the plasma membrane. Let's go over the various types.

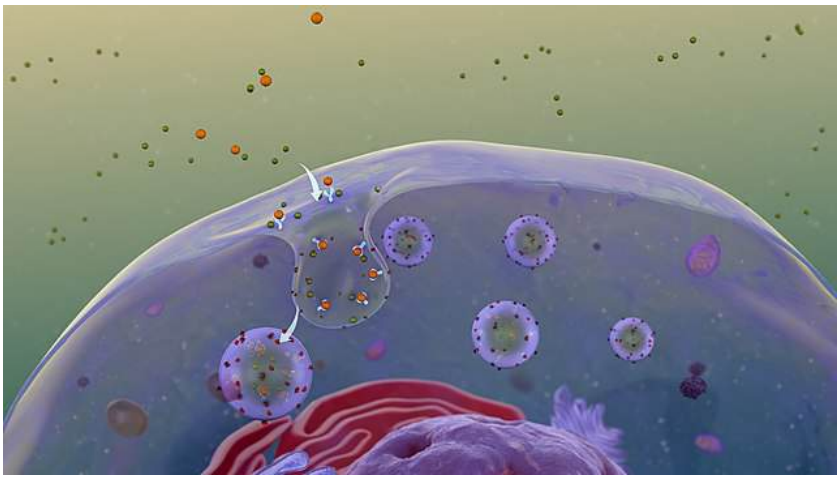
- **Phagocytosis**, or "cell eating," is the process by which a cell takes in large particles, such as other cells or relatively large particles. Once the vesicle containing the particle is enclosed within the cell, the vesicle merges with a lysosome for breaking down the material in the newly formed compartment.



- **Pinocytosis**, or "cell drinking," is a variation of endocytosis which involves a cell absorbing extracellular fluid. In reality, this is a process that takes in molecules, including water, which the cell needs from the extracellular fluid.



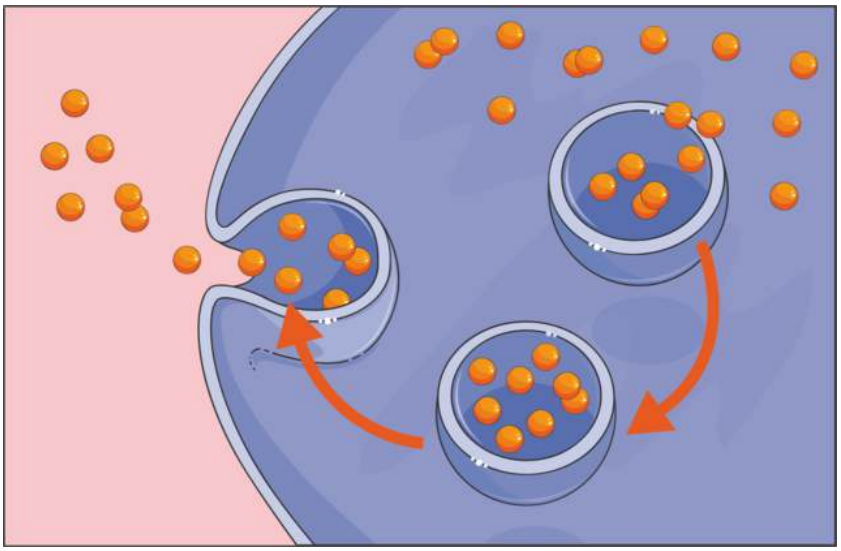
- **Receptor-mediated endocytosis** is a targeted variation of endocytosis employs receptor proteins in the plasma membrane that have a specific binding affinity for certain substances.



Although receptor-mediated endocytosis is designed to bring specific substances that are normally in the extracellular fluid into the cell, other substances may gain entry into the cell at the same site.

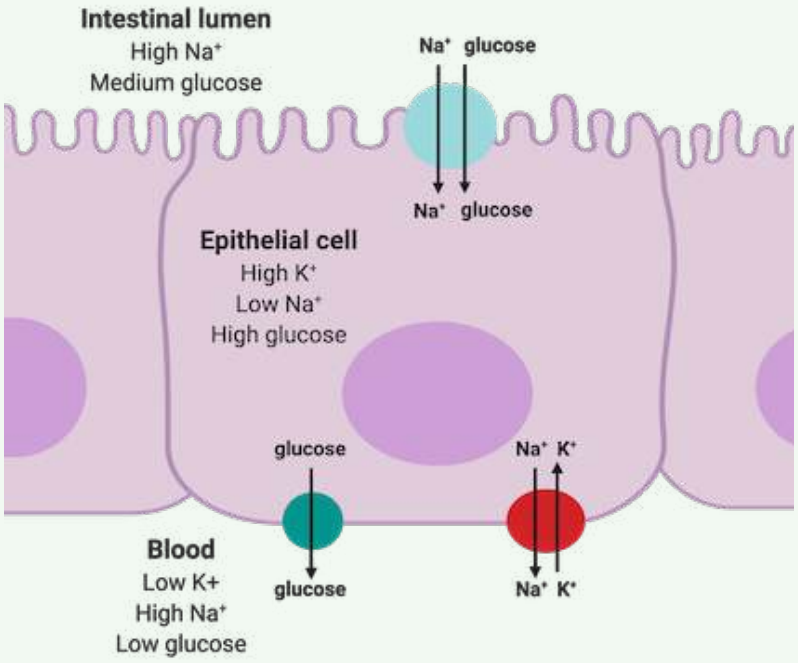
Exocytosis is the opposite of the processes we discussed above in that its purpose is to expel material from the cell into the extracellular fluid. Waste material is enveloped in a membrane and fuses with the plasma membrane's interior. This fusion allows

expulsion of the waste material into the extracellular space.



Problem 2.6.1 — Multiple Choice Question

The model below shows how glucose, sodium ions (Na^+), and potassium ions (K^+) move between the intestinal lumen, an epithelial cell, and the blood in the small intestine. The relative concentrations of glucose, Na^+, and K^+ inside and outside the epithelial cell are indicated.



Based on the model, which of the following movements does **NOT** require an input of energy?

(A) K^+ moving out of the blood into an epithelial cell
(B) glucose moving out of the intestinal lumen into an epithelial cell
(C) glucose moving out of an epithelial cell into the blood
(D) Na^+ moving out of an epithelial cell into the blood

Source: Khan Academy

Solution: The answer to this question involves the movement which occurs by passive transport, which does not require an input of energy. In each of options (A), (B), and (D), a substance travels from an area of lower concentration to an area of higher concentration. This occurs by active transport, which does require an input of energy. However, when glucose moves from an epithelial cell into the blood, it travels from an area of higher concentration to an area of lower concentration, or *down* its concentration gradient. This movement occurs via passive transport, therefore, the correct answer is $\boxed{\textbf{(C)}}$.

Problem 2.6.2 — Multiple Choice Question

Root hairs are tubular outgrowths of root epidermal cells in plants. These outgrowths help plants absorb water and nutrients by increasing root surface area.

Root hairs form when membrane-bound structures inside root epidermal cells carry macromolecules to one side of the cell. There, the structures fuse with the plasma membrane, releasing their contents outside the cell. The released macromolecules are then incorporated into the elongating cell wall of the root epidermal cell, which allows the root hair to continue growing.

A group of scientists discovered a plant that had no root hairs. The scientists determined that this phenotype was due to a genetic mutation that inhibited the process by which root hair growth takes place. This mutation was located in the *rth1* gene.

Based on the information above, which of the following cell processes did the *rth1* mutation most likely inhibit in the plant with no root hairs?

(A) Membrane transport mediated by transmembrane ATPases
(B) Receptor-mediated endocytosis
(C) Vesicle fusion during exocytosis
(D) Facilitated diffusion through membrane channels

Solution: The *rth1* mutation inhibited the cell process by which root hair growth takes place. According to the text, root hair growth occurs as macromolecules are released from one side of root epidermal cells. According to the text, macromolecules are released from root epidermal cells when membrane-bound structures inside the cells fuse with the plasma membrane. This describes vesicle fusion during exocytosis, a form of bulk transport. The correct answer is $\boxed{\textbf{(C)}}$.

§2.7 Facilitated Diffusion

Facilitated diffusion is a type of passive transport that allows for specific molecules to cross the plasma membrane. Though it's passive, facilitated diffusion requires specialized proteins called channel proteins and carrier proteins. In this process, molecules can move down their concentration gradient without requiring any energy input from the cell.

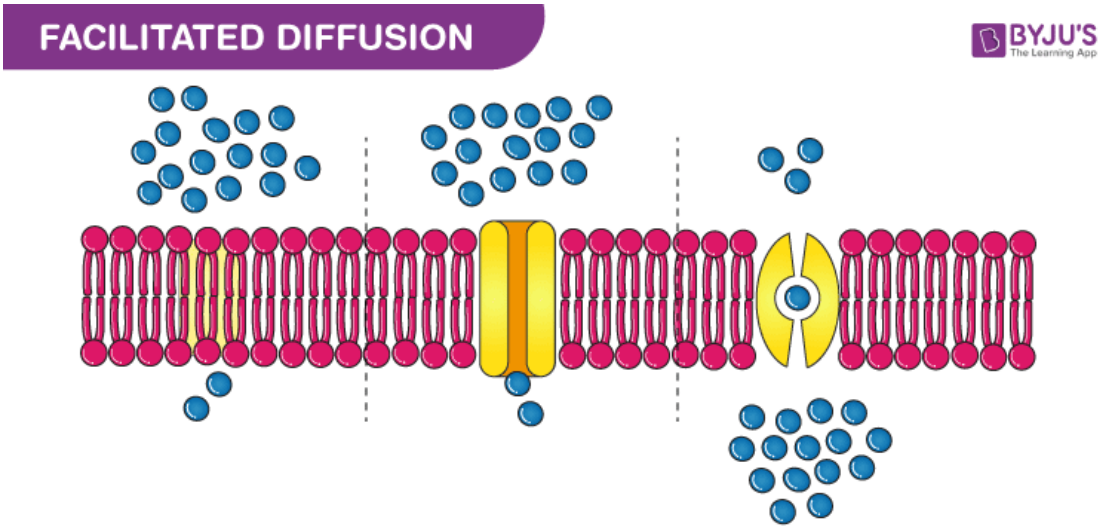


Image Credit: BYJU'S

Facilitated Diffusion: When and Why? When molecules cannot move easily enough through the plasma membrane, facilitated diffusion occurs. Molecules cannot pass through the phospholipid bilayer of the plasma membrane easily when particles are either charged or polar.

Channel Proteins **Channel proteins** are equipped to the plasma membrane to provide a hydrophilic passage through which the molecules can avoid the hydrophobic core. An example of a channel protein is aquaporins, which allow water (polar H_2O) to diffuse across the membrane. Aquaporins are essential for the health of plant cells, red blood cells, etc.

Nerve and muscle cells have gated ion channel proteins to enable the flow of charged ions such as sodium and potassium present in the sodium potassium pump of action potentials. These charged particles, e.g. Na^+ and K^+, need channel proteins in order to move through the membrane. Once this is succesful, the membrane becomes polarized, which benefits the action potential (we will learn about this later). If an electrical signal is activated, these channel proteins open their gate to transmit these signals through the cells that need them.

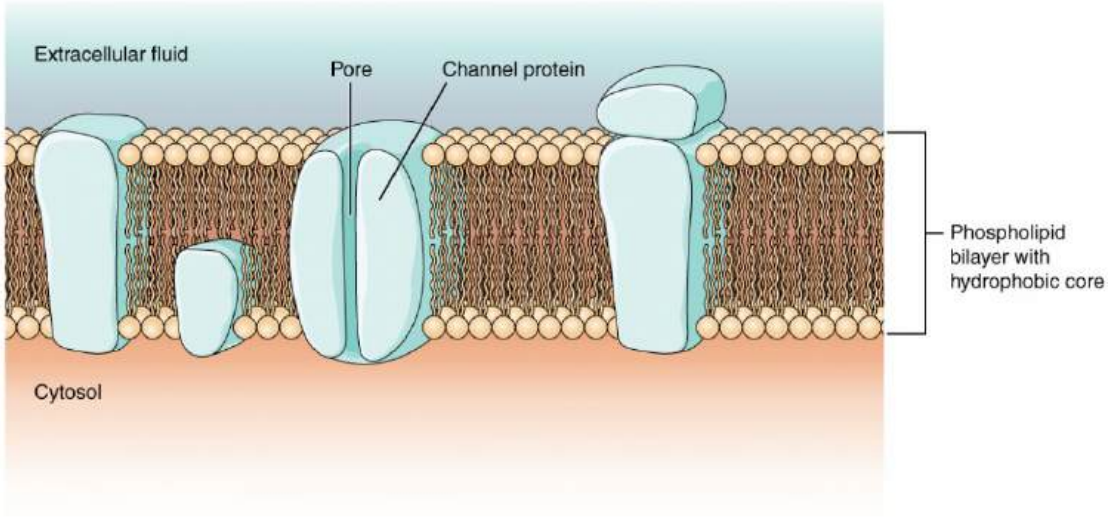


Image Credit: Lumen Learning

Carrier Proteins **Carrier proteins** are special proteins that adjust their shape to allow the flow of certain molecules through the membrane's concentration gradient. This can be compared to an enzyme-substrate complex. Make sure to remember that the rate of carrier protein function is lower than that of channel proteins. Carrier proteins provide an alternate and easier route for hydrophilic substances to diffuse across the membrane.

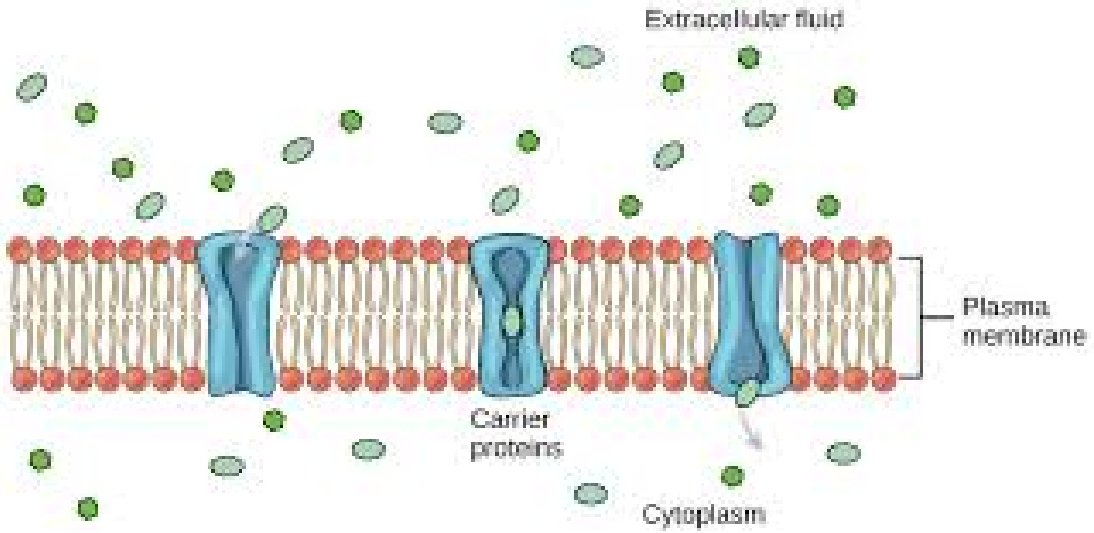


Image Credit: Lumen Learning

Problem 2.7.1 — Multiple Choice Question

Gastric acid is a digestive fluid that is made with the help of parietal cells in the stomach lining. The parietal cell plasma membrane maintains a concentration gradient of potassium ions (K^+) between the cell cytoplasm and the extracellular fluid. During the formation of gastric acid, K^+ moves down this gradient, passing from the cytoplasm into the extracellular space.

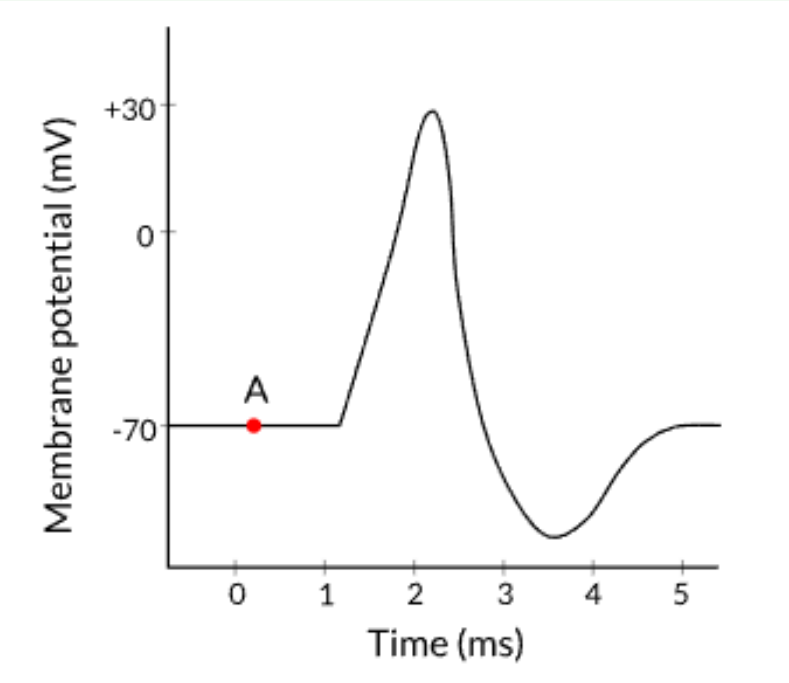
Which of the following is the most likely mechanism by which K^+ moves across the plasma membrane of a parietal cell during gastric acid formation?

(A) K^+ directly diffuses through the membrane bilayer.
(B) K^+ flows through aquaporins.
(C) K^+ passes through membrane channel proteins.
(D) K^+ is transported through membrane ATPases.

Solution: Eliminate (A); charged ions such as K^+ do not freely cross the hydrophobic bilayer of the cell membrane, and they require the help of membrane proteins. (B) is also incorrect; aquaporins only facilitate the passive transport of *water*, not ions. Finally, (D) is wrong because the text tells us that K^+ moves *down* its concentration, while membrane ATPases uses energy from ATP hydrolysis to transport substances *against* their concentration gradients. However, membrane proteins facilitate the diffusion of charged and polar substances across the membrane. Therefore, it is likely that K^+ exits a parietal cell by passing through special ion channel proteins. The correct answer is $\boxed{\textbf{(C)}}$.

Problem 2.7.2 — Multiple Choice Question

Neurons transmit information in the form of electrical signals called action potentials. During an action potential, an influx of positively charged ions causes the membrane potential to change from its resting value of approximately -70 mV to approximately $+30$ mV. This is immediately followed by the movement of more positively charged ions in the opposite direction, which helps return the membrane potential to its resting value. This process is represented in the following graph.



Which of the following statements best describes how the inside and the outside of the neuron are charged at Point A in the graph above?

(A) Both the inside and outside of the neuron have a net positive charge.
(B) The inside of the neuron has a net negative charge, and the outside has a net positive charge.
(C) Neither the inside nor the outside of the neuron has a net charge.
(D) Both the inside and outside of the neuron have a net negative charge.

Source: Khan Academy

Solution: This question appears pretty intimidating, but all you really have to do is be able to read the data and understand its meaning. At Point A in the graph, the neuron's membrane potential is -70 mV with respect to the inside of the cell. This means that the inside of the neuron has a net negative charge, and the outside has a net positive charge. That's consistent with option (B), but let's just rule out the others. (A) and (C) are not correct because the overall region must have no net charge. Meanwhile, (D) is not correct because a negative membrane potential inside the neuron would indicate the interior having a net negative charge, and the outside having a net *positive*, not negative, charge. The correct answer is $\boxed{\textbf{(B)}}$.

§2.8 Tonicity and Osmoregulation

The movement of water inside and out of the cell is essential to its survival. Water, like virtually all other substances, travels from a higher concentration of itself to a lower concentration of itself by default. This movement can have major impacts on a cell's structure and function.

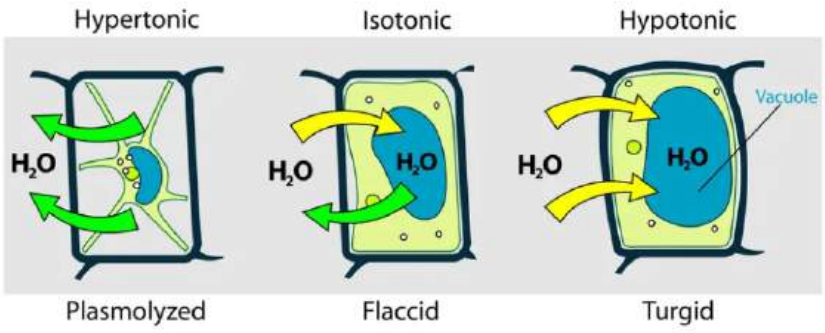
Tonicity: Three Types Depending on the amount of material outside of a cell compared to inside, the environment outside of a cell can be classified as **hypotonic**, **hypertonic**, or **isotonic** to the internal environment of a cell.

A hypotonic solution contains less solute outside the cell than inside. As a result, water will flow towards a higher solute concentration (and therefore a lower water concentration!), which in this case, is into the cell, causing it to expand.

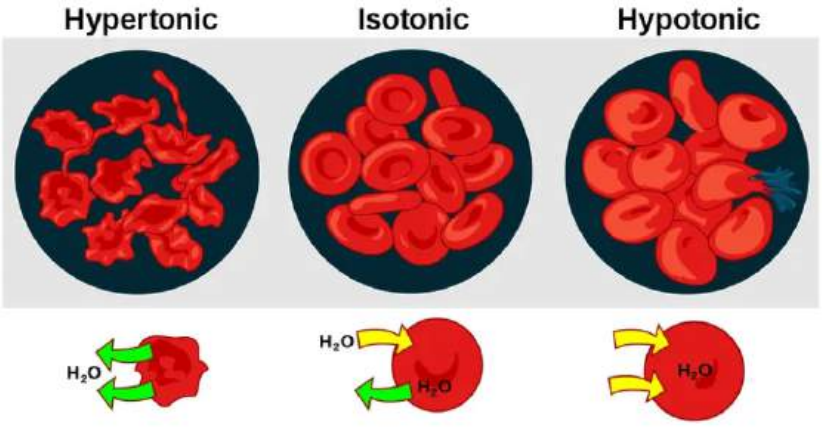
A hypertonic solution contains more solute outside the cell than inside. Pay close attention here; water will STILL move to where there is more solute, according to the definition of water potential. Specifically, water moves out of the cell, causing it to shrink.

Finally, an isotonic solution has equal amounts of solute both inside and outside the cell. As a result, water will flow both into and out of the cell to the same extent, implying no *net* movement.

Regardless of solution type, the cell does NOT change its underlying shape. Water simply attempts to move from an area of high concentration to an area of low concentration until there are equal amounts on both sides of the plasma membrane. This tendency is defined as **osmosis**. Osmosis allows organisms to control their internal solute composition and water potential.



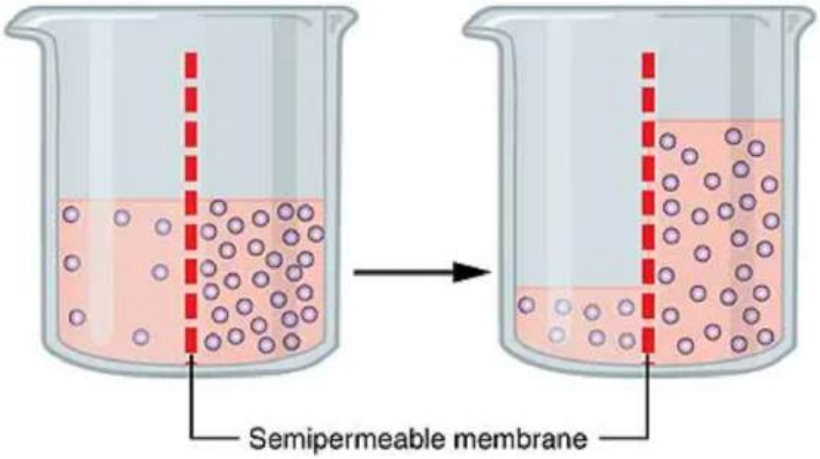
Above shows a plant cell, Image Credit: Wikipedia



Above shows an animal cell, Image Credit: Wikipedia

Osmosis As discussed briefly, osmosis is the process of diffusing water across a plasma membrane. In order to maintain **homeostasis**, or equilibrium in living systems, water will always want to move to a more concentrated area in an effort to equalize concentrations inside and outside the cell. Be on the lookout for osmosis if you encounter an AP Biology FRQ regarding homeostasis!

Generally speaking, water moving to the side with more solute refers to moving *down* the concentration gradient. This is because water can move across the membrane relatively easily with the help of aquaporin channels. However, certain substances, e.g. sugar, cannot cross the membrane as easily. In these situations, the water must exclusively move instead of the solute.



Plant cells have a unique organelle, the cell wall, which protects them from significant changes in osmotic pressure. The cell wall, being rigid, does not change in size, even though the cell membrane can shrink depending on the quantity of water inside the cell. Therefore, the cell membrane can expand and squeeze tightly against the cell wall if water returns to the cell.

Water Potential It's time for some math! Arguably one of the few mathematical aspects of AP Biology, water potential quantitatively describes osmosis and the direction

of water flow. The following equation can be found on your AP formula sheet:

$$\Psi = \Psi_p + \Psi_s$$
$$\Psi_p = \text{pressure potential}$$
$$\Psi_s = \text{solute potential}$$

In the context of water potential, water will always flow from a higher state to a lower state. The solute potential is the solute concentration in consideration of the water flow. If you add more solute, the water potential of the solution will be lowered, so it is likely for more water flows into the solution to counter it. This is done to maintain equilibrium within a cell.

The solute potential of a solution can be calculated using the following equation (also on your AP formula sheet):

$$\Psi_s = -iCRT$$
where:
$$i = \text{ionization constant}$$
$$C = \text{molar concentration}$$
$$R = \text{pressure constant}$$
$$\left(R = 0.0831 \, \frac{\text{L} \cdot \text{bar}}{\text{mol} \cdot \text{K}}\right)$$
$$T = \text{temperature in Kelvin} \, (^\circ\text{C} + 273)$$

Let's analyze this equation, one variable at a time.

- The ionization constant refers to the number of ions produced when a solute dissolves in water. When solid NaCl is placed in water, it separates into Na^+ and Cl^- ions, so $i = 2$. On the other hand, glucose, $C_6H_{12}O_6$, does not split into any ions when dissolved in water, so $i = 1$.
- The molar concentration refers to the number of moles of solute present in a given volume of water, with units of $\text{mol}\,\text{L}^{-1}$ or M.
- The pressure constant is used as stated. Don't worry about memorizing this as this is on your formula sheet!
- The temperature of the solute, in Kelvins, can be easily calculated by adding 273 to the Celsius temperature. In almost all cases, temperature will be given in Celsius, so don't worry too much about the Fahrenheit-Celsius relationship.

Problem 2.8.1 — Multiple Choice Question

A group of biology students weighed several potato cubes and placed them in open beakers containing various sucrose solutions at 30°C. The following day, the students weighed the potato cubes again and calculated the differences in mass.

It was determined that the solute potential equilibrium was reached at $0.35\,M$.

What is the solute potential of the potato cubes?

(A) 0.87 bar
(B) −8.8 bar
(C) −0.87 bar
(D) 8.8 bar

Solution: The solute potential is given by the equation $\Psi_s = -iCRT$. Sucrose is not an ionic substance, so we use an ionization constant of $i = 1$. Additionally, the molar concentration is $0.35\,\text{mol}\,\text{L}^{-1}$ and the temperature is $30°\text{C} + 273 = 303\,\text{K}$. Thus, we have

$$\begin{aligned}\Psi_s &= -(1)\left(0.35\,\text{mol}\,\text{L}^{-1}\right)\left(0.0831\,\text{L bar mol}^{-1}\,\text{K}^{-1}\right)(303\,\text{K}) \\ &\implies \boxed{\textbf{(B)}\ -8.8\,\text{bar}}\end{aligned}$$

Problem 2.8.2 — Multiple Choice Question

The solute potential of a plant cell is −12 bar, and its pressure potential is 3 bar. The plant cell is placed into a solution with a water potential of −8 bar.

What is the water potential of the cell, and in which way will water move?

(A) −8 bar; there will be no net movement of water
(B) −22 bar; water will move out of the cell
(C) −8 bar; water will move into the cell
(D) −22 bar; water will move into the cell

Solution: First, let's calculate the water potential of the plant cell. The cell has a pressure potential of 7 bar and a solute potential of −15 bar, so

$$\begin{aligned}\Psi &= \Psi_p + \Psi_s \\ &= 7 + (-15) \\ &= -8\,\text{bar}\end{aligned}$$

Now, we will compare the two water potentials to determine the whether water will move into or out of the cell. Remember that water moves from areas of higher water potential to areas of lower water potential. In this case, the water potential of the cell is *equal* to the water potential of the solution (both are −8 bar), there will be no net movement of water. The correct answer is $\boxed{\textbf{(A)}}$.

§2.9 Mechanisms of Transport

In this section, we will be looking at how all the different mechanisms of transport allow different types of organisms to live and function in the environment. We will start with a quick review of active transport, passive transport, endocytosis, and exocytosis. Then, we will observe how it takes many different mechanisms of transport to complete the process of creating chemical energy in the form of ATP. Finally, we will explore the ways that ion channels, pump proteins, etc. are used to facilitate membrane transport.

Cells: A Public Transit System? Recall that the cell membrane, also called the plasma membrane, is a thin and flexible barrier that surrounds a cell and separates the interior and exterior regions of the cell. It is made up of a phospholipid bilayer, a double layer with hydrophobic tails facing inward and hydrophilic heads facing outward. This bilayer acts as a barrier to the movement of ions and small molecules, allowing the cell to maintain its internal environment.

The plasma membrane also contains proteins responsible for a variety of functions, e.g. transport, signaling, and recognition. These proteins can be either integral or peripheral, depending on their location relative to the bilayer or the membrane surface, respectively. In this section, we will focus on the function of transport, with several classes of mechanisms:

1. **Active transport** is the movement of substances across the cell membrane using cellular energy. Active transport can be further classified as *primary* or *secondary*.
2. **Passive transport** is the movement of substances across the cell membrane *without* requiring cellular energy. Examples of passive transport include **diffusion**, **osmosis**, and **facilitated diffusion**.
3. **Endocytosis** is the process by which substances are absorbed by the cell through penetration of the plasma membrane. Some types of endocytosis include **phagocytosis**, **pinocytosis**, and **receptor-mediated endocytosis**.
4. **Exocytosis** is the process by which cells "spit out" substances via fusion of vesicles with the plasma membrane. Don't worry, we will discuss all of these mechanisms in further detail as you move along!

Active Transport Active transport is the movement of molecules across a cell membrane *against* a concentration gradient, which means the concentration of the substance is higher inside the cell than outside the cell, with the process thus requiring energy. This can also happen when the substance to be transported is too large or highly polar through the cell membrane by diffusion.

- **Primary active transport** involves direct transfer of molecules across the membrane using energy from **adenosine triphosphate, ATP**, the energy source of the cell.

Examples of primary active transport include the **sodium-potassium** pump and the **calcium** pump.

- **Secondary active transport** involves transfer of molecules across the membrane using energy stored in a different substance's concentration gradient. This process is usually regulated by special proteins called **cotransporters** or **exchangers**.

An example of secondary active transport is the facilitated diffusion of glucose into cells using the **glucose transporter (GLUT) protein**.

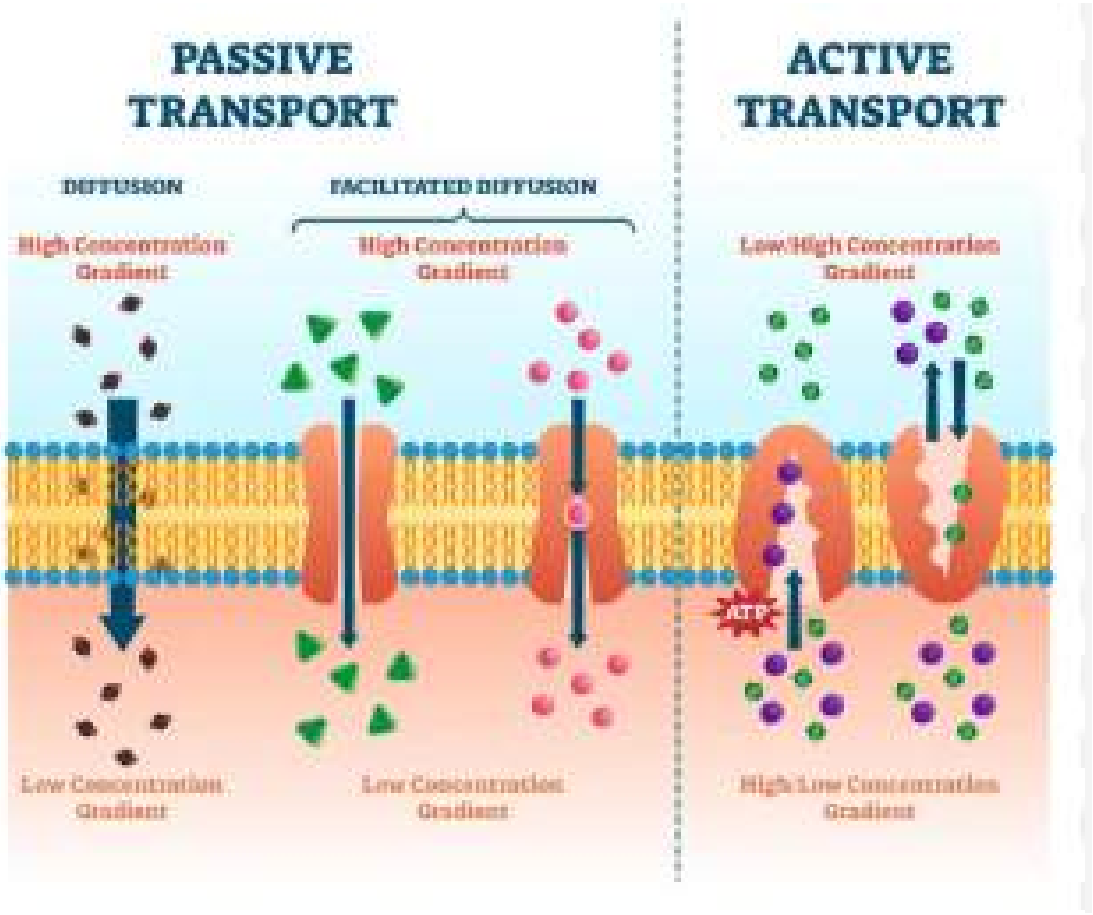


Image Credit: FutureLearn

Passive Transport Passive transport is the movement of molecules across a cell membrane *down* a concentration gradient, which does not require energy (ATP). Note that this is the opposite of active transport.

- Diffusion is the movement of molecules from a region of high solute concentration to a region of low solute concentration. This occurs due to random, thermal motion of the molecules, and requires no energy.
- Osmosis is the movement of water molecules from a region of high water concentration to a region of low water concentration, or high to low osmotic pressure, respectively. Similar to diffusion, osmosis occurs due to random, thermal motions, and also requires no energy.
- Facilitated diffusion is the movement of molecules across a membrane down a concentration gradient with the help of transport proteins. These proteins form channels or carriers through which the molecules can pass, but no energy is required.

Passive transport is highly effective at maintaining the cell's internal environment, or homeostasis.

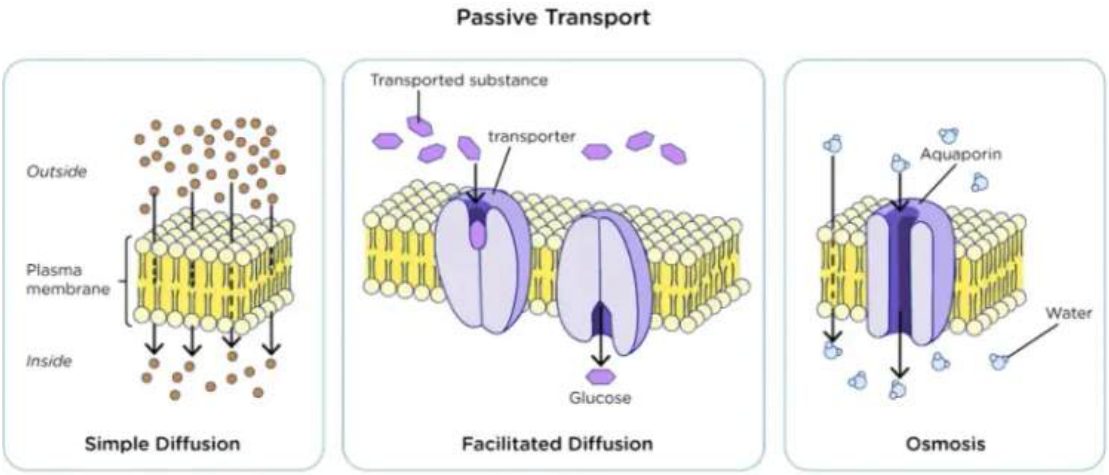


Image Credit: Jack Westin

Endocytosis In endocytosis, a substance is captured from outside the cell via engulfing it with the plasma membrane. The membrane folds over the substance and it becomes completely enclosed by the membrane. At this point a membrane-bound sac, or vesicle, pinches off and moves the substance into the cytosol. There are three main kinds of endocytosis:

1. Phagocytosis is the process by which a cell takes in *solid* particles, e.g. bacteria or cellular debris, by enclosing them in a **phagosome**, a type of vesicle. Phagocytosis is carried out by specialized cells called phagocytes, which are found in tissues such as the skin and the immune system.

2. Pinocytosis is the process by which a cell takes in *liquid* particles, usually extracellular fluid or dissolved substances, by enclosing them in small vesicles called **pinocytotic vesicles**. Pinocytosis is also known as "cell drinking" and is often referred to as a type of "non-specific" endocytosis.

3. Receptor-mediated endocytosis is a type of endocytosis that involves specific substances being internalized by binding to specific *receptors* on the surface of the cell. The receptors and the bound substances are then internalized in a vesicle called an **endosome**.

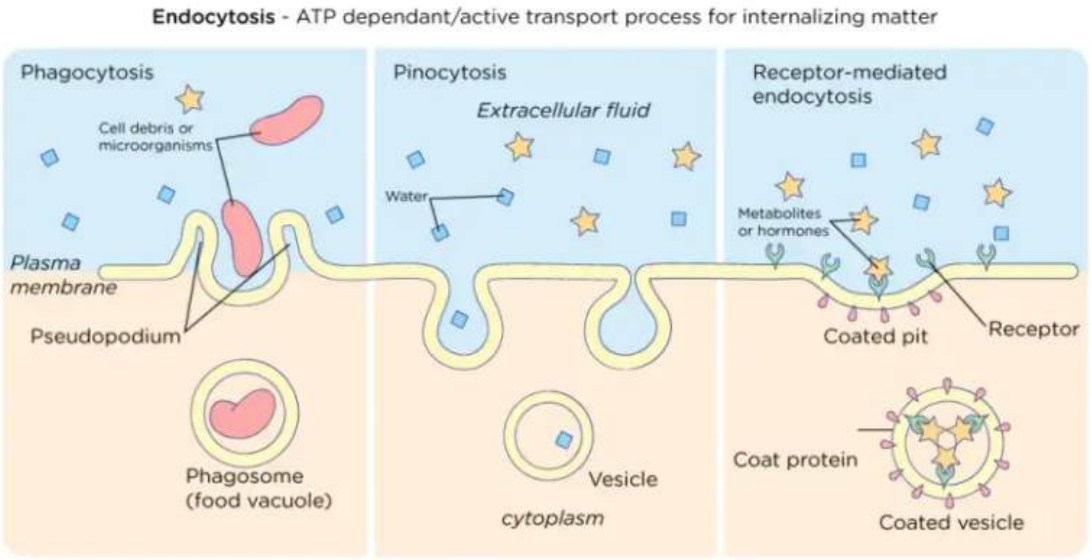


Image Credit: Jack Westin

Exocytosis In exocytosis, a cell secretes substances by expelling them out of the membrane. It is the opposite of endocytosis, where cells internalize substances by engulfing them in smaller organelles (vesicles). Exocytosis is a two-step process:

1. The substance that the cell wants to secrete, usually a protein or lipid, is *synthesized* within the cell and then transported to a storage organelle, called a vesicle.

2. The vesicle *fuses* with the plasma membrane, releasing the substance into the extracellular space. A special class of proteins, **SNAREs (soluble N-ethylmaleimide-sensitive factor attachment protein receptors)**, helps regulate this process. In plant and animal cells alike, exocytosis aids in the secretion of hormones, enzymes, and immune mediators; the elimination of waste products; and the communication between cells. It is also involved in the release of neurotransmitters from neurons and the exfoliation of cells in tissues such as the skin.

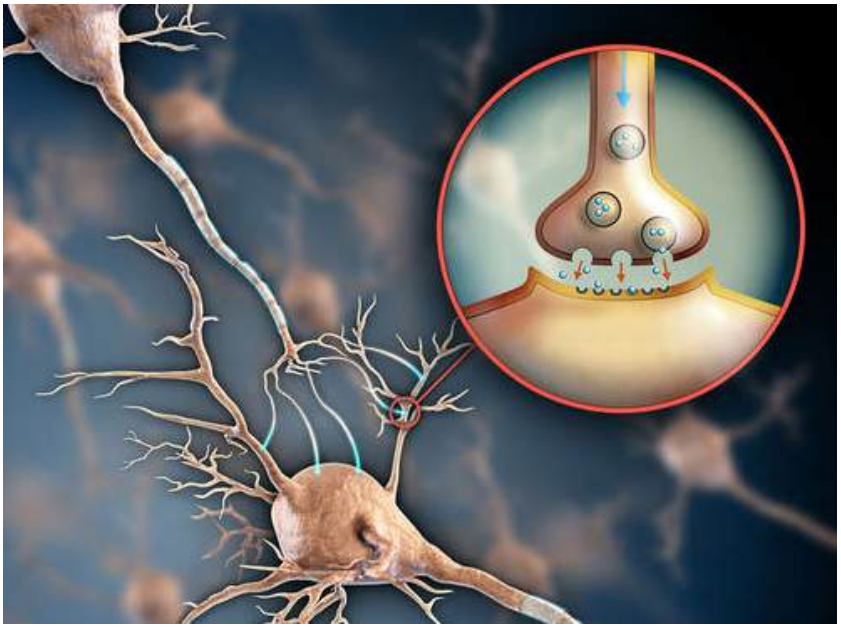


Image Credit: Biology LibreTexts

The above image shows an axon releasing dopamine through exocytosis.

Problem 2.9.1 — Multiple Choice Question

A eukaryotic cell is treated with a drug that inhibits actin polymerization. Which cellular transport process would be MOST directly impaired?

(A) Phagocytosis of bacterial cells
(B) Facilitated diffusion of glucose
(C) Protein pumping by the electron transport chain
(D) Ion movement through channel proteins

Solution: Actin polymerization is critical for processes that involve cell movement and structural changes, including phagocytosis. During phagocytosis, the cell extends its membrane around the bacteria, a process that requires the formation of actin filaments to drive the engulfment of the bacterial cells into the cell's interior. If actin polymerization is inhibited, this process would be most directly impaired. The correct answer is $\boxed{\textbf{(A)}}$.

Problem 2.9.2 — Multiple Choice Question

Which of the following cell organelles helps to transport large extracellular molecules into the cell?

(A) Vacuole
(B) Ribosome
(C) Nucleus
(D) Mitochondria

Solution: Ribosomes are responsible for the synthesis of proteins, the nucleus serves as the repository of genetic information in a cell, and mitochondria are responsible for generating chemical energy for important biological processes. Therefore, (B), (C), and (D) are incorrect. However, vacuoles are responsible for managing waste in cells, particularly, substances coming into the cell as well as expelling substances out of the cell. This is consistent with option $\boxed{\textbf{(A)}}$.

§2.10 Cell Compartmentalization

Compartmentalization in cells is the separation of the cell interior in distinct compartments with specific local conditions that allow the simultaneous occurrence of diverse metabolic reactions and processes. In this section, we will explain how compartmentalization improves cellular efficiency and specialization, describe how organelles create environments suited for specific processes, and more!

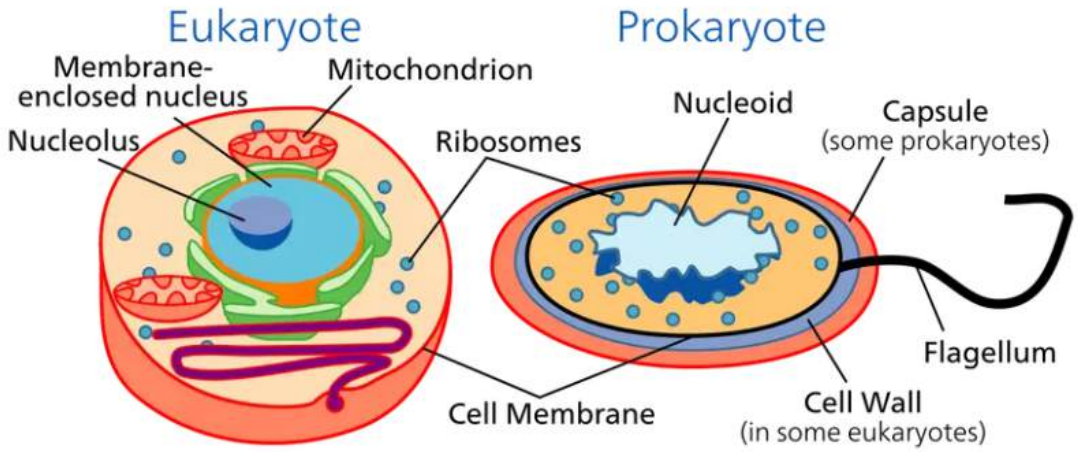
Cell Compartmentalization: An Overview We know that there are two types of cells, prokaryotic and eukaryotic. Prokaryotic cells do not possess a nucleus. One major difference between the two in terms of cell compartmentalization is the fact that eukaryotes compartmentalize their internal processes using **membrane-bound organelles**.

Specifically, in eukaryotic cells, after RNA is made from DNA in the **transcription** process, it moves to the **ribosome** for **translation**. The RNA has two choices as to where it can move out of the nucleus: to either a free-standing ribosome or to the **rough ER**. Additionally, the **mitochondria** has its own internal membrane, producing ATP.

In prokaryotic cells, however, RNA synthesizes proteins immediately after being produced by DNA, because they do not have a nucleus or endoplasmic reticulum. This will lead to more differences in transcription and translation, which will be discussed in a Unit 6.

The underlying idea is that eukaryotes minimize the amount of competing space and surface area, functioning more efficiently than prokaryotes.

Exploring Internal Membranes A major theme in Unit 2 is maximizing the **surface area to volume ratio**. Internal membranes, such as mitochondria and **chloroplasts**, make cellular processes more efficient by minimizing competing interactions and increasing the surface area to volume. In a more intuitive approach, if you already have the cell membrane for transport, there is likely less space available for ATP synthesis. Therefore, the process takes place within the organelles on a separate membrane. This increases the surface area to volume ratio because there are now more folding configurations for the cell membrane.



Problem 2.10.1 — Multiple Choice Question

Which of the following best describes compartmentalization in cells?

(A) The movement of materials across the cell membrane.
(B) Separation of cellular processes into different organelles.
(C) The synthesis of new macromolecules.
(D) The breakdown of nutrients to release energy.

Solution: The concept of cell compartmentalization is entirely for the purpose of minimizing surface area of competing interactions, allowing for more efficient carrying out of cellular processes. It involves the separation of a cell into specialized "compartments," called organelles, where more work can be accomplished with minimal constraints. All other answer choices are not relevant, so the correct answer is $\boxed{\textbf{(B)}}$.

Problem 2.10.2 — Multiple Choice Question

Which of the following best explains how modified proteins are transported within a compartmentalized cell?

(A) Modified proteins are transported in vesicles that travel between membrane-bound organelles within the cell.
(B) Modified proteins are transported within contiguous extracellular membranes that connect membrane-bound organelles.
(C) Modified proteins are transported within contiguous intracellular membranes that connect membrane-bound organelles.
(D) Modified proteins are transported in ribosomes that travel between membrane-bound organelles within the cell.

Solution: A compartmentalized cell has membrane-bound organelles that function together through the use of vesicles. Vesicles transport modified proteins by budding off one organelle and then fusing with another organelle. The correct answer is $\boxed{\textbf{(A)}}$.

§2.11 Origins of Cell Compartmentalization

In the previous section, we discussed what cell compartmentalization and the mechanism in which cells, prokaryotic and eukaryotic, divide themselves into distinct, specialized compartments (organelles) enclosed by membranes, allowing for efficient cellular and biochemical processes. In this section, we will explore the evolutionary aspects of what made cell compartmentalization possible and the theory of origin of such specialized organelles.

Prokaryotic Cells Prokaryotic cells are defined as small cells simply composed of DNA in the form of a circular ring that floats within the cell. These cells are believed to be the earliest life forms on Earth. Prokaryotes were estimated to have existed as early as 4 billion years ago, but eukaryotes only appeared 1.8 billion years ago. Many biologists believe that eukaryotic cells descended from prokaryotic cells, despite the latter being much more complex in structure. For example, eukaryotic cells contain mitochondrion, unlike prokaryotic cells.

Endosymbiotic Theory A very puzzling question in biology is, "Why do we have mitochondria in our cells but the mitochondria has its own membrane separate from the plasma membrane?" Currently, the **endosymbiotic theory** serves to explain how eukaryotic membrane-bound organelles existed in eukaryotic cells. The theory states that an early ancestor of all eukaryotic cells engulfed a prokaryotic cell, causing the prokaryotic to become an **endosymbiont**, defined as a cell within another cell.

These small endosymbionts were capable of providing extra energy for the cell, which served as an evolutionary advantage. As time went on, cells containing this extra prokaryotic cell were more fit, i.e. could survive and reproduce quickly. This led to the existence of eukaryotic cells! While we know prokaryotes generally lack internal membrane-bound organelles, they still possess internal regions with unique structures and functions. These regions are just not defined by outer membranes. The **cell wall** plays a key role in maintaining the cell's shape, protecting the interior, and preventing the cell from bursting when it takes up water.

Scientific Evidence In 1883, botanist **Andreas Schimper** discovered **plastids**, double membrane-bound organelles found in plant algae cells, underwent cell division just as bacteria did. Later in the 1950s and 60s, biologists found that mitochondria and plastids were composed of their own DNA. Even more convincing, the DNA closely resembled that of prokaryotes, rather than eukaryotes, and the mitochondrion was equipped with its own membrane, similar to a free-living cell. Thus, we conclude that the mitochondrion was once a prokaryote.

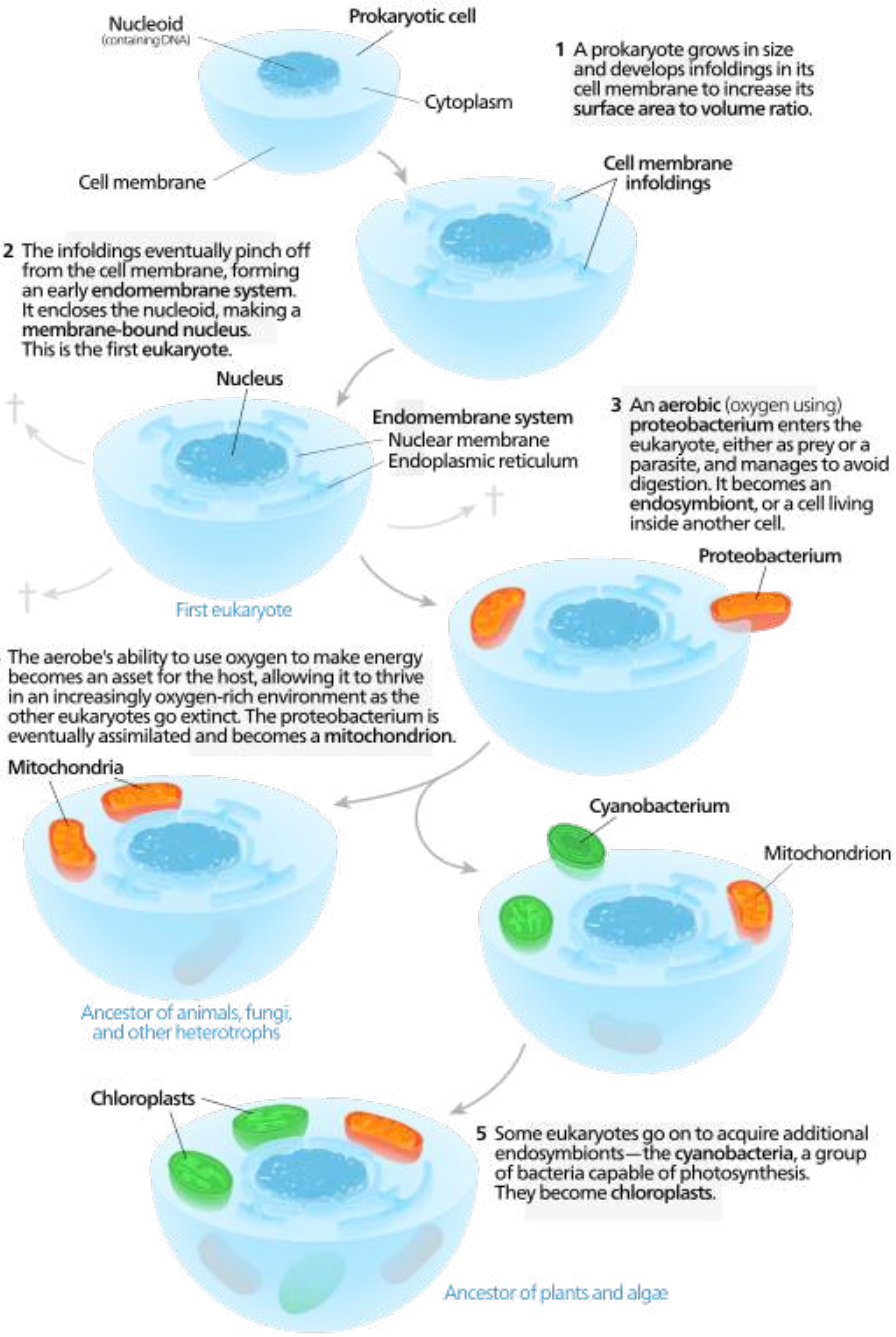


Image Credit: Biology LibreTexts

Problem 2.11.1 — Multiple Choice Question

The endosymbiotic theory explains the origin of which of the following?

(A) The cell membrane
(B) The nucleus
(C) Mitochondria and chloroplasts
(D) The endoplasmic reticulum

Solution: As stated in the text, the endosymbiotic theory primarily explains the origin of mitochondria and chloroplasts, suggesting they arose from free-living prokaryotic cells that were engulfed by early eukaryotic cells. Therefore, the correct answer is $\boxed{\textbf{(C)}}$.

Problem 2.11.2 — Multiple Choice Question

The endosymbiotic theory suggests which of the following?

(A) Eukaryotic cells evolved from prokaryotic cells through a process of cell fusion.
(B) Eukaryotic organelles evolved from free-living prokaryotes via endosymbiosis.
(C) Eukaryotic cells are simpler than prokaryotic cells.
(D) Prokaryotic cells evolved from eukaryotic cells through a process of cell division.

Solution: The endosymbiotic theory proposes that certain organelles, such as mitochondria and chloroplasts, were once free-living prokaryotic cells, which were engulfed by an early eukaryotic cell, but instead of being digested, they established a symbiotic relationship, where both organisms benefited. Over time, these engulfed prokaryotes evolved into the organelles we see in eukaryotic cells today, such as mitochondria (which are thought to have evolved from aerobic bacteria) and chloroplasts. Thus, the correct answer is $\boxed{\textbf{(B)}}$.

§2.12 Unit 2 Practice Questions

Problem 2.12.1 — 2013 AP Biology FRQ

The following data were collected by observing subcellular structures of three different types of eukaryotic cells.

RELATIVE AMOUNTS OF ORGANELLES IN THREE CELL TYPES

Cell Type	Smooth ER	Rough ER	Mitochondria	Cilia	Golgi Bodies
X	Small amount	Small amount	Large number	Present	Small amount
Y	Large amount	Large amount	Moderate number	Absent	Large amount
Z	Absent	Absent	Absent	Absent	Absent

Based on an analysis of the data, **identify** a likely primary function of each cell type and **explain** how the data support the identification.

Solution: We begin with cell type X. The presence of cilia—hair-like structures used for propulsion—suggests a role in movement. Moreover, the large number of mitochondria indicates the need for high energy expenditure, which is consistent with the active movement of the cell. These two pieces of evidence suggest that the likely primary function of cell type X is movement.

We now move on to cell type Y. It contains a large amount of both smooth and rough ER suggest, suggesting a high capacity for protein and lipid synthesis. Therefore, the likely primary function of cell type Y is the synthesis of hormones.

Finally, for cell type Z, we observe that there is an absence of all listed organelles, indicating that this cell is not performing any major functions or is experiencing programmable cell death. Thus, the likely primary function of cell type Z can be either dormancy or apoptosis.

Problem 2.12.2 — 2017 AP Biology FRQ

Estrogens are small hydrophobic lipid hormones that promote cell division and the development of reproductive structures in mammals. Estrogens passively diffuse across the plasma membrane and bind to their receptor proteins in the cytoplasm of target cells.

(a) **Describe** ONE characteristic of the plasma membrane that allows estrogens to passively cross the membrane.

(b) In a laboratory experiment, a researcher generates antibodies that bind to purified estrogen receptors extracted from cells. The researcher uses the antibodies in an attempt to treat estrogen-dependent cancers but finds that the treatment is ineffective. **Explain** the ineffectiveness of the antibodies for treating estrogen-dependent cancers.

Solution to part a: The plasma membrane of an animal cell possesses a special structure known as the phospholipid bilayer, a hydrophobic (nonpolar) medium through which small, lipid-soluble molecules such as estrogens can diffuse through the membrane in the absence of a transport protein. More specifically, estrogens are steroid hormones, classified as lipids, essentially "sliding" through the spaces between the phospholipid tails to reach the other side of the membrane.

Solution to part b: We know that the plasma membrane of a cell acts as a barrier, preventing large molecules such as antibodies from freely entering the cell. Additionally, estrogen receptors are located inside the cell (cytoplasm), so they cannot bind with antibodies circulating in the extracellular area (bloodstream). Because binding estrogen receptors with large antibodies is not a feasible process, the proposal for treating estrogen-dependent cancers with antibodies is ineffective.

Problem 2.12.3 — 2018 AP Biology FRQ

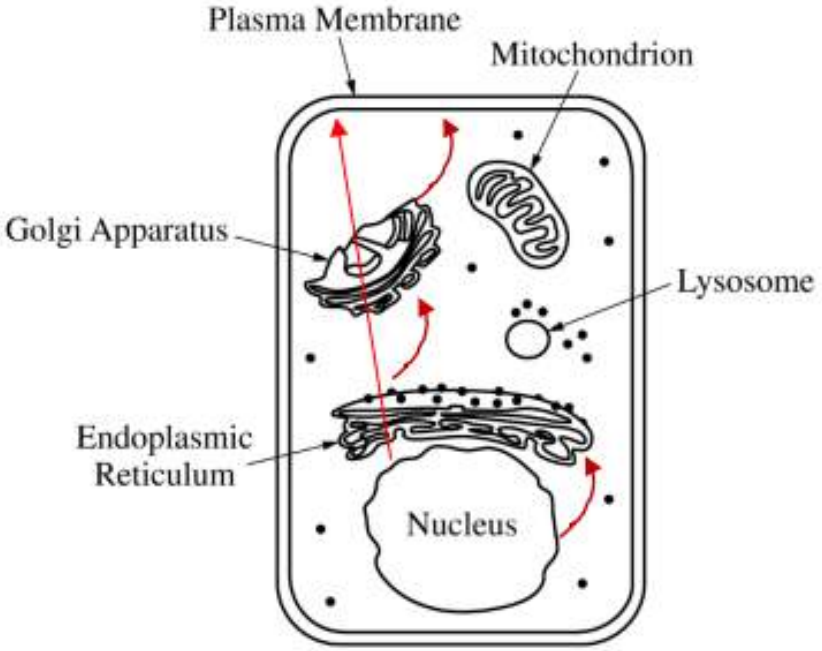
Cystic fibrosis is a genetic condition that is associated with defects in the CFTR protein. The CFTR protein is a gated ion channel that requires ATP binding in order to allow chloride ions (Cl^-) to diffuse across the membrane.

(a) In the provided model of a cell, **draw** arrows to describe the pathway for production of a normal CFTR protein from gene expression to final cellular location.

(b) **Identify** the most likely cellular location of the ribosomes that synthesize CFTR protein.

(c) **Identify** the most likely cellular location of a mutant CFTR protein that has an amino acid substitution in the ATP-binding site.

Solution to part a: We first consider the synthesis of the CFTR protein. In the nucleus, transcription occurs, and mRNA exits through nuclear pores into the cytoplasm. Then, ribosomes carry out the translation on the rough endoplasmic reticulum. The synthesized CFTR protein now moves from the rough ER to the Golgi apparatus, where it is modified. Finally, the vesicles transport the protein to the plasma membrane of the cell. Based on this diagram, our drawing should follow a pathway and have either continuous or multiple discontinuous arrows in this format:



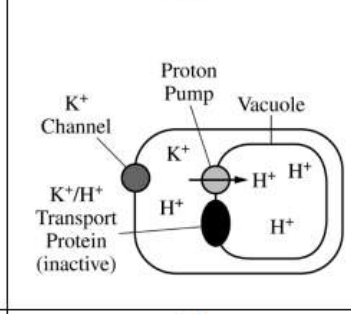
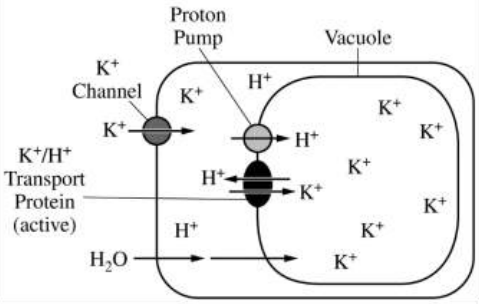
Make sure to label other important organelles present in a general cell diagram!

Solution to part b: We established the answer in our logical approach to part (a). The ribosomes that synthesize the CFTR protein are located in the rough endoplasmic reticulum (ER).

Solution to part c: The ATP-binding site is crucial for the CFTR channel to function properly, because it allows the necessary changes to open and close the protein channel as needed. An amino acid substitution causes a mutation in the ATP-binding site, affecting the CFTR protein's ability to bind ATP. However, the protein's inherent signaling sequences would remain intact, allowing it to be targeted to the plasma membrane.

Problem 2.12.4 — 2019 AP Biology FRQ

TABLE 1. CHANGES IN MORNING GLORY PETAL CELLS DURING FLOWER OPENING

	BUD	OPEN FLOWER
		
Vacuole pH	6.6	7.7
Flower Color	Red	Blue
Cell Volume	Small	Large

The petal color of the Mexican morning glory (*Ipomoea tricolor*) changes from red to blue, and the petal cells swell during flower opening. The pigment heavenly blue anthocyanin is found in the vacuole of petal cells. Petal color is determined by the pH of the vacuole. A model of a morning glory petal cell before and after flower opening is shown in Table 1.

(a) **Identify** the cellular component in the model that is responsible for the increase in the pH of the vacuole during flower opening AND **describe** the component's role in changing the pH of the vacuole.

(b) A researcher claims that the activation of the K^+/H^+ transport protein causes the vacuole to swell with water. **Provide reasoning** to support the researcher's claim.

Solution to part a: pH is a metric used to describe the number of hydrogen ions (H^+) in an aqueous environment. Also, it is based on a decreasing base-10 logarithm, so a higher pH would correspond to a lower concentration of H^+ ions and vice versa. Therefore, a cellular component responsible for increasing the pH of the vacuole during flower opening must cause the concentration of H^+ ions to decrease. Via inspection of the diagram, it is clear that the K^+/H^+ transport protein is responsible for this process. Specifically, it removes H^+ ions from the vacuole, which experiences an increase in pH.

Solution to part b: Since the vacuole swells with water, there is a high solute concentration inside the vacuole. When the K^+/H^+ transport protein is activated, the K^+ ions are transported into the vacuole, while H^+ ions are transported out, creating a hypertonic solution with a decreased water potential.

3 Cellular Energetics

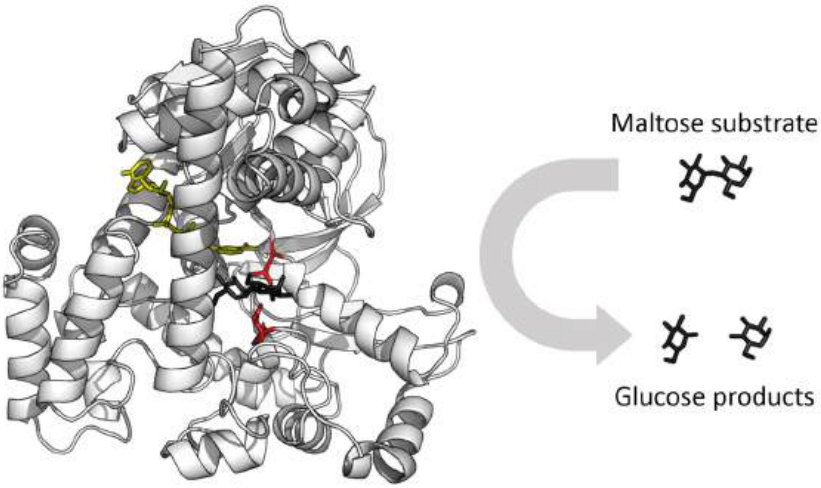
Cellular energetics explores how organisms manage energy resources like storage and utilization. In the context of this course, cellular energetics refers to the production of ATP (adenosine triphosphate) through cellular respiration and photosynthesis. In this unit, we will cover key concepts such as metabolism, ATP, and thermodynamics, laying the foundation for understanding life's energy processes.

§3.1 Enzyme Structure

In this section, we will learn about a special protein that speeds up biochemical reactions in cells: enzymes. Enzymes help facilitate biochemical reactions in our bodies. They aid in everything from breathing to digestion. In this section, we will focus on the molecular structure of enzymes that influences their function in cells.

Living Organisms and Energy The constant input of energy allows living systems to maintain their complex organization. Certain **metabolic processes**, such as cellular respiration and photosynthesis, are responsible for converting nutrients into usable energy. In addition to fueling cellular processes, the input of energy helps in maintaining the structure of the cell. However, for these processes to occur, enzymes are required.

Enzymes are a type of protein that serve as **catalysts**. They speed up chemical reactions in cells which enable them to carry out the many functions necessary for life. Enzymes are involved in various cellular processes, e.g. metabolism, cell division, and gene expression, and they are needed for cells to function properly.

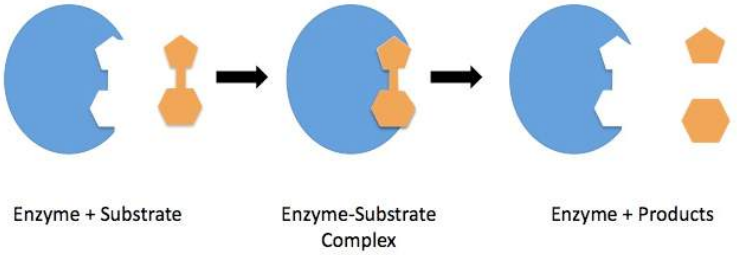


Shape of Enzymes This course emphasizes understanding the structure of enzymes and how it relates to their functions such as catalyzing the chemical reactions necessary for metabolism, growth, and reproduction in various living beings. Their structure plays an important role in their ability to perform such functions.

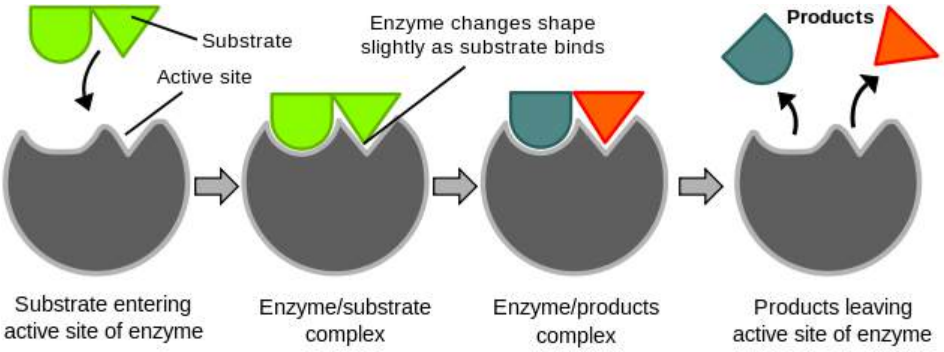
As with all proteins, enzymes consist of polypeptide chains, which are long chains

of amino acids. The unique amino acid sequence in an enzyme determines its **primary structure**. However, the actual complexity of enzymatic functions depends on higher levels of structure. The three-dimensional structure of enzymes can be divided into three categories:

- **Secondary structure**, which refers to the local patterning of amino acids, such as the creation of alpha-helices or beta-sheets.
- **Tertiary structure**, which refers to the overall 3D configuration of the enzyme, including the active site and other functional groups.
- **Quaternary structure**, which refers to the spatial relationship between multimeric (a complex of multiple identical or non-identical subunits) enzyme subunits. Essentially, enzymes bind to *substrate* molecules and catalyze specific biological processes. The active site of an enzyme is the location where the substrate binds and the chemical reaction occurs. The enzyme's 3D structure, including its active site, must be complementary to the substrate for the enzyme to bind it and catalyze the reaction.



Furthermore, enzymes are dynamic at a molecular level. They can change shape upon binding to a substrate or other molecules, a phenomenon known as the *induced-fit mechanism*. This conformational change can enhance the specificity and efficiency of the enzyme-substrate interaction, thus increasing the rate of the chemical reaction.



Active Site The active site is defined as the region of the enzyme where the substrate(s) bind and the chemical reaction occurs. This location is usually a depression or cleft on the surface of the enzyme which is often lined up with specific amino acids that interact with the substrate.

It is important to note that enzymes are highly specific and will only catalyze specific reactions. This is because the shapes of their active sites are unique, which only fits the substrate for which it is intended.

For an enzyme-mediated chemical reaction to occur, several conditions must be met.

1. The substrate must first bind to the active site of the enzyme. The active site is a specific region on the surface of the enzyme that is designed to interact with the substrate.

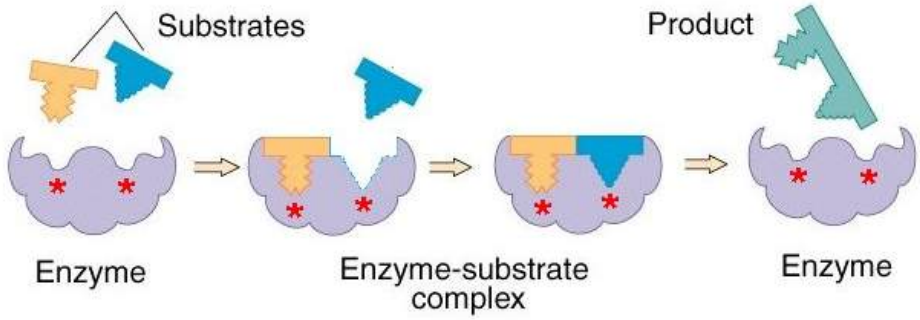
2. The shape and charge of the substrate must be compatible with the enzyme's active site in order to bind effectively. This reason is that active sites are designed with the sole purpose of fitting the substrate, and the amino acids located in the active site have specific ionic charges that interact with the substrate.

Note 3.1.1

If the shape or charge of the substrate is not compatible with the active site, the substrate cannot bind properly and a chemical reaction does not occur.

Induced Fit We describe induced fit as an enzyme catalysis mechanism where an enzyme changes its conformation or shape upon binding to the substrate, resulting in a tighter and more specific binding and ultimately, a more efficient catalytic reaction.

In induced fit, the enzyme's active site is not a rigid, previously formed structure that exactly matches the substrate's shape (such as a glove that easily fits into your hand), but rather a flexible structure that adjusts its shape upon binding to the substrate. As the substrate enters the active site, the enzyme's amino acid residues in the active site move a little to adjust their positions, resulting in a tighter fit between the enzyme and substrate. This tighter fit allows for more efficient formation of the transition state, which is the high-energy intermediate between the substrate and the products, and hence increases the rate of the reaction.



Induced-Fit Model of enzyme catalysis

The induced fit model has been compared to a hand-in-glove model, wherein it may be difficult to insert the first finger in the proper place, but once done, the other fingers enter easily because the glove is now properly aligned.

This mechanism of enzyme catalysis can also play a role in substrate specificity. When the enzyme's active site is flexible, it can adjust its conformation to fit a variety of different substrates. However, the adjustments it makes to bind different substrates may be different, and only the substrate that fits the active site the best will be catalyzed with the highest efficiency.

In addition, induced fit can also contribute to the regulation of enzyme activity by

controlling the rate of substrate binding and product release. Some enzymes can tightly bind the substrate only in certain conditions such as the presence of a *cofactor* or a specific environment, in these cases the induced fit mechanism is more relevant for the regulation of enzyme activity than for substrate specificity.

Problem 3.1.2 — Multiple Choice Question

Which of the following best describes the process of induced fit?

(A) A substrate binds to the active site of an enzyme, causing the conformation of the active site to change slightly.
(B) A substrate binds to an allosteric site on an enzyme, causing the conformation of the allosteric site to change slightly.
(C) A substrate changes conformation and then binds to the active site of an enzyme.
(D) A substrate binds to the active site of an enzyme without either structure changing conformation.

Solution: Option (A) describes allosteric regulation, where a substrate binds to a site other than the active site (the allosteric site), and this binding induces conformational changes in the enzyme that affect its activity at the active site, so eliminate it. Option (C) is the reverse of what is true; in induced fit, the substrate initiates a conformational change in the enzyme, but it does not actually change conformation first, so we eliminate it. (D) is not possible according to the induced fit definition; if neither substrate or active site change in conformation, no induced fit actually occurs, so we eliminate the option. The correct answer is $\boxed{\textbf{(A)}}$, because as the substrate enters the active site, the enzyme undergoes conformational changes to create a more optimal binding environment.

Problem 3.1.3 — Multiple Choice Question

Pancreatic amylase is a digestive enzyme found in the small intestine. It helps break down large starch molecules later in the digestive process. Pancreatic amylase is unable to break down lipids.

Which of the following best explains why pancreatic amylase is able to break down starches, but not lipids?

(A) Lipids are too hydrophobic to be broken down by enzymes.
(B) Enzymes bind only to their specific substrates.
(C) Lipids are too small to bind to enzymes.
(D) Enzymes denature in the presence of lipids.

Solution: We first eliminate option (A). Although lipids are hydrophobic (water-fearing), this does not explain why an enzyme cannot break them down. In addition, lipids can be large or small and still be recognized by the appropriate enzyme, so option (C) is also wrong. Denaturation refers to a change in the enzyme's structure that renders it inactive. Lipids can sometimes cause denaturation under extreme conditions, but this is not why pancreatic amylase cannot break down lipids, so option (D) is not the best

answer. However, we do know that enzymes are highly specialized and only interact with specific substrates. Pancreatic amylase is designed to bind to the specific chemical bonds in starch molecules, however, it does not possess the active site or shape necessary for binding to lipid molecules. This is consistent with **(B)**.

§3.2 Enzyme Catalysis

In biology, living systems experience many cellular and metabolic processes that are vital to sustaining life. However, these processes have to occur in such a way that the transfer of energy is stable and that organisms' energy states are not disrupted. Enzymes are important molecules involved in such processes. Particularly, they speed up biochemical reactions, enabling processes necessary for survival and growth.

Constant Input of Energy Metabolism, growth, and reproduction are important processes that occur within cells and organisms, and involve many different biomolecules (reference Unit 1 if you forgot these), such as enzymes, which catalyze chemical reactions and maintain proper functioning for cells and organisms.

Enzyme catalysis plays an important role in the complex organization of living systems by speeding up cellular functions. For example, our bodies have enzymes that help break down nutrients to generate energy, synthesize macromolecules such as DNA, RNA, proteins, and transfer genetic information between nucleic molecules.

This allows living systems to perform a variety of chemical reactions necessary to maintain life while preserving a relatively steady state, through constant input of energy and exchange of biological macromolecules.

The constant input of energy is not only important to the functioning of enzymes, but to also power the chemical reactions that they catalyze. Enzyme activity is usually combined with energy-consuming (endergonic) reactions such as the transfer of electrons, protons, or ATP hydrolysis (we learn about this in section 3.4).

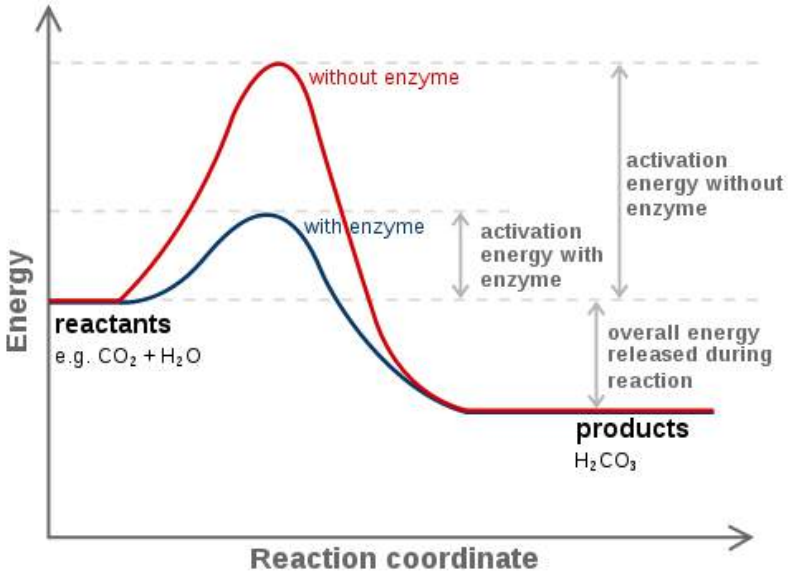
The exchange of macromolecules is another important aspect of the highly complex organization of living systems. Proteins and nucleic acids are constantly being synthesized, degraded, and recycled. Enzymes play an important role in this process by catalyzing the synthesis and breakdown of these molecules.

What is Catalysis? Catalysis refers to the process by which a **catalyst** speeds up a chemical reaction.

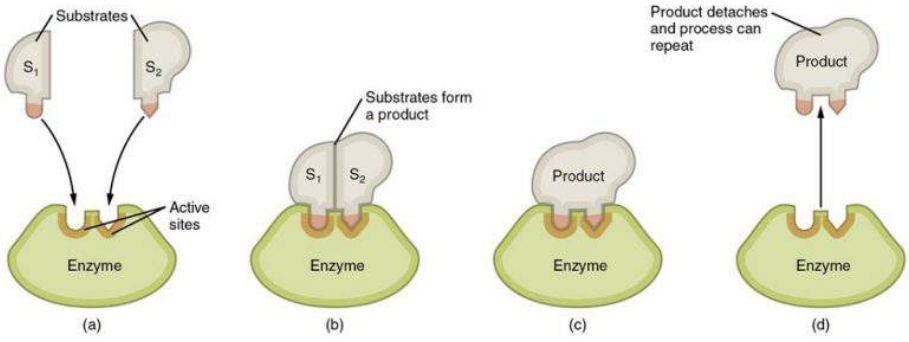
Specifically, catalysts provide an alternate reaction pathway with a lower **activation energy**. In other words, catalysts can speed up chemical reactions by offering an alternate way for reactants to transform into products. This can be achieved by:

- Changing the relative positions of atoms in the reactants, making it easier for them to form the products.
- Stabilizing the intermediate products or **transition states**, making the reaction proceed more smoothly.

- Providing an alternative and more favorable transition state for the reaction to proceed.



Enzymes: A Closer Look at the Behavior of Catalysts Enzymes are specific for the reactions they catalyze and the substrates (consider substrates as equivalent to reactants) they act on. They do this by having a unique 3D structure that allows them to bind to the substrates in a specific way, a process called **enzyme-substrate recognition**. This binding forms an intermediate complex called the **enzyme-substrate complex**, which is more reactive than the substrate alone.



As the enzyme catalyzes the reaction, the substrate is converted into products, which dissociate from the enzyme, now free to bind to other substrate molecules. Through this process, enzymes are reused several times.

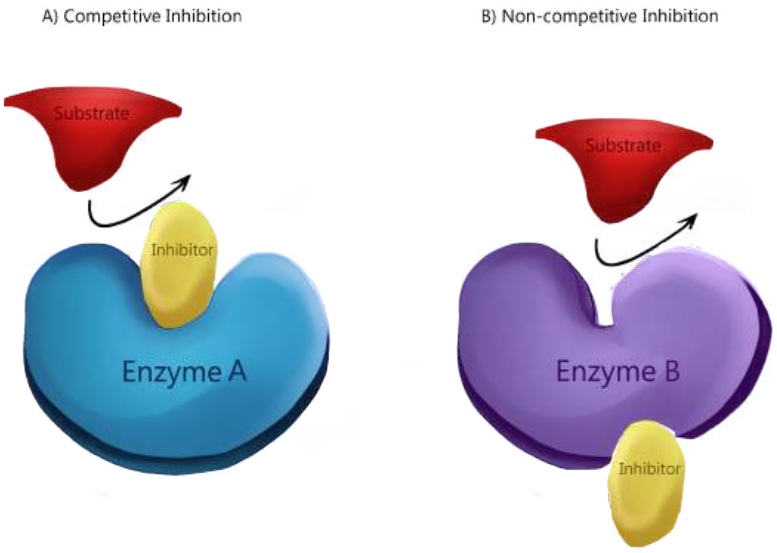
Factors Affecting Enzyme Activity The rate of an enzyme-catalyzed reaction is affected by several factors, e.g. the concentration of substrate, the presence of inhibitors or

activators, and the temperature and pH of the environment.

- Increasing substrate concentration can increase the rate of an enzyme-catalyzed reaction, up to a certain point, after which the rate levels off at a point known as the **saturation point**.
- Inhibitors are molecules that bind to enzymes and decrease the rate of reaction. They can do this by binding to the active site of the enzyme and preventing substrate binding, or by altering the shape of the enzyme so it cannot bind to the substrate.
- Activators are molecules that bind to enzymes and increase the rate of reaction. They can do this by increasing the stability of the enzyme-substrate complex, making it more likely that the substrate will bind to the enzyme.
- The temperature and pH of the environment also affect enzyme activity. Most enzymes have an *optimal* temperature and pH at which they function best. At temperatures or pH values outside this range, the enzyme may become denatured (break apart), or lose its shape, and can no longer function.

Enzyme Inhibitors Some substances can activate or inhibit various enzymatic processes. These are called **enzyme inhibitors**. We can summarize them in this bulleted list:

- **Competitive inhibitors** bind at the enzyme's active site, blocking the active site from the substrate, slowing catalysis.
- **Noncompetitive inhibitors** bind to the enzyme's allosteric site (other than the active site), altering the active site in such a way that it does not allow the substrate to bind, slowing catalysis.
- **Activators** can bind at various locations in an enzyme, allowing the enzyme to more successfully bind to the substrate, speeding up catalysis.



Problem 3.2.1 — Multiple Choice Question

Acetylcholine (ACh) is an important signaling molecule in the nervous system. After it transmits a signal, ACh is broken down by the enzyme acetylcholinesterase (AChE) in a reaction known as ACh hydrolysis.

Which of the following best describes the effect AChE has on the hydrolysis of ACh?

(A) AChE increases the activation energy of ACh hydrolysis, increasing the rate of the reaction.
(B) AChE increases the activation energy of ACh hydrolysis, decreasing the rate of the reaction.
(C) AChE decreases the activation energy of ACh hydrolysis, increasing the rate of the reaction.
(D) AChE decreases the activation energy of ACh hydrolysis, decreasing the rate of the reaction.

Solution: The enzyme AChE acts as a catalyst in the reaction of ACh hydrolysis. By definition, catalysts decrease the activation energy of a reaction, so we eliminate options (A) and (B). Decreasing the activation rate of a reaction causes its rate to increase, as the reactant molecules have to overcome a smaller barrier, eliminating option (D). The correct answer is **(C)**.

Problem 3.2.2 — Free Response Question

A scientist wants to study the effect of pH on the activity of an enzyme called "Protein P." He prepares a solution of the enzyme at a concentration of 0.125 mg/mL and adds it to a reaction mixture containing the substrate for the enzyme. Then he measured the rate of the reaction at different pH levels. The table below shows his results.

pH	Reaction Rate (mM/min)
7.0	0.10
7.5	0.15
8.0	0.20
8.5	0.15
9.0	0.10

Based on these results, answer the following questions:

(a) At which pH level is the enzyme most active?
(b) How does the activity of the enzyme change as the pH deviates from its optimal range?
(c) How would the activity of the enzyme be affected if the pH deviated too far from the optimal range? What changes to the enzyme might cause this to occur?
(d) In the living cells, the enzyme is surrounded by a variety of buffers that helps in maintaining the pH, what role do you think buffer play in this enzyme activity?

Solution to part a: The enzyme is most active at the instant when the rate of the chemical reaction is maximized. At a pH of $\boxed{8.0}$, the rate of the chemical reaction is maximized as 0.20 mM/min, so the enzyme is most active at this pH level.

Solution to part b: By inspection, as the pH deviates from its optimal range, the activity of the enzyme $\boxed{\text{decreases}}$.

Solution to part c: Enzymes have a specific pH range in which their functioning is optimal. The activity of the enzyme decreases significantly when the pH deviates too far from the optimal range; specifically, the enzyme may become denatured, or lose its shape, and can no longer function.

Solution to part d: Buffers are systems that can maintain the pH in the surrounding environments of enzymes. Specifically, if the pH becomes low, buffers can remove H^+ ions and vice versa.

§3.3 Environmental Impacts on Enzyme Function

Enzymes are great, but their function is often dictated by the environment around them. Therefore, we must always strive to maintain a suitable environment, so that these molecules can help us carry out life's major cellular and metabolic processes. In this section, we explore how temperature, pH, and substrate concentration affect enzyme function. We will also talk about denaturation and how it alters enzyme structure and disrupts activity. Finally, we will talk about inhibitors and how they affect the efficacy of enzyme-mediated processes.

Enzymes and the Environment Environmental changes affect the speed in which enzymes catalyze chemical reactions. Proteins that are denatured lose their function, but this can sometimes be reversed through a process known as **renaturation**. However, in most cases, denaturation is irreversible because of the detrimental environmental changes which caused it in the first place. There are many ways to denature a protein/enzyme, and this topic frequently appears on FRQs, so keep this in mind!

Temperature The temperature of the environment plays a big role in enzyme function. It can speed up or slow down several reactions. Generally, lower temperatures correlate to slower molecular speeds and vice versa. For example, in a relatively cold environment, there are less opportunities for an enzyme and substrate to interact with each other. This slows the rate of reaction and reduces the effect of the enzyme.

On the other hand, higher temperatures result in molecules moving more quickly and colliding more frequently. By definition, the rate of reaction also increases. However, a specific threshold temperature must not be exceeded. If this happens, the enzyme begins to denature. Specifically, too high temperatures cause the bonds—that hold amino acids in their 3D shape—to break. As an enzyme loses its shape, its *active site* and overall function becomes nonexistent. Recall from Unit 1, structure is important for function, so if the structure is significantly altered, the protein will malfunction.

For this reason, enzymes have an **optimal temperature range** in which they can function. Intuitively, enzymes working in the human body function best at around our

body temperature, 97 to 99 degrees Fahrenheit, or $\approx 37°C$. When temperatures are outside the optimal range, enzymes are not able to perform necessary life-sustaining reactions.

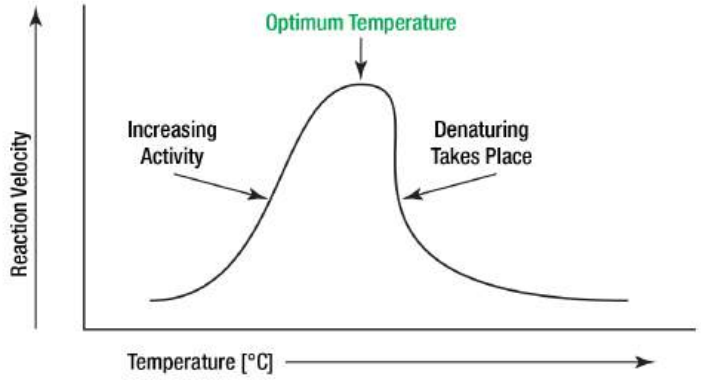


Image Credit: Worthington Biomedical

pH pH is a metric used to describe the number of **hydrogen ions** (H^+) present in a solution. When there is a high concentration of H^+, the solution has a low pH and is considered *acidic*. On the other hand, if there a small concentration of H^+ ions, the solution has a high pH and is considered *basic*. All enzymes have an **optimal pH** where they have the most activity. If the pH goes outside this optimal range, the activity of the enzyme slows down and the enzyme can denature, so the substrate can no longer bind to an active site.

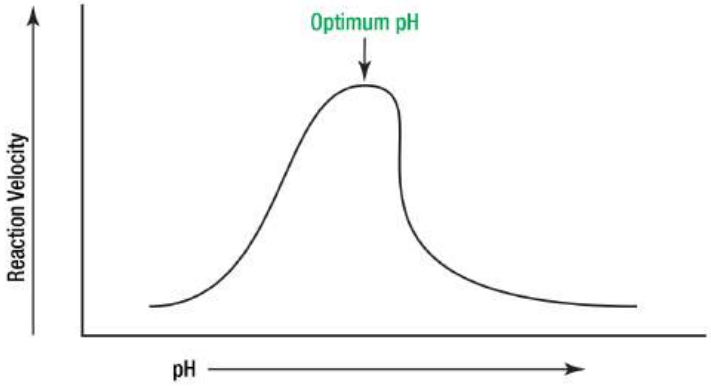


Image Credit: Worthington Biomedical

At 25°C, which is the standard temperature, most enzymes function best at a pH of 7, but this does not hold true for *all* enzymes. For example, **pepsin**, a digestive enzyme found in the stomach, works best at a pH of 2 because the environment is acidic. Similarly, enzymes located in the **lysosome** function best at an acidic pH.

Note 3.3.1

If pH values are outside the optimal range, hydrogen bonds will be altered by the imbalance, altering the structure of the protein and its function, causing the enzyme to get denatured.

Concentration If the concentration of either an enzyme or substrate is increased, the reaction rate should also increase, as there is greater likelihood for the two to interact. Ideally, the concentrations of both species should increase by about the same factor, because if only one were to increase, the other would act as a **limiting reagent**. An example of a limiting reagent is shown below.

The concentration of both enzymes and substrates can affect the overall rate of the reaction. Higher concentrations make it more likely that the two will react with one another, and vice versa. If either is in small quantities, there will be fewer molecules available to bring about a reaction.

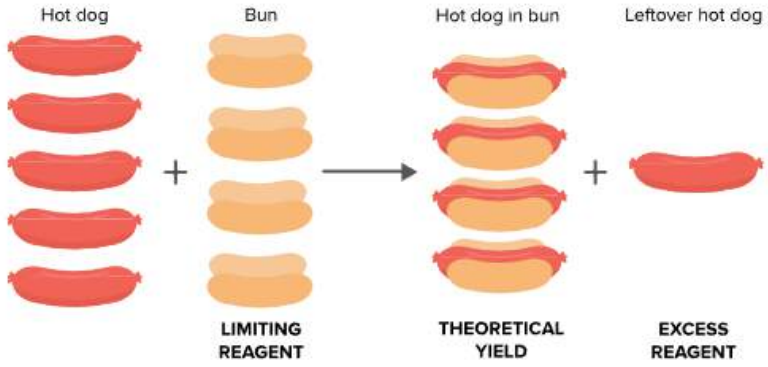


Image Credit: Khan Academy

As mentioned above, many situations can alter an enzyme's function, some of which can lead to denaturation. This can be either temporary or permanent, depending on the level of damage.

Our bodies maintain a strict range of temperatures and pH levels at which our enzymes can function optimally. If we enter a range that does not support enzyme activity, e.g. high temperatures, acidic/basic environment, our enzymes may denature, placing us in a life-threatening situation. Fortunately, we have a number of checks and balances to ensure that optimal ranges can be met for a certain duration.

Inhibitors Enzyme inhibitors are molecules that alter the structure of proteins, but do not denature them. **Competitive inhibitors** bind to the **binding site** that the substrate is supposed to bind to. In doing so, the protein is not altered in any way, but it's less likely for the substrate to bind to its enzyme.

Meanwhile, **noncompetitive inhibitors** actually alter the structure of the protein. They do not necessarily bind to the active site of the enzyme, but they bind somewhere else. This causes the original binding site to change its shape, which means the intended substrate cannot easily fit in.

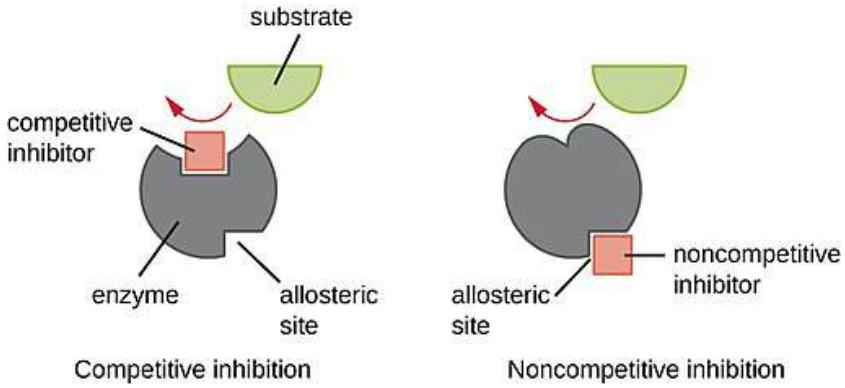
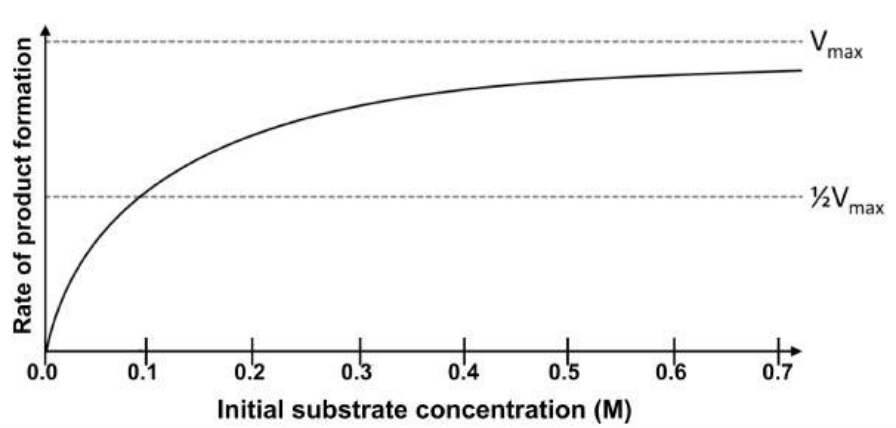


Image Credit: Chemistry LibreTexts

In general, enzyme inhibitors can decrease the rate of reaction. Depending on the situation, both competitive and noncompetitive inhibitors can or cannot be reversed.

Problem 3.3.2 — Multiple Choice Question

Several scientists are studying the effect of initial substrate concentration on the activity of an enzyme. They perform a series of enzyme-controlled reactions, keeping the concentration of enzyme constant but increasing the initial concentration of substrate in each trial. The graph below shows their results.



Based on the data above, which of the following best describes what happens to the rate of product formation at higher initial substrate concentrations?

(A) The rate of product formation decreases because almost all enzyme is bound to the substrate.
(B) The rate of product formation drops because there is no substrate available to bind to the enzyme.
(C) The rate of product formation decreases because there is no substrate available to bind with the enzyme.
(D) The rate of product formation drops because almost all of the enzyme is bound to the substrate.

Solution: We can immediately eliminate options (A) and (C); the rate of product for-

mation actually increases, not decreases, with increasing initial substrate concentration. However, the increase in rate of product formation is bounded, i.e. it levels off. We can notice a plateau in the rate of product formation as the initial substrate concentration reaches 0.7 M. This occurs because nearly all the enzyme has effectively bound to substrate (it helps to understand that the enzyme is the limiting factor, while there is an abundant supply of substrate), which is consistent with option $\boxed{\textbf{(D)}}$.

§3.4 Cellular Energy

Welcome to Cellular Energy! In this section, we explore what ATP is, its role in storing and transferring cellular energy, describe how ATP hydrolysis drives important cellular functions, and predict its effects on cellular processes for various organisms.

The Laws of Thermodynamics The **First Law of Thermodynamics** states that the total energy content in the universe is a fixed value. Put another way, energy cannot be created or destroyed. It can only be transferred from one object to another.

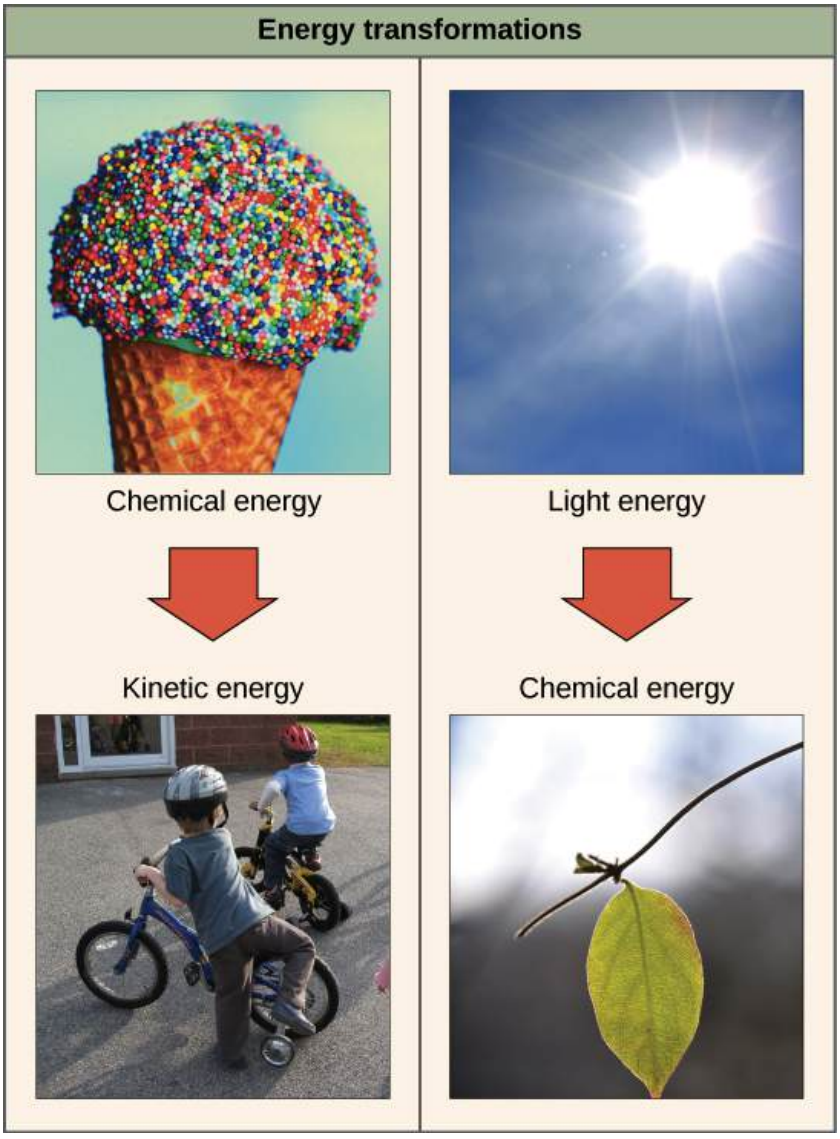


Image Credit: *OpenStax Biology*

This law might seem overly abstract, but if we start to take notice, we will find that energy transfers and transformations are so prevalent around us.

Example 3.4.1

Consider each of the following:

- In the form of light (radiant) energy, light bulbs are devices that transform electrical energy (from a power switch) into light (which is visible to us) energy.
- When one pool ball hits another (assume it is stationary), kinetic energy is transferred, causing the stationary ball to move.
- Plants convert the energy of sunlight (radiant energy) into chemical energy stored in organic molecules.
- You are converting chemical energy from your last meal into kinetic energy as you walk, breathe, and move your mouse to scroll through this book.

The important thing to realize here is that none of the above transfers are fully efficient. In each case, some of the initial energy is dissipated as thermal energy, or the more colloquial term, **heat**. Obviously, glowing light bulbs generate heat in addition to the light, but so do moving pool balls (through frictional heating between the ball and the surface), as do more complex chemical energy transfers involving metabolism of organisms. To learn about why this generation of heat is significant, keep reading as we move on to the **Second Law of Thermodynamics**.

Many students learn the First Law of Thermodynamics and get excited, thinking that if energy is never created and destroyed, then it can just be recycled over and over again, right?

Well, perhaps, but not quite. While energy cannot be created or destroyed, it does have tendency to change from more useful forms into less useful forms. In everyday life scenarios, there is always some energy content that is converted to an unusable form. Most of the times, this energy takes the form of heat.

It's important to note that heat *can* do work under specific circumstances, but it can never be converted into more favorable forms of energy with 100% efficiency.

If heat is not doing work, then it goes towards increasing the randomness (disorder) of the universe. Let me show you how. Consider two objects (say, two metal blocks) at different temperatures: the molecules are partitioned by speed, with those in the cooler object moving slowly and those in the hotter object moving quickly. If heat flows from the hotter object into the cooler object (as it will spontaneously), the molecules of the hot object slow down, and the molecules of the cool object speed up, until all the molecules are moving at the same average speed. This is the concept of **thermal equilibrium**.

The system will tend to move towards this more disordered configuration simply because it's more likely than the temperature-separated configuration (there are many more possible states corresponding to the disordered configuration).

Note 3.4.2

The degree of randomness or disorder in a system is called its **entropy**.

Since we know that every energy transfer results in the conversion of some energy to an unusable form (such as heat), and since heat that does not do work goes to increase the randomness of the universe, we can understand the Second Law of Thermodynamics as every energy transfer that occurs will *increase* the entropy of the universe.

The idea that spontaneous processes must increase the entropy of the universe applies greatly to living systems. After all, we humans are organized collections of matter. Each cell in our bodies has its own internal organization; they are organized into tissues, the tissues into organs, and the entire body maintains a meticulous system of transport, exchange, and commerce that keeps us alive. To clarify the concept of entropy in living systems, consider what happens to your body when you take a walk. As your leg muscles contract, you are using chemical energy from complex molecules such as glucose (sugars) and converting it to kinetic energy (through motion). However, a lot of your initial energy is dissipated as heat, and while it keeps you warm, much of it releases into your surroundings, increasing its entropy.

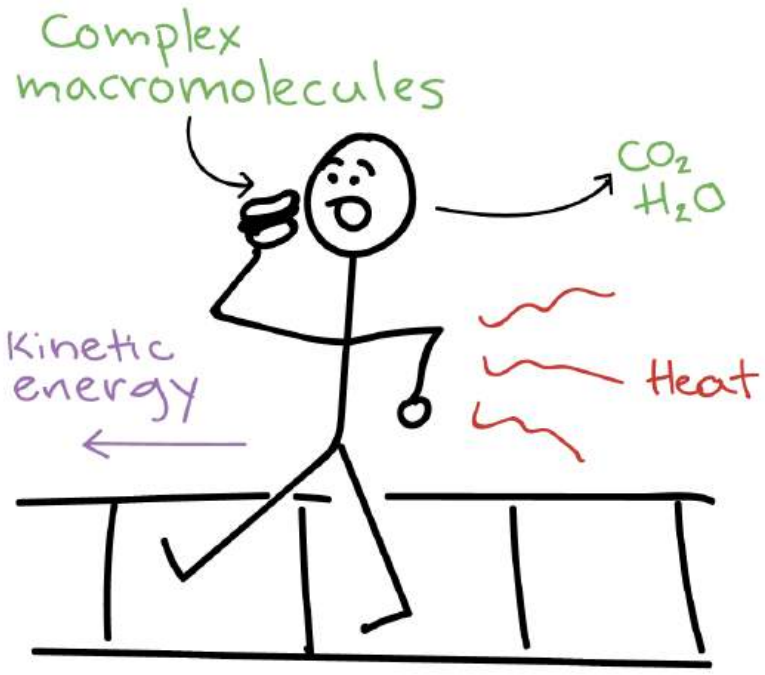


Image Credit: Khan Academy

To sum up, the high degree of organization in all organisms is maintained by a constant input of energy, and is offset by an increase in the entropy of the surroundings.

Structure and Hydrolysis of ATP **Adenosine triphosphate**, abbreviated as **ATP**, is a small but significant molecule. It is considered to be the major source of cellular energy. When ATP is broken down (hydrolyzed), the energy released is used to power various

endergonic cellular reactions. The diagram below shows the molecular structure of ATP.

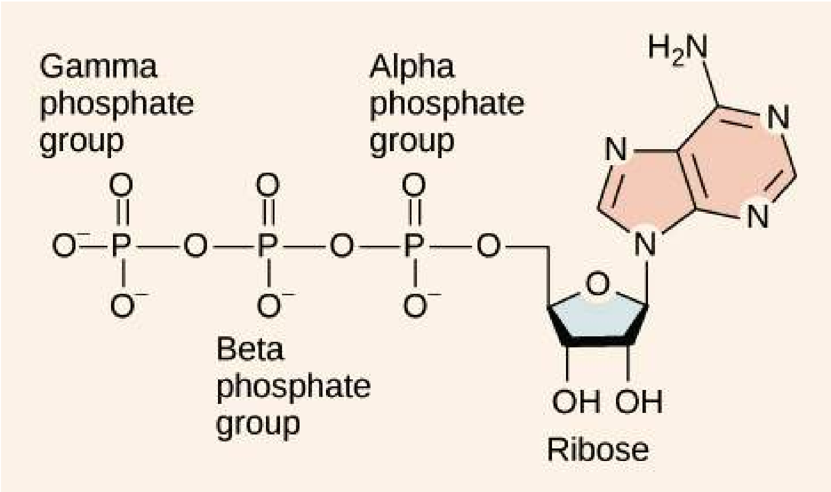


Image Credit: *OpenStax Biology*

ATP is an RNA nucleotide, which includes a chain of three phosphates, a five-carbon sugar (ribose) at the center, and a nitrogenous base at the end.

The three phosphate groups, in order of closest to furthest from the ribose sugar, are labeled alpha, beta, and gamma. ATP is made unstable by the three adjacent negative charges in its phosphate tail, which cause significant repulsion. The bonds between the phosphate groups are called **phosphoanhydride bonds**, and they may be referred to as "high-energy" bonds.

Phosphoanhydride bonds are considered "high-energy" bonds because an appreciable amount of energy is released when one of these bonds is broken in a hydrolysis (water-mediated breakdown) reaction. ATP is hydrolyzed to ADP in the following reaction:

$$\text{ATP} + \text{H}_2\text{O} \rightleftharpoons \text{ADP} + \text{P}_i + \text{energy}$$

Note: P_i is PO_4^{3-}, an inorganic phosphate group.

The $\rightleftharpoons$ arrow indicates that the hydrolysis of ATP to ADP, like most processes, is reversible. The reverse reaction, which generates from ATP from ADP and P_i, requires energy. Regeneration of ATP is important because cells tend to use up (hydrolyze) ATP molecules very quickly and rely on replacement ATP being constantly produced.

The regeneration of ATP is trivial, being the reverse or ATP hydrolysis:

$$\text{energy} + \text{ADP} + \text{P}_i \rightleftharpoons \text{ATP} + \text{H}_2\text{O}$$

Reaction Coupling Sometimes, cells use a strategy called **reaction coupling**, in which an energetically favorable (exergonic) reaction, such as ATP hydrolysis, is directly linked with an energetically unfavorable (endergonic) reaction. This happens through a shared **intermediate** in the metabolic pathway, so essentially a product of one reaction is "picked up" and used as a reactant in the second reaction.

When two reactions are coupled, they can be added together to give an *overall* reaction, and the free energy change, ΔG, will be equal to the sum of the ΔG values of the individual reactions. **As long as the overall ΔG is negative, then both reactions can take place**. For instance, we can add up a pair of generic reactions coupled by a shared intermediate, i, as follows:

$$\begin{aligned} \mathrm{A} &\rightleftharpoons i & \Delta G &= X \\ +\, i &\rightleftharpoons C + D & \Delta G &= Y \\ \hline \mathrm{A} &\rightleftharpoons \mathrm{C} + \mathrm{D} & \Delta G &= X + Y \end{aligned}$$

Notice that the intermediate, i, doesn't appear in the overall reaction.

Example 3.4.3

Case Study: Sucrose Production

The formation of sucrose is endergonic: its ΔG value is about $+27\,\mathrm{kJ/mol}$ under standard conditions. ATP hydrolysis is an exergonic process with a ΔG of around $-30\,\mathrm{kJ/mol}$ under the same conditions. Since the magnitude of ΔG is greater for ATP hydrolysis, this reaction can be coupled to synthesize sucrose.

$$\begin{aligned} \text{glucose} + \text{fructose} &\rightleftharpoons \text{sucrose} & \Delta G &= +27\,\mathrm{kJ/mol} \\ \mathrm{ATP} + \mathrm{H_2O} &\rightleftharpoons \mathrm{ADP} + \mathrm{P}_i & \Delta G &= -30\,\mathrm{kJ/mol} \\ \hline \text{glucose} + \text{fructose} + \mathrm{ATP} &\rightleftharpoons \text{sucrose} + \mathrm{ADP} + \mathrm{P}_i & \Delta G &= -3\,\mathrm{kJ/mol} \end{aligned}$$

In the first reaction, ATP transfers a phosphate group to glucose, forming a phosphorylated glucose group (glucose-P). This process is energetically favorable because ATP is an unstable molecule that really wants to lose its phosphate group.

In the second reaction, the glucose-P intermediate reacts with fructose to produce glucose. Because glucose-P is also pretty unstable, this reaction is also energetically favorable and occurs spontaneously.

ATP hydrolysis can also be coupled to other types of cellular reactions, e.g. protein shapes and transport of other substances.

Example 3.4.4

Consider the well-known **sodium-potassium pump**. It is not energetically favorable to move Na^+ out of or K^+ into a typical cell, because this movement opposes the concentration gradients of the ions. However, ATP provides the energy needed to transport these ions by way of a membrane protein called the sodium-potassium pump. You can refresh your knowledge on membrane proteins and concentration gradients by revisiting Unit 2!

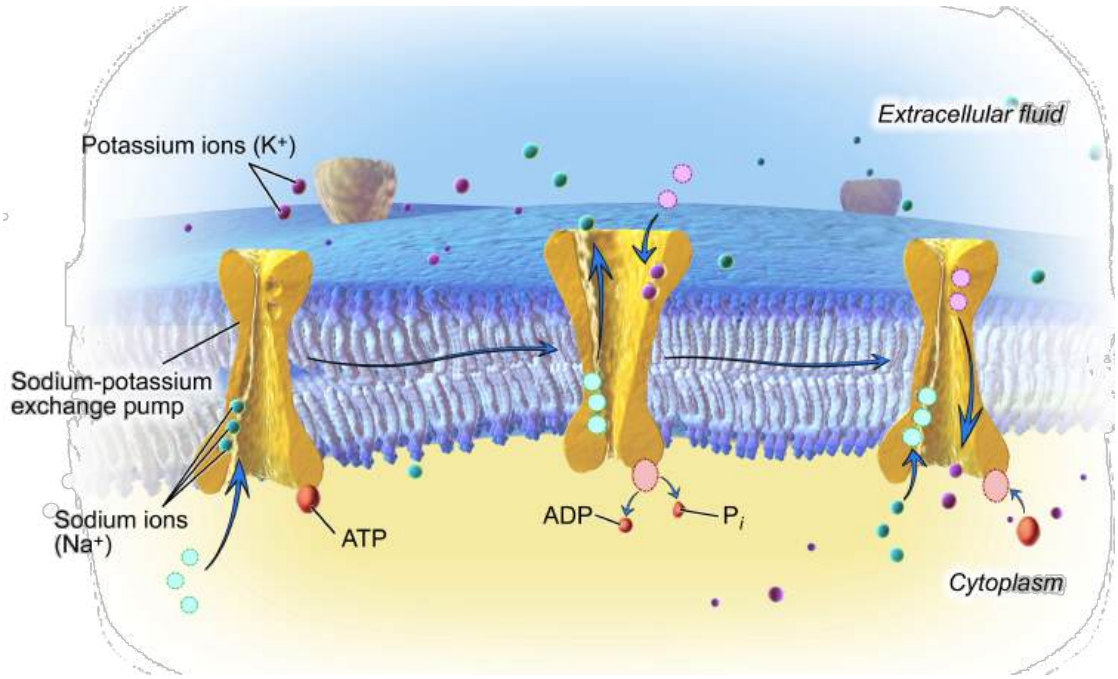


Image Credit: Adapted from The sodium-potassium exchange pump, by Blausen staff (CC BY 3.0)

Specifically, when ATP transfers a phosphate group to the pump protein, the result is ADP and a phosphorylated intermediate form of the pump. This form is highly unstable, so it changes its shape, facing the outside of the cell and releasing Na^+ ions. When extracellular K^+ bind to the phosphorylated pump, the phosphate group is lost, making the protein unstable in its current form. It returns to its original shape, releasing the K^+ inside the cell.

Metabolism: An Overview Cells constantly carry out numerous necessary reactions, and your body as a whole, alive and healthy. These reactions are often linked together in chains or pathways. All of the chemical reactions that take place inside of a cell are collectively referred to as the the cell's **metabolism**.

Let's observe the metabolic diagram below. It's a diagram of the core metabolic pathways in a eukaryotic cell, e.g. the cells that make up the human body. Each line represents a reaction, and each circle represents a reactant or product.

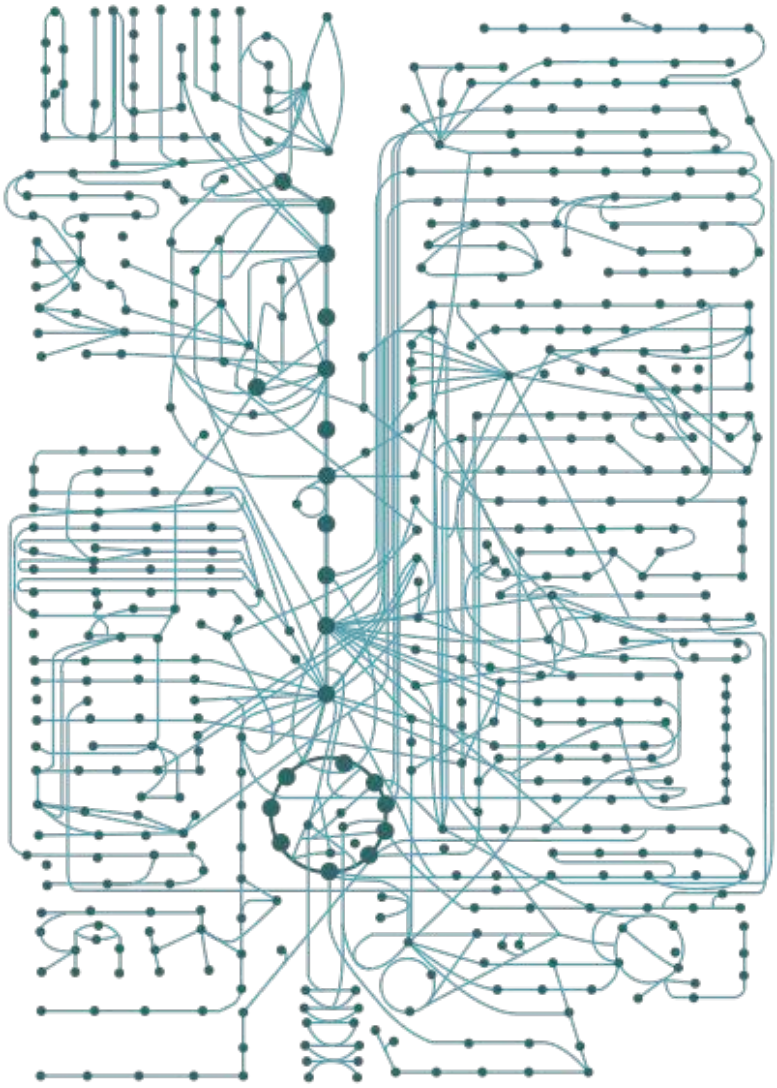


Image Credit: "Metabolism diagram," by Zlir'a (public domain)

In the metabolic web of the cell, some of the chemical reactions release energy and can happen spontaneously (without energy input). However, others need added energy in order to take place.

Cellular Respiration and Photosynthesis To make the idea of metabolism more concrete, let's look at two metabolic processes that are crucial to life on earth: those that build sugars (photosynthesis), and those that break them down (cellular respiration).

Cellular respiration is an exergonic process, an energy-releasing pathway. It is how many cells generate cellular energy from glucose ($C_6H_{12}O_6$). As a glucose molecule gradually breaks down, the process has an overall reaction of

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

Breaking down glucose releases energy, which is captured by the cell in the form of adenosine triphosphate, or **ATP**, a small molecule that provides cells a convenient way to store short-term energy.

After its synthesis, ATP can be used by other cellular reactions as an energy source. Cells use ATP to transfer energy in a standardized way, so they are sometimes described as the "energy currency" of the cell.

Photosynthesis, on the other hand, is an endergonic process, an energy-requiring metabolic pathway, which builds sugar molecules.

Plants and some species of photosynthetic bacteria produce sugars like glucose. In photosynthesis, they use the energy of sunlight to convert CO_2 gas into $C_6H_{12}O_6$ molecules. Although it takes place in many steps, the overall reaction for photosynthesis is actually just the one for cellular respiration flipped backwards!

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

Obviously, plants need energy to power their cellular processes, so some of the sugars are used by the plant itself. They can also provide a food source for animals that eat the plant, like the squirrel shown below. In either case, the glucose is broken down via cellular respiration, generating ATP to keep cells functioning properly.

Image Credit: *OpenStax Biology*

Anabolic and Catabolic Pathways Metabolic pathways can be divided into two categories based on their effects. Photosynthesis, which builds sugars out of smaller molecules, is a "building up," or **anabolic**, pathway. In contrast, cellular respiration breaks down sugar into smaller molecules and is a "breaking down," or **catabolic**, pathway.

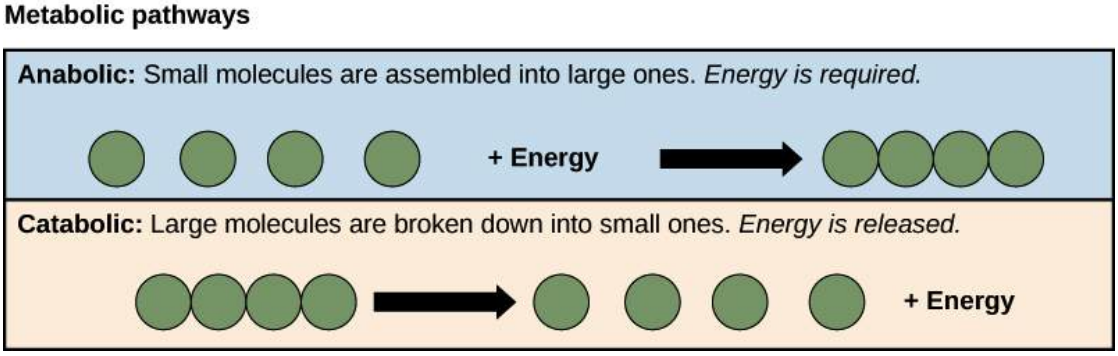


Image Credit: *OpenStax Biology*

Anabolic pathways are typically endergonic and require an input of energy.

Example 3.4.5

Here are some anabolic pathways:

- Building glucose from carbon dioxide (photosynthesis).
- Protein synthesize via amino acids or of DNA strands from nucleotides.

These biosynthetic processes are critical to the life of the cell, take place constantly, and use energy carried by ATP and other short-term energy storage molecules.

Catabolic pathways are typically exergonic and release energy.

Example 3.4.6

Energy stored in the bonds of complex molecules, such as glucose and fats, is released in catabolic pathways. It's then harvested in forms that can power the work of the cell (for instance, through the synthesis of ATP).

Fun Fact: The chemical reactions that take place in metabolic pathways almost always require some guidance. Each reaction step in a pathway is facilitated by a protein called an enzyme.

Problem 3.4.7 — Multiple Choice Question

Enzymes that catalyze consecutive steps in a metabolic pathway often cluster together in a cell.

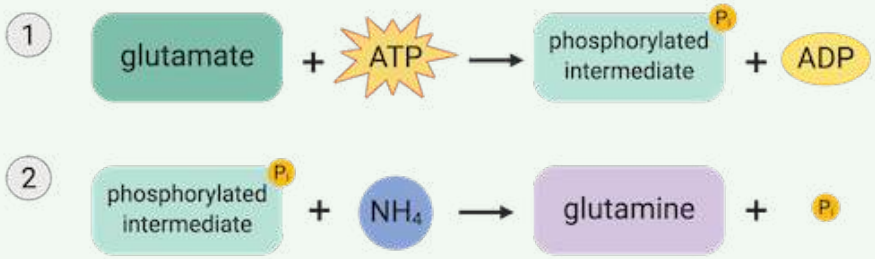
Which of the following statements describes a likely result of this clustering?

(A) The cell can be affected by toxic intermediates.
(B) Enzymes in a pathway do not have enough substrate to function efficiently.
(C) Pathway intermediates cannot enter alternative metabolic pathways.
(D) Enzyme crowding decreases the efficiency of each enzyme in the pathway.

Solution: For a metabolic pathway, the clustering of enzymes ensures that the product of one enzyme is efficiently transferred to the subsequent enzyme in the pathway. (A) is not correct; even if an intermediate molecule is toxic, this transfer of enzyme products helps prevent a net negative effect on the cell. Additionally, the information implies that a clustered enzyme likely has substrate near its active site, allowing it to function effectively, so we eliminate option (B). Finally, (D) is clearly wrong, because clustering helps *increase*, not decrease the efficiency of each enzyme in the pathway. However, as we discussed previously, pathway intermediates can potentially be toxic, but clustering prevents them from entering alternative metabolic pathways, protecting the cell from damage. This is consistent with option $\boxed{\textbf{(C)}}$.

Problem 3.4.8 — Multiple Choice Question

The enzyme glutamine synthetase facilitates the use of energy to combine glutamate and ammonia (NH_4), forming glutamine. The process occurs in two steps, as represented in the following diagram:



Which of the following statements best describes the process carried out by glutamine synthetase?

(A) Glutamine synthetase forms a phosphorylated intermediate by attaching a molecule of ATP to glutamate.
(B) Glutamine synthetase uses energy to hydrolyze ATP, which then drives the formation of glutamine from glutamate and ammonia.
(C) Glutamine synthetase forms glutamine by coupling two endothermic reactions, both of which occur in the enzyme's active site.
(D) Glutamine synthetase uses an exothermic reaction to drive an endothermic one by catalyzing the formation of a phosphorylated intermediate.

Source: Khan Academy

Solution: The enzyme glutamine synthetase facilitates the formation of glutamine from glutamate and ammonia, which is an endothermic reaction, by coupling it with ATP hydrolysis, which is an exothermic reaction. This occurs through the formation of a phosphorylated intermediate. The process catalyzes the attachment of an inorganic phosphate, denoted by P_i, not an ATP molecule, so we eliminate (A). In addition, we know that the hydrolysis of ATP is exothermic, so glutamine synthetase does not use energy, rather, ATP hydrolysis provides the energy required to synthesize glutamine, so we eliminate (B). Finally, according to the problem statement and diagram, production of glutamine from glutamate and ammonia is fueled by cellular energy (ATP). Thus, the overall process is equivalent to coupling an endothermic process with an exothermic process, not coupling two endothermic reactions, and (C) is wrong. Using the same logic which ruled out options (A), (B), and (C), we can conclude that $\boxed{\textbf{(D)}}$ is the best answer.

§3.5 Photosynthesis

Do you like trees? If not, you may want to show them some appreciation. We owe our existence to plants and other organisms that capture light. Much of life on Earth is possible because the Sun provides a continuous supply of energy to all ecosystems. All organisms need energy to fuel metabolic reactions of growth, development, and

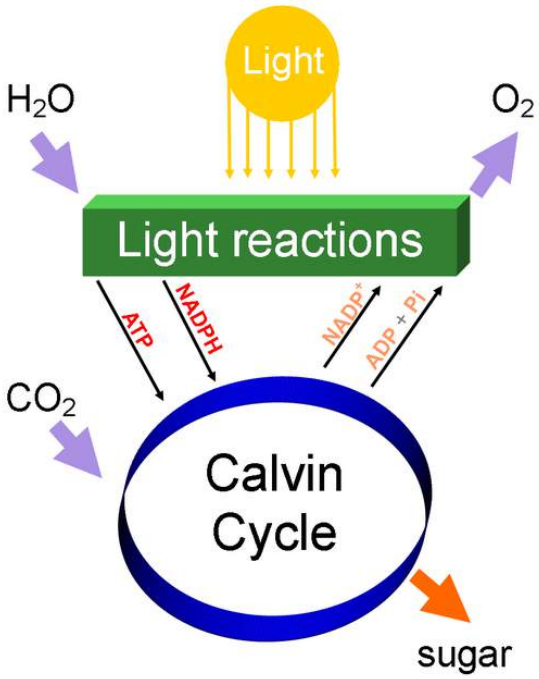
reproduction. However, the energy of light must be converted into chemical energy through a process known as photosynthesis.

Conversion of Light to Chemical Energy Photosynthesis is a chemical process defined by the following equation:

$$6H_2O + 6CO_2 \xrightarrow{\text{photosynthesis}} C_6H_{12}O_6 + 6O_2$$

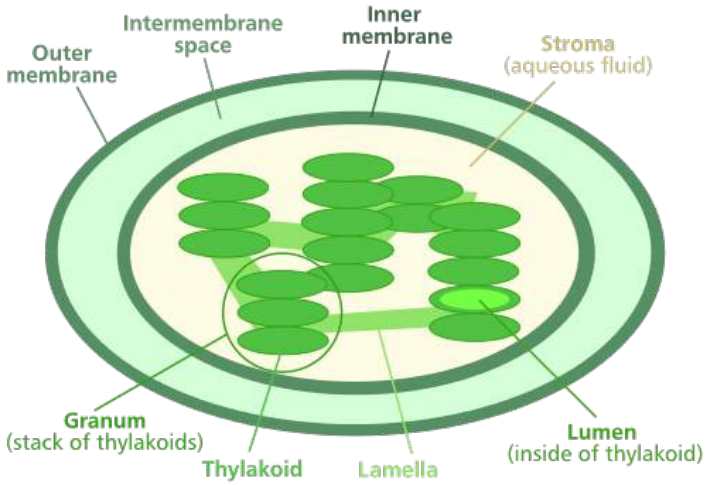
There are two types of species capable of this process: plants and photosynthetic bacteria. The overall reaction is spurred by the energy from a photon of light striking a pigment in the chloroplast. Scientists generally believe that photosynthesis first evolved in prokaryotic cells, i.e. those that lack a nucleus.

Photosynthesis is broken down into two major steps that depend on one another: **light-dependent reactions** and **light-independent reactions** (Calvin Cycle). Both processes occur in the chloroplast of a photosynthetic organism.



The Chloroplast: Unique to Plant Cells Recall from Unit 2 that chloroplasts are organelles located exclusively in plant cells. They are a type of *plastid* that contains chlorophyll (a pigment) and it is this organelle in which photosynthesis takes place.

Light-dependent reactions take place in the **thylakoid membranes** of the chloroplast. These structures are known as "pancakes" of the chloroplast because of their unique appearance as a stack of flattened disks. The pigment chlorophyll, responsible for the green color in many plants, contains electrons in an excited state, as energy is inputted by a photon of light. Let me describe this process below.



When light strikes the chloroplast, an electron from a chlorophyll molecule is excited and travels through the electron transport chain. In the process, a concentration gradient of hydrogen ions (H^+) is formed. This will be used later to produce ATP with the help of an enzyme called **ATP synthase**. The electron lost from chlorophyll is replaced by an electron from water. This generates more H^+ ions and the production of O_2 gas, which is then released by the plant.

Light-Dependent Reactions (Electron-Transport Chain) When light hits the pigments, it first hits **Photosystem II**, which is embedded in the internal membrane of the chloroplast and is responsible for exciting electrons from their ground state. This sudden jump in energy causes H^+ ions to move into the thylakoid space and to replenish electrons, the light splits water (in a process called *photolysis*) into two H^+ ions and half O_2 and electrons, to replace the missing electrons in Photosystem II. But wait, why are there missing electrons in the first place? The reason: electrons continue traveling down the thylakoid membranes, eventually bumping into **Photosystem I**, leaving Photosystem II altogether. As this continues, H^+ ions continue to be pumped into the membrane.

Naturally, H^+ ions prefer to leave the thylakoid space, but this can only be achieved by leaving through the transport protein called ATP (adenosine triphosphate) synthase, where **ADP (adenosine diphosphate)** is phosphorylated (gains another phosphate group) as H^+ ions pass through.

Meanwhile, other electrons in Photosystem I bind to electron carriers, usually **NADPH**. NADPH is a coenzyme used in anabolic reactions, which build large molecules from small molecules. It provides the high-energy electrons needed to form carbon-carbon bonds during photosynthesis. Electron carriers transport electrons in the form of H^+ ions. These electrons can then be used in other processes. In this case, the electrons will be used to form bonds in light-independent reactions in the Calvin Cycle.

Note 3.5.1

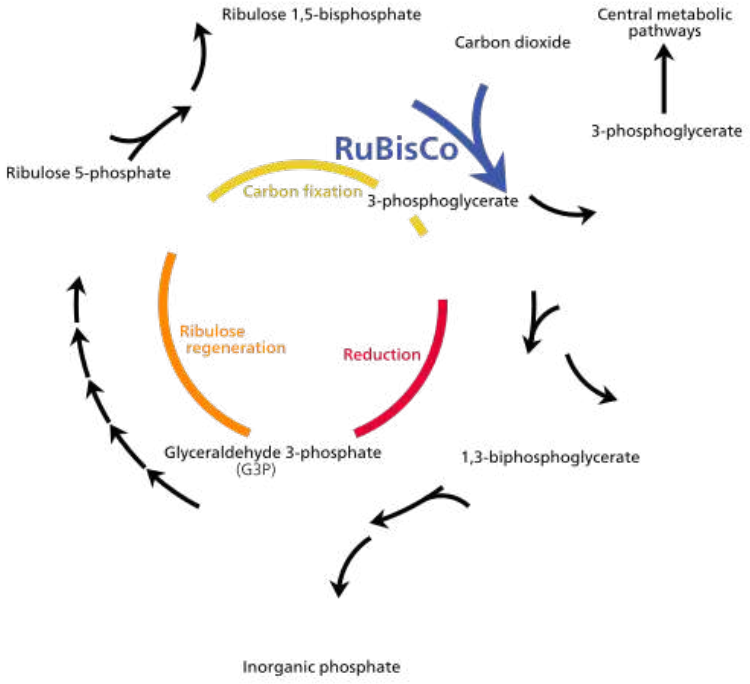
The ATP and electron carriers produced during light-dependent reactions are essential to the production of glucose in the light-independent reactions. The production of oxygen is toxic to plants, but it provides the rest of us the opportunity to breathe.

Light-Independent Reactions (Calvin Cycle) Light-independent reactions are named as such because they do not require light to proceed. The set of such reactions is referred to as the **Calvin Cycle**. These reactions take place in the **stroma** of the chloroplast. This is the jelly-like space between the thylakoid membrane stacks. With the support of ATP and NADPH, CO_2 is converted into sugar (glucose, $C_6H_{12}O_6$).

Generally, in the Calvin Cycle, dioxide is converted into an organic carbon source (usually glucose). First, the enzyme ribulose biphosphate carboxylase, abbreviated as *rubisco*, catalyzes the process of **carbon fixation**, which takes CO_2 from the air and converts it into an organic, usable form.

After CO_2 is fixed, it is converted to glucose. This is accomplished by electrons and energy that are required to form several carbon-carbon bonds. This is where the electron carriers and ATP from the light-dependent reactions come into play.

Various enzymes use the energy from ATP and electrons that are carried by carriers such as NADPH, to convert organic carbon into glyceraldehyde-3-phosphate, or **G3P**. The origin of G3P precedes that of several carbohydrates, e.g. starch, cellulose, and glucose. Cells can use G3P to create a number of energy and structural components.



Note 3.5.2

The ATP that is broken down into ADP and another phosphate group can be recycled and used again to form carbon-carbon bonds in light-dependent reactions. Similarly, NADPH becomes NADP+ after dropping off the H^+ ion. This can then be replenished by an electron in the light-dependent reactions.

Recap It may be difficult to visualize photosynthesis, but it is an important part of the AP Biology curriculum. Some tips include trying to draw out the process yourself and

explaining it to someone else.

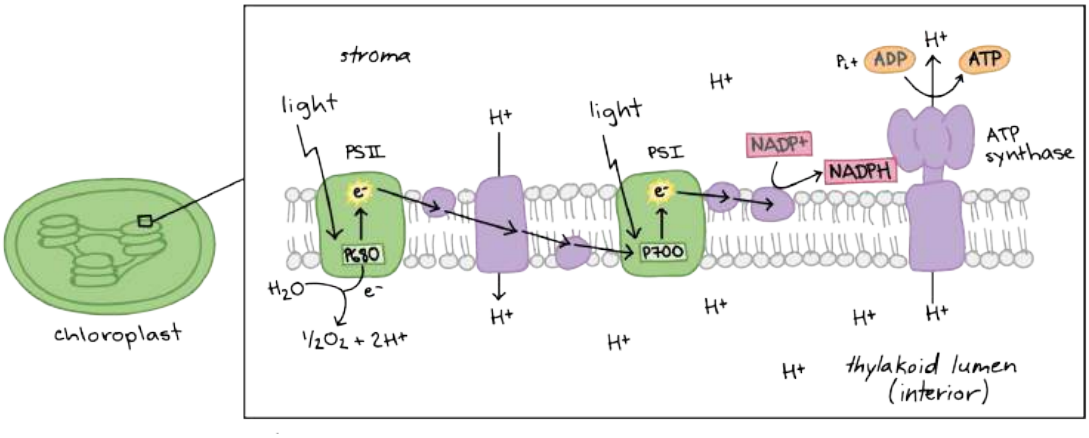


Image Credit: Khan Academy

The electron transport chain can be the most challenging, so it is necessary to understand all the cause-and-effect relationships. At the end of the day, the goal of photosynthesis is to create sugar. Finally, it helps to think of NADPH as a loaded dumptruck full of electrons.

Problem 3.5.3 — Multiple Choice Question

Which of the following best indicates that the light reactions of photosynthesis have completed and that the Calvin cycle has begun?

(A) Electrons are transferred across the electron transport chain (ETC) on the thylakoid membrane.
(B) ATP and NADPH accumulate in the stroma.
(C) An electrochemical gradient forms across the thylakoid membrane.
(D) A high concentration of carbohydrates is found in the thylakoid lumen.

Solution: Eliminate (A); this process occurs in the light reactions themselves, but does not indicate their completion. In addition, option (C) is also part of the light reactions, specifically, the generation of ATP through chemiosmosis. The electrochemical gradient drives ATP synthesis but does not indicate the end of the light reactions and the beginning of the Calvin cycle. The Calvin cycle is where carbohydrates are synthesized. A high concentration of carbohydrates in the thylakoid lumen would indicate an issue with the Calvin cycle, not the completion of the light reactions, so (D) is wrong. We know that the light reactions generate ATP and NADPH which are then used in the Calvin cycle to fix CO_2 into $C_6H_{12}O_6$. When these two molecules accumulate in the stroma (region outside thylakoid stacks), photosynthesis has reached the transition state between the light reactions and the Calvin cycle, consistent with option $\boxed{\textbf{(B)}}$.

Problem 3.5.4 — Multiple Choice Question

RuBisCO catalyzes the joining of carbon dioxide with RuBP during carbon fixation. In an experiment, researchers applied a toxin to a plant cell that inhibits RuBisCO.

Which of the following explains the most likely effect this toxin will have on the Calvin cycle?

(A) ATP synthase will not catalyze the formation of ATP on the thylakoid membrane.
(B) Carbon dioxide will not be converted into carbohydrates.
(C) Excited electrons will not be transferred across the electron transport chain.
(D) Carbon and oxygen will not be released after the breakdown of carbon dioxide.

Solution: Option (A) is incorrect. While the Calvin cycle needs ATP to function, inhibiting RuBisCO directly affects carbon fixation, not ATP synthesis. Option (C) is also incorrect. Although the Calvin cycle requires ATP generated by the electron transport chain, the inhibition of RuBisCO would not directly affect the electron transfer itself. Finally, option (D) describes a process that is the opposite of carbon fixation. RuBisCO is the key enzyme responsible for fixing carbon dioxide into the Calvin cycle by attaching CO_2 to RuBP. If this enzyme is inhibited, carbon dioxide cannot be incorporated into organic molecules, such as carbohydrates. The correct answer is $\boxed{\textbf{(B)}}$.

§3.6 Cellular Respiration

Cellular respiration is the process by which cells make energy by breaking glucose to produce ATP, which powers most cell activities. The general equation for cellular respiration is:

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

This process involves several steps: glycolysis, the oxidation of pyruvate, the Krebs Cycle (or citric acid cycle), and oxidative phosphorylation. The presence or absence of oxygen determines which processes are used. If there's no oxygen (anaerobic), cells use fermentation and glycolysis to make ATP. If there is oxygen (aerobic), cells can use all processes (aerobic cells only use glycolysis and fermentation if they don't have access to oxygen). Aerobic organisms, using oxygen, generate more ATP because they can fully use the electron transport chain.

Glycolysis Glycolysis occurs in the cytosol and is performed by all organisms. There are enzymes (catalysts) that are highly conserved in all organisms, so glycolysis was probably one of the first evolved metabolic processes. The process starts with a glucose molecule and 2 NAD^+ coenzymes. Glucose is oxidized (loses 2 electrons), and and the 2 NAD^+ are reduced to NADH. This uses 2 ATP, but provides 4 ATP, giving a net gain of 2 ATP. Glucose becomes a 3-carbon pyruvate and can move to the next step.

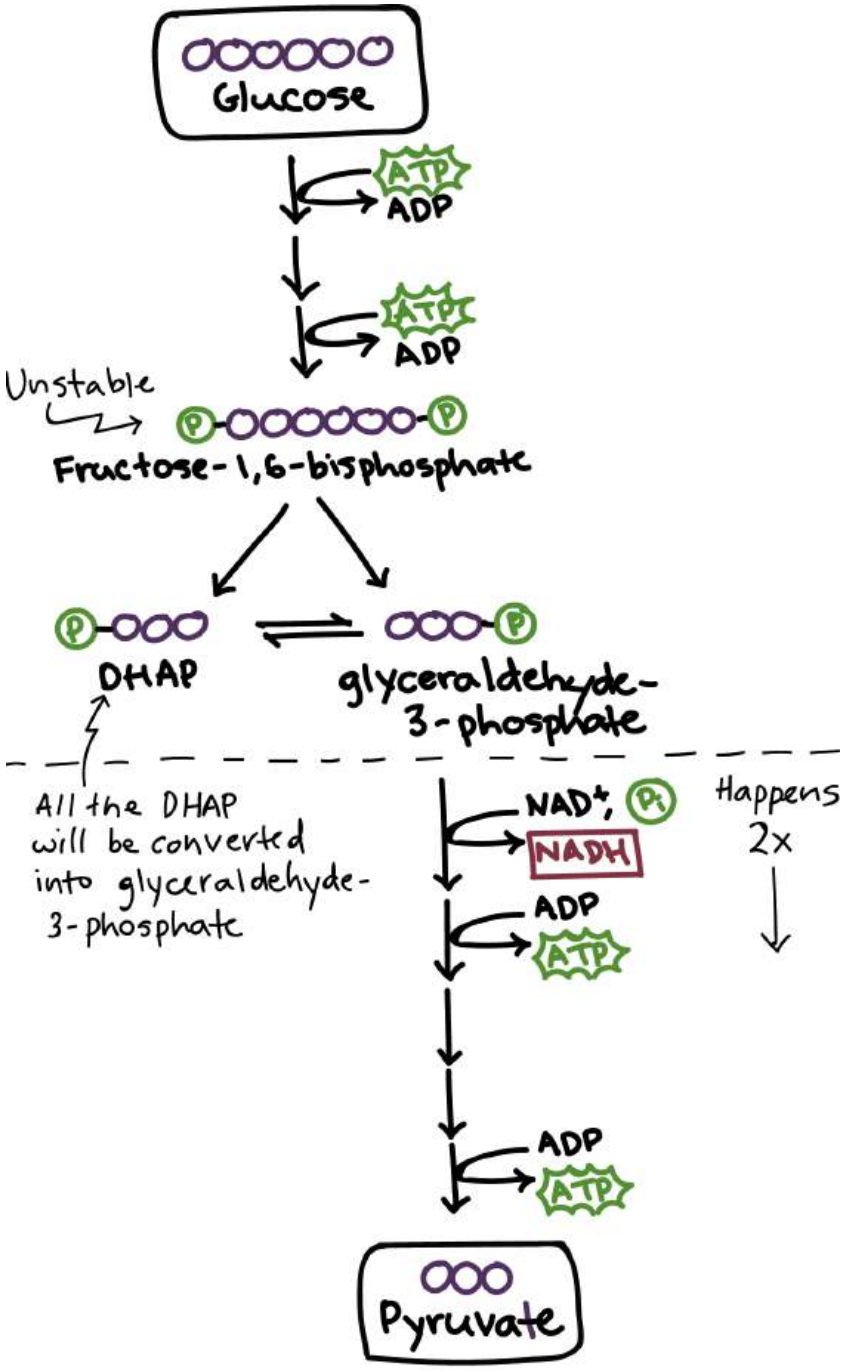


Image Credit: Khan Academy

Oxidation of Pyruvate The 2 pyruvates from glycolysis moves to the mitochondria for this step in aerobic organisms. Here, they're oxidized and NAD^+ is reduced to NADH. One carbon leaves each pyruvate as CO_2 and the pyruvates becomes 2-carbon acetyl groups. Coenzyme A attaches and delivers the acetyl groups to the Krebs cycle.

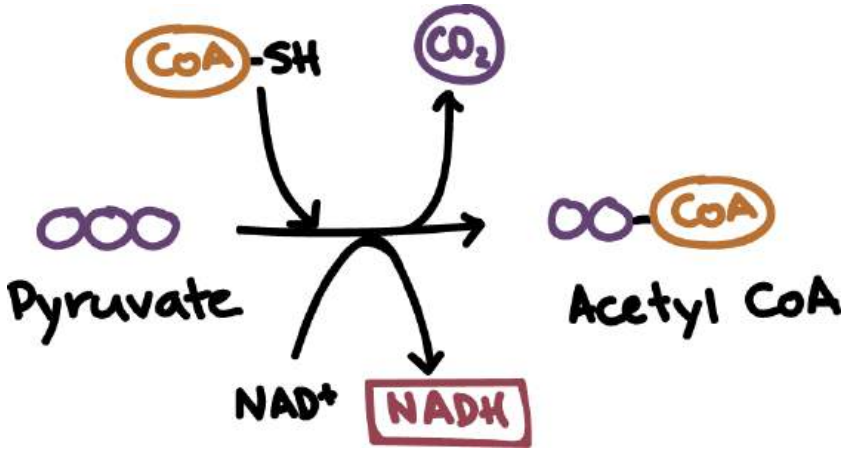


Image Credit: Khan Academy

Krebs Cycle The Krebs cycle, or citric acid cycle, occurs in the liquid matrix of the mitochondrion. Each acetyl group attaches to a 4-carbon intermediate. An enzyme catalyzes this reaction and 2 carbon dioxide molecules are released from each 6-carbon group. This regenerates new 4-carbon groups that can be reused. For each group, $3NAD^+$ are reduced to NADH, and FAD^+ is reduced to $FADH_2$. 1 ATP is generated through substrate-level-phosphorylation (where a phosphate group is added to ADP without the electron transport chain or chemiosmosis.

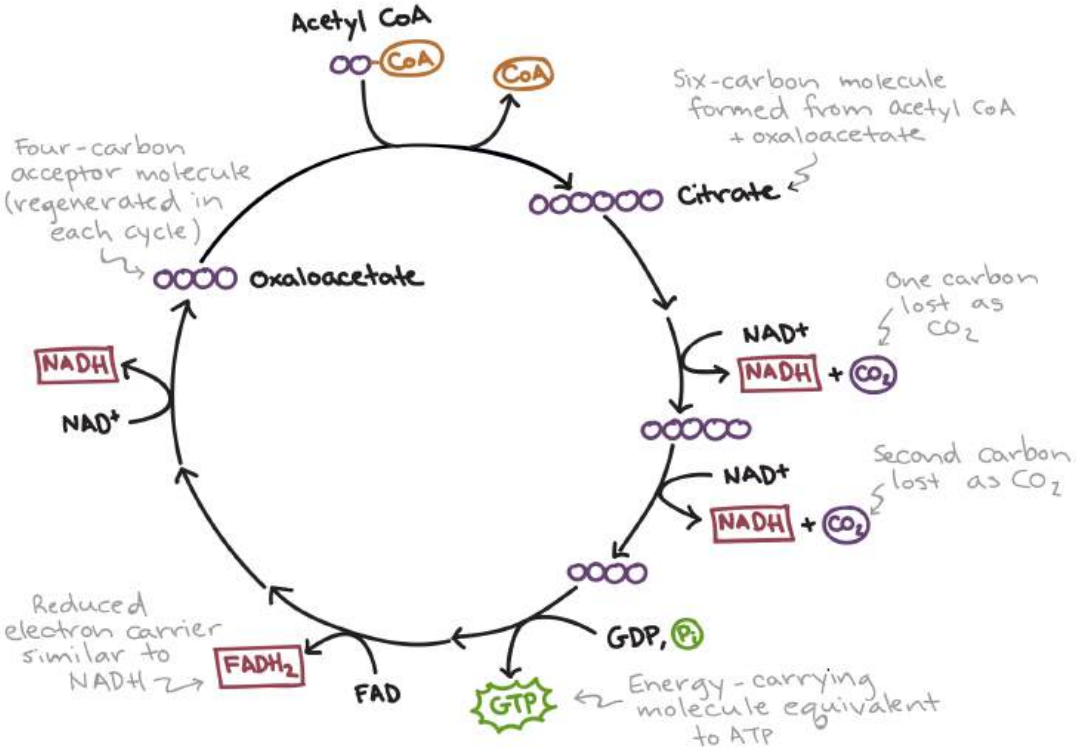


Image Credit: Khan Academy

Oxidative Phosphorylation Oxidative phosphorylation, the final stage of cellular respiration, harnesses energy from electron transport to create ATP, the cell's primary

energy currency, through a process called chemiosmosis. Oxidative phosphorylation is the process where energy, derived from the oxidation of molecules like NADH and $FADH_2$, is used to generate ATP. Oxidative phosphorylation takes place in the inner mitochondrial membrane, within the electron transport chain and the protein complex ATP synthase. First, electrons from NADH and $FADH_2$ are passed along the electron transport chain, releasing ATP (energy). The released energy is then used to pump protons (H^+ ions) from the mitochondrial region to the space within the membrane, creating a proton gradient. Finally, protons flow back down the gradient through ATP synthase, using the energy to convert ADP and inorganic phosphates to ATP. Oxygen accepts the last "batch" of electrons in the electron transport chain, reacting with them and protons to form water.

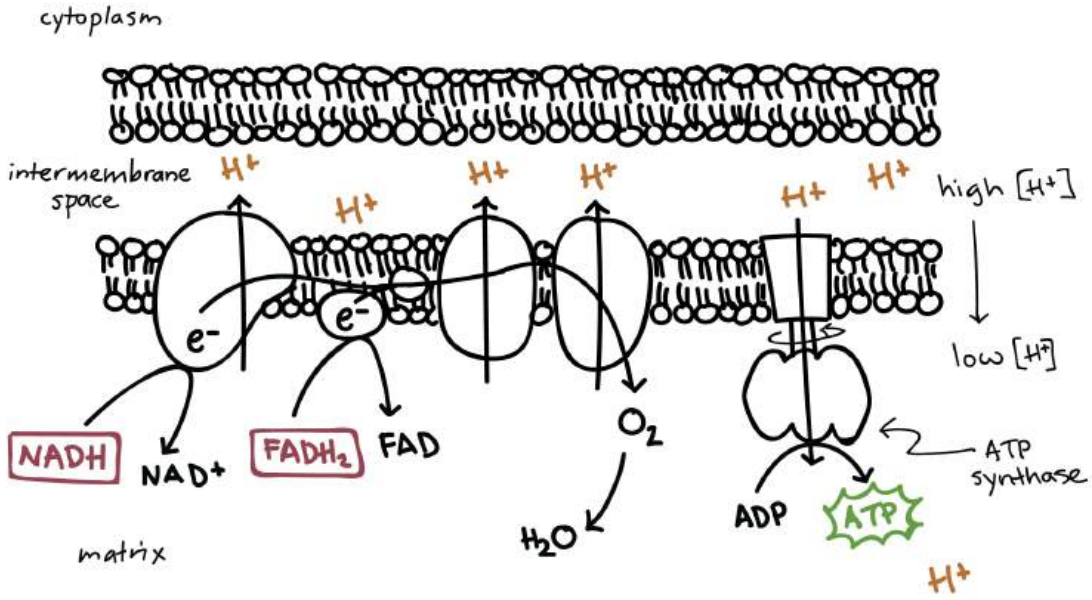


Image Credit: Khan Academy

Anaerobic Cellular Respiration Anaerobic respiration is a form of cellular respiration that takes place in the absence of oxygen. Both types involve electrons extracted from a fuel molecule that are passed through an electron transport chain, facilitating ATP synthesis. In anaerobic respiration, some organisms use sulfate, SO_4^{2-}, while others use nitrate, NO_3^-, as the final electron acceptor at the end of the electron transport chain.

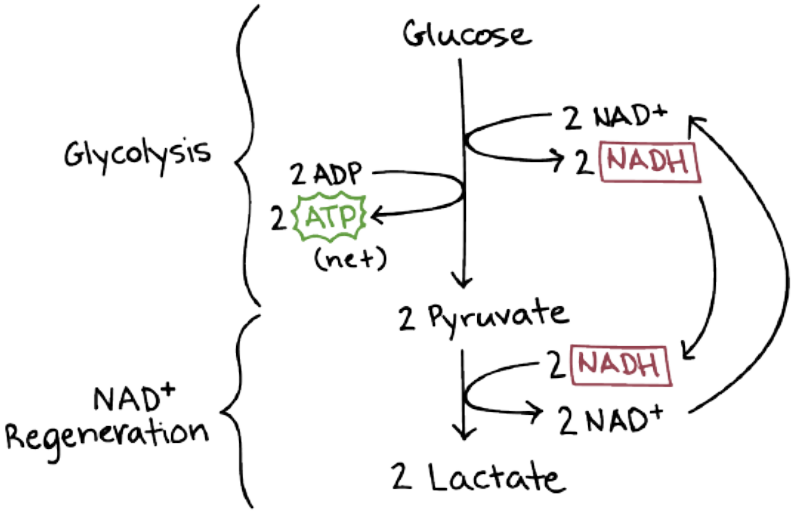
Generally, prokaryotes such as bacteria and archaea, organisms that live in low-oxygen environments rely on anaerobic respiration to break down fuels and produce energy. A type of archaea called methanogens, for example, can use CO_2 as a final electron acceptor, producing methane gas, CH_4, as a byproduct. Methanogens are found in soil and in the digestive systems of ruminants, a group of animals including cows and sheep.

Similarly, sulfate-reducing bacteria and some prokaryotes use SO_4^{2-} as a final electron acceptor, producing hydrogen sulfide, H_2S, as a byproduct.

Fermentation Fermentation is another anaerobic pathway for breaking down glucose, performed by many types of organisms and cells. In fermentation, the only energy extraction pathway is **glycolysis**, with one or two extra reactions tacked on at the end. The difference between fermentation and standard cellular respiration is that after

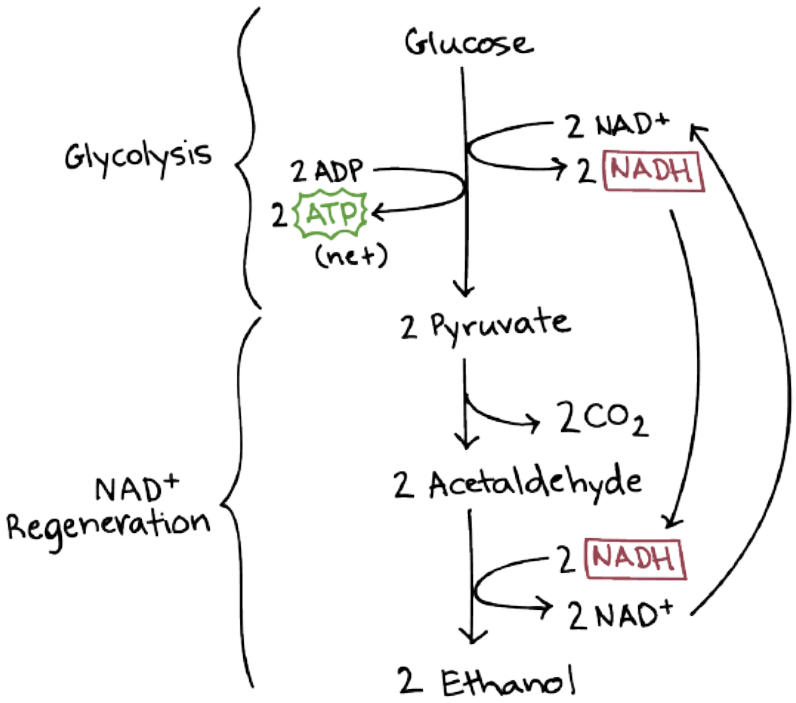
glycolysis, the pyruvate made in glycolysis does not continue through oxidation and the citric acid cycle, and the electron transport chain does not run. As a result, the NADH cannot drop off its electrons to oxidize into NAD^+. In fermentation, there are extra reactions to regenerate the NAD^+ electron carrier from NADH produced glycolysis. This is usually facilitated by pyruvate, the byproduct of glycolysis.

Lactic acid fermentation is a process by which NADH directly transfers its electrons to pyruvate, generating lactate as a byproduct. Lactate is the deprotonated form of lactic acid, thus its name. The bacteria that make yogurt, as well as the red blood cells in the cardiovascular system, carry out lactic acid fermentation due to their lack of mitochondria and inability to perform cellular respiration.



Occasionally, muscle cells carry out lactic acid fermentation, but only when there is too little oxygen for aerobic respiration to continue—when you've been exercising too hard. Lactic acid produced in muscle cells is transported through the bloodstream to the liver, where it's converted back to pyruvate and processed normally in the remaining reactions of cellular respiration.

Alcohol fermentation is the second form of fermentation for this course. In this process, NADH donates electrons to a derivative of pyruvate, producing ethanol (an alcohol). Going from pyruvate to ethanol takes two steps. First, a carboxyl group is removed from pyruvate and released as CO_2, producing a two-carbon molecule, acetaldehyde. Then, NADH passes its electrons to acetaldehyde, regenerating NAD^+ and forming ethanol.



Yeasts carry out alcohol fermentation to produce ethanol found in alcoholic beverages. Intuitively, alcohol is toxic in large quantities to yeast (just as it is to humans), so there is an upper limit on the percent composition of alcohol in these drinks. Depending on the strain and environmental conditions, yeast can tolerate about 5 to 21 percent ethanol.

Problem 3.6.1 — Multiple Choice Question

Inside these tanks, yeasts are busily fermenting grape juice into wine. Why do wine making tanks like these need pressure-release valves?

(A) The yeasts produce O_2 gas by cellular respiration.
(B) The yeasts produce CO_2 gas by lactic acid fermentation.
(C) The yeasts produce CO_2 gas by alcohol fermentation.
(D) The yeasts produce CO_2 gas by cellular respiration.

Source: "Metabolism without oxygen, Figure 3 by *OpenStax College, Biology*, CC BY 3.0

Solution: When yeasts ferment grapes into wine, this is the process of alcohol fermentation. As a byproduct, the yeasts produce carbon dioxide gas, which accumulates, causing the pressure in the tanks to rise. For this reason, pressure-releasing valves allow the CO_2 gas to be released, preventing it from overwhelming the environment. The correct answer is $\boxed{\textbf{(B)}}$.

Problem 3.6.2 — Multiple Choice Question

Which of the following best describes what will result when a glucose-fed yeast cell is placed in an anaerobic environment?

(A) The yeast cell will produce ATP through fermentation, generating CO_2 and ethanol as byproducts.
(B) The yeast cell will produce ATP through fermentation, generating lactic acid as a byproduct.
(C) Due to a lack of oxygen, the yeast cell will no longer produce ATP, and its ATP stores will be depleted.
(D) Due to the presence of oxygen, the yeast cell will produce ATP through oxidative phosphorylation.

Solution: We can first eliminate (C); yeasts can produce ATP whether or not oxygen is available, through either oxidative phosphorylation or fermentation. (D) is also incorrect; an anaerobic environment *lacks* oxygen, so yeasts cannot carry out oxidative phosphorylation in this situation. Yeasts use fermentation to produce ATP when oxygen is not available. However, they undergo alcohol fermentation, with byproducts of CO_2 and ethanol, not lactic acid. Thus, we eliminate (D) and the correct answer is $\boxed{\textbf{(A)}}$.

§3.7 Fitness

Fitness describes an organism's ability to survive and reproduce in a given environment. Since every organism is just an expression of a DNA molecule in a particular environment, fitness is really a measure of how well a DNA molecule can replicate itself. In this section, we will explain how ATP efficiency impacts an organism's fitness in its environment, relate energy production to survival and reproductive success, and more.

ATP Production and the Fitness of Organisms We define fitness as the fact that organisms have unique ways to survive and reproduce. Individuals with certain beneficial traits, known as adaptations, are more able to survive and reproduce in their natural environment.

Variations at the microscopic level of DNA and proteins are responsible for such adaptations. Specifically, differences in DNA allow organisms to produce different proteins. These proteins can then respond differently to stimuli from their environments.

In Unit 3, we focus on how some organisms are better than others at harnessing energy. For example, an organism might have a better ability to hunt and consume energy than another. In terms of cellular respiration, one organism may be able to perform aerobic respiration, while another is limited to anaerobic respiration. Any such differences will create a phenomenon known as **selective pressure**, which allows some organisms to survive and reproduce more than others.

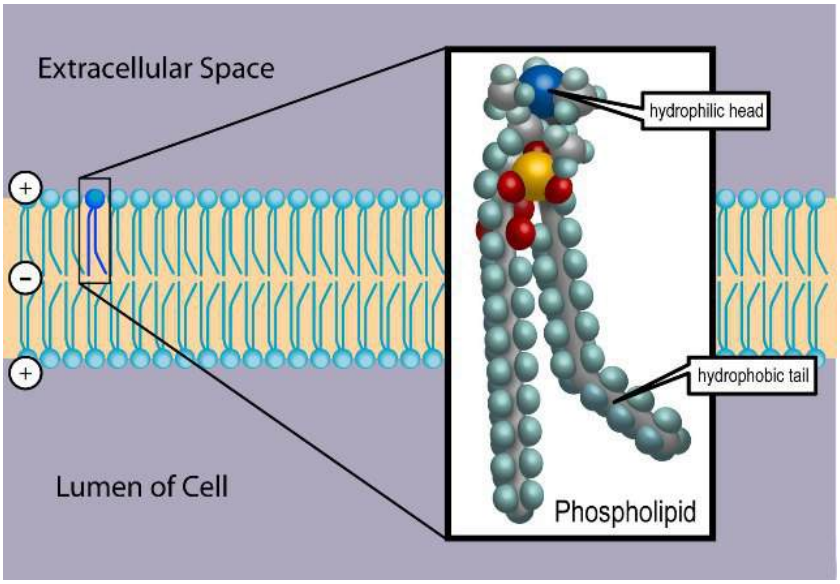
Note 3.7.1

Aerobic and anaerobic respiration are two types of cellular respiration. You can refresh on them in section 3.6.

The Benefit of Molecular Variation Organisms are able to respond to a wide range of environmental stimuli due to variations at the molecular level. This variation can take many forms, including differences in the *number and types of molecules* within cells, as well as *variations in the sequence of amino acids* that make up proteins.

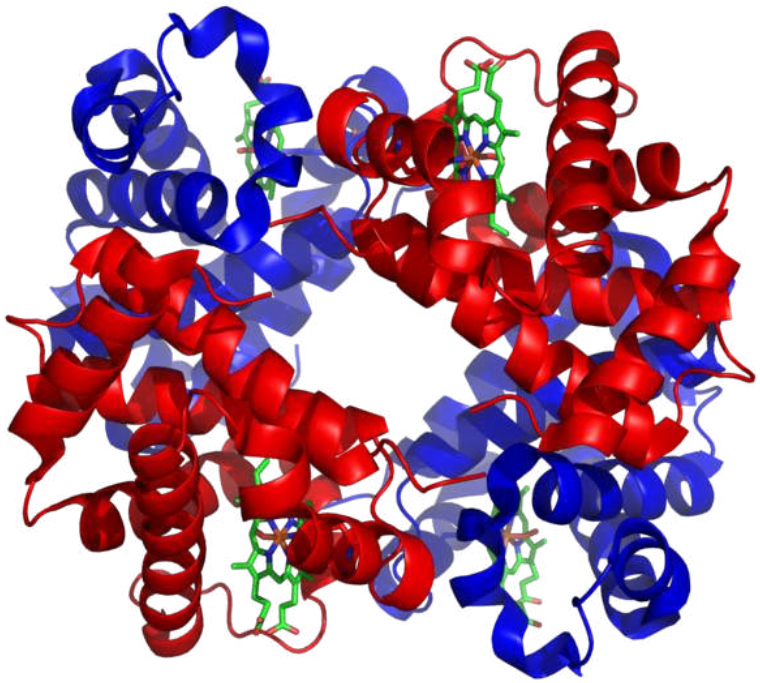
Example 3.7.2

The presence of phospholipids in cell membranes is one way in which organisms are allowed to survive and reproduce in different environments. Phospholipids play a crucial role in maintaining the identity and function of cell membranes. Specifically, different types of phospholipids have different melting points, so cells with a higher concentration of certain phospholipids can maintain their membrane identity at lower temperatures. Therefore, organisms in cold environments can adapt to the occasional harsh weather.



Example 3.7.3

Another way in which organisms can fit in different environments is the presence of important proteins. Hemoglobin is a protein that binds oxygen, allowing it to flow through the bloodstream, and different types of hemoglobin have different chemical properties. This results in organisms being able to maximize oxygen absorption in different developmental stages, such as the fetus, newborn, or adult.



Example 3.7.4

Chlorophyll is a key component of plant cells. It is a pigment in plants that absorbs light energy and converts it into chemical energy. Different types of chlorophyll allow plants to absorb and use different wavelengths of light for photosynthesis. Plants can use different parts of the light spectrum, giving them more flexibility when it comes to surviving and reproducing in various environments.

In general, organisms that are more capable of survival and reproduction pass on their DNA more frequently than those with less desirable traits. This causes successive generations to resemble the adaptations of the organism that is more fit. In these situations, environmental pressures can alter the genetic composition of a population over an extended period of time.

Problem 3.7.5 — Multiple Choice Question

In many animals, chemicals from the environment can be detected by olfaction, or a sense of smell. The ability to detect chemical odorants can be important for finding food and mates, establishing territory, and avoiding danger.

Odorants are recognized by a group of similar proteins called odorant receptors (ORs). Each receptor recognizes one or more specific chemicals from the environment and relays this information to the brain. The brain then interprets the combination of stimulated receptors as a certain odor.

Animals typically have large numbers of ORs encoded in their genomes, as demonstrated in the following table.

Species	Odorant receptor (OR) gene number
Human	388
Chimpanzee	450
Mouse	1200
Dog	1070

Given the information provided in the table, which of the following predictions is most likely?

(A) Dogs are less likely than chimpanzees to be able to detect a certain odorant in the environment.
(B) Humans have the ability to detect a greater number of odorants than dogs.
(C) Chimpanzees are more likely than mice to detect certain odors in a novel habitat.
(D) Mice have the ability to detect a greater number of odorants than humans.

Solution: The table shows the number of odorant receptor (OR) genes for each species. Mice have 1200 OR genes, while humans have only 388. Since the number of OR genes is directly related to the ability to detect different odorants, mice are more likely to detect a higher number of odorants than humans. This conclusion is consistent with $\boxed{\textbf{(D)}}$.

§3.8 Unit 3 Practice Questions

Problem 3.8.1 — 2010 AP Biology FRQ

An experiment was conducted to measure the reaction rate of the human salivary enzyme α-amylase. Ten mL of a concentrated starch solution and 1.0 mL of α-amylase solution were placed in a test tube. The test tube was inverted several times to mix the solution and then incubated at 25°C. The amount of product (maltose) present was measured every 10 minutes for an hour. The results are given in the table below.

Time (minutes)	Maltose Concentration (μM)
0	0
10	5.1
20	8.6
30	10.4
40	11.1
50	11.2
60	11.5

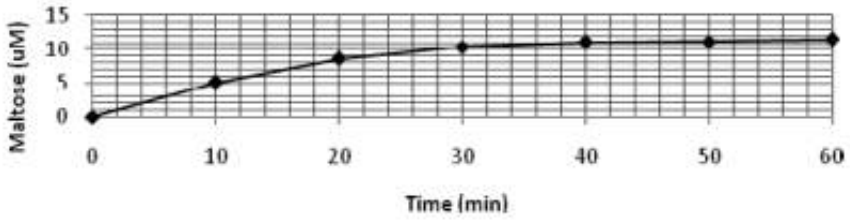
(a) **Graph** the data on the axes provided and **calculate** the rate of the reaction for the time period 0 to 30 minutes.

(b) **Explain** why a change in the reaction rate was observed after 30 minutes.

(c) **Draw** and **label** another line on the graph to predict the results if the concentration of α-amylase was doubled. **Explain** your predicted results.

(d) **Identify** TWO environmental factors that can change the rate of an enzyme-mediated reaction. **Discuss** how each of those two factors would affect the reaction rate of an enzyme.

Solution to part a: If we graph the maltose concentration (vertical axis) as a function of time (horizontal axis), we should end up with something like this:



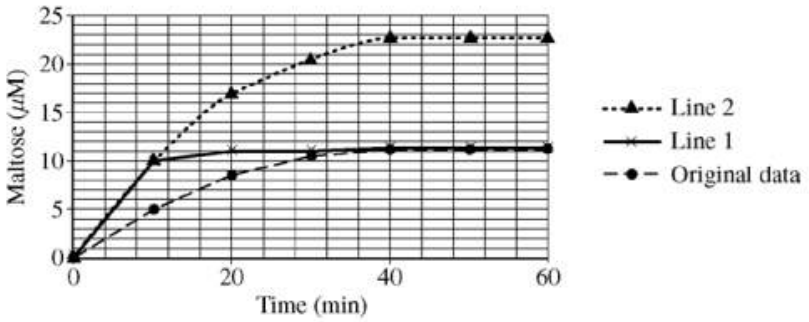
We can calculate the average rate of this reaction by dividing the change in maltose concentration (μM) by the change in time (min).

$$\text{rate} = \frac{\Delta \text{ concentration}}{\Delta t} = \frac{10.4 - 0}{30 - 0} = \boxed{0.347\ \mu\text{M/min}}$$

Solution to part b: Examining the graph, we see that the reaction rate starts to level

off, the shape of the graph being a plateau. This could have been caused by a number of factors. If the substrate is a limiting factor, then the enzyme cannot continue the reaction. In addition, the enzyme could have become inactive by about 35 to 40 minutes. Finally, certain environmental factors may have inhibited the formation of products in the chemical reaction, slowing its rate after this time.

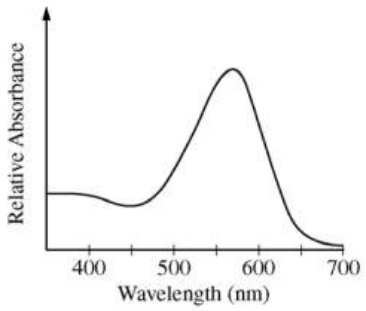
Solution to part c: If the concentration of α-amylase doubles, then the substrate is consumed more quickly because the overall product concentration remains the same. Alternatively, more product would form at each time step because twice as much enzyme is available; product formation levels off as the enzyme gradually loses its activity. This can be represented by the following two lines:



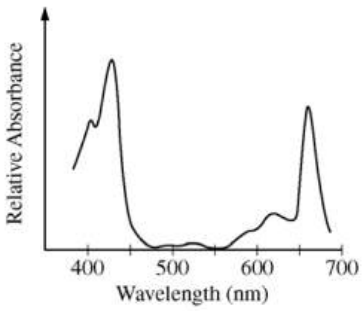
However, for this question, you are only supposed to draw one of the two!

Solution to part d: There are several factors that can influence the rate of an enzyme-mediated reaction, such as temperature, pH, enzyme inhibitors, etc. Let us choose temperature and pH. The rise in temperature generally speeds up the reaction, and the lowering of the temperature slows down the reaction. However, extreme high temperatures can cause an enzyme to lose its shape (denature). Enzymes have an optimal pH range in which they operate most effectively. Changing the pH outside of this range will slow enzyme activity and, as with temperature, extreme conditions can cause enzymes to denature.

Problem 3.8.2 — 2013 AP Biology FRQ



Graph I



Graph II

Color	Wavelength (nm)
Violet	380–450
Blue	450–475
Cyan	475–495
Green	495–570
Yellow	570–590
Orange	590–620
Red	620–750

An absorption spectrum indicates the relative amount of light absorbed across a range of wavelengths. The graphs above represent the absorption spectra of individual pigments isolated from two different organisms. One of the pigments is chlorophyll a, commonly found in green plants. The other pigment is bacteriorhodopsin, commonly found in purple photosynthetic bacteria. The table above shows the approximate ranges of wavelengths of different colors in the visible light spectrum.

(a) **Identify** the pigment (chlorophyll a or bacteriorhodopsin) used to generate the absorption spectrum in each of the graphs above. **Explain** and **justify** your answer.

(b) In an experiment, identical organisms containing the pigment from Graph II as the predominant light-capturing pigment are separated into three groups. The organisms in each group are illuminated with light of a single wavelength (650 nm for the first group, 550 nm for the second group, and 430 nm for the third group). The three light sources are of equal intensity, and all organisms are illuminated for equal lengths of time. **Predict** the relative rate of photosynthesis in each of the three groups. **Justify** your predictions.

(c) Bacteriorhodopsin has been found in aquatic organisms whose ancestors existed before the ancestors of plants evolved in the same environment. **Propose** a possible evolutionary history of plants that could have resulted in a predominant photosynthetic system that uses only some of the colors of the visible light spectrum.

Solution to part a: An organism containing bacteriorhodopsin appears purple because the pigment absorbs light in the green range of the light spectrum (495 nm to 570 nm). Alternatively, you could state that it *reflects* red and blue light, and the combination of

red and blue light appears purple. Therefore, Graph 1 shows the absorption spectrum likely generated by the pigment bacteriorhodopsin. Meanwhile, an organism containing chlorophyll *a* appears green in color because the pigment reflects green light. Therefore, Graph 2 shows the absorption spectrum likely generated by chlorophyll *a*.

Solution to part b: First, we should ignore Graph 1 because identical organisms in the experiment contain the pigment represented by Graph 2. Notice that the three groups are separated by the wavelength of light that illuminates them (650 nm, 550 nm, and 43 nm). According to Graph 2, 430 nm has a very high absorbance measure, 550 nm has an extremely low absorbance measure, and 650 nm has a medium absorbance measure.

According to Graph 2, the 3rd group would have the highest rate of photosynthesis, the 1st group would have the second highest rate of photosynthesis, and the 2nd group would have the lowest photosynthesis. We know this because Graph 2 shows that 430 nm has the highest absorbance measure, 650 nm has the second highest absorbance measure, and 550 nm has the lowest absorbance measure. Since the amount of light absorbed is directly proportional to the rate of photosynthesis, the rate of photosynthesis is highest in group 3, lowest in group 2, and in the middle for group 2.

Solution to part c: First notice that the question tells us to propose an evolutionary history for plants which resulted in a photosynthetic system that uses *only some* of the colors of the visible light spectrum. This statement indicates that the photosynthetic system which resulted from evolution cannot use every color on the visible light spectrum.

The first thing that should come to mind is that only certain colors supplied the plants with the appropriate amount of energy. Therefore, the plants evolved to absorb the colors that gave them the most energy, resulting in only some colors being used.

You could also discuss how absorbing shorter wavelengths implies a energy yield, which could overwhelm the plants. As a result, the plants evolved to **not** absorb ultraviolet (UV) light.

Problem 3.8.3 — 2017 AP Biology FRQ

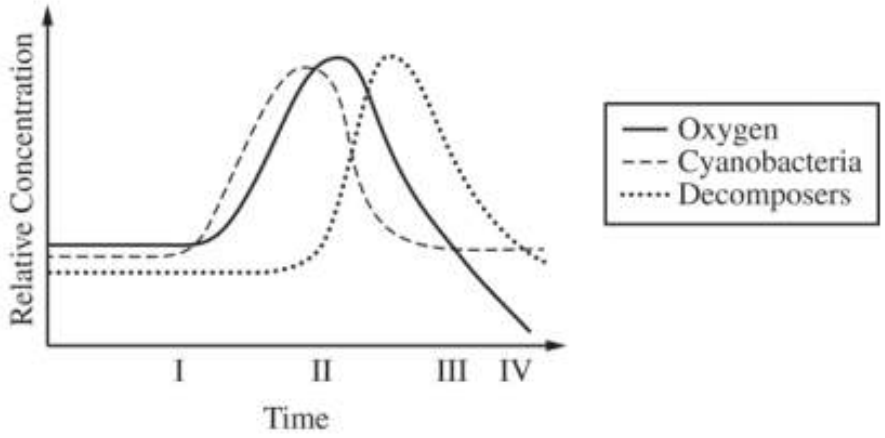


Figure 1. Characteristics of a pond community over time

Microcystis aeruginosis is a freshwater photosynthetic cyanobacterium. When temperatures increase and nutrients are readily available in its pond habitat, *M. aeruginosis* undergoes rapid cell division and forms an extremely large, visible mass of cells called an algal bloom. *M. aeruginosis* has a short life span and is decomposed by aerobic bacteria and fungi. **Identify** the metabolic pathway and the organism that is primarily responsible for the change in oxygen level in the pond between times I and II AND between times III and IV.

Solution: Between times I and II, the *M. aeruginosis* (cyanobacteria) population increases because of favorable conditions, allowing them to perform photosynthesis, consuming carbon dioxide and releases oxygen, as evidenced by the increase in oxygen levels in Figure 1.

Between times III and IV, decomposers/fungi/aerobic bacteria break down the organic matter from dead cyanobacteria through aerobic cellular respiration. This process consumes oxygen, causing a decline in oxygen levels in the pond, shown in Figure 1.

Problem 3.8.4 — 2021 AP Biology FRQ

Researchers hypothesize that the plant compound resveratrol improves mitochondrial function. To test this hypothesis, researchers dissolve resveratrol in dimethyl sulfoxide (DMSO). The solution readily passes through cell membranes. They add the resveratrol solution to mammalian muscle cells growing in a nutrient-rich solution (culture medium) that contains glucose. They measure ATP production at several time points after the addition of the resveratrol solution and find an increase in ATP production by the muscle cells.

(a) **Describe** the primary advantage for a mammalian muscle cell in using aerobic respiration over fermentation.

(b) **Identify** an appropriate negative control for this experiment that would allow the researchers to conclude that ATP is produced in response to the resveratrol treatment.

(c) **Predict** the effect on short-term ATP production when resveratrol-treated mammalian muscle cells are grown in a culture medium that lacks glucose or other sugars.

(d) The researchers find that resveratrol stimulates the production of components of the electron transport chain. The researchers claim that treatment with resveratrol will also increase oxygen consumption by the cells if glucose is not limiting. **Justify** the claim.

Solution to part a: We know that aerobic respiration occurs in the presence of oxygen, while fermentation occurs without oxygen. The former has a more complex pathway, involving glycolysis, the citric acid, and the electron transport chain, while the latter only involves glycolysis. As a result, aerobic respiration completely breaks down glucose into carbon dioxide and water, while fermentation partially oxidizes glucose into lactic acid or ethanol. The anaerobic pathway is much less energy-efficient, so a mammalian muscle cell is more advantageous in using aerobic respiration.

Solution to part b: If the researchers ran the experiment without adding resveratrol, this would induce a negative control in the experiment, as the electron transport chain would not be stimulated enough, leading to less oxygen available to accept transferred electrons. Alternatively, if the researchers treated the cells with DMSO alone, the oxygen consumption would likely remain at marginal levels, indicating that DMSO itself does not stimulate the electron transport chain or initial steps of cellular respiration.

Solution to part c: If resveratrol-treated mammalian muscle cells are grown in an environment lacking glucose or other sugars, then there will be little to no ATP production. This is because glucose is the primary fuel source for ATP production. With marginal amounts of glucose or other sugars, the cells cannot carry out the initial steps of cellular respiration, leading to a significant drop in ATP production.

Solution to part d: Resveratrol stimulates the production of components of the electron transport chain. Oxygen is highly important in the last stage of the electron transport chain because it reacts with protons and electrons, producing water, a byproduct of cellular respiration. By stimulating the production of these components, resveratrol essentially increases the capacity of the cell to transfer electrons and utilize oxygen, i.e. more transferred electrons allows for more required oxygen as the final electron acceptor.

Problem 3.8.5 — 2022 AP Biology FRQ

Fireflies emit light when the enzyme luciferase catalyzes a reaction in which its substrate, D-luciferin, reacts to form oxyluciferin and other products (Figure 1). In order to determine the optimal temperature for this enzyme, scientists added ATP to a solution containing D-luciferin, luciferase, and other substances needed for the reaction. They then measured the amount of light emitted during the first three seconds of the reaction when it was carried out at different temperatures.

$$\text{D-Luciferin} + O_2 + \text{ATP} \xrightarrow{\text{Luciferase}} \text{Oxyluciferin} + CO_2 + \text{AMP} + PP_i + \text{Light}$$

Figure 1. Light is emitted as a result of the reaction catalyzed by luciferase.

(a) **Describe** a characteristic of the luciferase enzyme that allows it to catalyze the reaction.

(b) **Identify** the dependent variable in the experiment.

(c) **State** the null hypothesis for the experiment.

(d) A student claims that, as temperature increases, there will be an increase in the amount of light given off by the reaction in the first three seconds. **Support** the student's claim.

Solution to part a: Generally, enzyme-mediated reactions can occur if the induced-fit mechanism is satisfied. Specifically, if the luciferase enzyme has an active site that can bind with the substrate, then the reactants will be brought together, favoring the formation of products. Alternatively, the charges on amino acid residues within the active site can impact substrate binding and catalysis, which ties into pH, significantly affecting enzyme efficiency.

Solution to part b: The scientists want to predict if the amount of light emitted during the first three seconds of the reaction is affected by the temperature. Therefore, temperature is free to vary (as the independent variable), while the amount of emitted light *depends* on the temperature, and is the dependent variable.

Solution to part c: In an experiment, the null hypothesis is a statement that assumes there is no effect, no relationship, or no significant difference between variables. Thus, in the context of this question, the null hypothesis is that temperature has no effect on the amount of light emitted in the duration of the reaction.

Solution to part d: We know that this claim by the student is true because higher temperatures increases the frequency of collisions between reactant molecules, as they are moving faster, resulting in an increase in reaction rate. In this context, an increase in the amount of light given off in the first three seconds indicates the rate of the reaction. Alternatively, you could state that a higher temperature results in the active site of luciferase to slightly conform, enhancing substrate binding.

Problem 3.8.6 — 2023 AP Biology FRQ

Noncyclic electron flow and cyclic electron flow are two major pathways of the light-dependent reactions of photosynthesis. In noncyclic electron flow, electrons pass through photosystem II, then components of a chloroplast electron transport chain, and then photosystem I before finally reducing $NADP^+$ to NADPH. In cyclic electron flow, electrons cycle through photosystem I and some components of the electron transport chain (Figure 1).

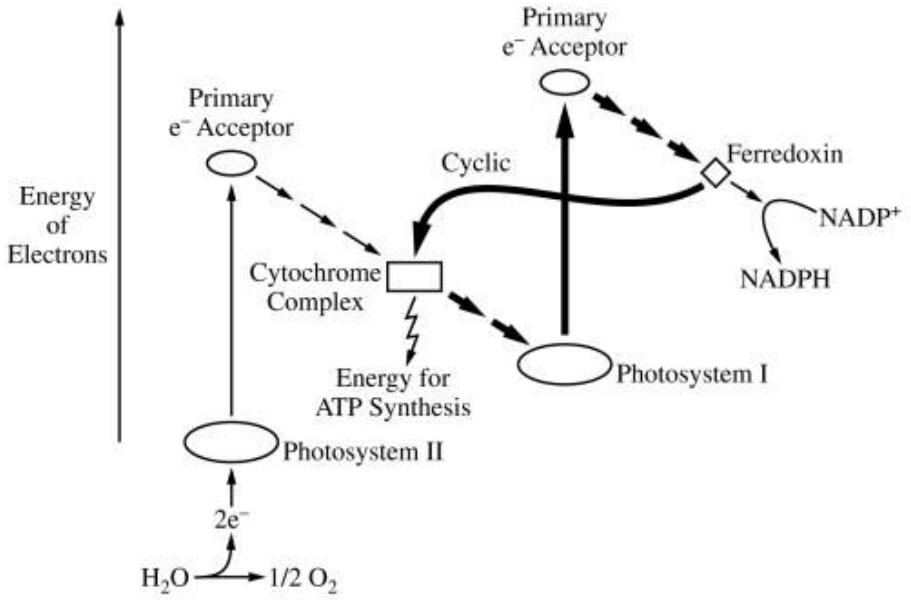


Figure 1. The pathways of noncyclic and cyclic (heavy arrows) electron flow. The cytochrome complex is a component of the electron transport chain between the two photosystems.

(a) **Describe** the role of chlorophyll in the photosystems of plant cells.

(b) Based on Figure 1, **explain** why an increase in the ratio of NADPH to $NADP^+$ will cause an increase in the flow of electrons through the cyclic pathway.

(c) Using rice plants, scientists examined the effect of a mutation that results in the loss of the protein CRR6. CRR6 is part of the photosystem I complex, and its absence reduces the activity of photosystem I. **Predict** the effect of the mutation on the rate of biomass (dry weight) accumulation.

(d) **Justify** your prediction in part (c).

Solution to part a: Chlorophyll is the primary pigment in plant cells responsible for capturing light energy, specifically within the photosystems. When a photon of light strikes a chlorophyll molecule, the light energy excites an electron in the chlorophyll molecule. This energized or excited electron is then passed along to other molecules in the photosystem, initiating the electron transport chain.

Solution to part b: If there is a high concentration of NADPH, there is less $NADP^+$ available to accept electrons from ferredoxin. As a result, electrons are redirected back to the cytochrome complex, and then to Photosystem I. This process is a part of the cyclic electron flow. The cyclic pathway primarily generates ATP, which can be used for other cellular processes.

Solution to part c: Note: biomass accumulation is defined as the increase in dry weight of the plant over time. A reduction in Photosystem I caused by a mutation in CRR6 directly impacts the plant's ability to synthesize carbohydrates. A reduced rate of carbohydrate synthesis will lead to a lower rate of biomass accumulation, therefore, mutant rice plants lacking functional CRR6 will exhibit a lower yield of biomass compared to wild-type plants.

Solution to part d: The Calvin cycle involves the synthesis of carbohydrates by plants. If the activity of Photosystem I is decreased, there will be insufficient ATP and NADPH in order to convert carbon dioxide into glucose. Since sugars are building blocks for plant biomass, the overall dry weight accumulation of the mutant plants are diminished.

4 Cell Communication and Cell Cycle

Our bodies are made up of trillions of cells that all have different responsibilities. In order for our bodies to function properly, these cells need to work together by communicating with each other. These cells also go through a process known as the cell cycle in order to create new cells. A neat way to remember the importance of regulating cell communication and the cell cycle is a checklist. In order for cellular processes to be performed correctly, there must be proper timing and coordination within the cell.

§4.1 Cell Communication

When they communicate, cells are like us humans! In short distances, cells can exchange information via cell-to-cell just as we do when talking to each other in close contact. Long distances, however, require a messaging system, like the Email or Text systems, but condensed so it can be applicable for cells. Most of the time, cells communicate over long distances, such as across an organism's body, by sending chemical signals back and forth.

Image Credit: punnybone

Communication via cell-to-cell contact When trying to communicate with another cell by initiating *direct contact* with it, a cell has two options: cell junctions and signal exchange via cell surface molecules.

Cell Junctions are responsible for joining two adjacent cells together, resulting in direct cell-to-cell communication between the pair of cells. There are three types of cell junctions: tight junctions (animal), gap junctions (animal), and plasmodesmata (plant).

Tight junctions are connections between adjacent cells that restrict the movement of molecules *between* two adjacent cells, and encourage movement *through* two adjacent

cells. Tight junctions are formed by protein chains that wrap around the cell membranes of two adjacent cells and squeeze them together to form a watertight seal.

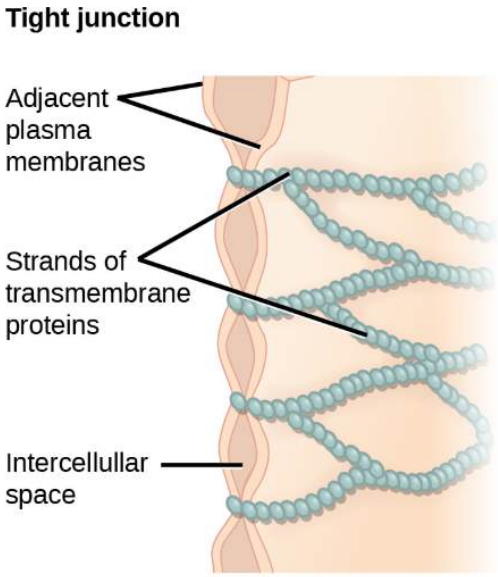


Image Credits: Mariana Ruiz Villareal and *OpenStax Biology*

As you can see from the image above, the plasma membranes of two adjacent cells are tightly held together by chains of trans-membrane proteins.

Gap Junctions are tiny channels that run between adjacent cells to allow for direct cell-to-cell communication and for the exchange of ions and small molecules. In addition to aiding the exchange of ions and small molecules, gap junctions allow for the exchange of electrical signals, which are particularly important in cells found within the cardiac system and muscles.

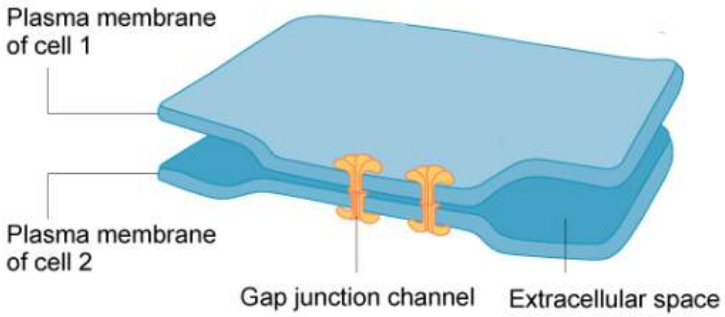


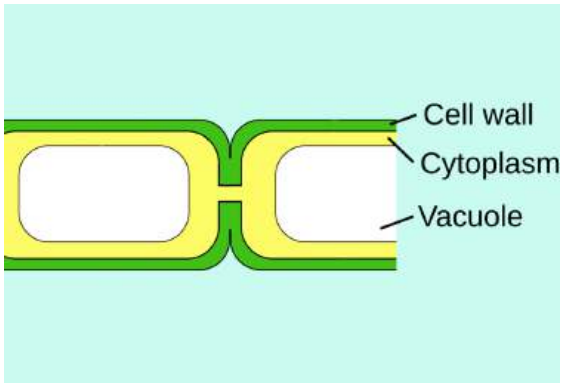
Image Credit: Adapted from Mariana Ruiz Villareal and *OpenStax Biology*
This diagram shows how gap junctions are set up between two adjacent cells. The yellow, shell-like protrusions outside of each channel are called connexons, and these act as the entry to the gap junction.

Plasmodesmata are channels that connect the cytoplasms of two adjacent plant cells.

Without plasmodesmata, plant cells would be blocked from exchanging molecules with each other by their cell walls, resulting in an unhealthy plant. Plasmodesmata are crucial for plants to absorb important molecules from their environment.

Note 4.1.1

For example, the presence of plasmodesmata in plant cells enables water to be transported from the roots to the rest of the plants.



Communication via chemical signaling When cells are so far apart that cell-to-cell communication is not possible, they must communicate by chemical signals, such as hormones and neurotransmitters. The three types of chemical signaling are paracrine signaling, synaptic signaling, and autocrine signaling.

Paracrine signaling is a mode of cellular communication in which a cell releases signaling molecules into the surrounding cytoplasm to travel to the target cells. A signaling molecule is a molecule that binds to a specific receptor on the target cell's surface. The binding of a molecule to the receptor results in a certain cellular response from the cell.

Example 4.1.2

Insulin, a signaling molecule, is responsible for ensuring that blood sugar levels in the body remain at a healthy level. When the blood sugar level of the body deviates from the healthy range, insulin is released into the cytoplasm by the pancreas, where it binds to specific receptors on the surfaces of cells. The binding of insulin to receptors on body cells results in the cells taking in glucose from the bloodstream to lower the amount of sugar in the blood.

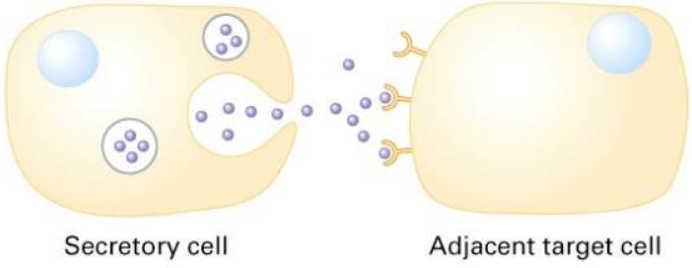


Image Credit: Eva Nogales 2008 MCB 110 UC Berkeley

The above image shows a cell sending signaling molecules to a nearby target cell that is covered in receptors.

Synaptic signaling is a type of chemical signaling that takes place between neurons and other cells at junctions called synapses. Synapses are special because they allow cells to exchange chemical signals *and* electrical signals. During synaptic signaling, a neuron releases neurotransmitters across the synapse, where they bind to specific receptors on the target cell's surface. Similarly to paracrine signaling, the binding of neurotransmitters to receptors evokes a certain response from the cell.

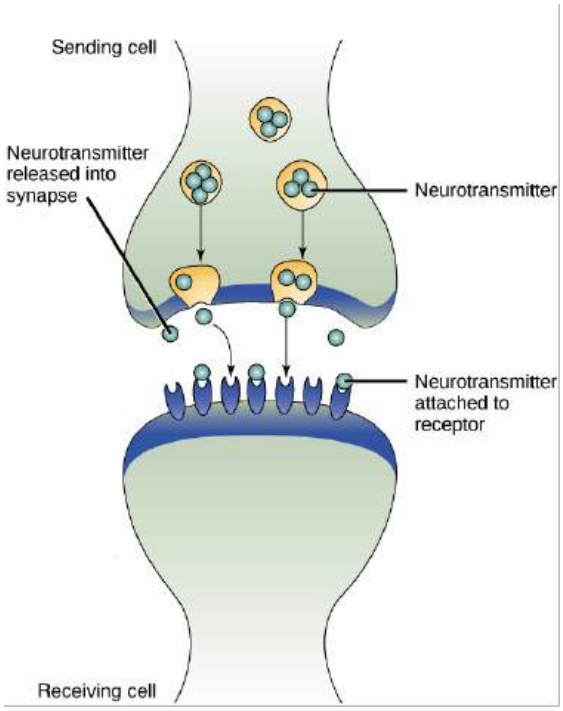


Image Credit: Khan Academy

In the above diagram, a sending cell releases neurotransmitters into the synapse, where they bind to receptors on the surface of a receiving cell.

In **autocrine signaling**, a cell reacts to its own signaling molecules. That might sound weird, but it is no different than writing future you a reminder on a sticky note. The process of autocrine signaling is simple: a sending cell releases signaling molecules that bind to the receptors of that same sending cell. You can probably guess what happens next: the binding of the signaling molecule to the receptors results in a specific response from the cell, depending on what signaling molecule is initially sent.

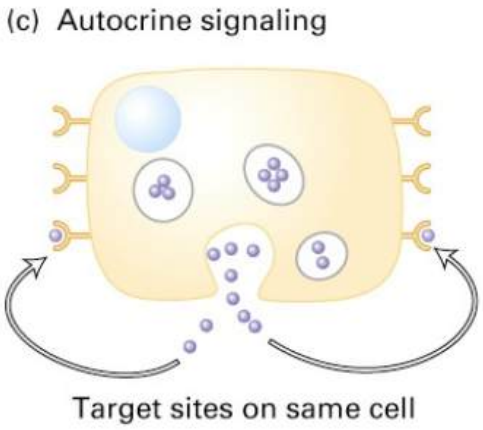


Image Credit: Adapted from Eva Nogales 2008 MCB 110 UC Berkeley

This diagram shows how the sending cell releases signaling molecules (purple circles) that end up binding to the receptors of the same sending cell.

Problem 4.1.3 — Multiple Choice Question

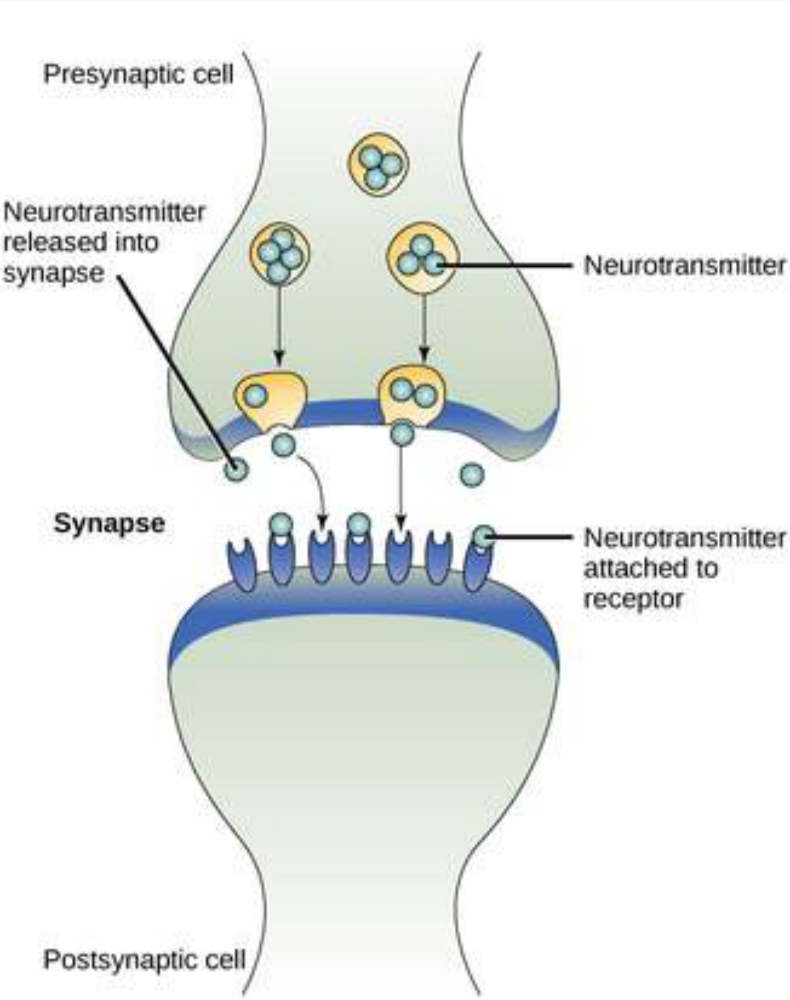
The tobacco mosaic virus (TMV) is a plant virus that infects a wide range of plants, including tobacco. In order to enter and travel through the cells of a plant, TMV produces a movement protein. This protein helps the virus travel directly between the cytoplasms of interconnected plant cells.

Which of the following best predicts how the movement protein modifies plant cells in order to help TMV travel from cell-to-cell?

(A) The movement protein modifies the vacuoles within plant cells.
(B) The movement protein increases the formation of transport vesicles within plant cells.
(C) The movement protein increases the formation of cell walls between plant cells.
(D) The movement protein modifies the plasmodesmata between plant cells.

Solution: Vacuoles in plant cells are not interconnected, so modifying this structure won't help TMV travel from cell-to-cell. Meanwhile, transport vesicles only move materials within a single plant cell, so modifying this structure won't help TMV travel in this manner. Increasing the formation of cell walls would actually make it *more* difficult for TMV to travel cell-to-cell because there are more boundaries between plant cells. However, the connections between plant cells which allow material to be transported from cell-to-cell−plasmodesmata−being modified would likely help TMV travel from one plant cell to another. The correct answer is $\boxed{\textbf{(D)}}$.

Problem 4.1.4 — Multiple Choice Question



Which of the following best describes the cell communication occurring in the figure above?

(A) A signal-emitting cell communicates with a nearby cell by releasing local regulators.
(B) A signal-emitting cell communicates with a far-away cell by releasing long-distance signaling molecules.
(C) A signal-emitting cell communicates with a far-away cell by releasing local regulators.
(D) A signal-emitting cell communicates with a nearby cell through direct cell-to-cell contact.

Source: Khan Academy

Solution: The figure shows a presynaptic cell releasing neurotransmitters to communicate with a postsynaptic cell. The cells are separated by a synapse, or the short gap between neurons, so they are close together. Also, the neurotransmitters travel across the synapse, so they are considered local regulators. The correct answer is $\boxed{\textbf{(A)}}$.

§4.2 Introduction to Signal Transduction

Signal transduction is when a cell takes an external signal, usually in the form of a signaling molecule, and converts it into a cellular response. Without signal transduction, cells would not be able to react to hormones, such as insulin and estrogen. Meanwhile, real-world applications, such as immunology, failure to manage and terminate signal transduction can cause uncontrolled cell growth (cancer) or any form of overstimulation that can harm the cell.

Components of a signal transduction pathway

- Signaling molecules: molecules sent our by a sending cell that are meant to bind to receptors of a target cell
- Receptors: Proteins on the surface of cells that serve as the binding site for signaling molecules and pass on the signal to the interior of the cell.
- Cell response: Once a signal is introduced to the cell by receptors, the cell responds in a certan way depending on what the signal is. For example, the binding of Acetylcholine to the receptors of a cell leads to muscle contraction.

Steps of a signal transduction pathway

1. **Reception** involves signaling molecules, sent from a sending cell that bind to receptors on the surface of a target cell. This causes a change in the shape of the cytoplasm of the inside of the receptor. Then, transduction occurs.
2. In **transduction**. the signal travels through a series of proteins, where it is amplified through cascade reactions. A **cascade reaction** occurs when a single molecule generates a response from multiple molecules.
3. Eventually, the cell generates a **response** to the amplified signal depending on the identity of the signaling molecule. An example of a response is when the cell activates the enzyme RNA polymerase, leading to gene transcription.

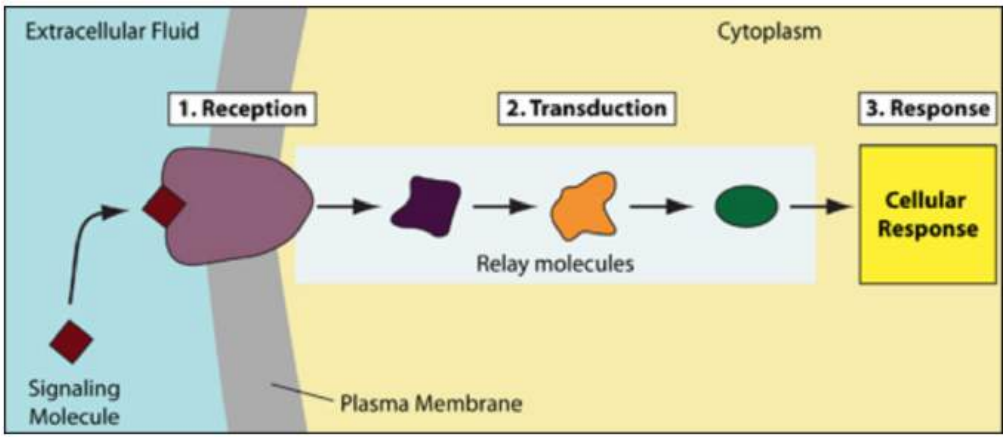


Image Credit: Biology LibreTexts

The above diagram shows the process of signal transduction. First, a signaling molecule binds to a receptor on the target cell. Then, the signal is converted, and amplified by relay proteins. Lastly, the amplified signals evoke a certain cellular response.

Reception Cell surface receptors span the entire cell membrane. They are important because most signaling molecules are too large to cross the plasma membrane.

The plasma membrane contains a phospholipid bilayer. The heads of the phospholipid are "water-loving" which are called hydrophilic. The tails of the phospholipid are "water-hating" which are called hydrophobic.

This bilayer is very important, as we discussed in Unit 2, as it creates a barrier between the interior and exterior of the cell.

Example 4.2.1

Ion channel receptors involve channels that open and close. These channels are used to allow charged particles to move across the membrane. Through this process, the ligand binds to the outside part of the cell and changes the form of the inside cytoplasm. This causes a G protein to bind and activate the enzyme adenylyl cyclase. Adenylyl cyclase converts ATP (energy) to cyclic-AMP. Finally, cyclic-AMP activates other molecules inside the cell which finally leads to the cellular response.

Transduction The essential question now is, "How exactly are proteins activated?" This is done via **phosphorylation**. Essentially, an already-existing protein gains a phosphate group, causing it to get "turned on" and carry out its function, while the ATP which provided the phosphate group is converted into ADP. Once this is over, the phosphate group will be removed, "turning off" the protein and conserving energy.

There is another important process in transduction called **amplification**. Not all signals lead to this, but it is a step that can and should be included. Amplification steps are a sequence of turning on communication pathways to amplify the response, or a process to make the transduction process faster. An example of this is the cAMP or the G-protein, which can be activated with GTP.

Note 4.2.2

Since transduction occurs in animal, bacterial, plant, and yeast cells, it indicates that the associated pathway has, more likely than not, evolved from a common ancestor! We will discuss evolution with more detail in Unit 7.

Response There isn't much on this case. Just understand that on the ligand, the response can be anything, e.g. activating an enzyme, transporting a molecule through standard procedures, etc.

Special Cases

- **Lipid hormones** are a special class of ligand. Since the cell membrane is composed of lipid, it does not require a receptor on its surface. Instead, lipid hormones can permeate the membrane without the assistance of a transport protein, with the receptor protein actually situated inside the cell. This reception actually produces a transcription factor, and an entirely new protein is synthesized from DNA to mRNA to ribosome. Because the protein is made from scratch in response to the

ligand, it can take quite some time to create an effective response. Fortunately, slower response time means a longer-lasting and more functional protein.

- A **secondary messenger** involves a receptor at the cell's surface receiving a ligand, activating the transport channel. Once the channel is opened, the secondary messenger enters the cell, binding to the appropriate protein to produce a messenger.

Problem 4.2.3 — Multiple Choice Question

Acetylcholine is a neurotransmitter that helps control muscle contraction. This neurotransmitter functions differently depending on which type of muscle it interacts with. For example, acetylcholine promotes muscle contraction in skeletal muscle but inhibits contraction in heart muscle.

Which of the following best explains why acetylcholine leads to different cellular responses in skeletal and heart muscle?

(A) Acetylcholine binds more tightly to receptors in skeletal muscle than in heart muscle.
(B) Acetylcholine binds to different types of receptors in skeletal and heart muscle.
(C) Acetylcholine binds to more receptors in skeletal muscle than in heart muscle.
(D) Acetylcholine binds with less affinity to receptors in heart muscle than in skeletal muscle.

Solution: Acetylcholine produces different cellular responses depending on the type of receptor it activates. In skeletal muscle, acetylcholine binds to ligand-gated ion channels, promoting muscle contraction. In heart muscle, it binds to G protein-coupled receptors, inhibiting contraction. The correct answer is $\boxed{\textbf{(B)}}$.

§4.3 Signal Transduction

This section focuses more closely on the signal transduction pathways organisms use to adapt to changing environmental conditions. Here, we will look at several specific pathways and identify the common elements they utilize and see the cellular responses they elicit. Most importantly, we will observe how these signal transduction pathways can lead to genetic responses that can significantly alter cellular structure or even lead to cell death.

The Environment's Role in Causing a Cellular Response The environment can significantly impact cells, prompting them to react in various ways. Numerous elements in the surroundings can affect the cell cycle. For instance, temperature, light, and chemicals are all factors that can shape how a cell behaves in response to its environment.

External Signals The environment can evoke a cellular response by providing external signals, such as temperature and light. Most of the time, external signals from the environment are chemical signals (hormones, toxic materials, chemicals, etc.), physical signals (temperature, light, etc.), or biological signals(other organisms).

Once an external signal from the environment interacts with receptors on the cell surface, the signal is converted and then amplified to produce the appropriate cellular response. Recall that the cellular response is unique for different substances. For example, while insulin causes cells to take in glucose, growth factors cause cells to divide.

Changes in Gene Expression A cell's gene expression is affected when the signal transduction pathway involves transcription factors. Transcription factors are proteins that control the expression of genes by binding to specific parts of DNA strands.

1. A signaling molecule binds to the receptors of a cell
2. The receptor converts the signal, where it is then amplified by proteins inside of the cell
3. Depending on what the amplified signal warrants, transcription factors are either activated or inhibited.
4. Inhibition of certain transcription factors can result in disruptions in the cell cycle, cell differentiation, and gene expression.

Protein Modification A signal transduction pathway can also result in the modification of a protein. In order for a protein to be modified, there must be a shape change or the addition/removal of a chemical group. The process is basically the same as that of a gene expression, except that the amplified signal results in the addition/removal of a chemical group on a protein or in a change of shape.

Note 4.3.1

Phosphorylation is when a kinase, an enzyme that transfers phosphate groups from ATP to proteins, adds a phosphate group to a protein, resulting in the protein being activated or deactivated.

Dephosphorylation is when a photophase, an enzyme that removes phosphate groups from proteins by breaking ester bonds. When a protein is dephosphorylated, it can be inactivated/activated, changed to an unstable state, and even interact differently with other cellular components.

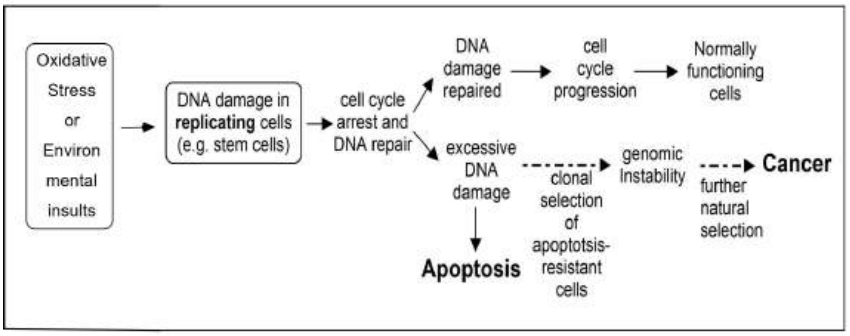
Changes in Metabolism The metabolism of cells can be altered, and even stopped, by signal transduction pathways. Specifically, signal transduction pathways can cause changes in the activity of metabolizing enzymes, gene expression, and nutrient transportation. Changes in any of these 3 activities will result in the metabolism of a cell being altered.

Changes in Cell Division Signal transduction pathways can have an effect on cell division by disrupting the cell cycle. These pathways can cause changes in cell division by activating or inhibiting the proteins responsible for moderating the cell cycle.

Apoptosis Apoptosis refers to the process by which damaged or dead cells are destroyed. A common term for apoptosis is "programmed cell death" because that is exactly what it is: intentional destruction of cells. Here are the steps of apoptosis:

1. A "death" signaling molecule binds to receptors on the target cell, or the cell that needs to be eliminated.

2. The signal is converted and amplified by relay proteins inside the cell.
3. The mitochondria releases *caspases*, enzymes that break down proteins, into the cellular environment.
4. The cell shrinks significantly in size and begins to form blebs, which are bulbous protrusions, on its plasma membrane.
5. DNA breaks down and the cell fragments into small vesicles, which are eaten by macrophages.

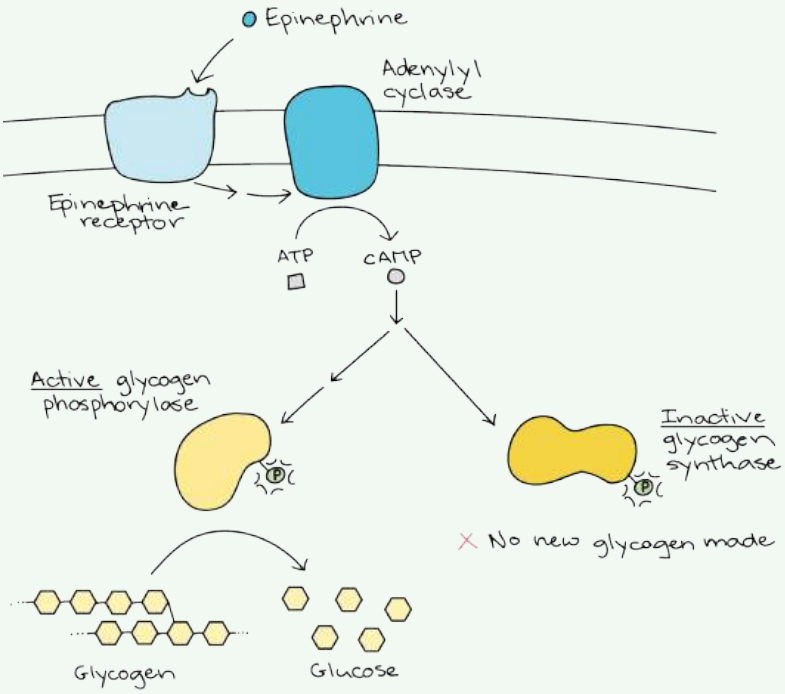


This flow chart shows how initial signals from the environment can lead to cancer if DNA damage is not repaired *and* apoptosis fails.

Note 4.3.2

Macrophages are immune cells that specialize in detecting, engulfing, and disposing of foreign substances, dead/damaged cells, and toxins. An interesting fact about macrophages is that they are basically shape shifters because they can switch from fighting against an aggressive pathogen (M1 Macrophage) to helping heal damaged cells (M2 Macrophage).

Problem 4.3.3 — Multiple Choice Question



The image above depicts the signal transduction pathway of epinephrine. During one step in the pathway, the enzyme glycogen phosphorylase is phosphorylated, which activates the enzyme.

If an inhibitor prevents glycogen phosphorylase from being activated during this pathway, which of the following will most likely occur?

(A) Glycogen synthase will be activated in place of glycogen phosphorylase.
(B) Epinephrine will not bind to the epinephrine receptor.
(C) Blood glucose levels will not increase in response to epinephrine.
(D) Glycogen levels will decrease in response to epinephrine.

Source: Khan Academy

Solution: During the signal transduction pathway of epinephrine, glycogen phosphorylase catalyzes the breakdown of glycogen into glucose. If an inhibitor prevents glycogen phosphorylase from being activated, then this breakdown will not occur. Thus, blood glucose levels will not increase in response to epinephrine. The correct answer is $\boxed{\textbf{(C)}}$.

Problem 4.3.4 — Multiple Choice Question

Thyroid-stimulating hormone (TSH) is a long-distance signaling molecule released by the anterior pituitary gland. Once released, TSH travels through the bloodstream to the thyroid gland, where it binds to G protein-coupled receptors called TSH receptors. This binding initiates signal transduction pathways that produce two thyroid hormones, T3 and T4.

In individuals with hypothyroidism, TSH is released by the pituitary gland normally, but these individuals have consistently low levels of T3 and T4.

Which of the following best explains why individuals with hypothyroidism have low levels of T3 and T4?

(A) A mutation in their TSH receptors decreases TSH recognition, resulting in decreased signal transduction.
(B) A mutation in their TSH receptors increases TSH recognition, resulting in increased signal transduction.
(C) A mutation in their TSH receptors decreases TSH recognition, resulting in increased signal transduction.
(D) A mutation in their TSH receptors increases TSH recognition, resulting in decreased signal transduction.

Solution: Low levels of T3 and T4 suggest that TSH signal transduction is decreased in individuals with hypothyroidism. Because signal transduction is initiated only when TSH binds with its receptor, a mutation that decreases TSH signal transduction would do so by decreasing TSH recognition. The correct answer is $\boxed{\textbf{(A)}}$.

§4.4 Changes in Signal Transduction Pathways

As you probably know by now, signal transduction pathways can have significant effects on the activity of a cell. But what happens when the pathway itself is changed?

Cell Aging Cell aging is one way in which a signal transduction pathway can be modified. When a cell ages, many of its components wear down due to mutations, improperly folded proteins, and stress. A common result of cell aging is reduced signal reception due to damaged receptors, leading to dysfunctional signal transduction pathways.

Example 4.4.1

The **p53 pathway** is a very important signaling pathway because it reduces the risk of a cancer outbreak by arresting, or stopping, the cell cycle when a dangerous error is detected. p53 is a protein that is highly involved in preventing cancer by inducing apoptosis, halting the cell cycle, activating DNA repair, and receiving signals of DNA damage.

Environment The environment can also modify a signal transduction pathway by affecting a cell's ability to receive signals. For example, a increase in pH level can change

the shape of cell receptors, resulting in changes in the binding behavior of receptors. Changes in how receptors bind to signaling molecules can result in a cell that is unable to respond to it's environment properly.

Mutations Finally, genetic mutations can significantly affect signal transduction pathways by changing the shape of signaling proteins. Changes in the shape of signaling proteins can result in excessive activation or inhibition of signal transduction pathways.

Note 4.4.2

Excessive activation is dangerous because it can result in uncontrolled cell growth, or cancer. Inhibition of a signal transduction pathway can be detrimental to cell function because it causes the cell to ignore signaling molecules, some of which could be carrying important signals.

Problem 4.4.3 — Multiple Choice Question

Mutations within genes coding for G protein-coupled receptors (GPCRs) can lead to one of two major outcomes—a loss-of-function or a gain-of-function. Loss-of-function mutations prevent signaling in GPCR pathways, even in the presence of signaling molecules. Gain-of-function mutations activate signaling in GPCR pathways, even in the absence of signaling molecules.

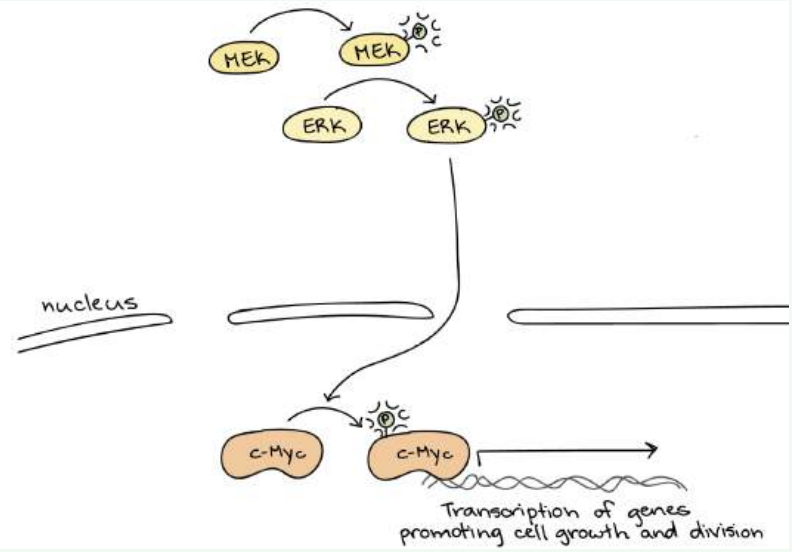
Which of the following will most likely be found in an individual with a gain-of-function GPCR mutation?

(A) Signal transduction pathways that are activated even if ligand-to-receptor binding does not occur
(B) Signal transduction pathways that are inactive if ligand-to-receptor binding does not occur
(C) Signal transduction pathways that are activated only if ligand-to-receptor binding occurs
(D) Signal transduction pathways that are inactive even if ligand-to-receptor binding occurs

Solution: A gain-of-function GPCR mutation leads to ligand-independent activation of signaling. It is impossible for the pathways to be inactive, so this eliminates (B) and (D). Moreover, this process occurs independently of ligand-to-receptor binding. So, signal transduction pathways will be constantly activated, even without the binding of a ligand to its receptor, eliminating (C). The correct answer is $\boxed{\textbf{(A)}}$.

Problem 4.4.4 — Multiple Choice Question

The information below shows and describes the intermediate steps of the MAP-K/ERK signaling cascade.



After MEK is activated, it phosphorylates and activates ERK. ERK goes on to phosphorylate and activate a variety of target molecules, including transcription factors like c-Myc that promote cell growth and division.

Which of the following toxins will most likely inhibit the phosphorylation of c-Myc?

(A) A toxin that prevents the phosphorylation of ERK
(B) A toxin that prevents c-Myc from activating ERK
(C) A toxin that prevents the removal of a phosphate group from ERK
(D) A toxin that prevents the dephosphorylation activity of MEK

Source: Khan Academy

Solution: After ERK is phosphorylated, it goes on to phosphorylate c-Myc. So, a toxin that prevents the phosphorylation of ERK will also prevent the phosphorylation of c-Myc. This information is most consistent with option **(A)**.

§4.5 Feedback Mechanisms

Feedback mechanisms refer to processes that cells use to maintain a state of balance that is often called homeostasis. Without feedback mechanisms, organisms would not be able to react to cues from the environment, such as scorching temperatures or a dramatic drop in pH.

Example 4.5.1

Sweating is a feedback mechanism that many organisms use to cool down. In order to cool down the body, sweat glands produce sweat, which is released onto the skin. Once on the skin, sweat droplets evaporate while taking some heat with them. On the other hand, when it is cold, we shiver in order to warm ourselves up. When we shiver, our muscles rapidly contract and expand, producing heat for our bodies. Like sweating, shivering serves to bring the body's internal temperature to a healthy range.

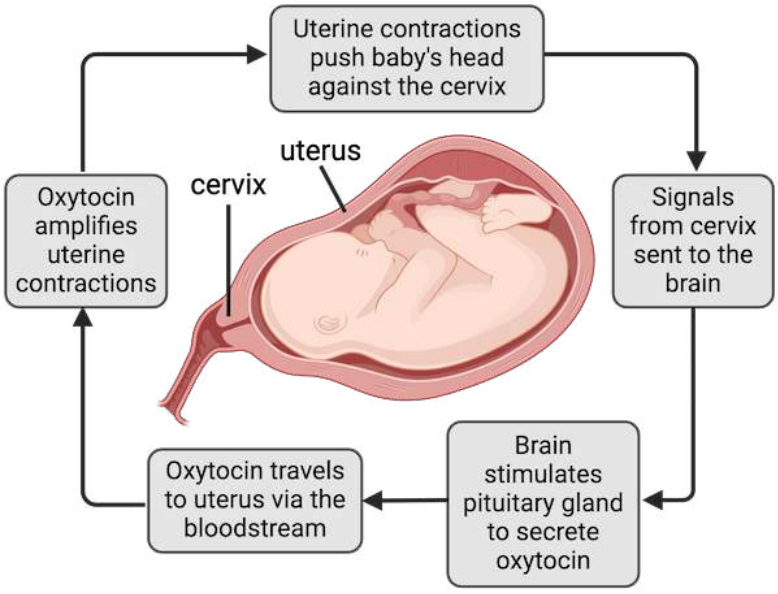
Positive Feedback Mechanisms Positive feedback mechanisms encourage systems to move away from their initial stable state toward a new, sometimes extreme state. In order to do so, positive feedback mechanisms take a system's response to stimuli and amplify it. Unlike negative feedback mechanisms, positive feedback mechanisms do not help an organism stay in homeostasis, rather, they encourage systems to change into something new.

Example 4.5.2

Blood clotting is a positive feedback mechanism because platelets that initially arrive at the injury site release chemicals that require more platelets. This snowball effect continues until a blood clot is formed and the bleeding stops.

Example 4.5.3

Another more relatable example is a **social media trend**. Take the ice bucket challenge: the initial challengers who posted clips of themselves getting drenched in icy water encouraged the next round of challengers to do the same, and so on. Eventually, the ice bucket challenge became an international trend that attracted everyone, from CEOs to celebrities.



This diagram shows how the process of childbirth utilizes the positive feedback mechanism. As you can see, the pushing of the baby's head against the mother's cervix causes signals

to be sent to the brain, which then activate oxytocin secretion. The release of oxytocin causes contractions to become more frequent and intense. Eventually, the contractions become intense enough so the baby can exit the womb.

Problem 4.5.4 — Open-Ended Question

Explain why childbirth is an example of a positive feedback mechanism.

Solution: The pushing of the baby's head produces signals that travel to the brain and cause the secretion of oxytocin to increase. Increased oxytocin secretion causes more frequent contractions, which ultimately results in the birth of the baby.

Negative Feedback Mechanisms Negative feedback mechanisms try to keep organisms in homeostasis by regulating the processes that occur within organisms. For example, the main function of the AC in our houses is to keep the temperature inside at whatever level we set it at. When it gets too hot, the AC kicks on and blows cool air around the house to bring the temperature inside down to the level the thermostat is set to.

Example 4.5.5

A more biology-relevant example of negative feedback is the manner in which our bodies regulate blood sugar levels. When blood glucose levels rise, usually due to food consumption, the pancreas secretes insulin, a hormone that encourages cells to take in more glucose, resulting in a decrease in blood sugar levels.

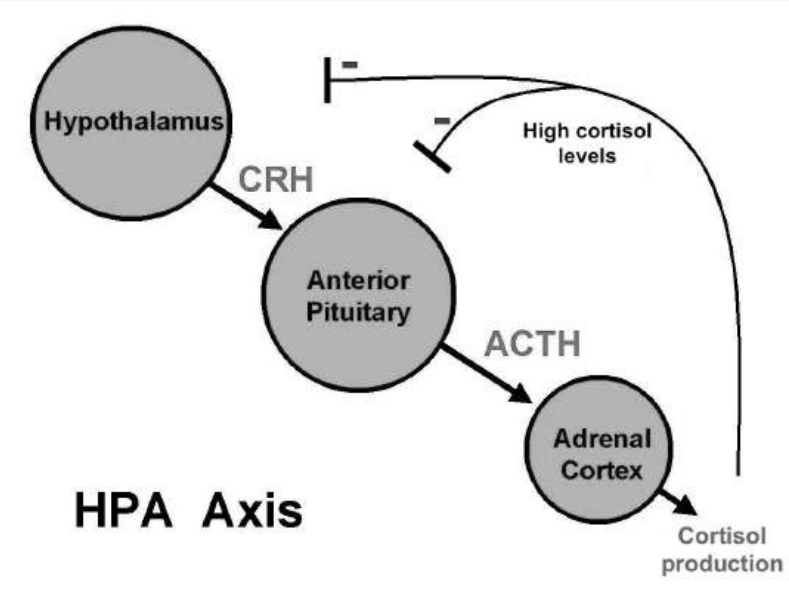
Problem 4.5.6 — Multiple Choice Question

Which of the following statements about feedback mechanisms is most accurate?

(A) Negative feedback mechanisms move a system further from its set point.
(B) Positive feedback mechanisms maintain a system at its set point.
(C) Negative feedback mechanisms return a system to its set point.
(D) Positive feedback mechanisms bring a system closer to its set point.

Solution: The correct answer is **(C)**. Negative feedback mechanisms *resist* changes in a system. When a system deviates from its set point, a negative feedback mechanism returns the system to its target value.

Problem 4.5.7 — Multiple Choice Question



In response to stress, the hypothalamic–pituitary–adrenal (HPA) axis coordinates the release of the steroid hormone cortisol, as summarized in the figure above. Inhaled corticosteroids (ICS) are a class of synthetic steroid hormones that are commonly used in the long-term treatment of persistent asthma.

Assuming that ICS function in the same way as naturally occurring cortisol, it is most likely that long-term, high-dose ICS use would

(A) reduce cortisol production
(B) stimulate cortisol production
(C) stimulate ACTH production
(D) stimulate CRH production

Source: Khan Academy

Solution: The correct answer is $\boxed{\textbf{(A)}}$. According to the figure, high cortisol levels initiate a negative feedback loop, which suppresses the activity of the HPA axis. ICS function in the same way as cortisol, so long-term, high-dose ICS use would likely also suppress the HPA axis, thereby reducing cortisol production.

§4.6 Cell Cycle

The cell cycle is the process by which cells grow and reproduce by dividing into two daughter cells. Without the cell cycle, cells would struggle to adapt to environmental changes and would lack the ability to reproduce. The cell cycle consists of two large stages: interphase and the mitotic phase.

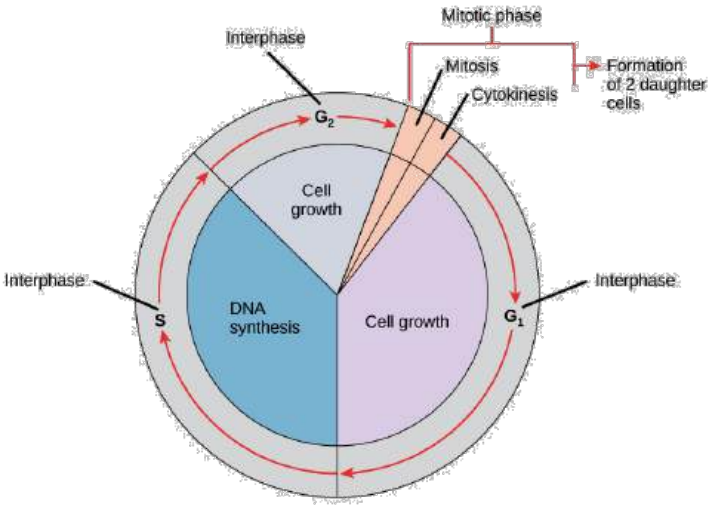


Image Credit: *OpenStax Biology*

Interphase During interphase, the cell grows and replicates DNA in preparation for cell division. Interphase accounts for about 90% of the cell cycle with the other 10% being the mitotic phase. Specifically, interphase consists of three sequential phases: G1 phase, S phase, and G2 phase.

G0 Phase The G0 phase is a period in the cell cycle where cells exist in a quiescent (inactive) state. Cells in this stage are not preparing for or undergoing division.

G1 Phase During the G1, or growth phase 1, the cell grows in size while synthesizing mRNA, enzymes, and proteins. These products are crucial for DNA replication and protein synthesis, or processes that are crucial to ensuring that cells produced during cell division have the appropriate genetic information.

After a cell goes through G1, it must pass a checkpoint. The G1 checkpoint checks that the cell is of adequate size, has undamaged DNA, and has enough energy (ATP). If a cell meets these requirements, it moves on to the S phase. But if a cell fails to meet these requirements, the cell can either enter a neutral state called the G0 phase. The G0 phase is basically a rest stop because it allows the cell to pause and repair any damage.

S Phase The S phase, or the synthesis phase, is when DNA is replicated. DNA must be replicated to ensure that each daughter cell receive a complete set of chromosomes after cell division. Compared to the rest of the phases in the cell cycle, S phase is the most meticulous because any errors in the replication of DNA can result in dangerous mutations and even cancer.

Just like the G1 phase, S phase is followed by a checkpoint that ensures DNA replication has occurred without any mistakes. If no mistakes are found, the cell continues to the G2 phase. But if any mistakes with DNA replication are detected, the cell cycle is halted until repairs take place. Errors in replicated DNA are detected by proteins, which halt the cell cycle and repair any damage.

Note 4.6.1

When an error is detected during the S phase checkpoint, it is crucial that the cell cycle is halted. Otherwise, daughter cells inherit damaged DNA, which can result in dangerous genetic abnormalities.

G2 Phase During the G2 phase, the cell makes final preparations for cell division. Preparations include protein synthesis, repair of damaged DNA, and continued cell growth. Additionally, cells replicate organelles like the mitochondria and produce proteins that are specialized for assisting with cell separation. Some proteins produced during the G2 phase, such as tubulin and actin, are crucial to the separation of cells during mitosis because they make up the **mitotic spindle**.

The mitotic spindle is composed of spindle poles, kinetochores, and microtubules. The **spindle poles** are important for organizing the distribution of chromosomes because they are like anchors, to which microtubules attach.

Kinetochores are responsible for helping to pull sister chromatids apart by first attaching to special regions on the chromosomes called centromeres. Once attached, kinetochores act as connection points for microtubules.

Microtubules are the building blocks that make up the mitotic spindle, so without them we would not have cell division. Microtubules also work together with kinetochores by attaching to them to pull sister chromatids apart.

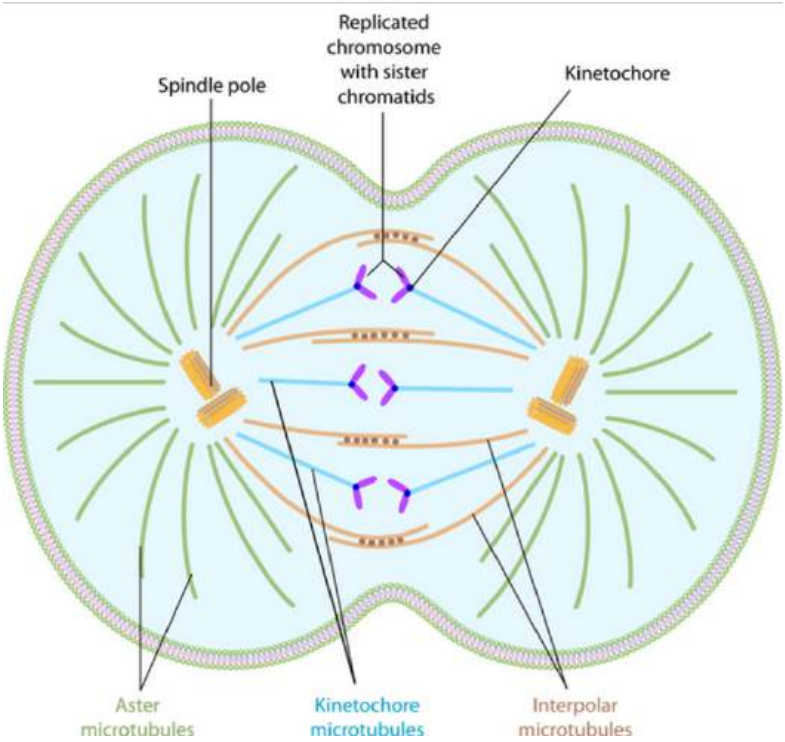


Image Credits: Scitable by Nature

Mitotic Phase The mitotic phase is when the cell actually splits into two separate, yet identical daughter cells, each an exact replica of the parent cell.

Mitosis Mitosis is the process by which a parent cell prepares for cytokinesis, or actual cell division.

1. Prophase: Chromatids condense into chromosomes, nuclear envelope dissolves, and the mitotic spindle forms
2. Metaphase: The mitotic spindle arranges chromosomes on the metaphase plate and kinetochores attach to spindle fibers from the mitotic spindle
3. Anaphase: Sister chromatids pulled apart by spindle fibers and moved to the nearest spindle pole
4. Telophase: Chromosomes disassemble into chromatin, nuclear envelope reappears, and the mitotic spindle breaks down. The cell now resembles a peanut:)

Cytokinesis After making it through mitosis, the cell undergoes cytokinesis. During cytokinesis, the cell's cytoplasm divides into two separate daughter cells, each with brand-new set of organelles and DNA. For the cytoplasm to divide, a cleavage furrow must form.

A **cleavage furrow** is a contractile ring, meaning it can contract, made up of proteins called actin and myosin. The cleavage furrow forms as a ring around the center of the parent cell and squeezes, eventually separating the parent cell into two separate daughter cells. The squeezing of the cleavage furrow is often referred to as "pinching" the cell. Keep in mind that the cleavage furrow is only used by animal cells and not by plant cells due to the presence of a rigid cell wall.

Problem 4.6.2 — Multiple Choice Question

In response to critically low nutrient levels, yeast cells often enter into a dormant, non-dividing state. This state allows yeast cells to survive until nutrient levels are restored, at which point the cells typically re-enter the cell cycle.

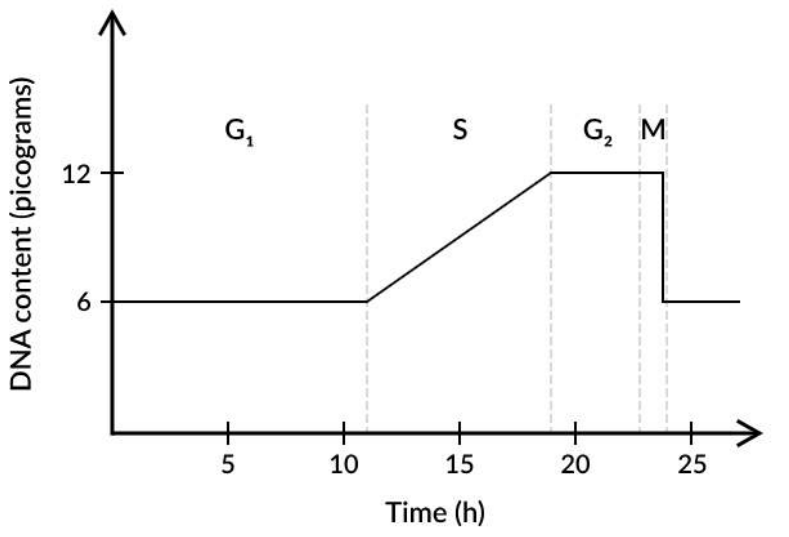
According to the information above, critically low nutrient levels cause yeast cells to

(A) transition into meiosis
(B) transition to G1 to G0 phase
(C) transition from G0 to G1 phase
(D) transition into mitosis

Solution: According to the text, yeast cells respond to low nutrient levels by entering into a dormant, non-dividing state. This scenario best describes the G0 phase, a resting state that cells enter from the G1 phase. Thus, $\boxed{\textbf{(B)}}$ is correct.

Problem 4.6.3 — Multiple Choice Question

The following graph shows how cellular DNA content changes over the course of a typical mitotic cell cycle in rapidly proliferating human cells.



Based on the graph, which of the following statements is correct?

(A) Human cells spend the majority of the cell cycle in interphase.
(B) The amount of cellular DNA remains constant throughout the cell cycle.
(C) The amount of cellular DNA is halved during interphase.
(D) Human cells spend the same amount of time in M phase as they do in interphase.

Source: Khan Academy

Solution: This question primarily tests our ability to analyze data along with apply fundamental biology concepts. (B) is incorrect. Via inspection of the graph, the cellular DNA content does *not* remain constant throughout the cell cycle. Now, we need to incorporate our knowledge of science to finally answer the question. Interphase consists of the G1, S, and G2 phases, and these phases together take about 23 hours in rapidly proliferating human cells. Let's analyze choice (D). As opposed to interphase, the M phase only takes 1 hour. Therefore, human cells spend significantly less time in the latter phase, making (D) incorrect. For (C), notice that the cellular DNA content is 6 picograms at the beginning of G1 phase and 12 picograms at the end of G2 phase. This amount is *doubled*, not halved, so (C) is wrong. However, when we compare the duration, we find that the entire cell cycle, including both interphase and M phase, takes 24 hours. Thus, humans spend more than 95% of the cell cycle in interphase, and the correct answer is $\boxed{\textbf{(A)}}$.

§4.7 Regulation of Cell Cycle

In order to protect the parent cell *and* future daughter cells from genetic mutations and dangerous disorders, the cell cycle has a checkpoint after each phase. These checkpoints are responsible for checking the products of each phase and deciding whether it can pass onto the next phase or not.

G1 Checkpoint When a cell enters the G1 checkpoint, the appropriate size, energy levels, and undamaged DNA are checked to eliminate the propagation of cells with damaged DNA. If a cell meets these requirements, it is given the green light to move on to the S phase.

S Checkpoint After getting through the S phase, cells reach the S checkpoint. The S checkpoint checks that cells have successfully replicated DNA *and* that the replicated DNA is undamaged. It is very very important that undamaged DNA is not allowed to progress in the cell cycle because it can result in daughter cells inheriting dangerous mutations.

If a cell meets the requirements of the S checkpoint, it moves on to the G2 phase. If not, the cell cycle is stopped while the appropriate repairs are administered by proteins and enzymes. Sometimes, when DNA is damaged beyond repair, the cell initiates apoptosis to save time, energy, and resources.

G2 Checkpoint After G2, cells are stopped by the G2 checkpoint. During the G2 checkpoint, DNA is checked again for any damage. In addition to DNA, the newly replicated proteins and organelles are checked to ensure that they are ready for cell division. If a cell passes the G2 checkpoint, it enters mitosis! If not, the cell cycle is paused until the damage is fixed.

M Checkpoint Lastly, we have the M checkpoint. This checkpoint occurs during mitosis, specifically metaphase, to check that the chromosomes are properly aligned along the metaphase plate and attached to the spindle fibers of the spindle poles. The M checkpoint is important because it prevents misalignment of chromosomes on the metaphase plate, which can result in unequal distribution of chromosomes to daughter cells. If the cell is given the green light, it moves on to anaphase. If not, the cell cycle is paused while damages are repaired.

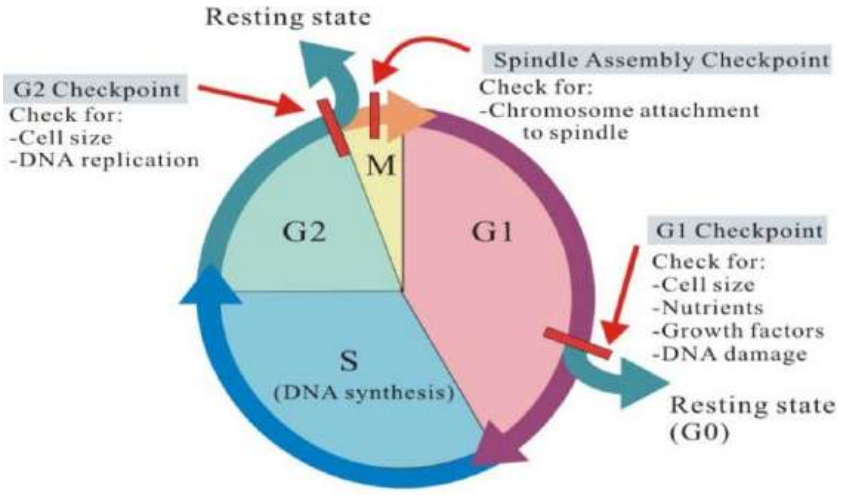


Image Credit: Lumen Learning

Problem 4.7.1 — Multiple Choice Question

What is the primary factor that causes the G1 checkpoint to fail?

(A) Errors in DNA replication.
(B) Insufficient cell growth.
(C) Misaligned chromosomes.

Solution: The G1 checkpoint occurs at the end of the G1 phase, before the cell transitions into the S phase. Being a growth phase, G1 would most likely have its checkpoint impaired by insufficient cell growth. The correct answer is **(B)**.

Problem 4.7.2 — Multiple Choice Question

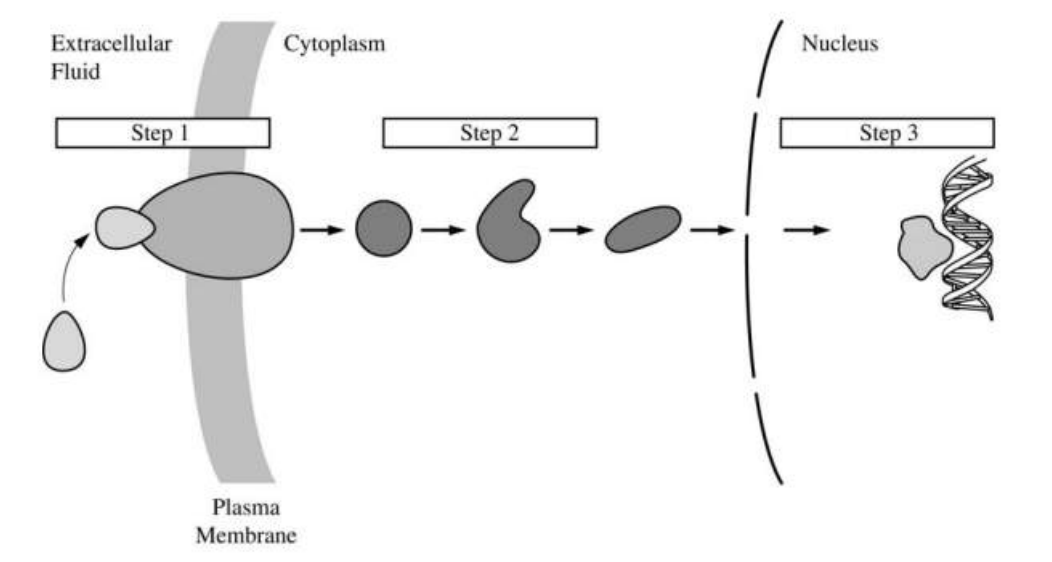
What is the primary factor that causes the M checkpoint to fail?

(A) Errors in DNA replication.
(B) Insufficient cell growth.
(C) Misaligned chromosomes.

Solution: The M checkpoint occurs during mitosis—specifically at the end of metaphase, before the cell transitions into anaphase. During metaphase, the cell's chromosomes line up at the metaphase plate in preparation for the separation. So, the primary factor that causes the M checkpoint to fail is misaligned chromosomes. The correct answer is **(C)**.

§4.8 Unit 4 Practice Questions

Problem 4.8.1 — 2013 AP Biology FRQ



The figure above represents a generalized hormone-signaling pathway. Briefly explain the role of each numbered step in regulating target gene expression.

Solution:

- In **Step 1**, we observe a hormone that binds to a receptor protein, located on the plasma membrane of the cell. This binding is specific to the hormone-protein system.
- In **Step 2**, the binding triggers signal transduction—a series of events inside the cell. A cascade of protein modifications is responsible for passing the signal.
- Finally, in **Step 3**, the protein is activated and enters the nucleus, interacting with DNA and influencing gene expression. This interaction can either activate or repress the transcription of certain genes, leading to variations in protein synthesis.

Problem 4.8.2 — 2018 AP Biology FRQ

Acetylcholine receptor (AChR) proteins are found at the synapse between neurons and skeletal muscle cells. Acetylcholine released from neurons binds to a specific site on the receptor proteins, which causes an ion channel in the receptors to open and allow sodium ions (Na^+) to enter muscle cells. The resulting depolarization of muscle cells initiates muscle contractions. Another molecule, nicotine, can also bind to certain types of AChR proteins and activate the receptors.

A researcher is investigating two different types of AChR proteins: type 1 and type 2. To determine which stimuli activate the receptors, the researcher exposes muscle cells expressing the different types of receptor proteins to stimuli and observes the results indicated in Table 1.

TABLE 1. RESPONSE OF AChR PROTEINS TO DIFFERENT STIMULI

AChR Protein Type	Acetylcholine	Nicotine
Type 1	+	+
Type 2	+	–

+ indicates activation
– indicates no activation

(a) **Describe** the difference in the structure AND function between AChR type 1 and AChR type 2.

(b) Acetylcholinesterase is an enzyme that breaks down acetylcholine in the synapse. **Describe** the effect of inhibiting acetylcholinesterase on the muscle cells with AChR type 2.

Solution to part a: First, the difference in structure! Since the table shows that both protein types activate when acetylcholine binds to them, we can ignore that information for now. On the other hand, the table shows that nicotine activates the receptors of type 1 proteins only.

Since activation of receptors depends on whether or not signaling molecules, or in this case acetylcholine and nicotine molecules, bind to specific receptor proteins on the surface of a muscle cell, we can assume that nicotine cannot bind to the receptors of a muscle cell. Therefore, there must be a disagreement in shape or chemical properties between nicotine and the muscle cell's receptors. In this case, you do not need to write about a difference in chemical properties unless you relate it to an inconsistency in shape.

Now we can tackle the difference in function between the two proteins. Since both types of protein receptor can bind to acetylcholine, but only the type 2 protein receptor can bind to nicotine, we can infer that the purpose of the type 1 protein receptor is to create a signal amplification in the presence of acetylcholine only.

Solution to part b: Since inhibiting acetylcholinesterase would result in a surplus of acetylcholine molecules, and the binding of acetylcholine molecules to receptor proteins

causes ion channels to open, we can infer that inhibiting acetylcholinesterase would result in ion channels being stuck in the open position.

Alternate answer: Since the binding of acetylcholine molecules to receptor proteins causes muscle contractions, and acetylcholinesterase breaks down acetylcholine molecules, we can infer that inhibiting acetylcholinesterase would result in frequent muscle contractions.

Alternate answer: Because the binding of acetylcholine molecules to receptor proteins results in the depolarization of muscle cells, and the enzyme acetylcholinesterase breaks down acetylcholine molecules, we can assume that inhibiting acetylcholinesterase would cause continued depolarization of muscle cells.

Problem 4.8.3 — 2019 AP Biology FRQ

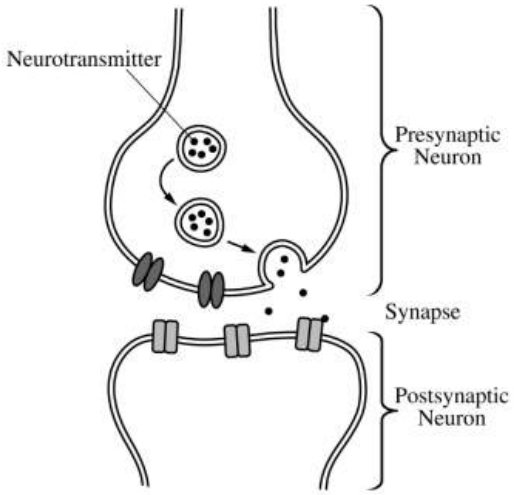


Figure 1. Release of neurotransmitters into the synapse in response to an action potential

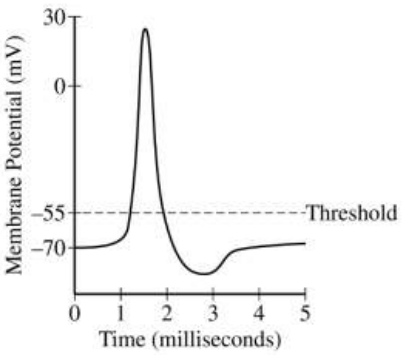


Figure 2. Model of a typical action potential in a neuron

Acetylcholine is a neurotransmitter that can activate an action potential in a postsynaptic neuron (Figures 1 and 2). A researcher is investigating the effect of a particular neurotoxin that causes the amount of acetylcholine released from presynaptic neurons to increase.

(a) **Describe** the immediate effect of the neurotoxin on the number of action potentials in a postsynaptic neuron. **Predict** whether the maximum membrane potential of the postsynaptic neuron will increase, decrease, or stay the same.

(b) The researcher proposes two models, A and B, for using acetylcholinesterase (AChE), an enzyme that degrades acetylcholine, to prevent the effect of the neurotoxin. In model A, AChE is added to the synapse. In model B, AChE is added to the cytoplasm of the postsynaptic cell. **Predict** the effectiveness of EACH proposed model. **Provide reasoning** to support your predictions.

Solution to part a: Firstly, the question says that the neurotoxin causes the amount of

acetylcholine released from presynaptic neurons to increase. In other words, the presence of the neurotoxin results in an increase in acetylcholine content. Because acetylcholine activates an action potential in the post-synaptic neuron, we can infer that the presence of the neurotoxin will result in more action potentials.

An increase in action potentials will not cause the threshold to also increase. A similar scenario is how many apples a tote bag can hold; you can't just increase the maximum amount of apples the bag can hold without changing the bag itself.

Solution to part b: Let's consider model A and model B separately.

For model A: Acetylcholine is present in the synaptic cleft, where AChE can directly degrade it, reducing its availability to bind to postsynaptic receptors. This prevents excessive action potentials caused by the increased acetylcholine release by the neurotoxin, so model A is effective.

For model B: Acetylcholine does not enter the postsynaptic cell's cytoplasm. Specifically, it binds to receptors on the cell membrane. The AChE in the cytoplasm cannot access acetylcholine in the synaptic cleft, leaving the effects of the neurotoxin ignored, so model B is highly ineffective.

Problem 4.8.4 — 2021 AP Biology FRQ

Polycystic kidney disease (PKD) is an inherited disease that causes water loss from the body and affects cell division in the kidneys. Because water movement across the cell is related to ion movement, scientists investigated the role of the Na^+/K^+ ATPase (also known as the sodium/potassium pump) in this disease. Ouabain, a steroid hormone, binds to the Na^+/K^+ ATPase in plasma membranes. Individuals with PKD have a genetic mutation that results in an increased binding of ouabain to the Na^+/K^+ ATPase. The scientists treated normal human kidney (NHK) cells and PKD cells with increasing concentrations of ouabain and measured the number of cells (Figure 1) and the activity of the Na^+/K^+ ATPase (Figure 2) after a period of time. The scientists hypothesized that a signal transduction pathway that includes the protein kinases MEK and ERK (Figure 3) may play a role in PKD symptoms.

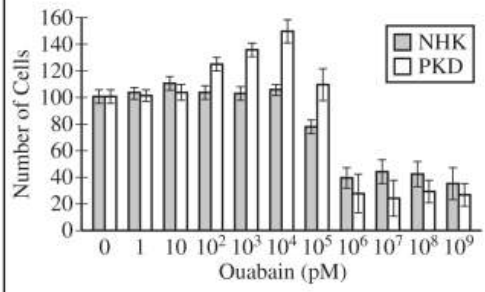


Figure 1. Cell number compared with the number of cells at 0 pM ouabain. Normal human kidney (NHK) cells and polycystic kidney disease (PKD) cells were treated with increasing concentrations of ouabain. Error bars represent $\pm 2SE_{\bar{x}}$.

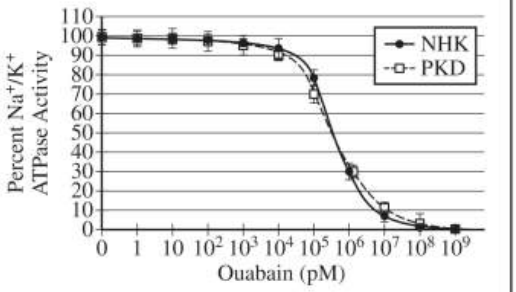


Figure 2. Percent Na^+/K^+ ATPase activity of NHK and PKD cells treated with increasing concentrations of ouabain. Error bars represent $\pm 2SE_{\bar{x}}$.

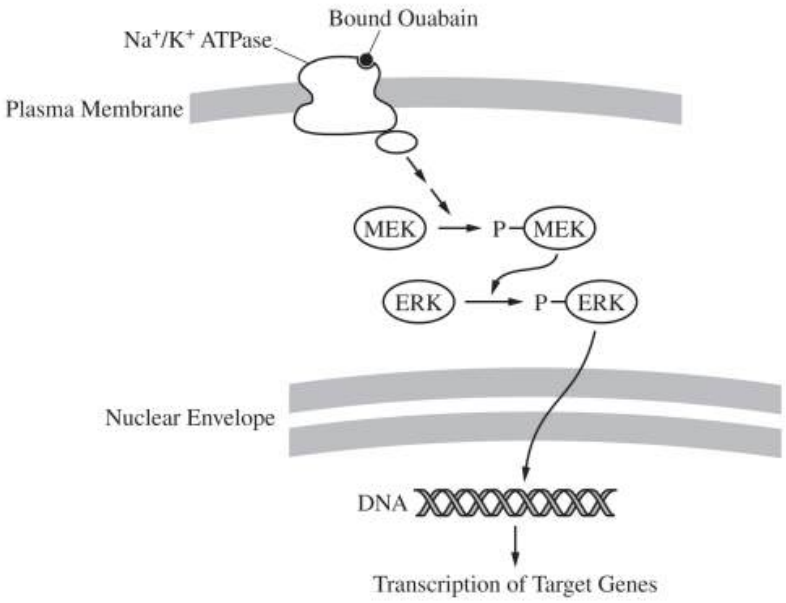


Figure 3. Signal transduction pathway hypothesized to play a role in the increased number of PKD cells

Problem 4.8.5 — 2021 AP Biology FRQ (cont.)

(a) **Describe** the characteristics of the plasma membrane that prevent simple diffusion of Na^+ and K^+ across the membrane. **Explain** why ATP is required for the activity of the Na^+/K^+ ATPase.

(b) **Identify** a dependent variable in the experiment represented in Figure 1. **Justify** the use of normal human kidney (NHK) cells as a control in the experiments. **Justify** the use of a range of ouabain concentrations in the experiment represented in Figure 1.

(c) Based on the data shown in Figure 2, **describe** the relationship between the concentration of ouabain and the Na^+K^+ ATPase activity in both normal kidney (NHK) cells AND in PKD cells. The scientists determined that Na^+K^+ ATPase activity in PKD cells treated with 1 pM ouabain is 150 units of ATP hydrolyzed/sec. **Calculate** the expected Na^+K^+ ATPase activity (units/sec) in PKD cells treated with 10^6 pM ouabain.

(d) In a third experiment, the scientists added an inhibitor of phosphorylated MEK (pMEK) to the PKD cells exposed to 10^4 pM ouabain. Based on Figure 3, **predict** the change in the relative ratio of ERK to pERK in ouabain-treated PKD cells with the inhibitor compared to with ouabain-treated PKD cells without the inhibitor. Provide reasoning to **justify** your prediction. Using the data in Figure 1 AND the signal transduction pathway represented in Figure 3, **explain** how the concentration of cyclin proteins may increase in PKD cells treated with 10^4 pM ouabain.

Solution to part a: Sodium and potassium ions cannot cross the plasma membrane via simple diffusion because of the membrane's hydrophilic exterior and hydrophobic interior. The plasma membrane's hydrophilic exterior and hydrophobic interior work in parallel to ensure that only small, non-polar molecules can cross by simple diffusion.

The sodium-potassium pump requires ATP because it pushes molecules against the concentration gradient of the cell. Whenever a molecule or ion is pushed against the concentration gradient, or from an area of low concentration to an area of high concentration, energy is required.

Solution to part b: The dependent variable is the number of cells because that is the variable which *changes as a result of* the ouabain concentration.

Using NHK cells as a control in this experiment is the proper procedure because it allows the researchers to pinpoints the specific effects that PKD has on kidney cells. Also, using NHK cells as a control provides researchers with a baseline to compare any results from non-control samples with.

Including different concentrations of ouabain allowed scientists to determine whether an increased concentration in ouabain has a greater effect on cells. Using different concentrations of ouabain also allows scientists to conclude the specific concentrations at which an effect occurs.

Solution to part c: Based on the data shown in figure 2, we can infer that the relationship between concentration of ouabain and sodium/potassium pump activity is inversely proportional because as ouabain concentration increases, sodium/potassium pump activity decreases.

Be super careful on this part! You might immediately think the answer is 30, but remember that the graph shows us the *percent* of sodium/potassium pump activity, not an actual measurement. Since the question tells us that at 1 picomolar (pM) of ouabain, the activity of the sodium/potassium pump is 150 ATP units hydrolyzed per second, and the graph shows that 1 pM of ouabain results in 100% of sodium/potassium pump activity, we can infer that at 10^6 pM of ouabain, the percent of sodium/potassium pump is approximately 30% of the original 100%. Thus, 30% of 150 is $\boxed{45}$ units of ATP hydrolyzed per second.

Solution to part d: Based on Figure 3, the ratio of ERK to pERK in ouabain-treated PKD cells after the inhibitor is introduced will remain the same because the MEK inhibitor prevents the phosphorylation of ERK.

According to Figure 1, the number of cells is at its maximum when the ouabain dose is 10^2. Since we know that an increase in cells means an increase in cell division, and cyclin proteins are required for proper cell division, we can conclude that the concentration of cyclin protein may increase in PKD cells treated with 10^4 pM of ouabain.

Problem 4.8.6 — 2023 AP Biology FRQ

In eukaryotic microorganisms, the PHO signaling pathway regulates the expression of certain genes. These genes, *Pho* target genes, encode proteins involved in regulating phosphate homeostasis. When the level of extracellular inorganic phosphate (Pi) is high, a transcriptional activator Pho4 is phosphorylated by a complex of two proteins, Pho80-Pho85. As a result, the *Pho* target genes are not expressed. When the level of extracellular Pi is low, the activity of the Pho80-Pho85 complex is inhibited by another protein, Pho81, enabling Pho4 to induce the expression of these target genes. A simplified model of this pathway is shown in Figure 1.

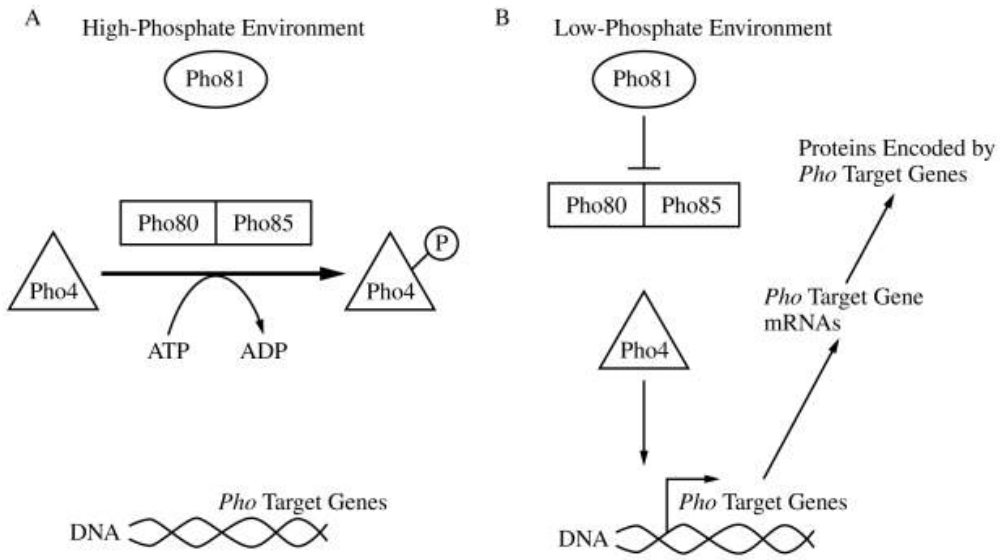


Figure 1. A simplified model of the regulation of expression of *Pho* target genes in (A) a high-phosphate (high-Pi) environment and (B) a low-phosphate (low-Pi) environment

To study the role of the different proteins in the PHO pathway, researchers used a wild-type strain of yeast to create it with a mutant form of Pho81 (*pho81mt*) and a strain with a mutant form of Pho4 (*pho4mt*). In each of these mutant strains, researchers measured the activity of a particular enzyme, APase, which removes phosphates from its substrates and is encoded by *PHOI*, a *Pho* target gene (Table 1). They then determined the level of *PHOI* mRNA relative to that of the wild-type yeast strain, which was set to 10.

TABLE 1. APase ACTIVITY AND RELATIVE AMOUNTS OF *PHO1* mRNA IN WILD-TYPE AND MUTANT STRAINS OF YEAST IN HIGH- AND LOW-PHOSPHATE ENVIRONMENTS

Yeast Strain	Mutation	APase Activity in High-Pi Environment ($mU/mL/OD_{600}$) $\pm 2SE_{\bar{x}}$	APase Activity in Low-Pi Environment ($mU/mL/OD_{600}$) $\pm 2SE_{\bar{x}}$	Relative Amounts of *PHO1* mRNA in High-Pi Environment $\pm 2SE_{\bar{x}}$	Relative Amounts of *PHO1* mRNA in Low-Pi Environment $\pm 2SE_{\bar{x}}$
Wild-type	None	0.5 ± 0.1	17.3 ± 0.9	0.1 ± 0.0	10 ± 2.0
pho81mt	Nonfunctional Pho81	0.4 ± 0.1	0.6 ± 0.1	0.7 ± 0.2	0.9 ± 0.8
pho4mt	Nonfunctional Pho4	0.5 ± 0.0	0.8 ± 0.2	0.6 ± 0.4	0.3 ± 0.1

Problem 4.8.7 — 2023 AP Biology FRQ (cont.)

(a) **Describe** the effect that the addition of a charged phosphate group can have on a protein that would cause the protein to become inactive. **Explain** how a signal can be amplified during signal transduction in a pathway such as the PHO signaling pathway.

(b) Based on Table 1, **identify** a dependent variable in the researchers' experiment. **Justify** the researchers' using the wild-type strain for the creation of the mutant strain. **Justify** the researchers' using mutant strains in which only a single component of the pathway was mutated in each strain.

(c) Based on the data in Table 1, **identify** the yeast strain and growth conditions that lead to the highest relative amount of *PHOI* mRNA. **Calculate** the percent change in APase activity in wild-type yeast cells in a high-Pi environment compared with that of wild-type cells in a low-Pi environment.

(d) In a follow-up experiment, researchers created a strain of yeast with a mutation that resulted in a nonfunctional Pho85 protein. Based on Figure 1, **predict** the effects of this mutation on *PHOI* expression in the mutant strain in a high-Pi environment. Provide reasoning to **justify** your prediction.

Solution to part a: Adding a charged phosphate to a protein would result in a shape change, which causes the protein to bind with different molecules and, in this case, become inactive. In a signal transduction pathway, a signal is amplified through a series of proteins, or secondary messengers, that receive the signal and then relay it to the interior of the cell.

Solution to part b: A dependent variable could be APase activity *or* Pho1 content. You can pick either as they are both correct answers and only one is required. Using the wild-type strain for the creation of the mutant strain reduces the effects of any genetic differences between different yeast strains, which ensures that any differences in enzyme activity is solely due to mutations.

Only changing one component of the pathway at a time makes it easier to conclude which specific mutation results in any observed differences.

Solution to part c: Based on the data in Table 1, we can conclude that the wild-type strain in a Low-Pi environment will have the highest relative amount of PHO*I* mRNA because both quantities $17.3 + .9 = 18.2$ and $17.3 - .9 = 16.4$ are larger than all other values shown in the data.

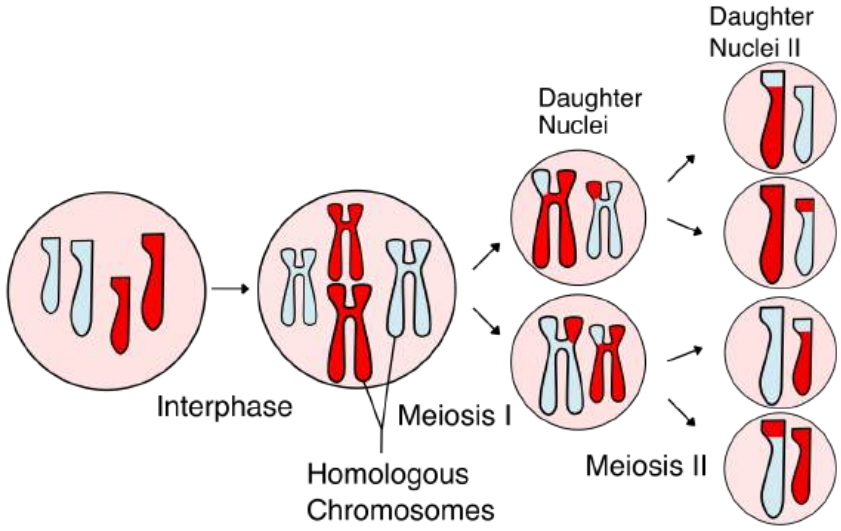
Solution to part d: Since the mutation results in a nonfunctional Pho85 protein, the Pho80-Pho85 complex will not be able to suppress Pho1 target genes. Therefore, Pho1 target genes will be expressed.

5 Heredity

Heredity explains how traits are passed from parents to offspring. It covers alleles, genotypes, and phenotypes, as well as Mendel's laws of inheritance and the role of chromosomes and DNA in genetic transmission. Beyond basic inheritance patterns, the study of heredity explores complex phenomena such as codominance, polygenic traits, and epigenetics. It also covers gene expression, genetic mutations, and modern applications such as genetic engineering.

§5.1 Meiosis

Meiosis is a type of cell division that reduces the chromosome number by half, and produces four non-identical haploid cells, which are used for sexual reproduction. Unlike mitosis, which results in two identical diploid daughter cells, meiosis ensures that the offspring inherit the correct amount of genetic material from each parent. This process occurs in two stages—Meiosis I and Meiosis II— that work together to divide and distribute genetic material.



Meiosis I Below is a detailed overview of each stage. The first stage of meiosis is the reduction division, where the chromosome number is halved. The stages of Meiosis I are as follows:

- **Prophase I:** Chromosomes condense and become visible. Homologous chromosomes (chromosomes with the same genes but potentially different alleles) pair up in a process called **synapsis**. These pairs of chromosomes, now called **tetrads**, exchange genetic material through **crossing over**.
- **Metaphase I:** The tetrads align along the cell's equator. The homologous chromosomes line up randomly, ensuring genetic diversity due to **independent assortment**.
- **Anaphase I:** Homologous chromosomes are pulled to opposite poles of the cell. Unlike mitosis, the sister chromatids remain attached to each other at this stage.

- **Telophase I:** The chromosomes reach opposite poles, and the cell begins to divide into two. Each daughter cell now contains half the original chromosome number (haploid).
- **Cytokinesis:** The cytoplasm divides, resulting in two haploid cells.

Meiosis II Meiosis II is similar to mitosis, where the sister chromatids are separated. This division does not reduce the chromosome number further but results in four non-identical haploid cells.

- **Prophase II:** The chromosomes condense, and the nuclear membrane dissolves in both haploid cells.
- **Metaphase II:** Chromosomes align at the equator of the two haploid cells.
- **Anaphase II:** The sister chromatids are pulled to opposite poles of each cell.
- **Telophase II:** Chromatids reach the poles, and the cells divide, resulting in four non-identical haploid daughter cells.
- **Cytokinesis:** The cytoplasm divides, leading to four non-identical haploid gametes.

Importance of Meiosis Meiosis plays a critical role in ensuring that organisms inherit the correct number of chromosomes. By reducing the chromosome number by half, meiosis ensures that fertilization restores the diploid number, maintaining genetic stability across generations. Additionally, the processes of crossing over and independent assortment create genetic diversity, which is crucial for evolution and adaptation.

§5.2 Meiosis and Genetic Diversity

Meiosis is not only essential for reducing chromosome numbers, but also serves a vital function in increasing genetic diversity within sexually reproducing populations. Genetic diversity is important because it provides the raw material for evolution, allowing populations to adapt to changing environments and challenges. This section will explore how meiosis contributes to genetic diversity through processes such as crossing over and independent assortment.

Mechanisms that Increase Genetic Diversity There are two primary mechanisms during meiosis that contribute to genetic variation: **crossing over** and **independent assortment**.

Crossing Over During prophase I of meiosis, homologous chromosomes undergo a process known as **crossing over**. In this process, chromatids from homologous chromosomes exchange segments of their genetic material. This results in new combinations of alleles on each chromosome. The occurrence of crossing over ensures that each gamete carries a unique set of alleles, which increases genetic variation.

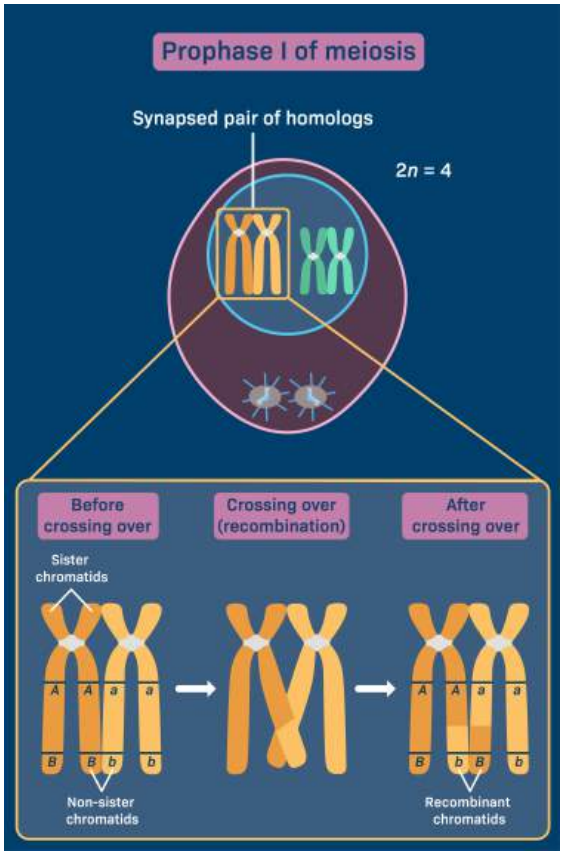


Image Credit: LabXchange

For example, if one chromosome has alleles A and B, and its homologous chromosome has alleles a and b, crossing over can produce chromosomes with allele combinations like A and b, or a and B, rather than just A and B or a and b. This reshuffling of genetic information is one of the key ways that meiosis generates genetic diversity.

Independent Assortment Independent assortment is the random arrangement and separation of homologous chromosomes during the metaphase I of meiosis. Each pair of homologous chromosomes can align in one of two ways, with either the maternal or paternal chromosome going to each daughter cell. The random orientation of each chromosome pair during metaphase I means that the combination of chromosomes in each gamete is unique. For humans, with 23 pairs of chromosomes, the potential number of different combinations of chromosomes in the gametes due to independent assortment is 2^{23}, over 8 million combinations. This randomness further increases genetic diversity by ensuring that offspring inherit a unique set of genetic material.

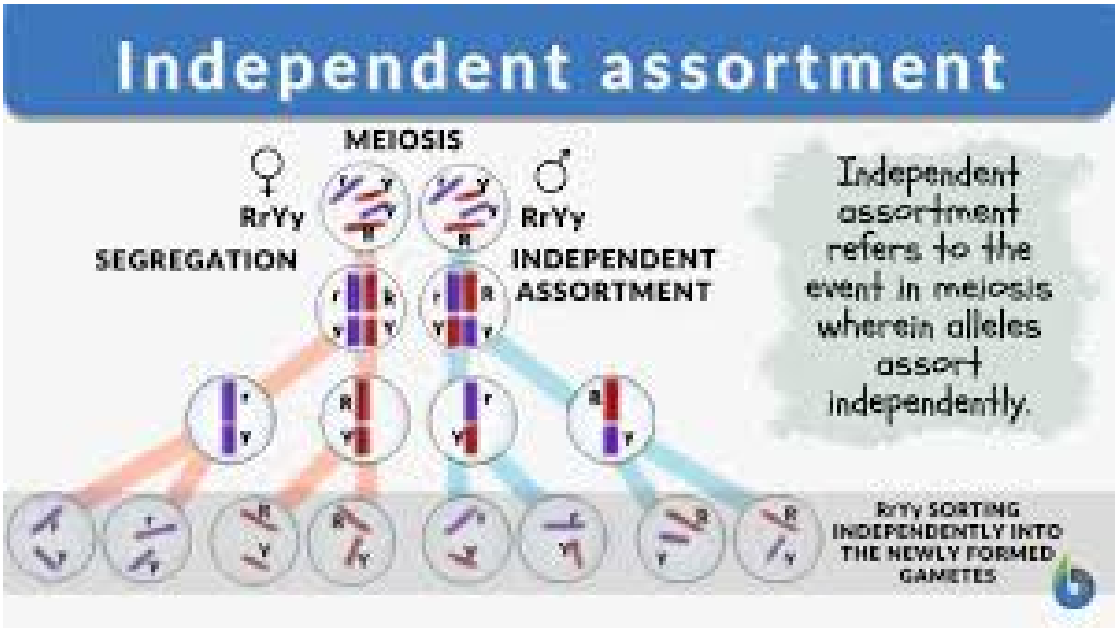
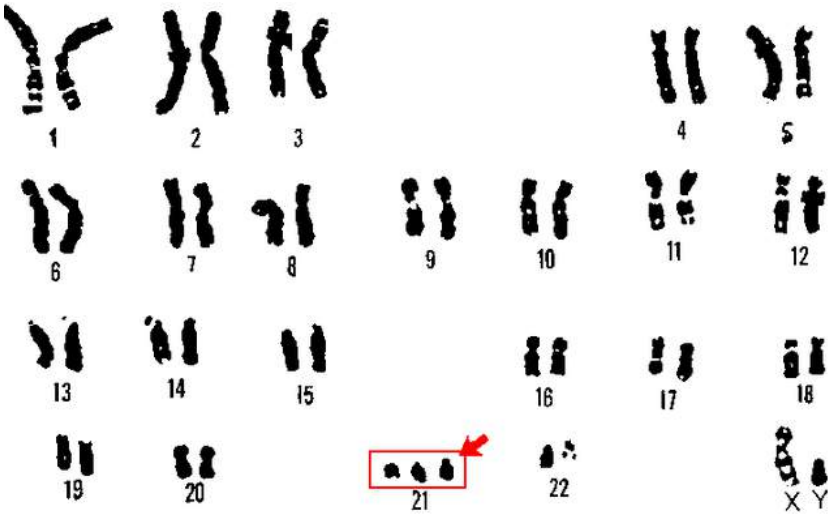


Image Credit: Biology Online

Genetic Variation and Evolution Genetic diversity is the driving force behind evolution. Variations within the genetic makeup of individuals in a population provide the raw material for natural selection. Natural selection favors individuals with traits that help them survive and reproduce in their environment. These advantageous traits become more common in the population over time. Without genetic diversity, a population would be highly susceptible to diseases, environmental changes, or other pressures, because there would be a lesser chance of individuals having advantageous traits. Meiosis, through crossing over and independent assortment, ensures that sexual reproduction creates a population with diversity of genetic traits, making them more adaptable to changing environments.

Genetic Disorders and Meiosis Errors While meiosis is essential for genetic diversity, errors in the process can lead to genetic disorders. One common type of error is **non-disjunction**, where homologous chromosomes or sister chromatids fail to separate properly during meiosis. This results in gametes with an abnormal number of chromosomes, which can lead to disorders such as:

- **Down syndrome:** A genetic condition caused by the presence of an extra chromosome 21 (trisomy 21).
- **Turner syndrome:** A condition where females have only one X chromosome instead of two.
- **Klinefelter syndrome:** A condition in which males have an extra X chromosome (XXY instead of XY).



These disorders highlight the importance of proper chromosome separation during meiosis, as errors in the process can lead to severe consequences for an individual's health.

Conclusion Meiosis ensures genetic diversity. The mechanisms of crossing over and independent assortment shuffle genetic material, resulting in genetically unique gametes that contribute to the variation seen in offspring. This genetic variation is important for evolution, as it provides the genetic foundation for natural selection to act upon. However, mistakes during meiosis can lead to genetic disorders, underscoring the significance of accurate chromosome division.

Problem 5.2.1 — Multiple Choice Question

Even though humans are approximately 99.9% identical in their genetic makeup, an incredible amount of variation is seen among individuals of the species. This genetic variation is greatly influenced by the process of meiosis.

Of the following events that occur during meiosis, which contributes most to genetic diversity in the human population?

(A) Separation of sister chromatids during meiosis II
(B) Recombination between homologous chromatids during meiosis I
(C) Condensation of chromatin during meiosis I
(D) Alignment of sister chromatids at the metaphase plate during meiosis II

Solution: During meiosis I, homologous chromatids exchange genetic material through a process called recombination, or crossing over. This process creates new gene combinations in the gametes that are not found in the original parental chromosomes, which contributes to genetic diversity. The correct answer is $\boxed{\textbf{(B)}}$.

Problem 5.2.2 — Multiple Choice Question

The formation of ova, or female reproductive cells, occurs when diploid germ cells undergo meiosis. In female swamp wallabies (*Wallabia bicolor*), diploid germ cells contain 10 chromosomes.

At the beginning of meiosis I, a female wallaby germ cells contains

(A) 10 homologous pairs of chromosomes comprising a total of 10 chromatids
(B) 5 homologous pairs of chromosomes comprising a total of 20 chromatids
(C) 5 homologous pairs of chromosomes comprising a total of 10 chromatids
(D) 10 homologous pairs of chromosomes comprising a total of 20 chromatids

Solution: A diploid cell has 2 complete sets of chromosomes. So, in a diploid female wallaby germ cell containing 10 chromosomes, there are $\frac{10}{2} = 5$ homologous pairs of chromosomes. Each of the 10 chromosomes consists of 2 sister chromatids after DNA replication, so the 5 pairs of chromosomes contain $10 \cdot 2 = 20$ chromatids total at the beginning of meiosis I. The correct answer is $\boxed{\textbf{(B)}}$.

§5.3 Mendelian Genetics

Mendelian genetics is the study of how genes are inherited from one generation to the next, based on principles established by Gregor Mendel in the 19th century. Mendel's experiments with pea plants helped shape our understanding of inheritance and set the stage for modern genetics. His laws of inheritance, which include the Law of Segregation and the Law of Independent Assortment, describe how alleles are passed on to offspring and how genetic traits are distributed across generations.

Gregor Mendel's Experiments Gregor Mendel, an Austrian monk, conducted experiments with pea plants (Pisum sativum) in the mid-1800s. He chose pea plants because they had clear, easily observed traits, such as flower color, seed shape, and plant height. Mendel cross-bred plants with different characteristics and analyzed the patterns of inheritance across multiple generations. Mendel's experiments led to the formulation of several key principles of inheritance:

- **Dominant and Recessive Alleles:** Mendel observed that some traits were expressed in the offspring, while others were hidden in the presence of dominant alleles. The dominant allele masks the expression of the recessive allele.
- **Genotypes and Phenotypes:** The genotype refers to the genetic makeup of an organism, while the phenotype refers to the observable traits. For example, a plant's genotype may be heterozygous (Rr) or homozygous (RR or rr), but its phenotype would show whether it has a dominant or recessive trait.
- **Pure-breeding and Hybrid Crosses:** Mendel also investigated the inheritance patterns of hybrid offspring (F1 generation) and their subsequent crosses (F2 generation). Those experiments revealed predictable ratios in the second generation.

Mendel's Laws of Inheritance Mendel's observations led to the development of two fundamental laws of inheritance: the Law of Segregation and the Law of Independent Assortment.

Law of Segregation The Law of Segregation states that each individual receives two alleles for each trait, one from each parent, and these alleles segregate, or separate, during the formation of gametes.

As a result, each gamete (egg or sperm) carries only one allele for each gene. When gametes fuse during fertilization, the offspring inherit one allele from each parent, thereby restoring the correct pairing of alleles. For example, in a cross between two pea plants with the genotype `Pp` (where `P` is the dominant allele for purple flowers and `p` is the recessive allele for white flowers), the offspring can inherit either the `P` or the `p` allele from each parent.

Law of Independent Assortment The Law of Independent Assortment is one of the key principles in genetics. It states that alleles for different traits separate independently during the formation of gametes. This means that the inheritance of one trait does not affect the inheritance of another trait. For example, if a plant has the genotype `RrYy`, where `R` is the allele for round seeds and `Y` is the allele for yellow seeds, these alleles will be assorted independently during gamete formation. During this process, the plant can produce gametes with the following combinations of alleles: `RY`, `Ry`, `rY`, and `ry`.

Due to independent assortment, alleles for each trait are passed on to offspring independently, which increases genetic variation. The idea that different traits are inherited separately is important because it means that offspring can inherit a mix of alleles from both parents, leading to a lot more genetic diversity. This was an important discovery

in understanding how traits are passed down through generations and is a fundamental concept in Mendelian genetics.

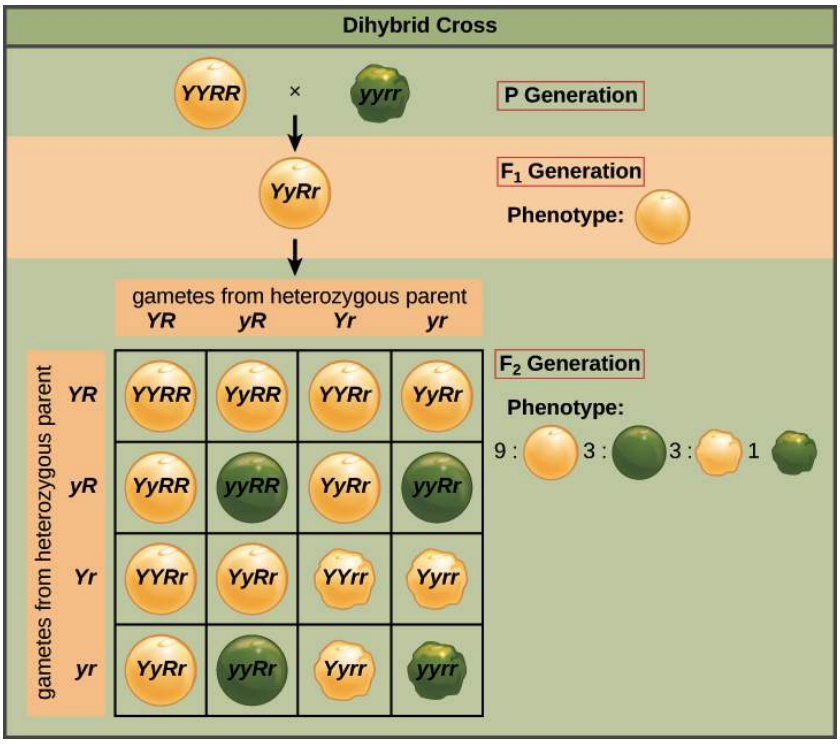


Image Credit: *OpenStax College, Biology*

Punnett Squares and Probability Punnett squares are used to predict the genetic outcomes of a cross between two organisms. By organizing possible gametes and their combinations, a Punnett square helps geneticists calculate the probabilities of different genotypes and phenotypes in the offspring. For example, in a monohybrid cross (a cross involving a single trait), a Punnett square can be used to determine the probability that offspring inherit dominant or recessive alleles.

	P	p
P	PP	Pp
p	Pp	pp

In this example, a cross between two heterozygous pea plants (Pp × Pp) results in the following genotypic ratio: 1 PP: 2 Pp: 1 pp. The phenotypic ratio would be 3 purple flower plants (due to the presence of at least one dominant allele) to 1 white flower plant (with the recessive pp genotype).

Extensions of Mendelian Genetics While Mendel's laws apply to many traits, some genetic phenomena do not follow simple Mendelian inheritance patterns. These extensions include:

- **Incomplete Dominance:** In some cases, neither allele is completely dominant over the other. The heterozygous offspring exhibit an intermediate phenotype. For example, in the case of flower color in snapdragons, crossing red-flowered (RR) with white-flowered (WW) plants results in pink-flowered (RW) offspring.

- **Codominance:** In codominance, both alleles are fully expressed under heterozygous conditions. For example, in human blood types, alleles A and B are co-dominant, so individuals with the genotype `AB` express both A and B antigens in their red blood cells.
- **Polygenic Inheritance:** Some traits are controlled by multiple genes, and their expression results in continuous variation, such as human height or skin color. These traits do not follow simple dominant-recessive inheritance patterns.
- **Gene Linkage:** Genes located close to each other on the same chromosome (linked genes) tend to be inherited together. This phenomenon, known as genetic linkage, can affect the outcomes of genetic crosses.

Parent Genotype	Offspring Genotype	Phenotype
PP (Purple) and pp (White)	Pp (Purple)	Purple
Pp (Purple) and Pp (Purple)	PP, Pp, Pp, pp	Purple and White (3:1 ratio)

The above table shows Mendelian inheritance of flower color in pea plants.

Problem 5.3.1 — Multiple Choice Question

A group of students are studying flower color inheritance in the garden pea plant (Pisum sativum). They obtain a purple-flowered pea plant of unknown ancestry, allow it to self-pollinate, and collect 60 of its seeds. After planting the seeds, they observe the growth of 42 purple-flowered plants and 18 white-flowered plants.

Which of the following best explains the flower colors seen in the offspring?

(A) A somatic mutation in the flower color gene produced the white flower color.
(B) White flower color is a trait recessive to purple flower color.
(C) The flower color changes as the plants mature.
(D) Purple flowers and white flowers are codominant.

Solution: In the experiment, the students allowed a purple-flowered parent to self-pollinate. This resulted in offspring that included both purple and white-flowered plants, indicating that the purple-flowered parent was a carrier of the white flower trait. As a carrier, the purple-flowered parent did not express the white flower trait, so white flower color must be a trait recessive to purple flower color. Therefore, the correct answer is $\boxed{\textbf{(C)}}$.

Problem 5.3.2 — Multiple Choice Question

A biologist is studying the genetics of a particular species of plant. He knows that one plant may contain hundreds of individual seeds, each of which is the result of a separate fertilization event. He determines that seed shape is controlled by a single gene with two alleles. The dominant allele results in round seeds, and the recessive allele results in wrinkled seeds.

In a follow-up experiment, the biologist crosses two heterozygous plants.

Which of the following is the best prediction for the frequency of wrinkled seeds that would result from this cross?

(A) 0.00
(B) 0.25
(C) 0.50
(D) 0.75

Solution: A heterozygous plant has one dominant round seed allele and one recessive wrinkled seed allele. When two heterozygous plants are crossed, by definition, there is a 25% chance that an offspring will have the two recessive wrinkled alleles needed to express the wrinkled seed trait. The correct answer is $\boxed{\textbf{(B)}}$.

§5.4 Non-Mendelian Genetics

While Gregor Mendel's laws of inheritance provide the foundation for understanding genetic inheritance, not all genetic traits follow Mendelian patterns. Non-Mendelian genetics refers to inheritance patterns that deviate from Mendel's laws due to factors such as incomplete dominance, codominance, multiple alleles, polygenic inheritance, gene linkage, and epistasis. These patterns of inheritance can explain the wide variety of complex genetic traits seen in many organisms.

Incomplete Dominance Incomplete dominance occurs when neither allele is completely dominant over the other, resulting in a phenotype that is a combination of the two parental traits. This differs from Mendel's classic dominant-recessive relationship, where one allele completely masks the effect of the other. In the case of incomplete dominance, heterozygous offspring express an intermediate phenotype that is distinct from both dominant and recessive traits.

Example 5.4.1

Consider snapdragon colors. The red flower allele (R) and the white flower allele (W) are neither completely dominant nor recessive. When a red-flowered plant (RR) is crossed with a white-flowered plant (WW), the offspring inherit one red allele and one white allele, resulting in pink flowers (RW). The inheritance of incomplete dominance can be predicted using a Punnett square. Crossing a red-flowered plant (RR) with a white-flowered plant (WW) results in pink offspring (RW).

	R	R
W	RW	RW
W	RW	RW

In this case, all offspring will have the genotype RW, and the phenotype will be pink flowers. The Punnett square shows that the red and white alleles segregate equally, with no allele completely dominant over the other.

F2 Generation: Segregation of Traits When two heterozygous F1 plants (RW) are crossed, the resulting F2 generation will exhibit a phenotypic ratio of 1:2:1. In this case, the F2 generation will contain:

- 1 red-flowered plant (RR),
- 2 pink-flowered plants (RW),
- 1 white-flowered plant (WW).

	R	W
R	RR	RW
W	RW	WW

This demonstrates how alleles segregate independently, and the phenotypic ratio in the F2 generation reflects the inheritance of incomplete dominance.

Key Features and Biological Significance Incomplete dominance leads to an intermediate phenotype in heterozygous individuals. This pattern of inheritance contributes to genetic diversity within populations by allowing new combinations of traits. The blending of traits in incomplete dominance can sometimes offer evolutionary advantages, such as increasing the likelihood of attracting different pollinators in plants, leading to greater reproductive success.

Codominance Codominance is a type of inheritance pattern in which both alleles of a gene are equally and independently expressed in the heterozygous condition. Unlike incomplete dominance, where traits blend, codominance results in offspring that display both parental traits simultaneously. Neither allele is dominant or recessive and both contribute equally to the phenotype of the individual.

A classic example is in the human ABO blood group system, which involves three alleles: `A`, `B`, and `O`. The `A` and `B` alleles are co-dominant with each other, meaning that individuals with the genotype `AB` express both A and B antigens on the surface of their red blood cells. This results in AB blood type, where both A and B traits are visible in the phenotype.

Codominance leads to the distinct expression of both alleles. An individual with the `AB` genotype does not show a blend of A and B but instead expresses both antigens fully and independently.

The inheritance pattern for the ABO blood group system can be shown in the table below.

	A	B
A	AA	AB
B	AB	BB

Based on combinations of alleles, the four possible blood types are

- `AA` or `AO` type A blood, with only antigen A red blood cells.
- `BB` or `BO` results in type B blood, with only antigen B in the red blood cells.
- `AB` results in type AB blood, where both A and B antigens are expressed simultaneously, demonstrating co-dominance.
- `OO` results in blood type O, with no A or B antigens on the red blood cells.

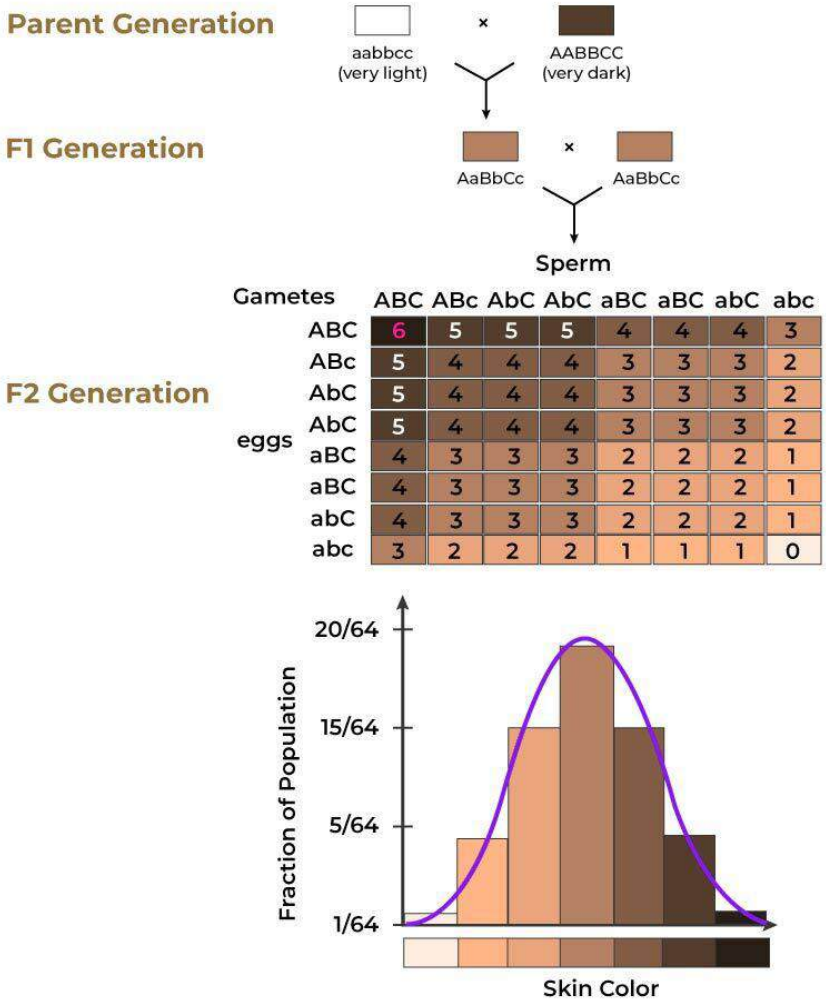
The codominancy of the alleles allows for the expression of both alleles in individuals with the `AB` genotype (blood type AB). This inheritance pattern adds complexity to the genetic inheritance of blood types. Biologically, codominance increases genetic diversity. Offspring inherit and express both alleles in their phenotype, contributing to greater variation within the population. This variation can introduce advantageous traits that help species adapt to specific environments, supporting their survival.

While an individual can inherit only two alleles (one from each parent), the existence of these three alleles creates multiple combinations and a greater variety of phenotypes.

Having multiple alleles in a population increases genetic diversity. The frequencies of ABO alleles vary across different populations due to evolutionary factors, such as resistance to diseases like malaria, where certain blood types may offer survival advantages.

Multiple alleles exist beyond the ABO system. In rabbits, coat color is determined by multiple alleles, and in some animals and plants, traits like fur color, flower color, or disease resistance are influenced by them. This variation helps species adapt to changing environments, playing a key role in evolution and natural selection.

Polygenic Inheritance Polygenic inheritance occurs when multiple genes work together to determine a trait. Instead of fitting clear categories, these traits have a range of possibilities, because different genes add up and interact. Examples of polygenic traits include skin color, height, weight, and the chances of developing certain diseases. Skin color is influenced by multiple genes and alleles. These genes affect how much melanin is produced and distributed throughout the skin, and this is the reason why skin color has a whole range of shades. Polygenic inheritance is why traits vary from person to person.

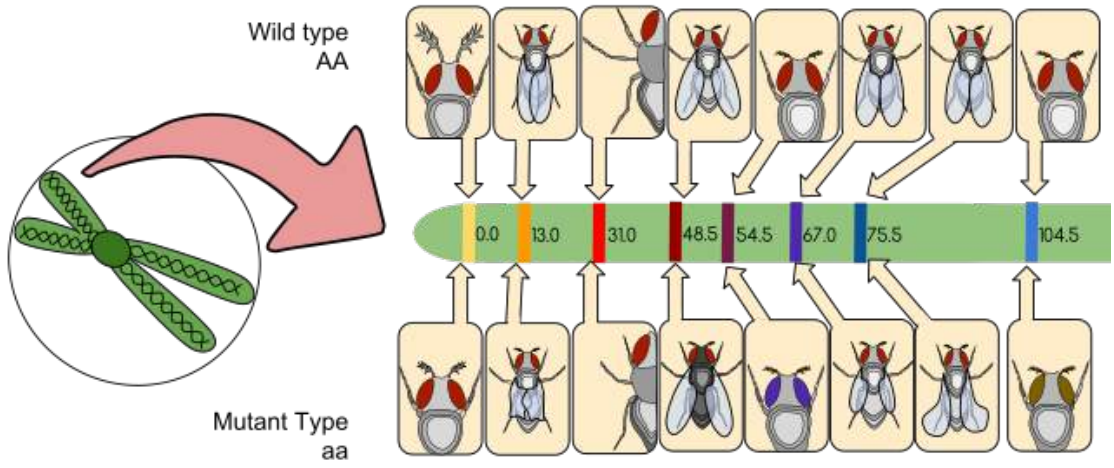


Unlike traits that follow Mendel's simple dominant-recessive patterns, polygenic traits are In contrast to characteristics that exhibit Mendel's straightforward dominant-recessive patterns, polygenic characteristics are determined by the combined effect of alleles at various loci. The greater the number of alleles that influence a characteristic, the greater the chance an individual will express an extreme phenotype, e.g., extremely light or dark skin. Polygenic characteristics tend to have a broad range of phenotypic expressions, usually in a normal distribution, in which most individuals possess fewer extreme phenotypes and intermediate phenotypes. This is the result of an additive effect of each gene. The variation found in human populations, such as height, eye color, and skin color, is a textbook example of polygenic inheritance in action. It is a great way to understand scenarios involving complex traits and their variation within populations.

Gene Linkage Gene linkage is the tendency for genes located close to each other on the same chromosome to be inherited together. This occurs because genes that are physically close are less likely to be separated during recombination in meiosis. As a result, linked genes do not assort independently, which contradicts Mendel's law of independent assortment. In a typical Mendelian dihybrid cross, where the genes are

on different chromosomes, the expected phenotypic ratio is 9:3:3:1. However, when the genes are linked, offspring will show more parental combinations of traits and fewer recombinant offspring, leading to a deviation from this expected ratio.

The strength of gene linkage depends on the distance between genes on the chromosome. Genes that are closer together are more likely to be inherited together, while genes that are farther apart have a higher chance of being separated during recombination. This likelihood of recombination is measured in centimorgans (cM). Linkage studies are valuable for mapping genes on chromosomes and understanding inherited diseases. They help identify genes responsible for certain traits and provide insights into why some diseases are inherited together more frequently than expected.



Epistasis Epistasis is a form of gene interaction where one gene can mask the expression of another gene at a different locus. This means that the phenotype produced by one gene can be dependent on the alleles inherited at a second gene locus. Epistasis is an important aspect of inheritance, as it demonstrates that the expression of certain traits can be influenced by the interaction between different genes, not just the alleles at a single locus.

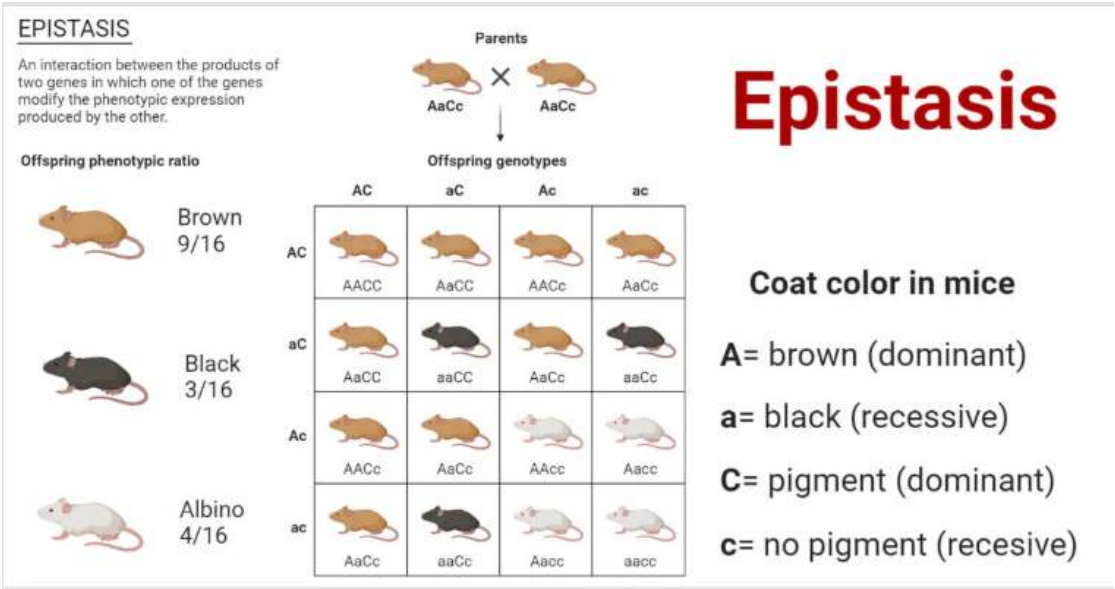


Image Credit: Microbe Notes

In Labrador retrievers (dog breed), coat color is controlled by two genes: the `B` gene, which determines the color (black or brown), and the `E` gene, which regulates whether the color is expressed. The `B` gene has alleles `B` (black) and `b` (brown), while the `E` gene has alleles `E` (expresses color) and `e` (causes yellow).

The `ee` genotype at the `E` locus is epistatic to the `B` gene, meaning it suppresses the expression of both black and brown coat colors. Therefore, if a dog inherits two copies of the `ee` allele, regardless of the `B` genotype, the coat will be yellow. This results in three possibilities: black, brown, and yellow, with yellow being epistatic over the other two.

	`B`	`b`
`EE` or `Ee`	Black or Brown	Black or Brown
`ee`	Yellow	Yellow

Epistasis can be found in many other organisms and traits, and it is an important concept for understanding how complex phenotypes are determined. The presence of epistasis can complicate genetic predictions, as the phenotype for a given trait may not follow the expected patterns based solely on the alleles at one gene locus. Instead, the expression of traits may depend on the interaction of multiple genes, creating more complex inheritance patterns.

Sex-Linked Inheritance: General Overview Sex-linked inheritance is the inheritance of genes located on the sex chromosomes (X or Y), particularly the X chromosome. In humans and other animals, sex chromosomes determine an individual's biological sex.

Males have one X and one Y chromosome (XY), while females have two X chromosomes (XX). Because males have only one X chromosome, they are more likely to express recessive X-linked traits. This is because they don't have a second X chromosome to mask the expression of the recessive allele. In females, recessive X-linked traits are only expressed if both the X chromosomes carry the recessive allele. If a female inherits a dominant allele on one X chromosome and a recessive allele on the other, the dominant allele will be expressed, and will cover the effect of the recessive allele. This difference in inheritance patterns leads to sex-specific expression of certain traits.

Examples of X-Linked Inheritance For color blindness present in humans, the gene responsible for color blindness is found on the X chromosome. Males who inherit one copy of the recessive allele (X`b`Y) will show the trait because they have only one X chromosome, with no second X chromosome is available to mask the effect. Females, however, will need to inherit two copies of the recessive allele (X`b`X`b`) in order to be color blind, since the presence of one dominant allele on one of the X chromosomes will repress the recessive allele and repress the expression of color blindness.

The different patterns of inheritance of sex-linked traits in males and females explain why these traits are generally more common in males than in females. Other examples of X-linked traits include hemophilia, a blood clotting disorder, and muscular dystrophy, a progressive muscle degeneration. Sex-linked inheritance is essential to understand when identifying genetic disorders and the prevalence in different sexes.

Problem 5.4.2 — Multiple Choice Question

In chickens, the sex-determining chromosomes are called Z and W. Male roosters have two Z chromosomes, and female hens have one Z chromosome and one W chromosome. A gene located on the Z chromosome determines the color patterning of a chicken's feathers. The allele for barred, or black-and-white striped, feathers is dominant to the allele for solid-colored feathers.

Chickens also have many autosomes, or non-sex chromosomes. A gene located on one of these autosomes determines the shape of the comb, which is the fleshy growth on top of a chicken's head. The allele for a shape called pea comb is dominant to the allele for a shape called single comb.

A barred female heterozygous for the pea comb allele is crossed with an unbarred male homozygous for the pea comb allele.

What proportion of the resulting offspring is expected to be male with barred feathers and a pea comb?

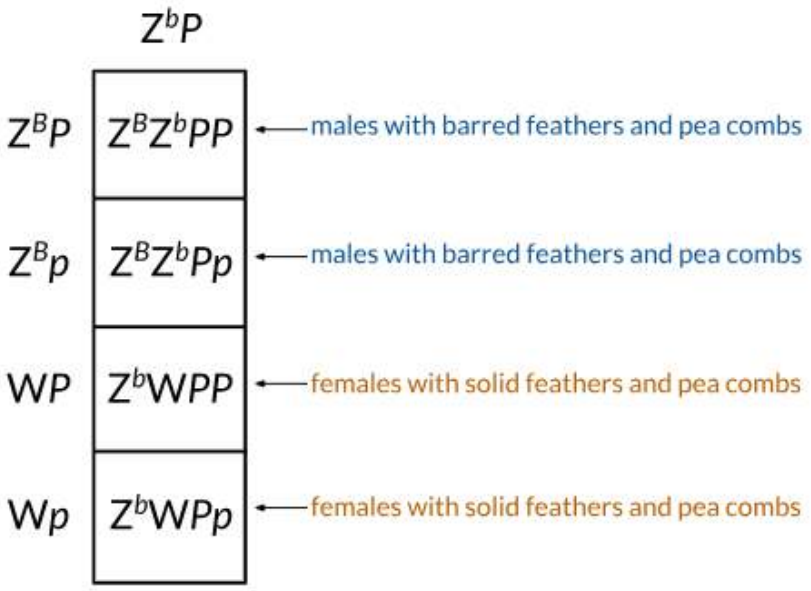
(A) approximately $\frac{1}{4}$

(B) approximately $\frac{1}{2}$

(C) approximately $\frac{3}{4}$

(D) None of the offspring will be male with barred feathers and a pea comb.

Solution: To solve this problem, we first need to determine the genotypes of the parents in the cross. We can represent the allele for barred feathers as B and the allele for having a pea comb as P. So, the genotype of the barred female heterozygous for the pea comb allele is $\mathrm{Z}^b\mathrm{W}Pp$, and the genotype of the unbarred male homozygous for the pea comb allele is $\mathrm{Z}^b\mathrm{Z}^bPP$. Considering the possible genotype combinations for the offspring, we find that the female parent produces four gametes, Z^BP, Z^Bp, $\mathrm{W}P$, and $\mathrm{W}p$, while the male counterpart produces a single gamete Z^bP. Here is a cross diagram describing the interaction between the two individuals:



According to this diagram, two of the four offspring genotypes correspond to males with barred feathers and a pea comb, so the desired proportion is $\frac{2}{4} = \frac{1}{2}$, which corresponds to answer choice $\boxed{\textbf{(B)}}$.

§5.5 Environmental Effects on Phenotype

Environmental factors can also determine an organism's phenotype by responding to its genetic information to influence physical traits. While the genotype provides the genetic code, the environment in which an organism lives in can influence the expression of these genetic messages. These environmental factors can either be external, such as temperature, nutrition, light, and toxin exposure, or internal, such as fluctuations in hormone levels.

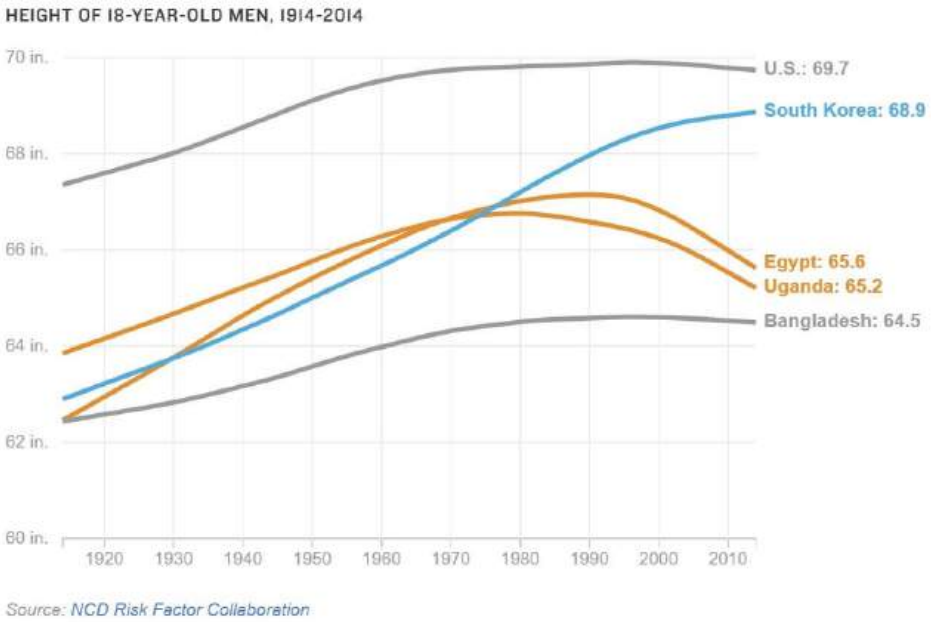


Image Credit: NCD Risk Factor Collaboration

Human height is a complex phenotypic trait determined by both environmental variability and genetic variability.

Example 5.5.1

Consider the Himalayan rabbit. The coat color of this rabbit is regulated by a temperature-dependent allele at the `C` locus. At elevated body temperatures, the rabbits' coats lighten, while at low body temperatures, the coat on its ears, nose, paws, and tail remains black. This coloration shows how environmental temperatures interact with genetic factors, and how outside conditions can influence the way genetic traits are expressed. Other environmental influences, such as diet and sunlight exposure, can also affect human traits, such as height, weight, and skin color.

Additionally, malnutrition during childhood can prevent growth, despite genetic potential for height. Similarly, sunlight can increase melanin synthesis in the skin and lead to darker skin color. All these examples show how environmental influences determine the phenotype and can modify it throughout an organism's life.

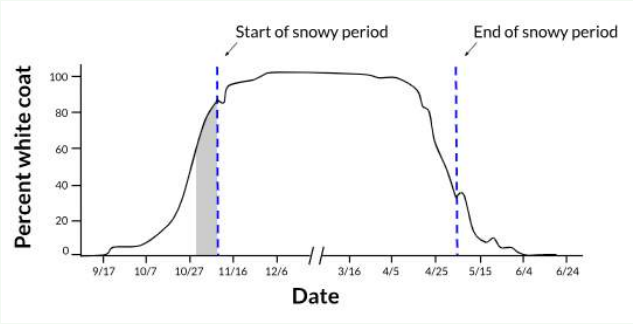
Trait	Genotype	Environmental Influence
Flower Color in Hydrangeas	Genetic	Soil pH affects the color
Human Height	Genetic	Nutrition/health affect growth potential
Coat Color in Siamese Cats	Genetic	Temperature affects color
Skin Color in Humans	Genetic	Sun exposure darkens skin tone

Table 5.1: Examples of how the environment influences the expression of genetic traits.

Problem 5.5.2 — Multiple Choice Question

Snowshoe hares display a seasonal change in coat color from brown to white (Figure 1). This transition occurs as a result of changes in gene expression during the autumn, which is when summer coats are replaced by winter ones. The timing of this transition allows the hares to remain camouflaged from predators during the winter.

A group of scientists studied a certain snowshoe hare population in Western Montana for a period of three years. They found that, on average, the hares' coats transitioned to white before the ground was fully covered in snow (Figure 2), which put the hares at risk for increased predation. This mismatch between molting time and snow cover was due to winter weather arriving later in the year than usual.



Based on the information above, which of the following statements is most likely true about the coat color transition in snowshoe hares?

(A) The transition from a brown to a white coat is the result of gene expression changes induced by autumn daylengths.
(B) The transition from brown to white coats is an adaptation to climate change, which is predicted to shorten snow duration in the snowshoe hare's habitat.
(C) The transition from brown to white coats occurs as the genes for having a white coat become more common in the population during the transition from fall to winter.
(D) The transition from a brown to a white coat is due to gene expression changes that are influenced by the amount of snow on the ground in late autumn.

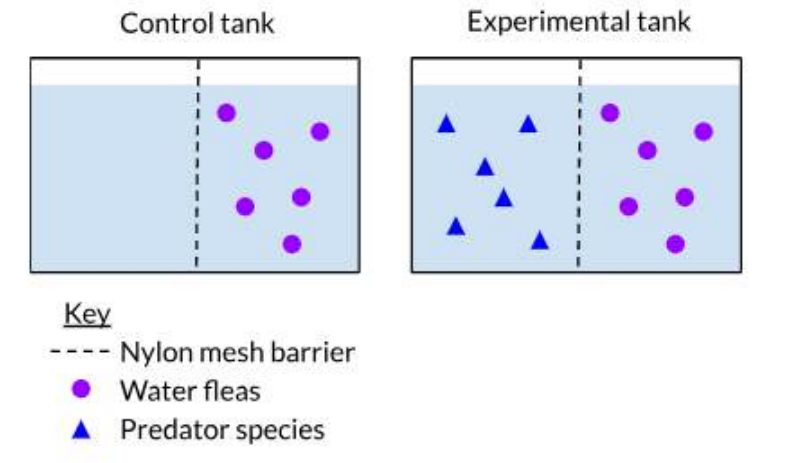
Solution: According to the text, the gene expression changes that lead to the coat color transition occur every year in autumn, and therefore are likely initiated by a signal from the environment. The mismatch between fur color and snow cover tells us that this signal is likely independent of weather conditions. Instead, it is likely that the coat

color transition is induced by the short daylengths that occur in autumn. Therefore, the correct answer is **(A)**.

Problem 5.5.3 — Multiple Choice Question

Daphnia cucullata are tiny aquatic animals called water fleas. These animals have a protective covering on their head called a helmet, which can come in different sizes.

A researcher predicts that helmet size in water fleas depends on chemical cues from predators in the environment rather than on inherited differences. To test this prediction, the researcher sets up two tanks which are represented in the diagram below. The researcher compares the helmet sizes of the water fleas raised in the control tank to those raised in the experimental tank.



Which of the following statements describes an essential part of the researcher's experimental design?

(A) The water fleas used must be at different stages of development at the start of the experiment.
(B) The tanks must be filled with water taken from a lake where water fleas are naturally found.
(C) The chemical that initiates helmet formation in water fleas must be isolated before the experiment is carried out.
(D) The water fleas used in the experiment must all have the same genotype.

Solution: The experiment described above tests the prediction that helmet size in water fleas is not an inherited trait, but instead depends on chemical cues from predators in the environment. So, to ensure that the results of the experiment are not due to inherited differences, the water fleas in the control and experimental tanks must have the same genotype. Thus, the correct answer is **(D)**.

§5.6 Chromosomal Inheritance

Chromosomal inheritance refers to the transmission of hereditary information in the form of chromosomes, which are gene-containing bodies. In eukaryotic organisms, chromosomes are located in the nucleus and occur as a pair, each inherited from one parent. The behavior of chromosomes, particularly during meiosis, is a vital part of the inheritance of characteristics and the transmission of hereditary material from generation to generation.

Chromosomal Theory of Inheritance Walter Sutton and Theodor Boveri generally get credit for the insight that genes are found on special hereditary structures known as chromosomes.. Sutton, who was American, studied chromosomes and meiosis in grasshoppers. Boveri, who was German, studied the similar mechanisms in sea urchins.

In 1902 and 1903, the duo published research proposing what we now call the chromosome theory of inheritance. This theory states that individual genes are found at specific locations on particular chromosomes, and that the behavior of chromosomes during meiosis can explain why genes are inherited according to Mendelian genetics principles.

Image Credit: *OpenStax College, Biology*

Ironically, the chromosome theory of inheritance was proposed before there was any direct evidence that traits were carried on chromosomes, and it was highly controversial in the beginning. Eventually, the work of geneticist **Thomas Hunt Morgan** and his students, who studied the genetics of fruit flies, had confirmed the theory.

T.H. Morgan and His Fruit Flies Morgan chose the fruit fly, *Drosophila melanogaster*, for his genetic experiments. What fruit flies may lack in charisma (depending on your taste in insects), they make up for in practicality: they're cheap, easy, and fast to grow. You can raise hundreds of them in a small bottle with concentrated sugar sludge at the bottom, and many geneticists perform this study today!

Morgan's crucial, chromosome theory-verifying experiments began when he found a mutation in a gene affecting fly eye color. This mutation made a fly's eyes white, rather than their normal red.

Unexpectedly, Morgan found that the eye color gene was inherited in different patterns by male and female flies.. Male flies have an X and a Y chromosome (XY), while female flies have two X chromosomes (XX). Morgan quickly realized the eye color gene was being inherited in the same pattern as the X chromosome.

A "Sex-Limited" Pattern of Inheritance The first white-eyed fly Morgan found was male, and when this fly was crossed with normal, red-eyed female flies, the F1 generation offspring were all red-eyed, indicating the white color was a recessive allele.

However, when the F1 flies were crossed with each other, all of the female F2 flies were red-eyed, while approximately half of the male F2 were white-eyed. It was clear that the male and female flies were inheriting the trait in different patterns. In fact, they were inheriting it in the same pattern as a particular chromosome, the X.

Pulling together all of his observations, Morgan correctly stated that the gene must lie on, or be very tightly associated with, the X chromosome. His student, Calvin Bridges, showed that rare male or female flies with unexpected eye colors were produced through nondisjunction (failure to properly separate) of sex chromosomes during meiosis—essentially, the exception that proved his teacher's proposition.

Morgan also found mutations in other genes that were not inherited in a sex-specific pattern. We now know that genes are located on both sex and non-sex chromosomes, in all species!

Homologous Chromosome Segregation and Genetic Diversity During meiosis, homologous chromosomes (chromosomes of the same kind but with different alleles) are separated into separate gametes (sperm or egg cells). This ensures that each gamete receives only one set of each chromosome and only one allele for every gene. Gametes combine during fertilization and return to the diploid number of chromosomes, with the offspring receiving one chromosome from each parent. This chromosomal inheritance

causes genetic variation and ensures that genes are passed down to offspring by their parents.

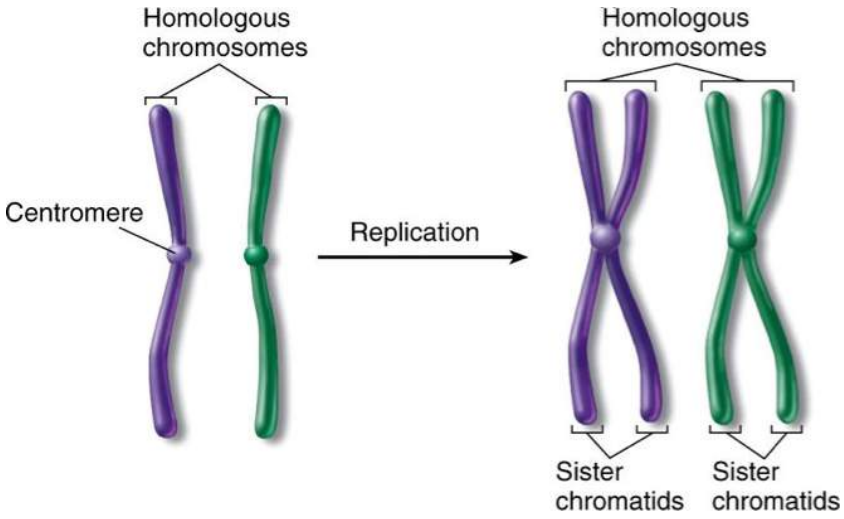


Image Credit: Biology Stack Exchange

Chromosomal Abnormalities and Sex Chromosome Inheritance Apart from the normal inheritance of chromosomes, conditions of chromosome disorder can also occur. For example, in Down syndrome, one has an extra copy of chromosome 21, which is a trisomy (three copies of chromosome 21) that affects growth and acquires physical and mental characteristics. Similarly, sex chromosomes determine biological sex. Males receive one X and one Y chromosome (XY), and females receive two X chromosomes (XX). Sex chromosomes follow an inheritance pattern and are responsible for determining traits that are linked to sex.

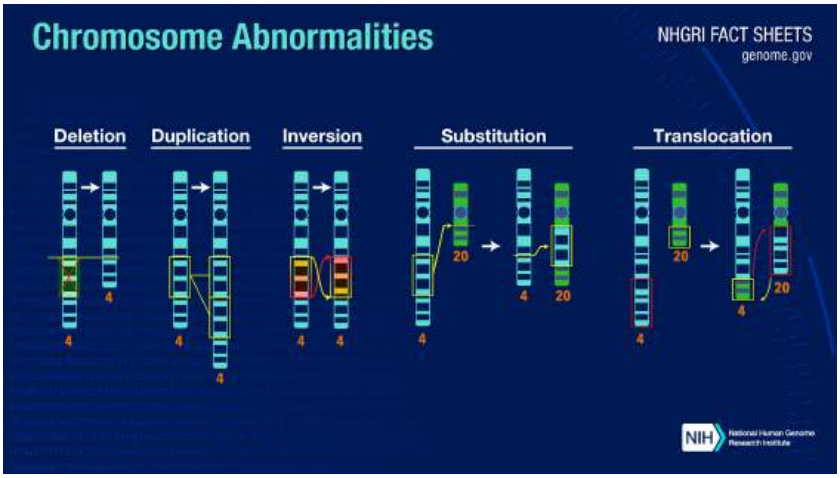


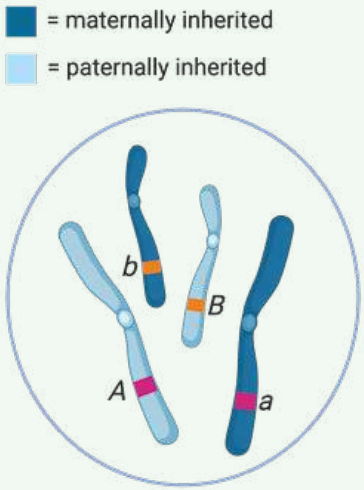
Image Credit: National Human Genome Research Institute

Parent Genotype	Offspring Genotype	Phenotype (Color Blindness)
X^BX^b and X^BY	X^BX^B (Daughter)	Normal Vision
X^BX^b and X^bY	X^bX^b (Daughter)	Color Blindness
X^BY and X^BX^b	X^BY (Son)	Normal Vision
X^bY and X^bX^b	X^bY (Son)	Color Blindness

Table 5.2: Example of X-linked inheritance in humans (Color Blindness).

Problem 5.6.1 — Multiple Choice Question

The diagram below shows two pairs of homologous chromosomes in a diploid cell. The larger chromosomes have different alleles of Gene A, and the smaller chromosomes have different alleles of Gene B.

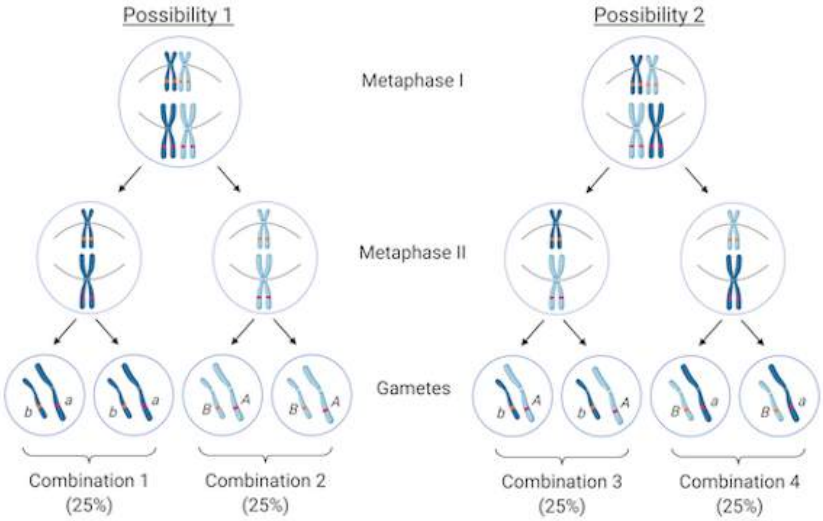


If the cell undergoes meiosis, which of the following is true regarding the allele combinations in the resulting gametes?

(A) Allele combination Bb is more likely to occur in a gamete than allele combination Ab is.
(B) Allele combination AB is just as likely to occur in a gamete as allele combination Ab is.
(C) Allele combination Aa is just as likely to occur in a gamete as allele combination aB is.
(D) Allele combination ab is less likely to occur in a gamete than allele combination AB is.

Solution: (Adapted from Khan Academy)

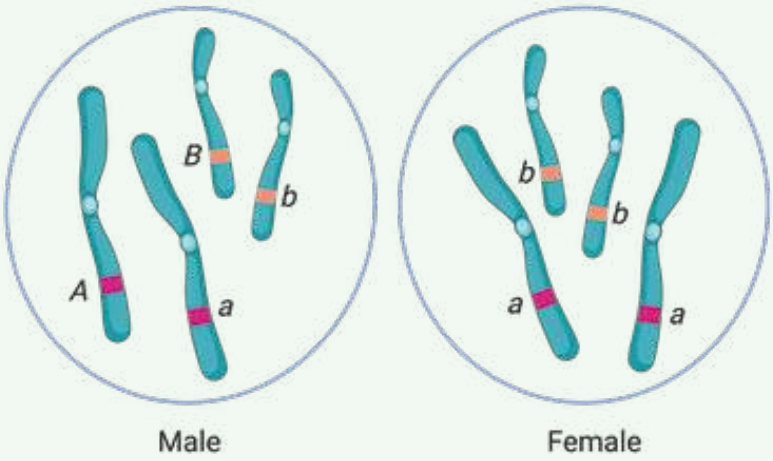
During meiosis I, pairs of homologous chromosomes align randomly along the metaphase plate. So, for two pairs of homologous chromosomes in a cell, there are two ways the pairs can line up relative to one another during metaphase I.



According to the diagram, there are four possible allele combinations in the resulting gametes: ab, AB, Ab, and aB. In addition, the diagram shows us that each combination is equally likely to occur. Therefore, allele combination AB is just as likely to occur in a gamete as allele combination Ab is, which is consistent with option $\boxed{\textbf{(B)}}$.

Problem 5.6.2 — Multiple Choice Question

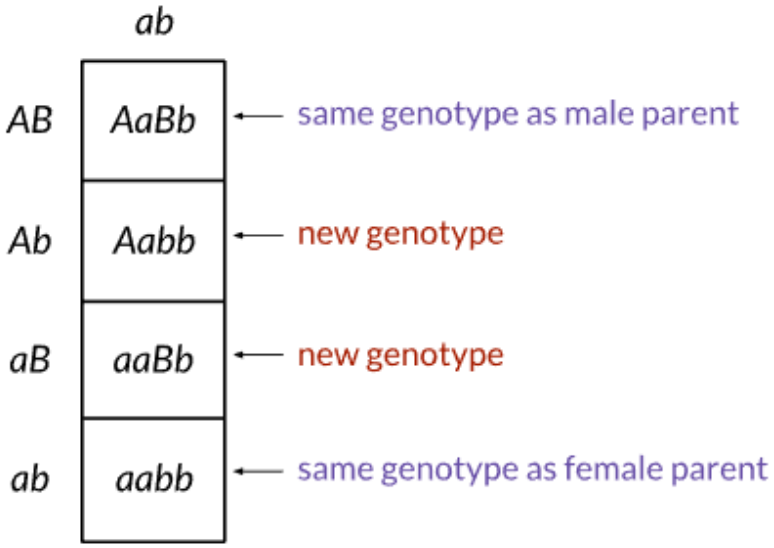
The following diagram depicts two diploid cells, one from a male and one from a female of the same species. In each cell, two pairs of homologous chromosomes are shown. The larger chromosomes have different alleles of Gene A, and the smaller chromosomes have different alleles of Gene B.



If the male and female mate, which of the following will be true about their offspring?

(A) All of the offspring will have a different genotype than either parent.
(B) Roughly half of the offspring will have a different genotype than either parent.
(C) None of the offspring will have the same genotype as the male parent.
(D) Roughly half of the offspring will have the same genotype as the female parent.

Solution: First, let's determine the parental genotypes: According to the diagram, the genotype of the male parent is $AaBb$ and the genotype of the female parent is $aabb$. Now, let's consider the genotypes of the offspring produced by both male and female parents. The male produces four gametes AB, Ab, aB, and ab, while the female produces only one gamete ab. This cross can be represented in the diagram below:



Of the four offspring genotypes in this diagram, two correspond to parental genotypes and two are new genotypes. This is consistent with option $\boxed{\textbf{(B)}}$.

§5.7 Unit 5 Practice Questions

Problem 5.7.1 — 2003 AP Biology FRQ

In fruit flies, the phenotype for eye color is determined by a certain locus. *E* indicates the dominant allele and *e* indicates the recessive allele. The cross between a male wild-type fruit fly and a female white-eyed fruit fly produced the following offspring.

	Wild-type Male	Wild-type Female	White-eyed Male	White-eyed Female	Brown-eyed Female
F1	0	45	55	0	1

The wild-type and the white-eyed individuals from the F1 generation were then crossed to produce the following offspring.

F2	23	31	22	24	0

(a) Determine the genotypes of the original parents (P generation) and explain your reasoning. You may use Punnett squares to enhance your description, but the results from the Punnett squares must be discussed in your answer.

(b) Use a Chi-squared test on the F2 generation data to analyze your prediction of the parental genotypes. Show all your work and explain the importance of your final answer.

(c) The brown-eyed female in the F1 generation resulted from a mutational change. Explain what a mutation is, and discuss two types of mutations that might have produced the brown-eyed female in the F1 generation.

Critical Values of the Chi-Squared Distribution

Probability (p)	Degrees of Freedom (df)				
	1	2	3	4	5
0.05	3.84	5.99	7.82	9.49	11.1

The formula for Chi-squared is:

$$X^2 = \Sigma\left[\frac{(o-e)^2}{e}\right]$$

where o = **observed** number of individuals

e = **expected** number of individuals

Σ = the **sum of the values** (in this case, the differences, squared, divided by the number expected)

Solution to part a: Eye color in fruit flies is controlled by a gene on the X chromosome. Males (XY) only have one X chromosome, so their phenotype expresses whichever allele they inherit. Females have two X chromosomes and can be homozygous or heterozygous. Looking at the F1 generation, we can see that all males have white eyes, which means

they all received the recessive allele from the mother. We already know that one of the X chromosomes of the female flies is recessive (white). All the females from the F1 generation had wild-type eyes, which means they received the dominant allele from their father. From this, we can conclude that the male parent had wild-type $\boxed{(\mathrm{X}^E\mathrm{Y})}$ eyes and the female parent had $\boxed{(\mathrm{X}^e\mathrm{X}^e)}$ white eyes.

Solution to part b: The chi-square formula is: $\chi^2 = \Sigma\left(\mathrm{O}_i - \mathrm{E}_i\right)^2/\mathrm{E}_i$, where O_i = observed value (actual value) and E_i = expected value. For this problem's calculation:

$$\begin{aligned}\chi^2 &= \frac{(23-25)^2}{25} + \frac{(31-25)^2}{25} + \frac{(22-25)^2}{25} + \frac{(24-25)^2}{25} \\ &= \frac{(-2)^2}{25} + \frac{(6)^2}{25} + \frac{(-3)^2}{25} + \frac{(-1)^2}{25} \\ &= \frac{4}{25} + \frac{36}{25} + \frac{9}{25} + \frac{1}{25} \\ &= \frac{50}{25} = 2.0\end{aligned}$$

Using the chi-square table, the critical value of 0.05 significance level is 7.815. Since $2 < 7.815$, we fail to reject the null hypothesis. In other words, we support the null hypothesis of the study.

Solution to part c: A mutation is a heritable change in the genetic code (DNA) of an organism. One type of mutation is a point mutation, where a single nucleotide base is changed, inserted or deleted from a DNA or RNA sequence of the genome of an individual in the F1 generation. Another type of mutation is a frameshift mutation, where a deletion or insertion in a DNA sequence shifts the overall sequence reading for an individual.

Problem 5.7.2 — 2015 AP Biology FRQ

Both mitosis and meiosis are forms of cell division that produce daughter cells containing genetic information from the parent cell.

(a) **Describe** TWO events that are common to both mitosis and meiosis that ensure the resulting daughter cells inherit the appropriate number of chromosomes.

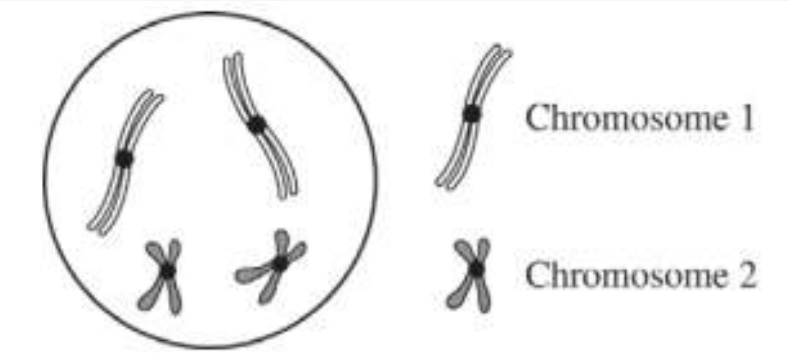
(b) The genetic composition of daughter cells produced by mitosis differs from that of the daughter cells produced by meiosis. **Describe** TWO features of the cell division processes that lead to these differences.

Solution to part a: Before both mitosis and meiosis begin, the cell copies its DNA during the S phase of interphase. This ensures that each chromosome contains two identical sister chromatids, so when the cell divides, each daughter cell gets a complete set of genetic material. During cell division, chromosomes line up at the cell's center (metaphase) and are then pulled apart (anaphase) by spindle fibers. This process ensures that each daughter cell receives the correct number of chromosomes. In mitosis, this

happens once, while in meiosis, it occurs twice to create haploid cells.

Solution to part b: Two easy-to-remember features of both cell division processes (mitosis and meiosis) are the presence and characteristics of crossing over and number of divisions/resulting cells. Crossing over does not take place in mitosis, however, it occurs in meiosis when homologous chromosomes−those of the same type−are lined up. Moreover, mitosis involves a single cell undergoing one division, forming two cells, while meiosis involves a cell undergoing two divisions, resulting in four cells.

Problem 5.7.3 — 2016 AP Biology FRQ

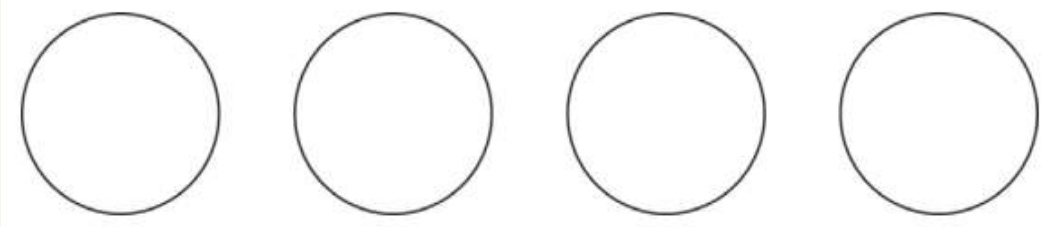


In a certain species of plant, the diploid number of chromosomes is 4 ($2n = 4$). Flower color is controlled by a single gene in which the green allele (G) is dominant to the purple allele (g). Plant height is controlled by a different gene in which the dwarf allele (D) is dominant to the tall allele (d). Individuals of the parental (P) generation with the genotypes $GGDD$ and $ggdd$ were crossed to produce F_1 progeny.

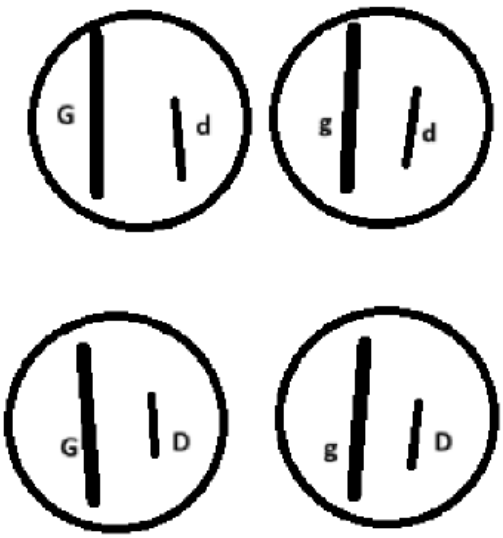
(a) **Construct** a diagram below to depict the four possible normal products of meiosis that would be produced by the F_1 progeny. Show the chromosomes and the allele(s) they carry. Assume the genes are located on different chromosomes and the gene for flower color is on chromosome 1.

(b) **Predict** the possible phenotypes and their ratios in the offspring of a testcross between an F_1 individual and a $ggdd$ individual.

(c) If the two genes were genetically linked, **describe** how the proportions of phenotypes of the resulting offspring would most likely differ from those of the testcross between an F_1 individual and a $ggdd$ individual.



Solution to part a:



This drawing (courtesy of Amaan Shafi) is a little crude, but make sure that your answer has one half of chromosome 1 and one half of chromosome 2 in each circle. When crossing *GGDD* with *ggdd*, the genotype combinations are *GD*, *Gd*, *gD*, and *gd*. Make sure that there is one circle for each genotype combinations, so you should use all 4 circles in your answer.

Solution to part b: You can figure this part out with our answer to the previous question! In part (a), we concluded that the four possible genotype combinations are *GD*, *Gd*, *gD*, and *gd*. In this scenario, *G* means green, *g* means purple, *D* means dwarf, and *d* means tall. Therefore, a genotype combination of *GD* results in a green, dwarf plant. I picked *GD*, but you could state any of the four genotype combinations.

Solution to part c: If the two genes (flower color and plant height) are genetically linked, the proportions of phenotypes in the resulting offspring from the test cross would differ significantly from the expected ratios for unlinked genes. Linked genes are located close together on the same chromosome, so they tend to be inherited together. In a test cross involving linked genes, the majority/greater than 50 percent of offspring will exhibit parental phenotypes (green dwarf and purple tall plants) because crossing over during meiosis is less likely to occur between closely linked genes. Meanwhile, less than 25 percent would be green tall plants and less than 25 percent would be purple dwarf plants.

Problem 5.7.4 — 2022 AP Biology FRQ

During meiosis, double-strand breaks occur in chromatids. The breaks are either repaired by the exchange of genetic material between homologous nonsister chromatids, which is the process known as crossing over (Figure 1A), or they are simply repaired without any crossing over (Figure 1B). Plant breeders developing new varieties of corn are interested in determining whether, in corn, a correlation exists between the number of meiotic double-strand chromatid breaks and the number of crossovers.

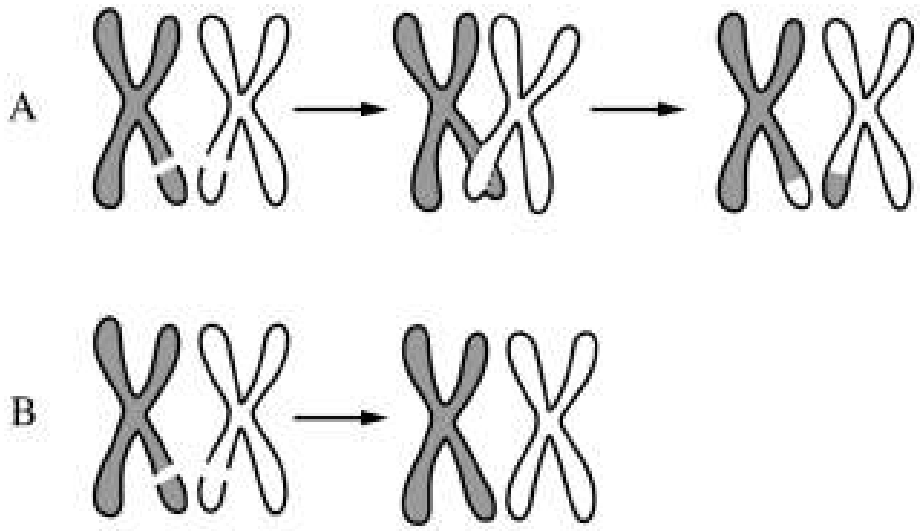


Figure 1. Double-strand breaks in chromatids are repaired with crossing over (A) or without crossing over (B).

Using specialized staining and microscopy techniques, scientists counted the number of double-strand chromatid breaks and the number of crossovers in the same number of meiotic gamete-forming cells of six inbred strains of corn (Table 1).

TABLE 1. NUMBER OF CHROMATID DOUBLE-STRAND BREAKS AND AVERAGE NUMBER OF CROSSOVERS IN INBRED STRAINS OF CORN

Strain of Corn	Number of Double-Strand Breaks	Average Number of Crossovers ($\pm 2SE_{\bar{x}}$)
I	710	19.5 ± 0.5
II	650	18.0 ± 0.7
III	600	17.5 ± 1.0
IV	510	16.0 ± 1.0
V	425	14.0 ± 0.5
VI	325	11.0 ± 1.5

Problem 5.7.5 — 2022 AP Biology FRQ (cont.)

(a) The double-strand breaks occur along the DNA backbone. **Describe** the process by which the breaks occur.

(b) Using the template in the space provided for your response, **construct** an appropriately labeled graph that represents the data in Table 1 and allows examination of a possible correlation between double-strand breaks and crossovers. Based on the data, **determine** whether corn strains I, II, and III differ in their average number of crossovers.

(c) Based on the data, **describe** the relationship between the average number of double-strand breaks and the average number of crossovers in the strains of corn analyzed in the experiment.

(d) Crossing over (Figure 1A) creates physical connections that are required for proper separation of homologous chromosomes during meiosis. A diploid cell with four pairs of homologous chromosomes undergoes meiosis to produce four haploid cells. Crossing over occurs between only three of the pairs. **Predict** the number of chromosomes most likely present in each of the four haploid cells. Provide reasoning to **justify** your prediction. **Explain** how plant breeders can use the information in Table 1 to help develop new varieties of corn.

Solution to part a: These breaks occur via hydrolysis between the sugars and phosphates/nucleotides. Specifically, the covalent bonds between the sugars and phosphates/nucleotides are broken by the addition of water molecules.

Solution to part b:

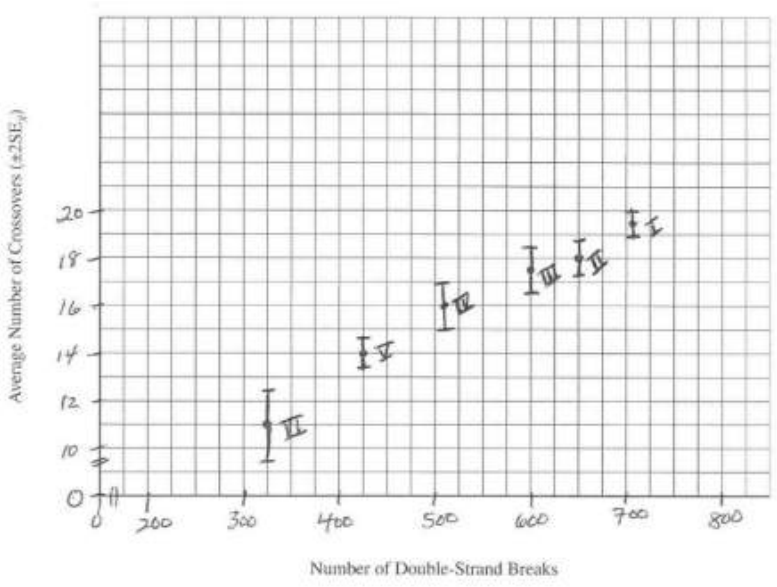


Image Credit: College Board

In order to earn full credit, the axes must be scaled appropriately, the X, Y graph with separate points for the average number of crossovers for each strain, and the presence of accurate error bars (within 2 standard error margins of the mean).

We observe no statistical difference in the average number of crossovers between strains II and III, and that strain I is different (specifically, it is higher) in the average number of crossovers compared with strains II and III, making it statistically different.

Solution to part c: According to Table 1, for the strains of corn, as the average number of double-stranded breaks increases, so does the average number of crossovers in the strains of corn analyzed in the experiment. This indicates a direct, positive relationship/correlation.

Solution to part d: If crossing over occurs between only three out of four pairs of homologous chromosomes in a diploid cell, in the four resulting haploid cells ($n = 4$), two will have $4 - 1 = 3$ chromosomes and two cells will have $4 + 1 = 5$ chromosomes. This is because during meiosis I, three homologous pairs separate normally, and one pair does not separate, i.e. it experiences nondisjunction, and in meiosis II, the sister chromatids separate normally. Plant breeders can use this information to increase the number of double-stranded breaks, which may lead to more crossovers that increase genetic variation.

Problem 5.7.6 — 2023 AP Biology FRQ

Elevated levels of CO_2 increase the rate of photosynthesis and growth in plants. Scientists studying the mechanisms involved in these increases examined a variety of species and found that when plants are exposed to elevated levels of CO_2, there is an increase in the number of chloroplasts per cell. To investigate whether the elevated levels of CO_2 have a similar effect on the number of mitochondria in plant cells, the scientists then selected six of these species to quantify the number of mitochondria per cell when the plants were exposed to both normal and elevated levels of CO_2 (Table 1).

TABLE 1. AVERAGE NUMBER OF MITOCHONDRIA IN PLANTS EXPOSED TO NORMAL AND ELEVATED LEVELS OF CO_2

Species	Mitochondria at Normal CO_2 (per 100 μm^2 of cell area) $\pm 2SE_{\bar{x}}$	Mitochondria at Elevated CO_2 (per 100 μm^2 of cell area) $\pm 2SE_{\bar{x}}$
1	1.0 ± 0.10	1.6 ± 0.10
2	0.4 ± 0.05	0.9 ± 0.08
3	0.5 ± 0.07	0.9 ± 0.10
4	0.3 ± 0.03	0.6 ± 0.06
5	0.7 ± 0.06	1.5 ± 0.22
6	1.3 ± 0.15	2.4 ± 0.22

(a) **Describe** the role of the inner mitochondrial membrane in cellular respiration.

(b) Using the template in the space provided for your response, **construct** an appropriately labeled graph that represents the data in Table 1. **Determine** which species show(s) a difference in the number of mitochondria between normal and elevated levels of CO_2.

(c) Based on the data in Table 1, **describe** the relationship between the level of CO_2 and the average number of mitochondria per unit area of a cell.

(d) The leaves of a particular plant species are typically green, but scientists notice a plant in which the leaves have white stripes. They determine that the stripes result from a mutation in the mitochondrial DNA that interferes with the development of chloroplasts. The scientists crossed plants using pollen from the plant with white-striped leaves and ovules from a plant with green leaves. **Predict** the phenotype(s) of the leaves of offspring produced from this cross. Provide reasoning to **justify** your prediction. **Explain** why plants with the same genotype are able to differ in the structure and/or number of certain organelles in response to changes in atmospheric levels of CO_2.

Solution to part a: The inner mitochondrial membrane serves as the site for the electron transport chain (ETC) and oxidative phosphorylation. It contains proteins that transfer electrons from NADH and $FADH_2$ to oxygen, generating a proton gradient across

the membrane. This gradient powers ATP synthase, the enzyme which plays a critical role in ATP production.

Solution to part b: We need to simply plot the data given in Table 1, owing to appropriate axis scaling and labeling, correct data points and error bars (within 2 standard errors of the mean), and demonstrating that all species show a difference in number of mitochondria between normal and elevated levels of CO_2. The result should look something like this:

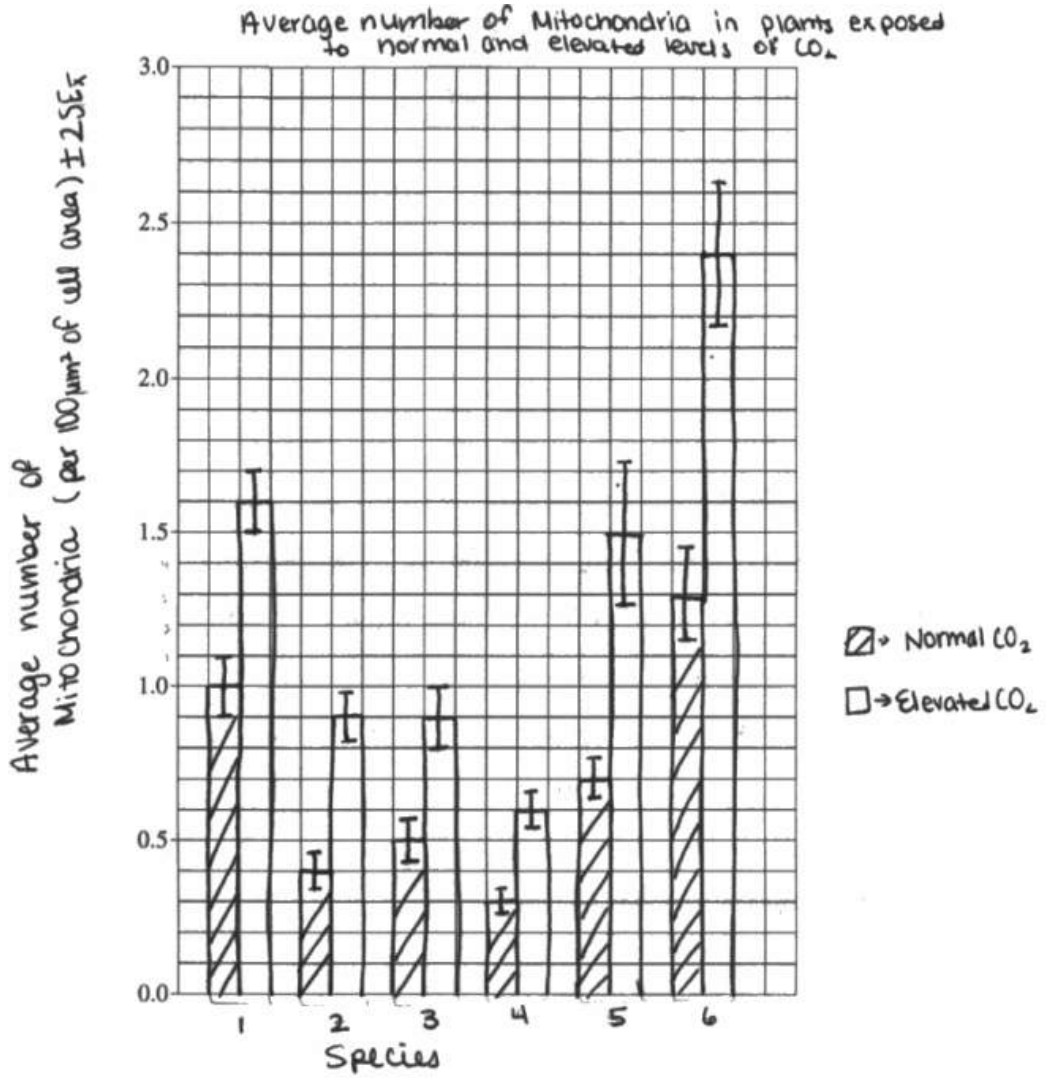


Image Credit: College Board student sample A (2023 FRQ 2)

Solution to part c: Via inspection of the data in Table 1, we observe that for each species, there is greater average mitochondria count under elevated levels of CO_2 (than under normal CO_2). In other words, the number of mitochondria increases as the CO_2 level increases, indicating a positive relationship/correlation.

Solution to part d: The leaves will be all green, or not possess white stripes. This is because all offspring have the same leaf phenotype as the ovule-producing plant;

mitochondria is maternally inherited from and transferred by the ovule. We also need to explain why plants with the same genotype are able to differ in structure and/or certain organelles in response to changes in atmospheric CO_2 levels. It's important to note that the environment can affect gene expression, causing difference in the observable characteristics (phenotypes) of plants.

6 Gene Expression and Regulation

In cellular structures, DNA serves as the blueprint, and transcription and translation convert this information into functional proteins. These processes are tightly regulated to ensure that cells function properly. Understanding them helps scientists develop medical treatments, create genetically modified crops, find new ways to improve health, and tackle global challenges.

§6.1 DNA and RNA Structure

In this section, we'll take a closer look at the structures of DNA and RNA - two important molecules that carry the instructions for life. By understanding their structures, we can better see how they store and pass on genetic information.

The Structure of DNA Deoxyribonucleic acid, or **DNA**, is a double-stranded molecule that provides instructions for the growth, development, and reproduction of all living organisms. DNA is made up of two chains of nucleotides twisted into a double helix. Each nucleotide is made up of three components: a **phosphate group**, **deoxyribose sugar**, and **nitrogenous base**. The nitrogenous bases are divided into two groups: the *purines* (adenine and guanine) with two rings and the *pyrimidines* (cytosine and thymine) with one ring. The "rungs" of the helix are formed by the unique way bases pair, with adenine pairing with thymine and guanine pairing with cytosine. Hydrogen bonds between complementary base pairs hold the two DNA strands together. The backbone of the ladder-like structure is made up of sugar-phosphate. Because of its structure, DNA is compact and stable, but also being flexible enough to go through processes like transcription and replication.

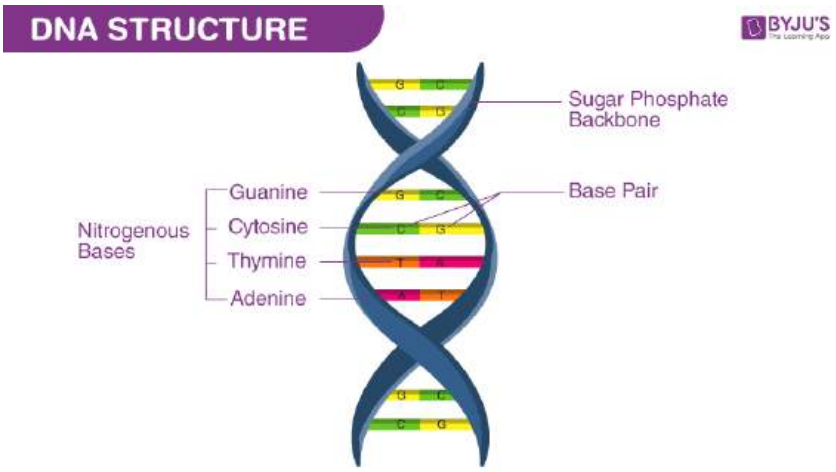


Image Credit: BYJU'S

The Structure of RNA **RNA** is a single-stranded molecule that is involved in the synthesis of proteins and serves a variety of functions within the cell. Although nucleotides make up both DNA and RNA, there are several significant distinctions between them.

The sugar in RNA is **ribose**, rather than deoxyribose in DNA, and RNA contains the nitrogenous base **uracil** instead of thymine. In RNA, uracil pairs with adenine instead of thymine. RNA's single-stranded structure allows it to fold into multiple shapes, depending on its specific function. **Messenger RNA (mRNA)**, **transfer RNA (tRNA)**, and **ribosomal RNA (rRNA)** are the most frequently found types of RNA involved in protein production.

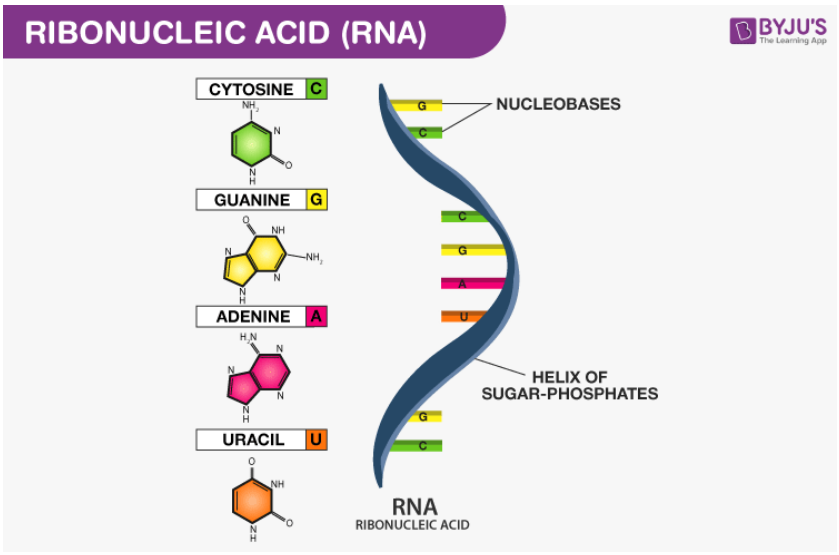


Image Credit: BYJU'S

Comparing DNA and RNA While both DNA and RNA are essential for life, they differ in several important ways:

- **Strand structure**: DNA is double-stranded, while RNA is single-stranded.
- **Sugar**: DNA contains deoxyribose, whereas RNA contains ribose.
- **Bases**: DNA uses thymine, while RNA uses uracil.
- **Function**: DNA stores genetic information, while RNA is involved in the translation of that information into proteins.

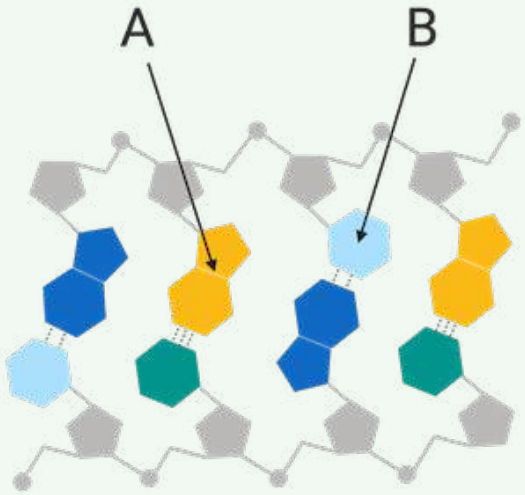
Understanding these structural differences helps explain how DNA and RNA work together in the process of gene expression and protein synthesis.

The Central Dogma of Molecular Biology The flow of genetic information in a cell follows the **central dogma**: DNA is transcribed into RNA, and RNA is translated into protein(s). This process is fundamental to life and ensures that genetic information is accurately passed from one generation to the next and is used to build the proteins that carry out the cell's functions.

Conclusion The structures of DNA and RNA are vital to their respective functions in the cell. DNA serves as the long-term storage of genetic information, while RNA acts as a messenger, translating that information into the synthesis of proteins. The interplay between these molecules is what allows cells to function, grow, and reproduce.

Problem 6.1.1 — Multiple Choice Question

The following diagram shows nucleotide base-pairing in a double-stranded DNA molecule. The nitrogenous bases in two of the nucleotides are labeled.



Which of the following correctly compares nitrogenous bases A and B?

(A) Nitrogenous base A is a pyrimidine, while nitrogenous base B is a purine.
(B) Nitrogenous base A is a purine, while nitrogenous base B is a pyrimidine.
(C) Nitrogenous bases A and B are both pyrimidines.
(D) Nitrogenous bases A and B are both purines.

Source: Khan Academy

Solution: We can determine whether a nitrogenous base is a pyrimidine or a purine by looking at its ring structure: Pyrimidines have a single-ring structure, while purines have a double-ring structure. According to the diagram, nitrogenous base A has a double-ring structure. In contrast, nitrogenous base B is shown as having a single-ring structure. Thus, base A and base B are a purine and pyrimidine, respectively, which is consistent with option $\boxed{\textbf{(B)}}$.

Problem 6.1.2 — Multiple Choice Question

Zika fever is an illness caused by the Zika virus, which is spread to people by mosquitoes of the genus *Aedes*.

The nucleotide composition of the Zika virus genome is shown in the following table.

Nucleotide	Percentage of Zika virus genome
Adenine (A)	27.7%
Uracil (U)	21.3%
Cytosine (C)	21.9%
Guanine (G)	29.1%

According to the data in the table, the Zika virus genome is made up of

(A) double-stranded RNA
(B) single-stranded DNA
(C) single-stranded RNA
(D) double-stranded DNA

Solution: First, let's look at the types of nucleotides in the Zika virus genome. According to the table, the genome contains adenine, uracil, cytosine, and guanine. Uracil is found only in RNA and not in DNA. So, the Zika virus genome is made up of RNA. Next, we observe the percentages of complementary nucleotides in the Zika virus genome. If the RNA that makes up the genome were double-stranded, we would expect the percentages of complementary nucleotides to be roughly equal. However, the percentages of adenine and uracil are *unequal*, as are those of cytosine and guanine. Thus, the RNA is most likely single-stranded, which is option $\boxed{\textbf{(C)}}$.

§6.2 Replication

In this section, we will go over the process of **DNA replication**, a mechanism that allows cells to divide and pass on genetic information to daughter cells. Replication ensures that each new cell receives an exact copy of the DNA, ensuring that new cells have the same genetic information as the original cell.

What is DNA Replication? DNA replication is the process by which a cell makes an identical copy of its DNA. This is a crucial step during **cell division** (mitosis or meiosis) that ensures each daughter cell inherits a complete set of genes. Replication occurs during the **S phase** of the cell cycle and is highly accurate, thanks to proofreading mechanisms.

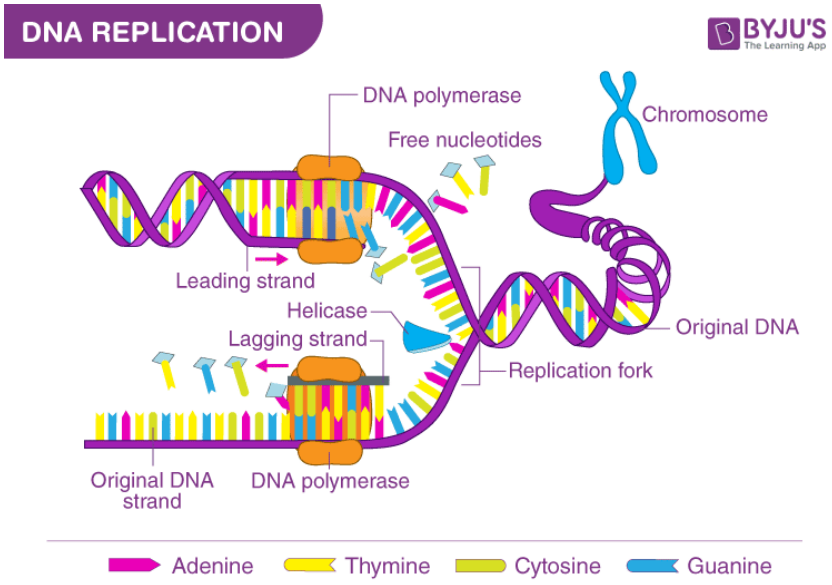


Image Credit: BYJU'S

The process of DNA replication involves several key steps and enzymes, which work together to unwind the DNA, replicate the strands, and seal the new DNA strands.

Key Steps in DNA Replication DNA replication follows a semi-conservative model, so each new DNA molecule consists of one original (parental) strand and one newly synthesized strand.

1. **Initiation**: Replication begins at specific locations on the DNA molecule called *origins of replication*. The enzyme **helicase** unwinds the double helix by breaking the hydrogen bonds between complementary base pairs. This creates two strands for replication.

2. **Primer binding**: Before DNA polymerase can begin synthesizing the new strand, a short RNA primer is synthesized by the enzyme **primase**. This primer provides the 3' hydroxyl group needed for the addition of new nucleotides.

3. **Elongation**: The enzyme **DNA polymerase** adds nucleotides to the growing DNA strand, matching the complementary base pairs (A with T, C with G). DNA polymerase can only add nucleotides in the 5' to 3' direction, so the new strand is synthesized in this direction. The leading strand is continuosly synthesizesin the 5' to 3' direction, while the lagging strand is synthesized in short segments called *Okazaki fragments*.

4. **Removal of primers and gap filling**: The RNA primers are removed by the enzyme **exonuclease**, and the gaps are filled with DNA nucleotides by DNA polymerase.

5. **Ligation**: The enzyme **ligase** seals the sugar-phosphate backbone, joins the Okazaki fragments on the lagging strand, and ensures the DNA molecule is complete and continuous.

The Role of Key Enzymes in DNA Replication DNA replication is a fundamental biological process that requires multiple specialized enzymes, each performing specific functions:

- **Helicase**: Unwinds the DNA double helix by breaking the hydrogen bonds between complementary bases.
- **Primase**: Synthesizes short RNA primers that provide a starting point for DNA synthesis.
- **DNA polymerase**: Adds nucleotides to the growing DNA strand by complementary base pairing.

Leading and Lagging Strands The structure of DNA, with its antiparallel strands, requires a complex replication process. During DNA replication, the two strands of the DNA double helix must duplicate in opposite directions. One strand, the *leading strand*, is continuously synthesized in the 5' to 3' direction. The other strand, called the *lagging strand*, is synthesized discontinuously in short segments called *Okazaki fragments*. These fragments are then linked by DNA ligase to form a continuous strand.

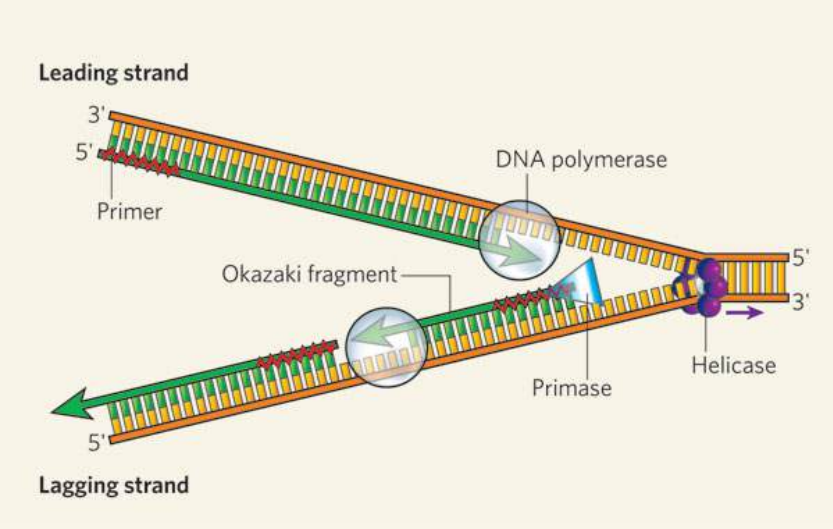


Image Credit: Nature

Proofreading and Error Correction DNA replication is a highly accurate process, but errors can still occur. DNA polymerase has proofreading capabilities that allow it to detect and correct errors in base pairing during replication. If an incorrect base is added, the enzyme removes it and replaces it with the correct nucleotide. This ensures that the final DNA product is an exact copy of the original.

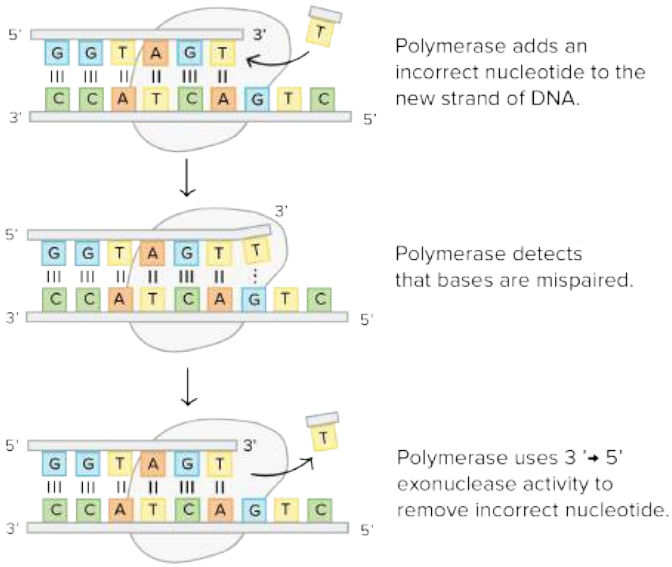


Image Credit: Khan Academy

Problem 6.2.1 — Multiple Choice Question

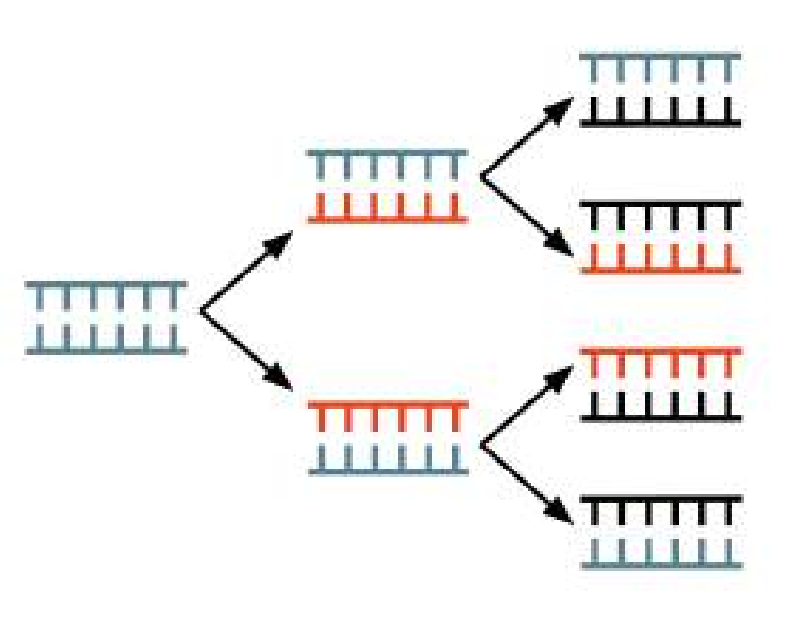
In DNA replication, which of the following events happens during both leading and lagging strand synthesis?

(A) DNA polymerase synthesizes a single, continuous strand of DNA.
(B) Topoisomerase separates complementary strands of DNA.
(C) RNA primers help initiate DNA synthesis.
(D) Ligase joins together multiple Okazaki fragments.

Solution: RNA primers are required for DNA polymerases to begin synthesizing new strands of DNA. This is true during both leading and lagging strand synthesis. The correct answer is $\boxed{\textbf{(C)}}$.

Problem 6.2.2 — Open-Ended Question

Why does the following model most accurately represent the process of DNA replication over two cell divisions?



Source: Khan Academy

Solution: During replication, each strand of a DNA molecule serves as a template for a new, complementary strand. This means that each daughter DNA molecule is made up of one parental and one newly-synthesized strand. Therefore, the above model accurately represents DNA replication over two cell divisions.

§6.3 Transcription and RNA Processing

Transcription is the process by which an RNA molecule is synthesized from a DNA template. This is a crucial step in gene expression, because it converts genetic information in DNA into RNA, which is then translated into a protein. The process occurs in the nucleus of eukaryotic cells and in the cytoplasm of prokaryotic cells, and is carried out by the enzyme *RNA polymerase*, which synthesizes complementary RNA strands based on the DNA template.

Steps of Transcription Transcription involves three main steps: initiation, elongation, and termination. During **initiation**, RNA polymerase binds to the promoter region of the gene, signaling the start of transcription.

In the **elongation** phase, RNA polymerase moves along the DNA template, synthesizing the RNA strand by adding complementary RNA nucleotides.

Transcription ends during **termination**, when RNA polymerase reaches a termination signal and releases the newly synthesized RNA molecule.

This ensures that the RNA sequence matches the DNA sequence, with uracil replacing thymine. Transcription ends in the **termination** stage when RNA polymerase reaches a specific DNA sequence that signals a stop. The synthesized RNA strand is then released.

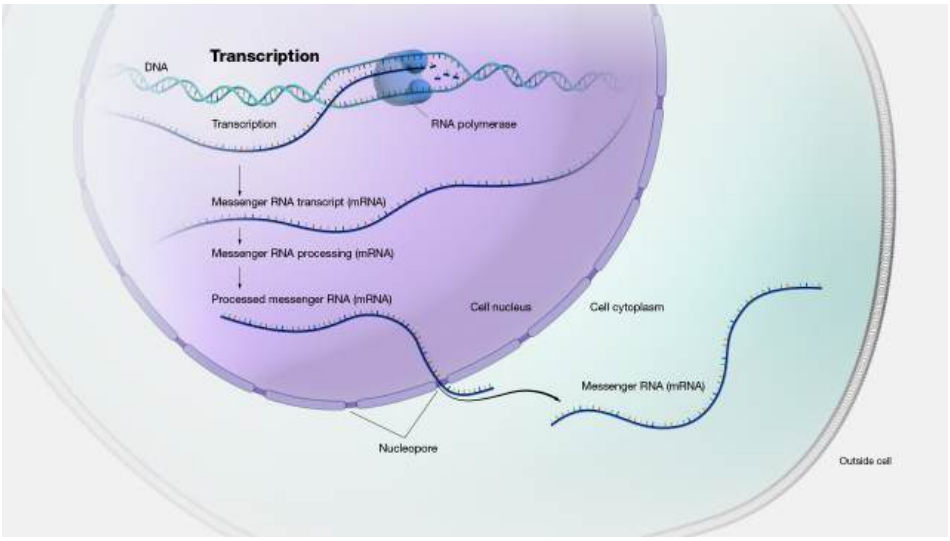


Image Credit: National Human Genome Research Institute

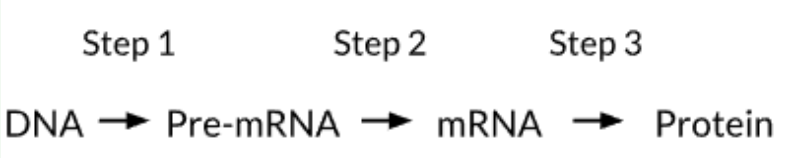
Modifications to RNA In prokaryotes, the RNA transcript is immediately ready for translation (prokaryotes don't have a nucleus), but has to undergo processing for eukaryotes. One important modification is *capping*, where a modified guanine nucleotide is added to the 5' end of the RNA. This helps protect it from degrading and aids in ribosome recognition.

A similar step is *polyadenylation*, where a tail of adenine nucleotides is added to the 3' end. This poly-A tail increases stability and helps transport the RNA out of the nucleus.

Another important part of this phase is *splicing*, which removes non-coding segments called introns and joins coding parts called exons. This process ensures that the final messenger RNA (mRNA) only contains the necessary instructions for building a protein. In some cases, splicing can occur in different ways, allowing a single gene to create multiple protein variations.

Problem 6.3.1 — Multiple Choice Question

The following diagram represents the flow of genetic information from DNA to protein.



Which of the following describes an event that occurs during Step 1 in the diagram?

(A) tRNAs and rRNAs are used to add amino acids to a growing polypeptide chain.
(B) mRNAs are translated into pre-mRNAs in the cytosol.
(C) pre-mRNAs are produced by RNA polymerase using a template molecule.
(D) pre-mRNAs are processed to include only certain exons.

Source: Khan Academy

Solution: Step 1 represents transcription, or the production of pre-mRNAs from a DNA template. This step is carried out by RNA polymerase. The correct answer is $\boxed{\textbf{(C)}}$.

Problem 6.3.2 — Multiple Choice Question

A researcher creates a mutant eukaryotic cell line that lacks the enzyme poly(A) polymerase. Which of the following would be the MOST immediate consequence of this mutation?

(A) Increased rate of transcription initiation
(B) Improved splicing of introns from pre-mRNA
(C) Enhanced translation efficiency at ribosomes
(D) Decreased mRNA stability in the cytoplasm

Solution: Poly(A) polymerase adds the poly-A tail to mRNA, which primarily functions to protect mRNA from degradation and increase its stability in the cytoplasm. An absence of poly(A) polymerase would cause a decrease in mRNA stability, so the correct answer is $\boxed{\textbf{(D)}}$.

§6.4 Translation

Translation is the process by which genetic information is carried by mRNA and used to build proteins. This process occurs in ribosomes in the cytoplasm. mRNA is a "message" written with nucleotides, and translation turns it into the "language" of amino acids, which are the building blocks of proteins.

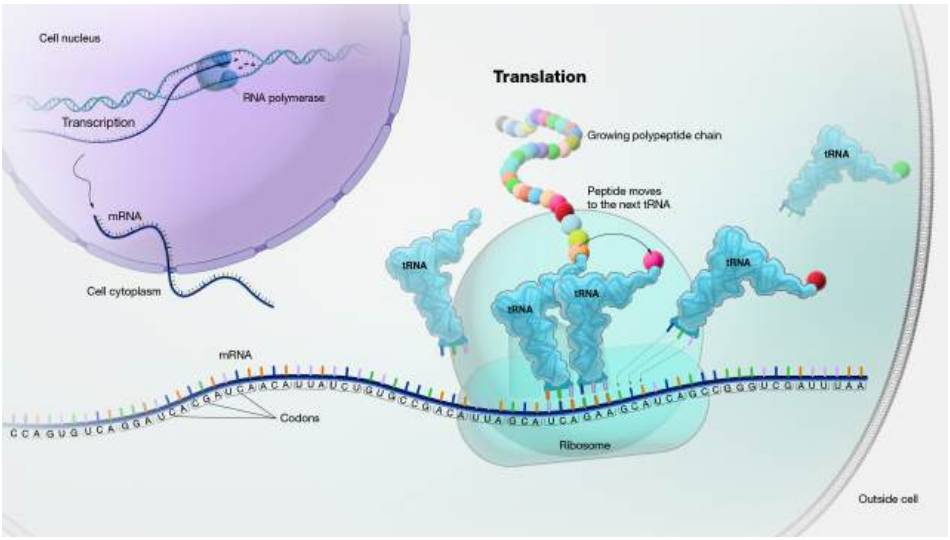


Image Credit: National Human Genome Research Institute

Steps of Translation Translation can be broken down into 3 main steps: initiation, elongation, and termination.

1. Initiation: This is the start of translation. First, the small ribosomal subunit attaches to the mRNA strand at the start of the codon. Then, the tRNA brings in the first amino acid to pair with the start codon. The large ribosomal subunit then attaches to form a complete ribosome.

2. Elongation: Once initiation is complete, elongation begins. Here, transfer RNA molecules continue bringing in amino acids to the ribosome. Each tRNA has an anticodon corresponding to the codons on the mRNA, ensuring that the correct amino acid is added to the chain. The ribosome moves along the mRNA and reads the codons, and each new amino acid is added one by one.

3. Termination: Translation ends when the ribosome reaches a stop codon. Now, a release protein enters the ribosome and signals the new protein to detach. The ribosome disassembles, and the mRNA is released.

Importance of Translation Without translation, cells would not be able to synthesize the necessary proteins for their functioning. Moreover, translation is critical because it converts genetic information into actual molecules that carry out a cell's work.

Problem 6.4.1 — Multiple Choice Question

Which of the following models best depicts how the genetic information in a retrovirus is eventually translated into proteins?

(A) DNA in the retrovirus → RNA in the host cell → Proteins
(B) RNA in the retrovirus → DNA in the host cell → RNA in the host cell → Proteins
(C) RNA in the retrovirus → mRNA in the host cell → Proteins
(D) DNA in the retrovirus → mRNA in the host cell → Proteins

Solution: Genetic information in retroviruses has a different flow of information than that of the host cell—from RNA to DNA. This is made possible by an enzyme called reverse transcriptase. After the viral RNA genome is converted into DNA by reverse transcriptase, this DNA version of the viral genome integrates into the host genome. Once integrated, host enzymes transcribe viral DNA into RNA, and this RNA will be translated into viral proteins. This is consistent with option **(B)**.

Problem 6.4.2 — Multiple Choice Question

How does the translation process in prokaryotes differ from that in eukaryotes, and what advantage does this difference provide to prokaryotic organisms?

(A) Prokaryotic translation occurs in the cytoplasm, while eukaryotic translation happens in the endoplasmic reticulum.
(B) Prokaryotes have a unique set of tRNAs that allow for the incorporation of non-standard amino acids.
(C) Prokaryotes use different ribosomes than eukaryotes, enabling more efficient protein folding.
(D) Prokaryotes can initiate translation before transcription is complete, allowing for faster protein synthesis.

Solution: Options (A), (B), and (C) should all be eliminated, as none of them correctly describe the transcription process in general or make conceptual sense. We know that prokaryotes can initiate translation before transcription is complete because of them lacking a nuclear membrane, which allows for coupled transcription-translation, which provides a significant speed advantage in protein synthesis. We choose option **(D)**.

§6.5 Regulation of Gene Expression

Regulatory Sequences Regulatory sequences are DNA regions that help control gene expression. They determine whether a gene is turned on or off, and the level at which a gene is expressed. These sequences are typically located near promoter regions and interact with regulatory proteins to enhance or inhibit translation.

There are many different types of regulatory sequences with their specific functions.

Enhancers increase gene expression, while silencers decrease it. Promoters are the binding sites for RNA polymerase and other initiation factors, and terminators signal the end of transcription. Regulatory proteins, or transcription factors, bind to sequences and adjust transcription rates. They can encourage or block RNA polymerase from binding to the promoter, controlling gene activity.

Epigenetic Changes **Epigenetics** refers to changes in gene activity that do not involve altering the DNA sequence itself. These changes affect how accessible DNA is to transcription mechanisms and how they can be inherited by future cells. One common epigenetic modification is DNA methylation, which silences genes by attracting methyl-DNA binding proteins. Another important modification is histone acetylation and methylation, which affects how tightly DNA is wrapped around histones, influencing gene accessibility.

Environmental factors, such as diet or exposure to toxins, can lead to epigenetic changes that may affect health later in life. Some diseases like cancer are associated with rare epigenetic modifications. Scientists are continuing to develop therapies that can target the enzymes responsible for these modifications to treat these conditions.

Gene Expression and Phenotypes An organism's phenotype is the set of observable traits it has and depends on which genes are expressed and at what level.

At this point, we define **cell differentiation**. Specifically, cells play a specialized role by expressing certain sets of genes. For example, muscle cells produce actin and myosin, while nerve cells express neurofilaments. This differentiation is carefully controlled through transcription, post-transcription, and post-translation mechanisms.

Coordinated Gene Regulation in Prokaryotes and Eukaryotes Gene regulation allows cells to efficiently manage the expression of genes in similar processes. In prokaryotes, genes that serve related functions are often grouped into operons and transcribed as a single mRNA. A well-known example is the *lac* operon, which is responsible for lactose and metabolism in bacteria.

Note 6.5.1

You do not need to know specific operons, but just know how inducible and repressible ones work.

The *lac* operon is an inducible system, a system that is off except in the presence of the correct inducer, lactose. A repressor protein usually blocks transcription by binding to the operator. When lactose is present, it deactivates the repressor, allowing transcription to begin. The catabolite activator protein (CAP) enhances transcription when glucose levels are low. The genes *lacZ*, *lacY*, and *lacA* are transcribed to facilitate lactose breakdown. Unlike inducible operons, repressible operons are normally active but can be turned off when necessary.

When tryptophan levels are high, a repressor binds to the operator and blocks transcription. If tryptophan levels are low, the operon remains active. In eukaryotic cells, groups of genes can be regulated by the same transcription factors. These proteins bind to DNA and coordinate gene expression. For example, genes involved in cell growth and division may share a common regulatory factor to ensure synchronized action. Similarly, genes

responding to environmental changes may be controlled by the same transcription factor, allowing the organism to adapt accordingly. Understanding coordinated gene regulation is important for studying development, disease, and response to external stimuli.

Problem 6.5.2 — Multiple Choice Question

A researcher is studying gene expression in eukaryotes and observes that a specific gene is expressed at high levels in liver cells but not in skin cells. When analyzing the DNA sequence upstream of this gene, which element is MOST likely responsible for this tissue-specific expression pattern?

(A) Terminator sequences that prevent transcription in skin cells
(B) Enhancer sequences bound by liver-specific transcription factors
(C) Introns that are alternatively spliced in different tissues
(D) Poly-A tail that stabilizes mRNA in liver cells

Solution: Enhancers are regulatory sequences that bind tissue-specific transcription factors to increase transcription in particular cell types, explaining the differential expression between liver and skin cells. Thus, the correct answer is **(B)**.

Problem 6.5.3 — Multiple Choice Question

In an experiment, researchers treated embryonic stem cells with a chemical that inhibits DNA methyltransferase. Which of the following outcomes would most likely result from this treatment?

(A) Decreased mutation rate in rapidly dividing cells
(B) Accelerated cell differentiation into specialized tissues
(C) Increased expression of genes normally silenced in differentiated cells
(D) Enhanced specificity of tissue-specific transcription factors

Solution: DNA methylation typically silences genes; inhibiting this process would lead to increased expression of genes that would normally be repressed during differentiation, potentially disrupting normal cell differentiation patterns. Thus, the correct answer is **(C)**.

§6.6 Gene Expression and Cell Specialization

In this section, we focus on how different types of cells within an organism develop specialized functions by expressing different sets of genes, a process called "differential gene expression," despite all cells having the same DNA genome; essentially, the key to cell specialization lies in the way genes are turned on or off in a particular cell, allowing various functions within a single organism.

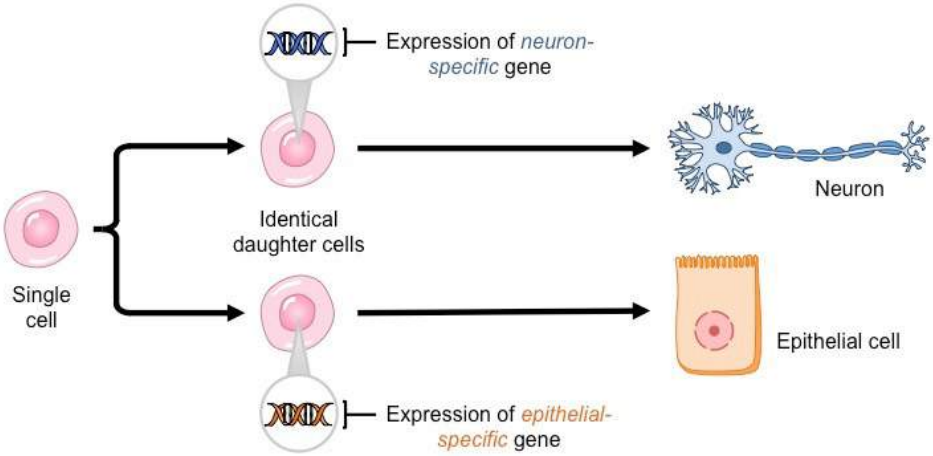
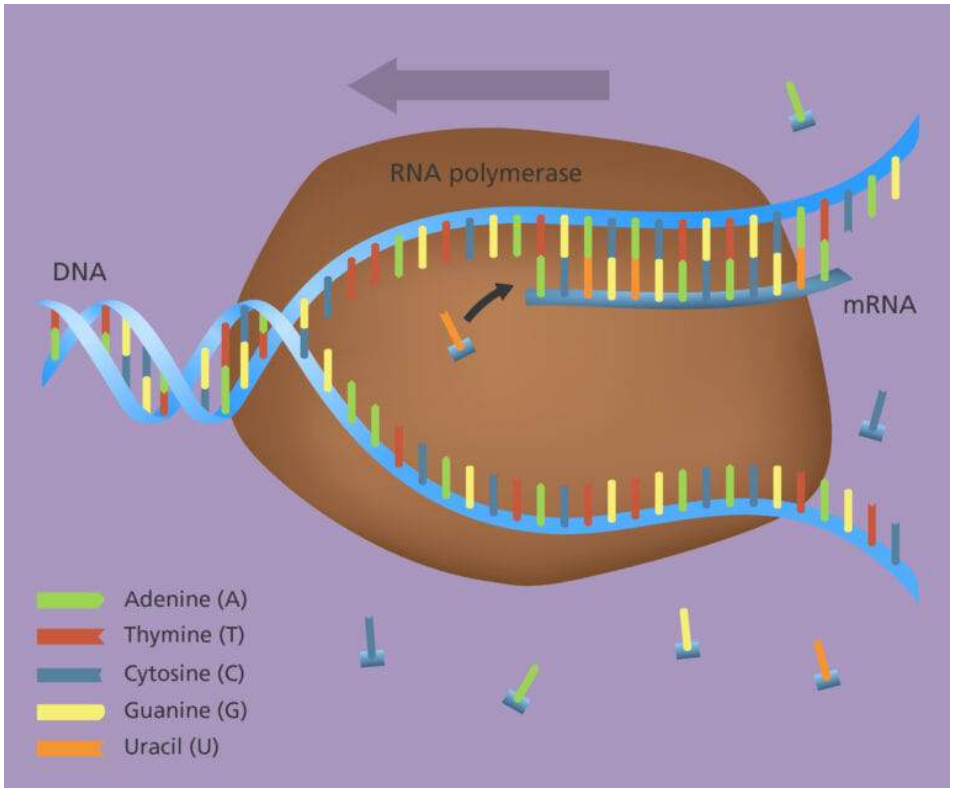


Image Credit: BioNinja

Transcription RNA polymerase and transcription factors bind to **promoters** to initiate the transcription process. We define promoters as specific regions of DNA located upstream of the transcription initial site so that it can be decided whether the gene will be expressed before the enzymes reach this point. They serve as the binding sites for RNA polymerase and various transcription factors, which work hand in hand to initiate the transcription process. Promoters typically contain a TATA box, a DNA sequence recognized by the TATA-binding protein (TBP)—a component of the RNA polymerase complex.

In addition to the TATA box, promoters also contain other **cis-acting elements**, moderators of the promoter's activity. Enhancers are cis-acting elements that can increase the transcriptional activity of a promoter, whereas silencers are cis-acting elements that can decrease the transcriptional activity of a promoter.

On the other hand, we have **negative regulatory molecules** that can inhibit gene expression by binding to DNA and blocking transcription. These molecules include **repressors** and **transcriptional corepressors**. Repressors are proteins that bind to specific sequences in the promoter region of a gene and prevent the binding of RNA polymerase and transcription factors. Meanwhile, transcriptional corepressors are molecules that bind to activating transcription factors and prevent them from binding to the promoter region of a gene. The equilibrium between positive and negative regulatory molecules dictates the extent of gene expression within a cell and is crucial in regulating the cell's physiological functions.



Gene Regulation and Expression Gene regulation is the process by which gene expression is controlled in a cell. Differential gene expression is the process by which different genes are expressed at different levels in different cells or at different times in the same cell. The differential expression of genes results in the production of different cell products and influences the function of the cell.

The use of **small RNA molecules**—noncoding RNAs that are typically 20-25 nucleotides long and are involved in various cellular processes (including gene regulation)—is one way in which gene expression can be regulated.

A class of small RNA molecules is **microRNAs (miRNAs)**—small non-coding RNAs that bind to the **3' untranslated regions (3'UTRs)** of specific target mRNAs. These RNA molecules can effectively block the translation of their target mRNAs, or promote their degradation, to repress gene expression. This explains the ability of miRNAs to regulate gene expression at the post-transcriptional level.

Other classes of small RNA molecules are **small interference RNAs (siRNAs)** and **PIWI-interacting RNAs (piRNAs)**. siRNAs are double-stranded RNAs that are processed by the RNA-induced silencing complex (RISC) to generate single-stranded siRNAs that can target specific mRNAs for degradation, whereas PIWI-interacting RNAs (piRNAs) are small non-coding RNAs that are involved in the silencing of transposable elements in the genome.

Note 6.6.1

There is no need to memorize each small RNA molecule for the AP exam, but you should know that there are different molecules exist for different gene regulation processes within living cells.

Problem 6.6.2 — Multiple Choice Question

What role do microRNAs (miRNAs) play in the regulation of gene expression?

(A) They increase promoter activity by acting as enhancers.
(B) They can suppress gene expression by inhibiting translation or promoting degradation of target mRNAs.
(C) They bind to activating transcription factors and prevent them from binding to promoters.
(D) They bind to promoters to initiate transcription.

Solution: miRNAs are primarily involved in post-transcriptional regulation, meaning that they act after the mRNA has been transcribed. They do not directly influence promoter activity or transcription initiation, so we eliminate (A). In addition, miRNAs do not interact directly with transcription factors or DNA promoters, so we eliminate (C) and (D). MicroRNAs (miRNAs) are small non-coding RNA molecules that primarily function to regulate gene expression by binding to the 3' untranslated region (UTR) of target messenger RNAs (mRNAs). This binding can lead to either the degradation of the target mRNA or the inhibition of its translation into protein, effectively suppressing gene expression, which is consistent with $\boxed{\textbf{(B)}}$.

Problem 6.6.3 — Multiple Choice Question

In a series of experiments, researchers found that protein X binds to specific DNA sequences and recruits histone deacetylases to that region. The most likely function of protein X in gene regulation is:

(A) A termination factor that signals the end of transcription
(B) A splicing factor that removes introns from pre-mRNA
(C) An activator that increases RNA polymerase processivity
(D) A transcriptional repressor that promotes chromatin condensation

Solution: Protein X exhibits negative feedback regulation by recruiting histone deacetylases, which remove acetyl groups from histones, promoting chromatin condensation and making DNA inaccessible for transcription. The correct answer is therefore $\boxed{\textbf{(D)}}$.

§6.7 Mutations

Mutations are changes in an organism's DNA that occur either by mistake during DNA replication or as a result of environmental factors. These changes can affect proteins and

alter how the organism looks or functions. Some mutations do not have a noticeable effect, but others can create genetic differences that influence natural selection and help drive evolution.

Point Mutations A point mutation is a change in one nucleotide. The subsequent changes depend on where it is and which nucleotide is substituted. Types of point mutations include:

- **Silent mutations** do not change the amino acid sequence due to the redundancy of the genetic code.
- **Missense mutations** result in a different amino acid and can alter the protein's function.
- **Nonsense mutations** lead to an early stop codon and produces a nonfunctional protein.

Insertions and Deletions **Insertions** and **deletions** occur when a nucleotide is added or removed from a DNA sequence. If the number of nucleotides added or deleted is not a multiple of three, then a **frameshift mutation** occurs. This changes the reading frame and will significantly alter the amino acid sequence on the polypeptide chain.

Effects of Mutations of Phenotypes Mutations can be classified according to their impact:

- **Beneficial mutations** provide an advantage to the organism's current state.
- **Neutral mutations** don't have a significant effect on the organism's phenotype.
- **Harmful mutations** cause diseases or reduce the organism's fitness.

Example 6.7.1

A well-known example of a harmful mutation is the **sickle cell mutation**, which alters the hemoglobin protein. Individuals with one allele of the mutation have resistance to malaria, while those with two copies develop sickle cell disease.

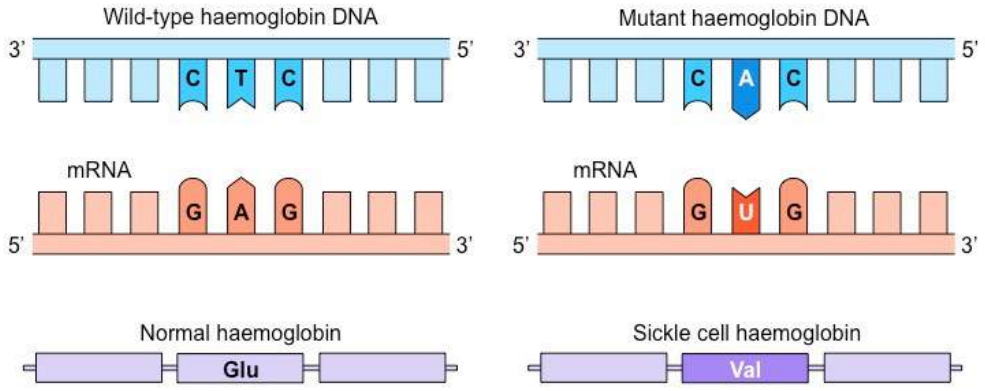


Image Credit: BioNinja

Chromosomal Mutations Mutations can affect the entire chromosome. In plants, additional sets of chromosomes can lead to an increase in size and genetic diversity. Mutations introduce genetic variation, which is important in evolution. Natural selection acts on these variations and favors beneficial mutations while eliminating harmful ones. Over time, this leads to adaptation for the species.

Note 6.7.2

We will discuss the concept of natural selection and evolution in Unit 7.

Horizontal Gene Transfer In bacteria, genetic variation is introduced through **horizontal gene transfer**, which occurs through several factors:

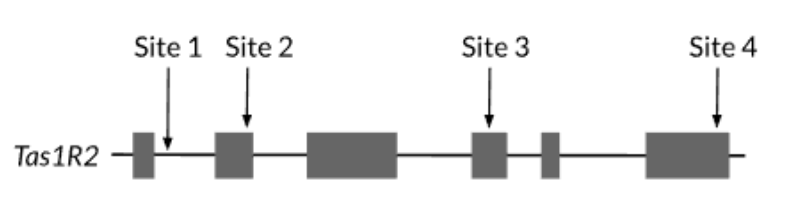
- **Transformation** - absorbing free DNA from the environment.
- **Transduction** - transferring DNA using viruses.
- **Conjugation** - direct transfer between cells.
- **Transposition** - movement of DNA segments within or between DNA molecules.

This process allows for a rapid spread of traits such as antibiotic resistance.

Problem 6.7.3 — Multiple Choice Question

TAS1R2 is a receptor protein that helps humans and other animals taste molecules that are sweet. The TAS1R2 protein is encoded by the *TAS1R2* gene.

The structure of the *TAS1R2* gene is shown in the diagram below. In the diagram, rectangles represent exons and horizontal lines represent introns.



Which of the following *TAS1R2* gene mutations is *most* likely to affect a person's ability to taste molecules that are sweet?

(A) a two base-pair deletion at Site 1 that removes two "G-C" nucleotide pairs from the gene sequence
(B) a single base-pair substitution at Site 2 that changes a tyrosine-encoding amino acid (TAC) to a stop codon (TAA)
(C) a single base-pair substitution at Site 3 that changes one alanine-encoding codon (GCC) to another (GCA)
(D) a single base-pair insertion at Site 4 that shifts the reading frame for subsequent codons

Solution: A gene mutation is likely to affect an organism's phenotype if the mutation has a significant effect on the amino acid sequence of the encoded protein. If a single base-pair substitution changes a tyrosine-encoding codon to a stop codon, the amino acid sequence following the substitution will not be translated. If this substitution occurs toward the beginning of the gene, most of the protein's amino acid sequence will be missing. This is consistent with option **(B)**.

Problem 6.7.4 — Multiple Choice Question

The *Mc1r* gene encodes the melanocortin-1-receptor protein (MC1R). MC1R is found in pigment-producing cells and helps regulate skin and hair color in mammals.

An alignment between six amino acids of the wild type MC1R protein and a mutant form of the protein is shown in the following table.

Position	19	20	21	22	23	24
Wild type MC1R	Thr	Gly	Val	Pro	His	Leu
Mutant MC1R	Thr	Ala	Phe	Leu	Thr	Ser

The mutant form of the MC1R protein is encoded by a version of the Mc1r gene with a mutation in its coding sequence.

Based on the information in the table, which of the following best describes the mutation in the Mc1r gene?

(A) a three-nucleotide deletion of the 20th codon of the *Mc1r* gene
(B) a single base-pair substitution in the 20th codon of the *Mc1r* gene
(C) a silent mutation in the 20th codon of the *Mc1r* gene
(D) a single base-pair deletion in the 20th codon of the *Mc1r* gene

Source: Khan Academy

Solution: We can easily eliminate option (C), as a silent mutation in the 20th codon of the *Mc1r* gene would not the change the amino acid at position 20 of the protein. Between options (A), (B), and (D), the last answer is most likely the best description of the mutation; a single base-pair deletion would shift the gene's reading frame, changing the amino acids at subsequent positions. This is consistent with the information in the table, so the correct answer is in fact **(D)**.

§6.8 Biotechnology

Biotechnology is the use of living organisms, cells, and biological systems to develop products and technologies that improve human life. It is used in many fields, including medicine, agriculture, and environmental sciences. One of the most important tools in

biotechnology is genetic engineering, which allows scientists to modify an organism's DNA and change their expression of certain traits.

Genetic Engineering Genetic engineering is a process in which scientists change the DNA of an organism by adding or removing certain genes. This can be used to make plants more resistant to pests, produce more effective drugs, and study diseases. Scientists use special tools to cut and insert DNA, such as:

- **Recombinant DNA** This is DNA created by combining genetic material from different organisms. It is inserted into bacteria or other organisms to produce important substances such as insulin.

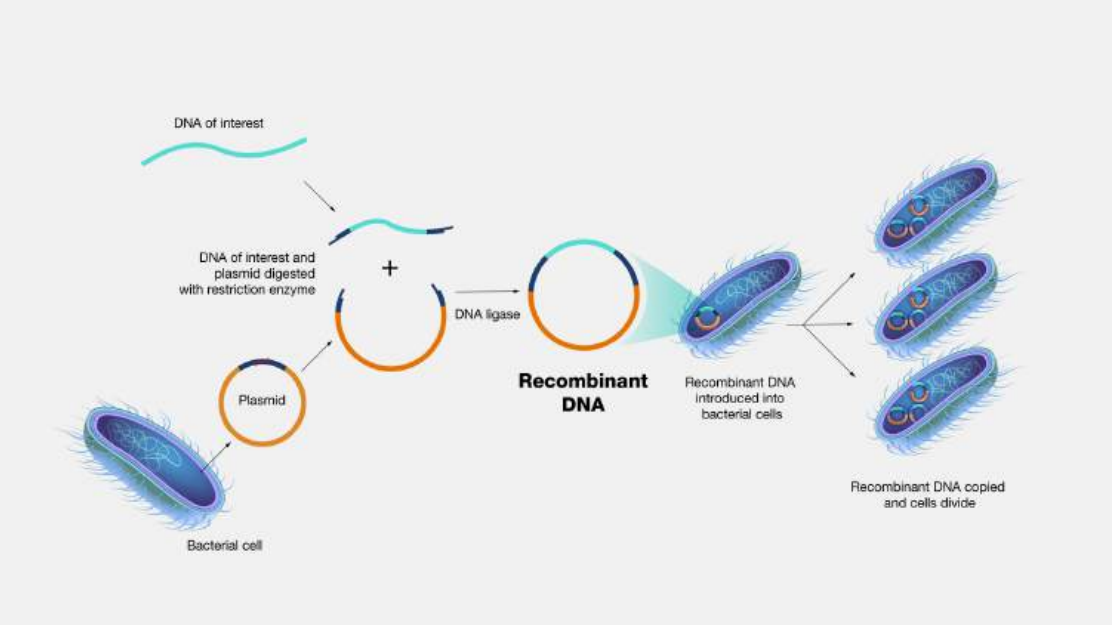


Image Credit: National Human Genome Research Institute

- **Polymerase Chain Reaction (PCR)** This technique helps scientists make millions of copies of a DNA sequence, which is useful for research and medical tests. It was also a huge part of the mapping in the Human Genome Project and helped with the diagnosis of genetic disorders.

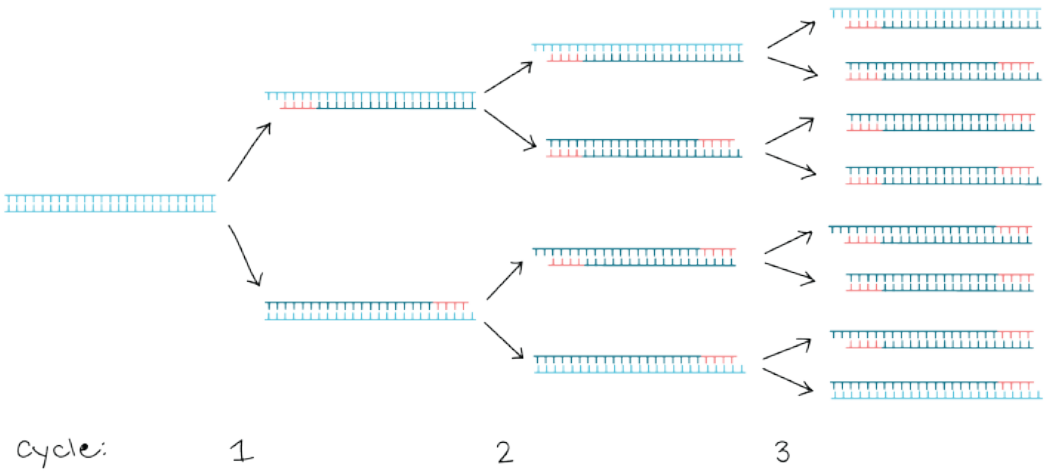


Image Credit: Khan Academy

- **Gel Electrophoresis** This technique is used to separate and analyze DNA, RNA, or proteins according to their length and charge. It is used in molecular biology, forensic science, and genetic research.

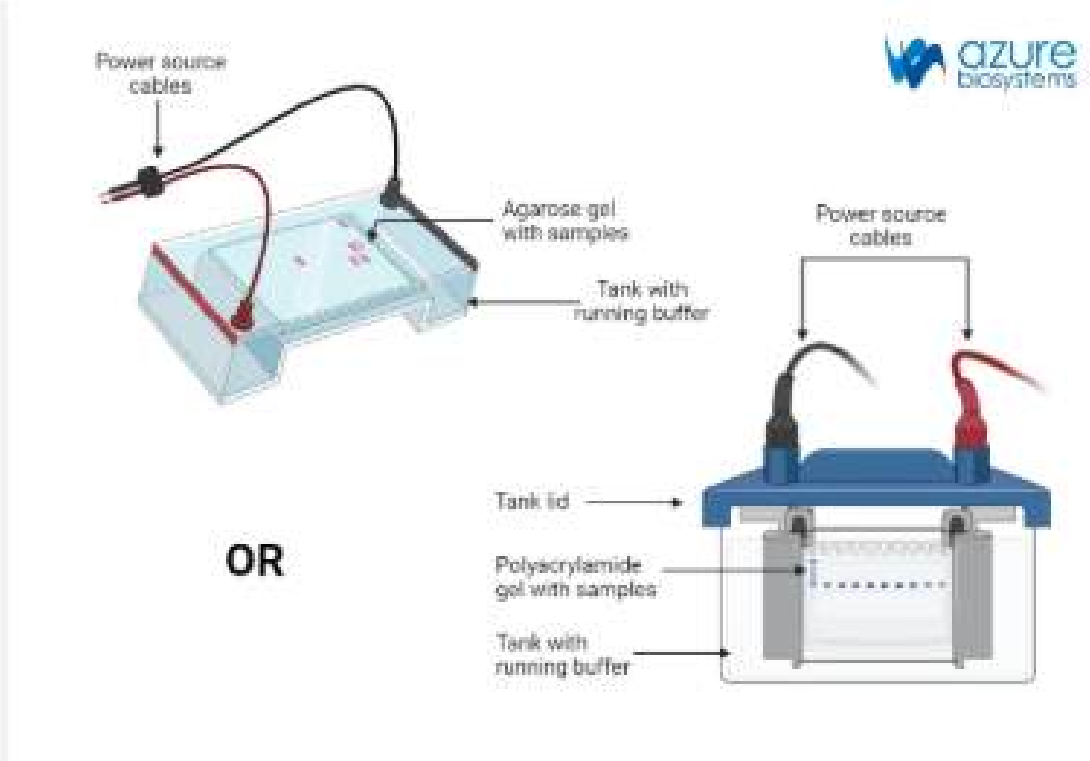


Image Credit: Azure Biosystems

- **Gene Cloning** This process is used by scientists to copy specific genes and insert them into host organisms (like bacteria) for future study and to produce proteins.

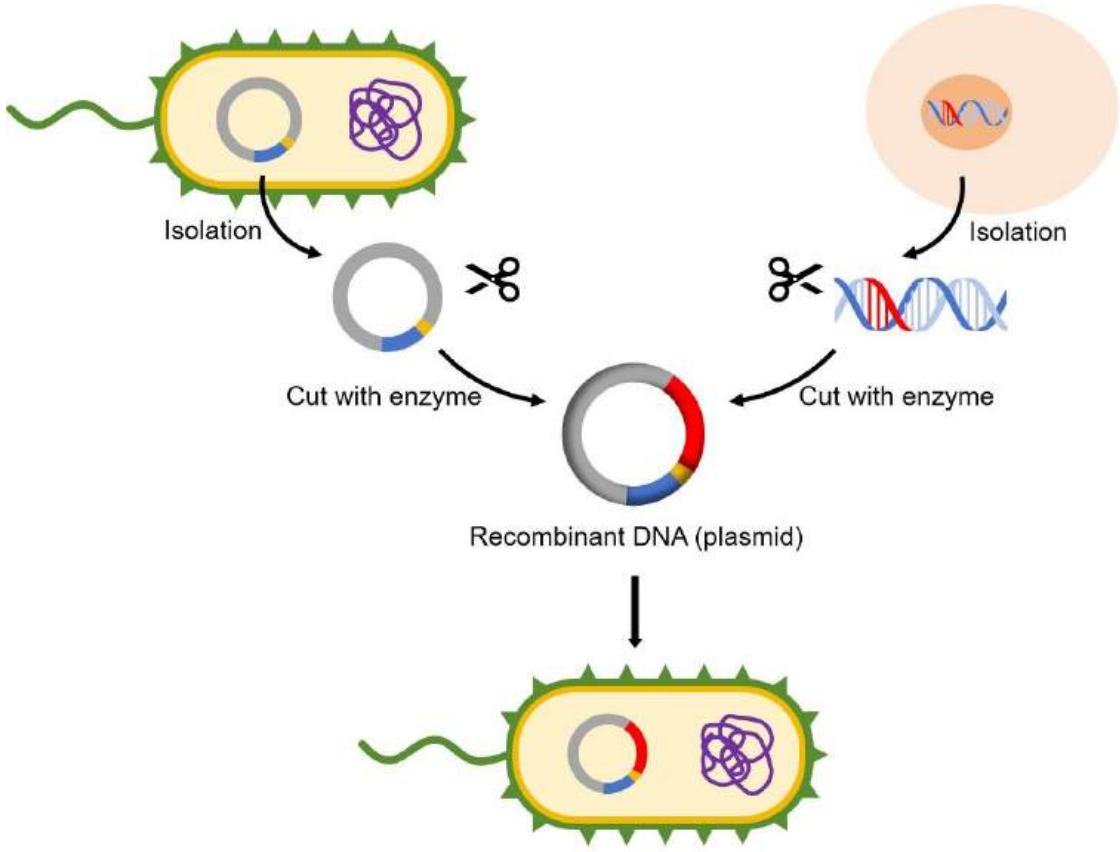


Image Credit: Creative Biolabs

Applications of Biotechnology Biotechnology has many beneficial effects in medicine, agriculture, environmental science, forensic science, and industry.

Medicine: Biotechnology is used to develop new drugs, therapies, and vaccines. Scientists use **CRISPR-Cas**9, a gene-editing technique, to modify or treat genetic disorders. Studies on how an organism's genetic makeup influences their drug response help personalize medicine. Genetically engineered plants and animals are also produced for medical purposes.

Agriculture: Genetically modified organisms (GMOs) are used to improve crop yields, resistance, and increase nutrition. Scientists modify crop genes to help plants grow faster, survive harsh conditions, and reduce the need for herbicides and pesticides. *Transgenic plants* have also been developed to provide additional nutrients.

Environmental Science: Biotechnology helps by cleaning oil spills, reducing waste, and developing renewable energy sources safely. Engineered bacteria can decompose plastic and other pollutants, and reduce environmental damage. **Biofuels** offer a renewable alternative to fossil fuels and help to reduce greenhouse gas emissions.

Forensic Science: DNA technology is used in criminal investigations to identify suspects and solve crimes. **DNA typing** allows scientists to analyze genetic material found at

crime scenes and compare it with known samples. **PCR** and **gel electrophoresis** help to process and interpret genetic evidence.

Industrial Applications: Biotechnology is used to produce biofuels, bioplastics, and industrial enzymes. These innovations help create more sustainable industrial processes by reducing the use of non-renewable sources and decreasing the environmental impact.

The Future of Biotechnology Biotechnology continues to advance with new discoveries. Scientists are exploring artificial organs, genetic disease treatments, and more. **Genomics** is being used to fight diseases and improve human health, and synthetic biology is used to design and construct new biological systems for biologically-based chemicals and new materials. As biotechnology advances, ethical concerns have also arisen. The issues include the safety of genetically modified organisms (GMOs), gene editing in humans, and privacy concerns about genetic data. Scientists and society must work together to ensure that biotechnology is used responsibly and ethically.

Problem 6.8.1 — Multiple Choice Question

A researcher wants to produce human insulin using bacteria. Which of the following correctly describes a key step in this biotechnology application?

(A) Introducing a plasmid containing the human insulin gene into bacteria
(B) Extracting insulin directly from bacterial chromosomes
(C) Injecting bacterial proteins into human cells
(D) Fusing bacterial and human cells to form hybrids

Solution: The correct answer is **(A)**. Bacterial transformation involves introducing foreign DNA (like the human insulin gene) into bacteria using plasmids as vectors, allowing bacteria to produce human proteins.

Problem 6.8.2 — Multiple Choice Question

A scientist creates a recombinant plasmid containing a gene of interest and needs to identify bacterial colonies that have successfully taken up the plasmid. Which genetic engineering approach would be most effective?

(A) Conducting Western blotting on all colonies
(B) Performing PCR on all bacterial colonies
(C) Using fluorescent in situ hybridization
(D) Including an antibiotic resistance gene in the plasmid

Solution: The correct answer is **(D)**. Including an antibiotic resistance gene in the plasmid allows for selection of transformed bacteria by growing them on media containing the antibiotic, where only cells containing the plasmid will survive.

§6.9 Unit 6 Practice Questions

Problem 6.9.1 — 2013 AP Biology FRQ

The table below shows the amino acid sequence of the carboxyl-terminal segment of a conserved polypeptide from four different but related species. Each amino acid is represented by a three-letter abbreviation, and the amino acid residues in the polypeptide chains are numbered from the amino end to the carboxyl end. Empty cells indicate no amino acids are present.

	Relative Amino Acid Position									
Species	1	2	3	4	5	6	7	8	9	10
I	Val	His	Leu	Val	Glu	Glu	His	Val	Glu	His
II	Val	His	Leu	Lys	Glu	Glu	His	Val	Glu	His
III	Val	His	Leu	Val	Glu	Glu	His	Val		
IV	Val	His	Leu	Val	Arg	Trp	Ala	Cys	Met	Asp

(a) Assuming that species I is the ancestral species of the group, **explain** the most likely genetic change that produced the polypeptide in species II and the most likely genetic change that produced the polypeptide in species III.

(b) **Predict** the effects of the mutation on the structure and function of the resulting protein in species IV. **Justify** your prediction.

Solution to part a: The polypeptide in species II was most likely produced by a point mutation or missense mutation due to a single amino acid change at position 4 (Val to Lys). On the other hand, the polypeptide produced in species III likely occurred via a mutation that introduced a stop codon after the codon for Val. This is because the polypeptide was terminated after the Val at position 8.

Solution to part b: We have three possibilities:

1. The protein may have a different structure and change in function.
2. The protein may have a different structure but no change in function.
3. The protein may have no structural or functional changes.

Let's unpack these one by one.

For the first case, a change in the amino acid sequence of the protein beginning at position 5 could alter the overall structure or individual structural regions, which could interfere with the protein's functional properties.

For the second case, a change in the amino acid sequence could alter the shape/conformation/folding/etc. region of the protein, but does not affect the separate, functional

region(s) of the protein.

For the last case, the answer is trivial. A change in the amino acid sequence could simply not interfere with any of the structural or functional regions of the protein.

Problem 6.9.2 — 2015 AP Biology FRQ

Smell perception in mammals involves the interactions of airborne odorant molecules from the environment with receptor proteins on the olfactory neurons in the nasal cavity. The binding of odorant molecules to the receptor proteins triggers action potentials in the olfactory neurons and results in transmission of information to the brain. Mammalian genomes typically have approximately 1,000 functional odorant-receptor genes, each encoding a unique odorant receptor.

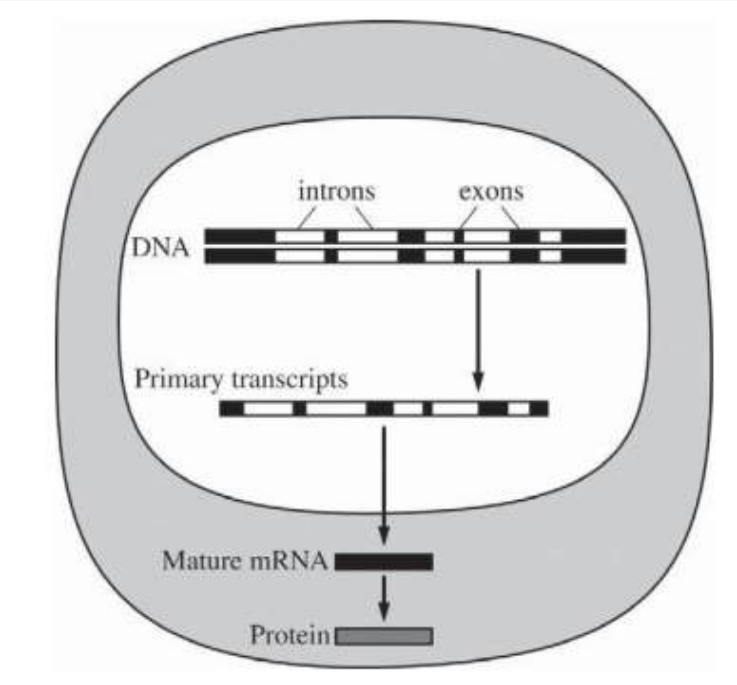
(a) **Describe** how the signal is transmitted across the synapse from an activated olfactory sensory neuron to the interneuron that transmits the information to the brain.

(b) **Explain** how the expression of a limited number of odorant receptor genes can lead to the perception of thousands of odors. Use the evidence about the number of odorant receptor genes to **support** your answer.

Solution to part a: This question tests our knowledge on cell-to-cell signaling pathways. Neurons can be thought of as cells of the central nervous system (CNS). In this case, the olfactory neuron (associated with the sense of smell) releases neurotransmitters, which bind to receptors in the postsynaptic neuron.

Solution to part b: At the molecular level, one odorant molecule can potentially be recognized by more than one odorant receptor, or an odorant receptor could bind to more odorant molecules. In mathematical terms, this makes sense, as there are more combinations for possible odors detected by the mammal. Alternatively, control of the CNS could have signals integrated within the brain, resulting in more interactions among olfactory neurons. Another alternate response would be to discuss genetic reasons, i.e. alternate splicing/processing of pre-mRNA or primary transcript, resulting in multiple odorant receptors being produced from a gene.

Problem 6.9.3 — 2016 AP Biology FRQ



The figure represents the process of expression of gene X in a eukaryotic cell.

(a) The primary transcript in the figure is 15 kilobases (kb) long, but the mature mRNA is 7 kb in length. **Describe** the modification that most likely resulted in the 8 kb difference in length of the mature mRNA molecule. **Identify** in your response the location in the cell where the change occurs.

(b) **Predict** the length of the mature gene X mRNA if the full-length gene is introduced and expressed in prokaryotic cells. **Justify** your prediction.

Solution to part a: In the process of RNA processing, the introns (represented by the white rectangles) were removed as the primary transcripts were converted into the mature mRNA. Also, we know that RNA processing takes place in the nucleus (for a eukaryotic cell).

Solution to part b: The key concept to realize here is that mRNA processing almost never takes place in prokaryotes, because these organisms posses no introns or exons. Thus, the length of the mature gene X mRNA in a prokaryotic cell should be longer than that in the eukaryotic cell. Specifically, the predicted length should be approximately equal to the length of the primary transcript in the shown figure, or $\boxed{15 \text{ kb}}$.

Problem 6.9.4 — 2017 AP Biology FRQ

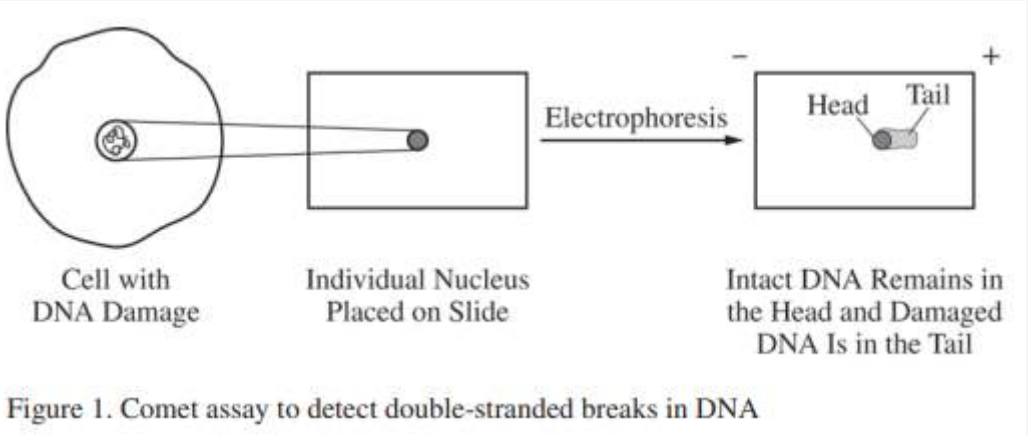


Figure 1. Comet assay to detect double-stranded breaks in DNA

A comet assay is a technique used to determine the amount of double-strand breaks in DNA (DNA damage) in cells. The nucleus of an individual cell is placed on a microscopic slide coated with an agarose gel. An electric current is applied to the gel that causes DNA to move (electrophoresis), and the DNA is stained with a fluorescent dye. When viewed using a microscope, undamaged DNA from the nucleus appears as a round shape (the head), and the fragments of damaged DNA extend out from the head (the tail). The length of the tail corresponds to the amount of the damage in the DNA (see Figure 1).

(a) To explain the movement of DNA fragments in the comet assay, **identify** one property of DNA and **provide reasoning** to support how the property contributes to the movement during comet assay technique.

(b) In a different experiment, cells are treated with a chemical mutagen that causes only nucleotide substitutions in DNA. **Predict** the likely results of a comet assay for this treatment.

Solution to part a: Since DNA can come in different sizes, and the agarose gel used in electrophoresis is porous, DNA molecules of different sizes travel across the gel at different speeds, eventually getting caught in the appropriate gel pore. Alternatively, you could state that since DNA is negatively charged, it will spontaneously migrate towards the positive side of an electrophoresis gel.

Solution to part b: A configuration of only heads (or one with no tails) will appear in a comet assay test run on cells treated with the chemical mutagen because this specific technique only detects breaks in DNA, not nucleotide substitutions.

Problem 6.9.5 — 2019 AP Biology FRQ

		STRAINS		
	MEDIUM	Wild Type	Mutant 1	Mutant 2
Treatment I	All amino acids present	+	+	+
Treatment II	No amino acids present	+	–	–
Treatment III	All amino acids present EXCEPT methionine	+	–	+
Treatment IV	All amino acids present EXCEPT leucine	+	+	–

Table 1. The data show the growth of haploid *Saccharomyces cerevisiae* yeast strains on media that differ in amino acid content. A plus sign (+) indicates that the yeast strains grow, and a minus sign (–) indicates that the strains do not grow.

The yeast *Saccharomyces cerevisiae* is a single-celled organism. Amino acid synthesis in yeast cells occurs through metabolic pathways, and enzymes in the synthesis pathways are encoded by different genes. The synthesis of a particular amino acid can be prevented by mutation of a gene encoding an enzyme in the required pathway. A researcher conducted an experiment to determine the ability of yeast to grow on media that differ in amino acid content. Yeast can grow as both haploid and diploid cells. The researcher tested two different haploid yeast strains (Mutant 1 and Mutant 2), each of which has a single recessive mutation, and a haploid wild-type strain. The resulting data are shown in Table 1.

(a) **Identify** the role of treatment I in the experiment.
(b) **Provide reasoning** to explain how Mutant 1 can grow on treatment I medium but cannot grow on treatment III medium.
(c) Yeast mate by fusing two haploid cells to make a diploid cell. In a second experiment, the researcher mates the Mutant 1 and Mutant 2 haploid strains to produce diploid cells. Using the table provided, **predict** whether the diploid cells will grow on each of the four media. Use a plus sign (+) to indicate growth and a minus sign (–) to indicate no growth.

		STRAINS			
	MEDIUM	Wild Type (haploid)	Mutant 1 (haploid)	Mutant 2 (haploid)	Diploid Cells Produced by Mating Mutant 1 and Mutant 2
Treatment I	All amino acids present	+	+	+	
Treatment II	No amino acids present	+	–	–	
Treatment III	All amino acids present EXCEPT methionine	+	–	+	
Treatment IV	All amino acids present EXCEPT leucine	+	+	–	

Solution to part a: The role of treatment I is the control, which shows the effects when all amino acids are present. Specifically, treatment I allows the researcher to be confident that any changes in experimental outcome are exclusively attributed to the different treatment types.

Solution to part b: Mutant 1 developed a single recessive mutation that prevented it from synthesizing methionine, so it couldn't survive in treatment III. It survived in treatment 1 because it contained all the amino acids. This is because mutant 1 can use methionine only when present in its medium, but it cannot actually synthesize the amino acid.

Solution to part c: If both mutant I and II survive in treatment 1, then they are both expected to survive in a diploid cell. Now, let's move onto treatment 3; mutant I cannot synthesize methionine but mutant II can, the diploid cell can still survive. Treatment 4 simply involves the opposite, so the diploid cell possesses the gene which allows its survival. In treatment 2, however, students tend to mess up because of the double negative. Actually, mutant I lacks the genetic material that mutant II possesses, and vice versa, so when mated, the result actually involves a diploid cell that allows overall growth. Therefore, there will be growth (denoted by a + sign) in all four cells of the fourth column.

Problem 6.9.6 — 2022 AP Biology FRQ

Researchers are studying the use of RNA vaccines to protect individuals against certain diseases. To develop the vaccines, particular cells are first removed from an individual. Then mRNAs coding for specific proteins from a pathogen are introduced into the cells. The altered cells are injected back into the individual, where the cells make the proteins encoded by the introduced mRNAs. The individual then produces an immune response to the proteins that will help to protect the individual from developing a disease if exposed to the pathogen in the future.

When introduced into cells, the mRNAs used for vaccines must be stable so that they are not degraded before the encoded proteins are produced. Researchers developed several modified caps that they hypothesized might make the introduced mRNAs more stable than mRNAs with the normal GTP cap. To test the effect of the modified caps, the researchers produced mRNAs that differed only in their cap structure (no cap, the normal cap, or modified caps I, II, III). They introduced the same amount of each mRNA to different groups of cells and measured the amount of time required for half of the mRNAs to degrade (mRNA half-life) and the total amount of protein translated from the mRNAs (Table 1).

TABLE 1. EFFECT OF mRNA CAP STRUCTURE ON mRNA HALF-LIFE AND PROTEIN TRANSLATED FROM THE INTRODUCED mRNA

5′ Cap Structure	mRNA Half-Life $\pm 2SE_{\bar{x}}$ (hours after introduction into cells)	Total Amount of Protein Translated from mRNA $\pm 2SE_{\bar{x}}$ (relative to amount in normal cap)
No cap	1.41 ± 0.02	0.011 ± 0.000
Normal GTP cap	16.10 ± 1.83	1.000 ± 0.007
Modified cap I	15.50 ± 1.57	4.777 ± 0.042
Modified cap II	27.00 ± 2.85	13.094 ± 0.307
Modified cap III	18.09 ± 0.81	6.570 ± 0.075

(a) Based on the data, **identify** which cap structure is most likely to protect the end of the mRNAs from degradation.

(b) Based on the data for the mRNAs with modified caps, **describe** the relationship between the mRNA half-life and the total amount of protein produced.

(c) Based on the data for the mRNA half-lives and the amount of protein produced, the researchers hypothesized that each mRNA molecule with modified cap I was translated more frequently than was each mRNA molecule with the normal GTP cap. **Evaluate** their hypothesis by comparing the data in Table 1.

(d) Introduction of mRNAs into cells allows the cells to produce foreign proteins that they might not normally produce. **Explain** why the production of a foreign protein may be more likely from the introduction of mRNA than DNA into cells.

Solution to part a: Modified cap II, because the total amount of protein and half-life

duration had the highest numbers. The total amount of protein shows that more protein had been preserved long enough to be translated.

Solution to part b: According to the data in Table 1, the longer the mRNA half-life, the more protein translated from mRNA relative to the amount in a normal cap. This indicates a positive correlation/relationship.

Solution to part c: The data support the hypothesis because the amount of protein produced from mRNA with modified cap I is significantly more (by a factor of 4, actually) than the amount of protein produced from mRNA with the normal GTP cap. However, the half-lives of the two mRNAs are the same.

Solution to part d: Foreign protein production is more likely to occur form the introduction of mRNA into cells rather than DNA because while protein production from DNA requires RNA polymerase transcription factors, mRNA can be directly translated into a protein. In other words, protein production from the mRNA does not depend on post-transcriptional pre-mRNA processing.

7 Natural Selection

Are you ready to learn the ins and outs of evolution? From how natural selection drives change to the different ways species arise and go extinct, we will take you on an exciting journey through the history of life on Earth. Learn about speciation, extinction, population genetics, common ancestry, causes of evolution, and much more.

§7.1 Introduction to Natural Selection

Natural selection is one of the main components of evolution. It can actually change the phenotypic ratios of species and/or populations using "survival of the fittest." To summarize this idea in a sentence: those that have traits that are more advantageous to their survival are more likely to survive and pass those traits onto their offspring.

Charles Darwin's Theory of Evolution This thought was first introduced by biologist **Charles Darwin** in his theory of evolution. After studying the population and evolutionary patterns of birds in South America, he came up with three major propositions:

1. Species change over time.
2. Divergent species can be traced back to a common ancestor.
3. **Natural selection** is a mechanism of evolution where organisms with traits better-suited to their environment are more likely to survive and reproduce, passing on those advantageous traits to future generations.

This variation in traits can be beneficial and help the organism survive and reproduce better than others. According to Darwin's theory of natural selection, four key conditions must be met:

1. **Variation exists**: Individuals in a population have their own unique traits.
2. **Traits are heritable**: These variations can be passed from parents to offspring
3. **Differential survival**: Some trait variations help individuals survive better
4. **Differential reproduction**: Survivors with beneficial traits have more offspring

When these conditions exist, natural selection spontaneously occurs. Organisms with traits that help them survive and reproduce in their environment will have more children, while those with less favorable traits will have fewer children or none at all. Over many generations, this leads to adaptation – the process where populations become better suited to their environment.

Darwin's Finches: A Case Study Darwin's finches of the Galapagos Islands are a textbook example of natural selection. When Darwin visited these islands, he noticed

that each island had its own unique finch species with unique beak sizes and shapes.

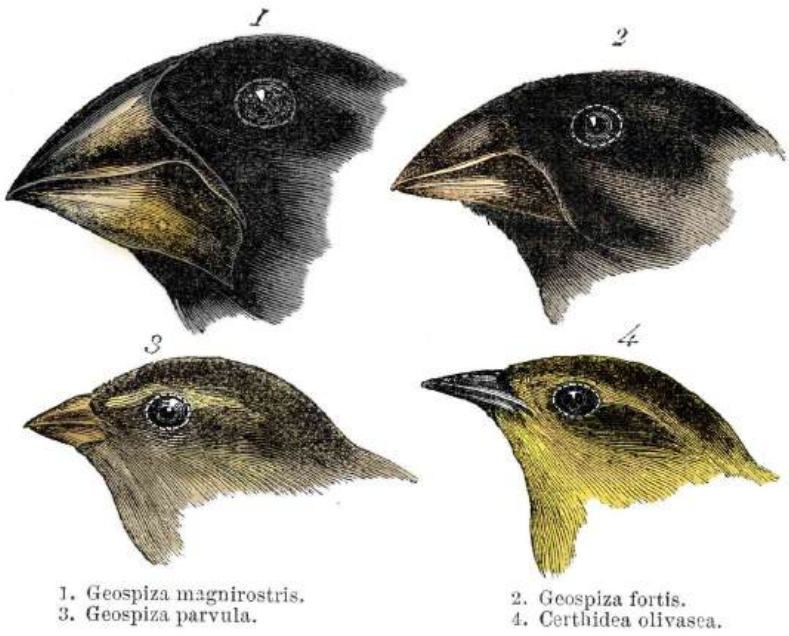


Image Credit: ThoughtCo

This example clearly shows adaptation:

- Finches on islands with hard seeds had strong, thick beaks for cracking them open.
- Finches on islands with insects had thin, pointed beaks for catching bugs.
- All these different finches likely came from a common ancestor that first arrived on the islands.

Darwin realized these differences weren't random but resulted from adaptation to different food sources on each island. Birds with beaks better suited to the local food survived better and had more babies, passing on those beneficial beak traits to future generations. Scientists still study Darwin's finches today to better understand how natural selection works at the genetic level!

Evolutionary Fitness When biologists say "fitness," they are not referring to physical health. Instead, evolutionary fitness means reproductive success−how well an organism passes its genes to the next generation. We can measure fitness via the following:

- Number of offspring an organism can produce
- The survival rate of those offspring
- The offspring's ability to reproduce relative to their parents

The fitness of an organism can be increased via the following:

- Surviving to reproductive/fertile age
- Finding mates to reproduce with
- Producing more offspring or healthier offspring

- Ensuring the survival of those offspring (parental care)

Example 7.1.1

Consider the case of animals' skin color. camouflage coloring might help prey animals avoid predators, allowing them to live long enough to reproduce. Animals without this helpful trait might get eaten before they can have babies, so their traits wouldn't be passed on. Over time, the camouflage trait would become more common in the population, as natural selection would favor it.

Environmental Factors in Natural Selection Certain traits can simultaneously help or harm an organism, depending on the environment. There are two certain factors that create pressures that shape evolutionary processes.

Biotic factors include all living aspects of an ecosystem, but are not limited to:

- Predators and prey
- Competitors
- Parasites and disease-causing bacteria
- Available food sources

Consider the predator-prey factor. Specifically, faster prey might escape predators more effectively, while predators might evolve better hunting strategies to counteract this, creating what scientists call an "evolutionary arms race."

Abiotic factors include all non-living aspects of an ecosystem, but are not limited to:

- Temperature
- Rainfall
- Soil composition
- Geographic location
- pH levels
- Light and energy availability

For example, in cold environments, animals with thicker fur have a survival advantage, but in hot environments this becomes a survival disadvantage (as it can cause overheating).

It is also important to understand that environmental stability has a big effect on the possible mechanisms of natural selection. We can summarize this concept in the table below.

Environmental Type	Effect on Selection	Example
Stable	Consistent selection for specific traits	Deep ocean environments select for specific adaptations that remain beneficial over long periods
Gradually changing	Selection shifting traits in one direction	Climate warming selecting for heat tolerance
Fluctuating	Selection for versatility and adaptability	Seasonal environments selecting for organisms that can adjust to different conditions
Suddenly changing	Strong selection pressure, possible extinction	Volcanic eruption creating new survival challenges

Image Credit: Fiveable

Types of Natural Selection Natural selection can operate in different ways, depending on which variations in traits are favored in a particular environment.

Directional selection favors individuals at one extreme of a trait. This shifts the population's average trait value in one direction.

Example 7.1.2

During food shortages, giraffes that can reach higher leaves on trees would survive better. Thus, directional selection would involve giraffe neck lengths increasing over time.

Stabilizing selection favors individuals with middle-of-the-road trait values and selects against extremes. This narrows the range of variation.

Example 7.1.3

In the case of human birth weight, babies who measure average weight are more likely to survive than babies that are too small or too large.

Disruptive selection favors individuals at both extremes of a trait but selects against middle values. This can split a population into distinct groups.

Example 7.1.4

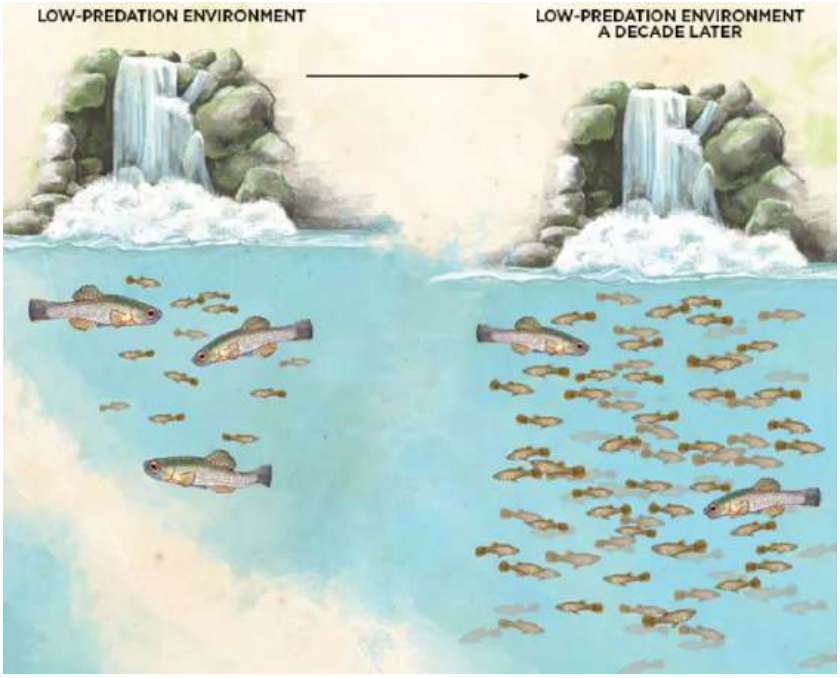
Finches with either very large beaks (for cracking large seeds) or very small beaks (for eating small seeds) surviving better than those with medium-sized beaks.

Natural Selection and Genetic Diversity Depending on the circumstances, natural selection can either increase or decrease the genetic diversity in a population.

- When strong selection eliminates unfavorable variations, leaving only individuals with specific desired traits, this *decreases* genetic diversity.
- When different environments favor different traits, preserving multiple variations, genetic diversity is overall maintained.

- When new mutations occur that prove beneficial and spread through the population, this *increases* genetic diversity.

It's important to understand how selection can affect genetic diversity so we can predict how populations may respond to environmental changes, such as fluctuations in climate or a disease outbreak.



Problem 7.1.5 — Multiple Choice Question

Which of the following scenarios would NOT lead to evolutionary change through natural selection in a population?

(A) Variation exists but provides no fitness differences
(B) Climate change alters which plant phenotypes survive drought
(C) A new predator selectively hunts individuals with bright coloration
(D) A mutation creates a novel enzyme that improves nutrient absorption

Solution: In each of options (B), (C), and (D) there is potential for natural selection to favor certain traits that will rescue the individuals from population decline. However, natural selection requires heritable variation that affects fitness. If variation exists but provides no fitness advantage or disadvantage, selection cannot act to change allele frequencies in the population. The correct answer is **(A)**.

Problem 7.1.6 — Multiple Choice Question

Which combination of factors would most effectively drive rapid natural selection in a population?

(A) Low mutation rate and gene flow
(B) Strong selection pressure and high heritability
(C) Genetic drift and founder effect
(D) Sexual selection and genetic recombination alone

Solution: Natural selection proceeds most rapidly when selection pressure is strong (creating large fitness differences) and traits have high heritability (allowing adaptive traits to be reliably passed to offspring). This is consistent with option **(B)**.

§7.2 Natural Selection

Importance of phenotypic variation in a population Imagine a herd of zebras that are all genetically similar, meaning that the genome of each individual zebra is a copy of its parent. What would happen if a deadly disease were introduced that targets the genome of the zebra herd? The population is toast!

To prevent a disaster like this, populations of different species have some degree of genetic variation among them, usually due to genetic recombination or random mutations.

The Environment's Role The environment has a significant influence on the phenotypic variation of a population by forcing the population to change or go extinct. Take the zebra herd for example; if the herd doesn't change, it will likely go extinct. But if a member of the herd was resistant to the disease, they could produce offspring that are also resistant to the disease. Once these offspring grow and mature, they will also reproduce, thereby contributing the disease resistance to the herd's gene pool.

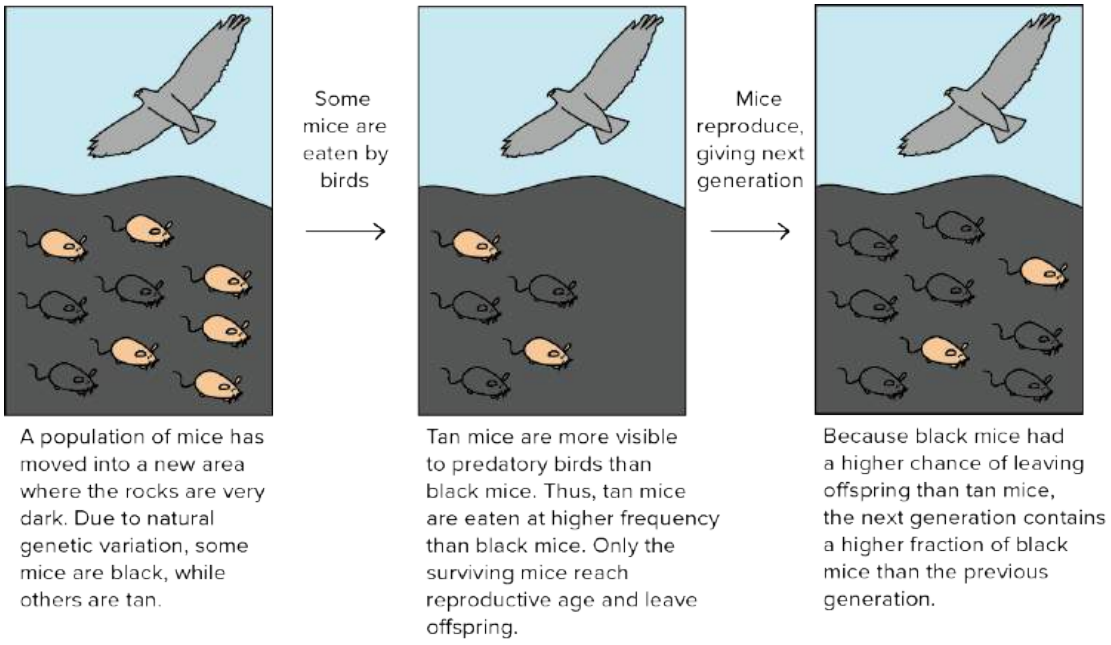


Image Credit: Khan Academy

Natural selection acts on the phenotypic variation in a population, which means that it affects the physical characteristics of a population. Specifically, natural selection affects the physical characteristics that help an organism survive and reproduce, such as the size of wings in birds or the color of the fur in mice. Because certain traits, such as larger wings or resistance to pesticides, allow for the organisms that possess them to live longer and be more successful in reproducing, these traits eventually become the most common trait. This brings us to our next concept: relative fitness.

Relative Fitness An organism's **relative fitness** is defined as how significant its contribution to the next generation's gene pool is. For example, an eagle with unusually sharp eyesight has a more positive contribution to the next generation's gene pool when compared with an eagle with below-average eyesight. As a result, organisms with lower relative fitness can struggle with finding a mate to reproduce with, often resulting in few offspring and minimal contributions to the next generation's gene pool.

Problem 7.2.1 — Multiple Choice Question

In a population of moths living in an industrial area with increasing pollution, which statement best explains the importance of phenotypic variation in wing coloration?

(A) It provides raw material for natural selection to act upon
(B) It allows individual moths to change color during their lifetime
(C) It ensures all moths will adapt simultaneously to pollution
(D) It guarantees beneficial mutations will occur when needed

Solution: Phenotypic variation provides the diversity upon which natural selection acts, allowing some variants (darker moths) to survive at higher rates in polluted envi-

ronments, while not guaranteeing any specific outcome. Thus, the correct answer is **(A)**.

Problem 7.2.2 — Multiple Choice Question

A researcher observes that a wildflower species is flowering 7-10 days earlier than it did 50 years ago in a region experiencing warming temperatures. Which mechanism best explains this shift in flowering time?

(A) Stabilizing selection maintaining flowering time consistency
(B) Phenotypic plasticity without genetic change
(C) Directional selection favoring early-flowering genotypes
(D) Genetic drift randomly altering flowering time alleles

Solution: Climate change creates selective pressure favoring individuals that flower earlier, resulting in directional selection that shifts the population's genetic composition toward earlier flowering times over generations. Thus, the correct answer is **(C)**.

§7.3 Artificial Selection

Artificial selection, or selective breeding, is when we, humans, strategically limit breeding between plants or animals so that we are left with offspring with phenotypic traits that we deem favorable. Artificial selection is often used by breeders that seek to make a profit from selling offspring, such as dog breeders and cow farmers.

Although it benefits those who monetize favorable offspring, artificial selection is detrimental to populations because it eliminates any chance that the population has any genetic diversity. As we saw with the genetically identical zebra herd back in section 7.2, any population that lacks genetic diversity is constantly in danger of extinction.

Example 7.3.1

In some cases, humans introduce new genes that result in favorable traits in a population. A prime example of human introduction of genes into a population are disease-resistant crops, such as corn and cabbage.

Artificial selection has been around for a long time, way before people understood what genetics actually was. Early farmers and animal breeders observed that offspring resembled their parents, and they used this knowledge to gradually shape the traits of domesticated species. Through artificial selection, humans have significantly affected variation in other species.

Artificial Selection and Genetic Diversity Humans can drastically affect the genetic diversity of other species via **selective breeding**. Some examples of increasing certain traits include, but are not limited to:

- Selecting for milk production in dairy farm cows
- Breeding dogs for specific behaviors or physical features (e.g. service dogs, training dogs, etc.)

- Developing sweeter, larger fruits in crop plants (e.g. festivals)
- Creating ornamental flowers with novel colors or shapes

Additionally, artificial selection can change genetic variation in ways including, but not limited to:

- Trying to mass produce certain traits can significantly lower genetic variation in a population.
- Creating genetic bottlenecks where only a small subset of genes continue in the population.
- Introducing specific traits from one population into another.
- Maintaining variations that might disappear in natural conditions

Distinguishing Artificial Selection from Natural Selection Artificial selection and natural selection are similar in the fact that they both change the genetic makeup of species' populations, but they differ in two primary ways:

1. **Selection pressure**. Environmental factors drive natural selection, while human preferences and intervention drive artificial selection.
2. **Direction**. Natural selection favors traits that enhance survival and reproduction in natural environments, while artificial selection favors traits humans find useful or appealing.

Just know that despite these differences, both artificial and natural selection operate on the same principle. That is, individuals with certain traits are more reproductively fit, and more likely to pass those traits to future generations and change the population's overall genetic makeup.

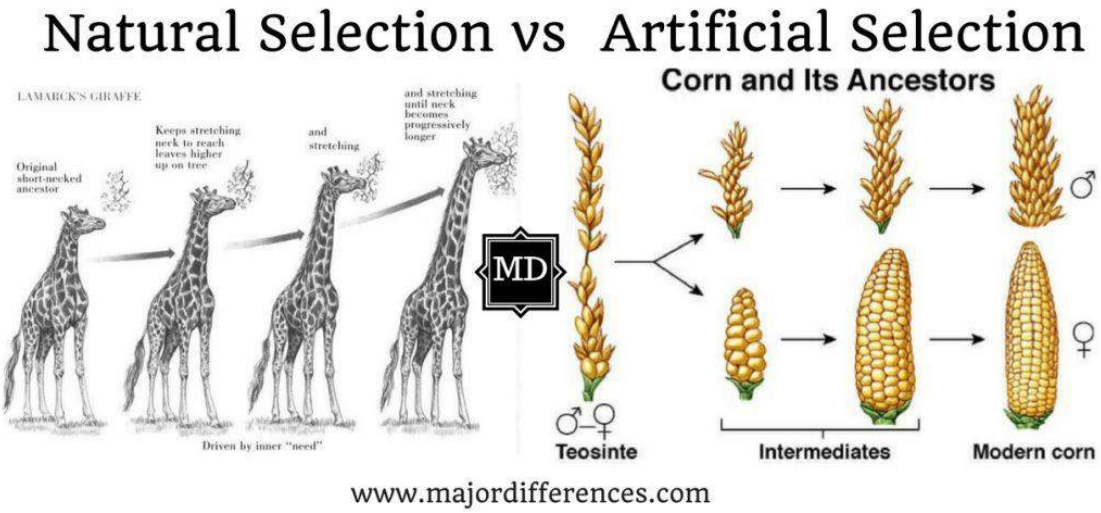


Image Credit: majordifferences.com

Convergent Evolution and Adaptions in Response to Pressures We define **convergent evolution** as a process taking place when similar selective pressures result in similar phenotypic adaptions in unique species and/or populations. Essentially, this happens when unrelated or distantly-related organisms face similar challenges in their environment, leading them to develop similar solutions independently.

§7.4 Population Genetics

Evolution occurs as a result of both random (mutations) and nonrandom events. Natural selection is the process by which organisms with better-suited traits survive and reproduce, passing on those traits to future generations. This chapter will review some of the processes that cause populations to evolve and some of the equations that are used to describe changes in populations.

Genetic Drift Genetic drift is the random loss of alleles in a population. It's more significant in smaller populations because it can have a larger impact on the gene pool than larger and more stable populations. If an allele is found in 10 percent of a $1,000$-member population, 100 of those individuals would have that allele. It would be likely that at least one of those individuals would survive and reproduce to pass on that allele. However, if there were only 10 members of that population, then if that one member failed to reproduce, the allele would be lost.

Gene flow, the transfer of alleles from one population to another, can contribute to genetic drift. Gene flow introduces new alleles to populations and increases genetic diversity. Gene flow and genetic drift both affect the genetic makeup of the population and directly affect the evolution of a species. While natural selection acts on existing traits, the other two mechanisms directly influence genetic variation. Understanding these processes helps explain how species evolve over time and how populations are connected.

Bottleneck Effect One cause of genetic drift is the bottleneck effect. A bottleneck occurs when the size of a population is greatly reduced. Natural disasters and human-made events are usually the causes for bottlenecks. Because a population becomes smaller, it is less likely to contain all the alleles from the previous population, and it will have less genetic diversity.

Example 7.4.1

In the 1800s, the northern elephant seal population experienced a population bottleneck. Hunting had reduced the population to fewer than 30 seals. Protection from several countries helped the population rebound to over $100,000$ individuals, but they are not as diverse as the southern elephant seals, which were not hunted.

Founder Effect Another cause of genetic drift is the founder effect, which occurs when a small group of individuals separates from a larger population to form a new community. Because this group has less genetic diversity, the new population ends up with less variation in its gene pool. Over time, certain traits become more common by chance, rather than any advantages. The founder effect is especially seen in isolated communities, where genetic traits become more frequent due to the limited gene pool.

Natural Selection in Populations Genetic drift and gene flow are important factors in speciation, a process by which new species are formed. When populations become separated and can no longer interbreed, they begin evolving independently. Over time, their genetic differences can become so large that even if they were to come together, they would not be able to have offspring that can survive and reproduce. When they reach this point, they are considered separate species.

As organisms adapt to their environment, they develop unique traits that help them survive. Speciation can occur gradually over long periods or occur quickly from sudden environmental changes. Other factors, such as competition for resources or the ability to adapt to different habitats, also influence how new species form. Natural selection shapes these populations by favoring traits that help them survive, which leads to more differences between them over time.

Problem 7.4.2 — Multiple Choice Question

A researcher studying mutation rates in bacteria observes that after exposure to UV radiation, the population shows increased genetic diversity. Which of the following represents the most likely evolutionary consequence of this observation?

(A) Directed evolution toward resistance against UV radiation regardless of other selective pressures
(B) Immediate speciation due to accumulated genetic differences
(C) Accelerated adaptive potential if some mutations confer fitness advantages in the current environment
(D) Guaranteed extinction as most mutations are deleterious

Solution: While mutations are random and many may be neutral or harmful, increased genetic diversity provides more variation for selection to act upon, potentially accelerating adaptation if some mutations happen to be beneficial in the current environment. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

Problem 7.4.3 — Multiple Choice Question

A scientist is studying the molecular structure of nucleotides and notes that purines have a double ring structure. Which of the following experimental observations would support this structural characteristic?

(A) Pyrimidines have higher molecular weights than purines
(B) Adenine and guanine absorb UV light at different wavelengths than cytosine, thymine, and uracil
(C) Adenine and thymine form three hydrogen bonds when paired
(D) All nucleotides show identical migration patterns in gel electrophoresis

Solution: The double ring structure of purines (A and G) causes them to absorb UV light at different wavelengths compared to the single-ring pyrimidines (C, T, and U), which would be observable in spectroscopic analysis. Thus, the correct answer is $\boxed{\textbf{(B)}}$.

§7.5 Hardy-Weinberg Equilibrium

Hardy-Weinberg equilibrium states that the genetic variation of a population will remain constant in the absence of external pressure. In other words, a population will not change

unless forced to do so by external forces, which can be natural or man-made.

Conditions for Hardy-Weinberg Equilibrium In order for Hardy-Weinberg equilibrium to occur, there are 5 important conditions:

1. **Large Population Size**: A larger population is less susceptible to changes in allele frequencies due to genetic drift because small changes in the population gene pool will not have a significant effect on the entire population. On the other hand, a smaller population is more susceptible to changes in allele frequencies due to genetic drift. Therefore, a larger population size is required to stay in Hardy-Weinberg equilibrium.

2. **Absence of Migration**: Individuals entering a population can introduce new alleles, resulting in a disruption to equilibrium. Similarly, individuals exiting a population can cause the population to become more susceptible to changes in allele frequency.

3. **No Net Mutations**: Mutations cause allele frequencies to change by introducing new alleles that quickly become superior to the preexisting alleles. Since the allele frequency does not remain constant, mutations cannot occur for a population in Hardy-Weinberg equilibrium.

4. **Random Mating**: A population that is in Hardy-Weinberg equilibrium has organisms that mate with each other without having preferences for specific genotypes. If some organisms mated with preferences, then certain organisms' would be more likely to be passed down due to the frequency with which they mate.

5. **No Natural Selection**: A population in Hardy-Weinberg equilibrium cannot be affected by natural selection between generations because natural selection will result in certain alleles being advantageous, rather than each allele having equal fitness. Eventually, alleles that are deemed superior will outnumber most other alleles, causing allele frequencies to change.

A population in true Hardy-Weinberg equilibrium is extremely rare simply due to the fact that the conditions for Hardy-Weinberg equilibrium describe a population that can survive without adapting to its environment.

Allele Frequency and Gene Pool The Hardy-Weinberg equation is a model used by scientists to determine if a population is evolving by producing expected values for allele frequencies. If the real-world allele frequencies differ from the calculated allele frequencies, then it is possible that the population is evolving. There are two different equations used for Hardy-Weinberg equilibrium: one for allele frequencies and one for genotype frequencies.

Hardy-Weinberg Equilibrium Equations The first equation reads:

$$p + q = 1$$

where:

- p is the frequency of allele A
- q is the frequency of allele B

This first equation is pretty simple to use: first, calculate the allele frequency for both allele A and B by dividing the number of allele A's by the total number of alleles, and then do the same for allele B. After you get a decimal answer for the allele frequencies of allele A and allele B, check to make sure that the sum of these decimals is 1. If not, then the population is not in Hardy-Weinberg equilibrium.

The second equation reads:

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

where:

- p^2 is the dominant homozygous allele frequency (AA)
- $2pq$ is the heterozygous allele frequency (Aa)
- q^2 is the recessive homozygous allele frequency (aa)

Note 7.5.1

Notice that $p^2 + 2pq + q^2$ is equal to the quantity $(p+q)^2$, so setting this equal to 1, we find that $p + q = \sqrt{1} = 1$, which is the first Hardy-Weinberg equilibrium equation!

Keeping all that in mind, the first thing to do in the process of calculating is to determine the frequency of the recessive genotype. This is the only genotype that can be determined from the phenotypic ratios (a dominant phenotype could be either homozygous dominant or heterozygous).

Problem 7.5.2 — Short Answer Question

A rare genetic disorder is caused by a recessive allele, "a", in a population. The frequency of the allele in the population is 0.02. Using the Hardy-Weinberg equilibrium, calculate the frequency of the dominant allele, "A", and the frequency of individuals who are homozygous recessive (aa) and heterozygous (Aa) for the disorder. Explain how you arrived at your calculations and what assumptions of the Hardy-Weinberg equilibrium are being made in this scenario.

Solution: To solve this problem, we first assign the frequency of the recessive allele, "a", as q and the frequency of the dominant allele, "A", as p. Since "A" and "a" are codominant, the sum of p and q is equal to 1. We will use the equation

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

We already know that $q = 0.02$, so using the first equation, $p = 1 - q = 1 - 0.02 = 0.98$. Thus, the frequency of individuals who are homozygous recessive is $q^2 = 0.02^2 = 0.0004$, or $\boxed{0.04\%}$. Similarly, we can find the frequency of individuals who are heterozygous is $2pq = 2\,(0.98)\,(0.02) = 0.0392$, or $\boxed{3.92\%}$.

Note 7.5.3

For this problem (and all other Hardy-Weinberg problems for that matter), we are assuming that all the conditions for equilibrium are met. Keep in mind that this model is theoretical, and real world populations almost never meet this criteria.

Problem 7.5.4 — Multiple Choice Question

A population of beetles shows allele frequencies that remain constant over several generations. A researcher wants to determine if this population is in Hardy-Weinberg equilibrium. Which of the following observations would most strongly suggest that the population is NOT in Hardy-Weinberg equilibrium?

(A) The population contains thousands of individuals
(B) Female beetles preferentially mate with larger males
(C) The population is geographically isolated
(D) Genotype frequencies match predicted H-W proportions

Solution: Non-random mating (female preference for larger males) violates one of the five conditions required for Hardy-Weinberg equilibrium, while the other options either support H-W equilibrium or don't necessarily violate its conditions. Thus, the correct answer is $\boxed{\textbf{(B)}}$.

§7.6 Evidence of Evolution

Scientists have compiled many forms of data across multiple disciplines to support evidence, which is technically a theory. Here are a few examples of data presented by the science community:

Morphological Evidence When analyzing morphological data, we will most likely encounter either **vestigial structures** or **homologous structures**, both of which will likely be tested on the AP exam.

Vestigial Structures Vestigial structures are characteristics that do not seem to serve an important function anymore. While they may have been crucial to the survival of ancestors, present-day organisms with vestigial structures likely do not require them to survive and reproduce.

Example 7.6.1

An example of a vestigial structure is wisdom teeth in human, which are so unimportant that most people have them removed. But during the time period of our ancestors, wisdom teeth were important because they helped grind vegetables, which was a crucial skill for our plant-loving ancestors.

Another example of a vestigial is pelvic bones in snakes because snakes no longer need support for their lower limbs, which they no longer have. Early snakes had legs, so it makes sense that modern-day snakes have pelvic bones as leftovers from their ancestors.

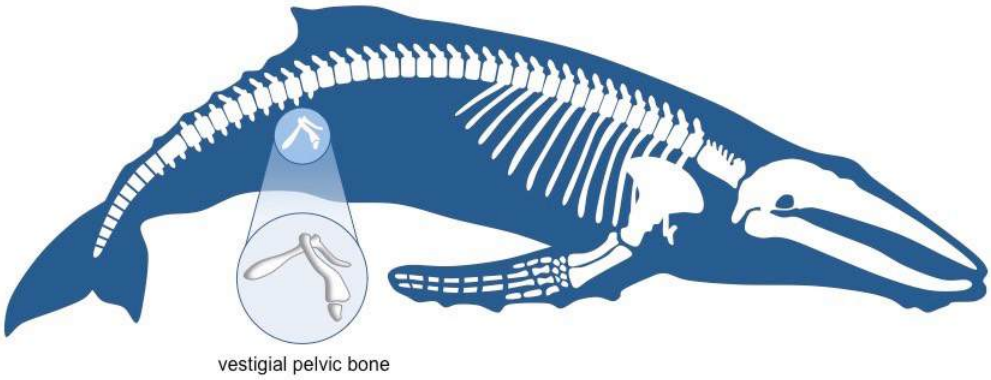


Image Credit: BioNinja

Homologous Structures Homologous structures are characteristics that are shared between different organisms, often serving different functions. The presence of a homologous structure indicates that the organisms that share said homologous structure have a common ancestor *and* have experience divergent evolution, resulting in multiple species.

Example 7.6.2

An example of a homologous structure is a bat's wing because it has a very similar structure to a human's arm and a whale's flipper, but serves a completely different function than a human's arm or a whale's flipper.

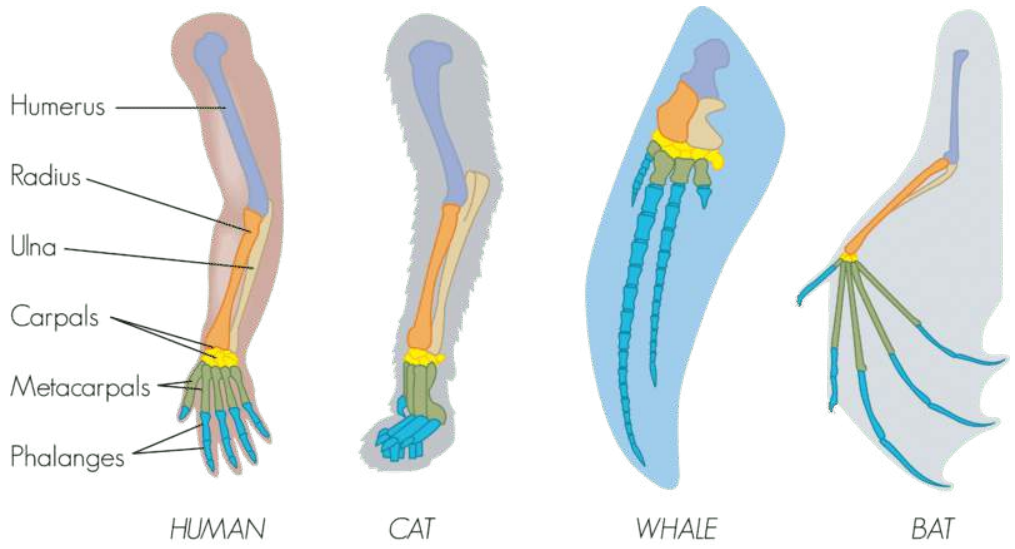


Image Credit: Sanibel Sea School

Molecular Evidence Scientists can also use evidence on the molecular level, such as DNA and protein sequences, to support the theory of evolution.

- DNA Evidence: We can determine how similar different organisms are by comparing their DNA sequences. Comparing DNA sequences helps us establish how genetically similar two organisms are, which can suggest a common ancestor if the similarity percent is high enough.
- Protein Evidence: Similarly to the comparison of DNA sequences, a high similarity between the protein sequences of two organisms may suggest a common ancestor.

Geographical Evidence There are several forms of geographical evidence used by scientists, but here are the forms covered by AP Biology:

- Fossils: Fossils are a great way to model the progression of adaptations in species, often resulting in discoveries of adaptive structures. Additionally, fossils can help to understand when organisms experienced major changes in physical form, such as when vertebrates migrated from water to land. Fossils can also be used to better understand the environment of ancient lifeforms, in turn allowing for scientists to determine possible environmental pressures of the past
- Radiometric Dating: When atoms are unstable, they break down until they reach a stable form. Scientists can use the half-life, or how long it takes for half of a substance sample to decay to 50% of its original amount, to determine exactly how old a fossil is. The isotope Carbon-14 is the most commonly used isotope for half-life investigations because Carbon-14 is found naturally in all living organisms.

Evidence of Common Ancestry There are certain fundamental features shared across all domains of life which support the theory of common ancestry, the most common being the universal genetic code.

Universal Genetic Code The universal genetic code is a sequence of amino acids that is used by all living organisms to turn DNA or RNA into protein. Since it's shared by all living organisms, the universal genetic code is a very strong piece of evidence that supports **the theory of common ancestry**.

Definition 7.6.3

The theory of common ancestry, proposed by Charles Darwin, states that all living organisms on Earth, from bacteria to humans, share a common ancestor. The quirks of each species rose from evolutionary changes over time, which were advantageous characteristic most of the time.

Problem 7.6.4 — Multiple Choice Question

A researcher is analyzing bone fragments from an ancient human settlement and wants to determine their age. The fragments contain 25% of the original carbon-14. Approximately how old are these bone fragments?

(A) $22,920$ years
(B) $17,190$ years
(C) $5,730$ years
(D) $11,460$ years

The carbon-14 isotope has a half-life of $5,730$ years. If there is 25% remaining, then the sample has undergone exactly two half lives ($100\% \to 50\% \to 25\%$), making it $5,730 \cdot 2 = 11,460$ years old. Thus, the correct answer is $\boxed{\textbf{(D)}}$.

Problem 7.6.5 — Multiple Choice Question

A researcher discovers fossils of whale ancestors showing a gradual reduction in hindlimb size over time. This morphological change is best explained by which evolutionary mechanism?

(A) Genetic drift randomly eliminating hindlimb genes
(B) Horizontal gene transfer from marine organisms
(C) Natural selection against fully functional hindlimbs in aquatic environments
(D) Convergent evolution with fish species

Solution: The fossil record showing gradual reduction in hindlimb size represents morphological evidence of natural selection favoring reduced hindlimbs as whales adapted to aquatic environments. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

§7.7 Common Ancestry

Evolution is, quite literally, about family trees. The concept of common ancestry is what tells us that all living things share a great-great-great-... grandparent from billions of years ago. This idea can explain the presence of similar traits and genetic patterns in nature. Evolutionary scientists and ecologists use DNA, body structures, and fossils as evidence of these family connections. By studying them, we can figure out the relative closeness of different species and how they have evolved over time.

Connecting Common Ancestry to Evolution

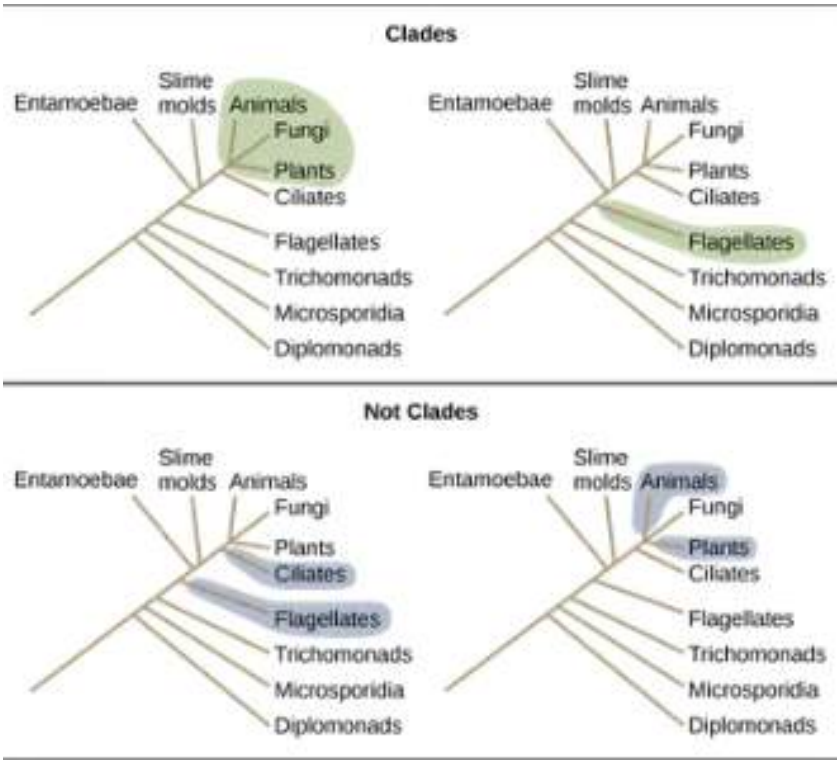


Image Credit: *OpenStax Biology*, 2e

Generally, when we connect common ancestry to evolution, we can understand the very significance of this concept as:

- Common ancestry proposes that all living organisms on Earth descended from a **single** ancestral species that lived billions of years ago.
- The **last universal common ancestor (LUCA)** is the hypothetical most recent common ancestor of all current life on Earth, likely existing around 3.5 to 3.8 billion years ago.
- Common ancestry explains similarities among species through inheritance of traits from shared ancestors.
  - Intuitively enough, closely related species share a more recent common ancestor than distantly related species.
- Common ancestry is a key component of **evolutionary theory**, providing a mechanism for explaining life's diversity through descent with modification.

- Common ancestry predicts a **nested hierarchy** of similarities and differences among species.
  - More closely related species share more traits than distantly related species.
  - This pattern of nested similarities strongly supports common ancestry.

  The principle of **parsimony** (Occam's razor) supports common ancestry as the simplest explanation for observed patterns of shared characteristics among living organisms.
  - Separate ancestry would require many more assumptions and events.

When making predictions and providing evidence, we use the following:

- Common ancestry predicts a **hierarchical pattern** of similarities and differences among species.
  - More closely related species should share more traits than distantly related species (nested hierarchy).
  - This prediction is strongly supported by evidence from comparative anatomy, embryology, and molecular biology.
- The universality of the genetic code, with minor variations, suggests descent from a common ancestor that used the same genetic code.
  - Independent evolution of the same genetic code in separate lineages is highly unlikely.
- **Homologous structures**, which are similar in structure and evolutionary origin but not necessarily function, support common ancestry.
  - Examples: forelimbs of mammals, birds, and reptiles have the same basic bone structure but have been modified for different functions (wings, arms, flippers).
- **Vestigial structures**, which are reduced or nonfunctional structures that were functional in ancestral species, provide evidence of common ancestry.
  - Examples: pelvic bones of whales, appendix in humans.
  - Suggests structures were inherited from a common ancestor and lost function over time due to changes in selection pressures.

Reading Phylogenetic Trees Phylogenetic trees (a.k.a. evolutionary trees, cladograms) are branching diagrams depicting hypotheses about evolutionary relationships (phylogeny) among taxa.

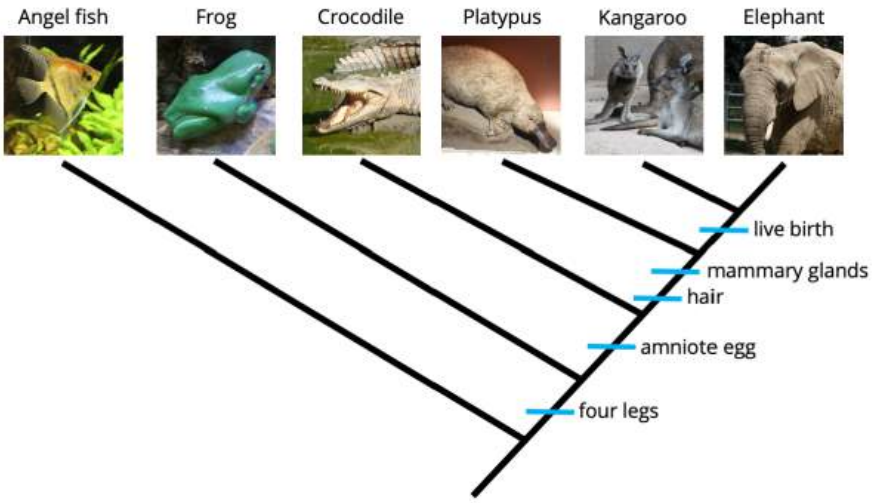


Image Credit: Digital Atlas of Ancient Life

When reading a phylogenetic tree, each branch represents two lineages **diverging** from a common ancestor. The unique branching pattern reflects the order in which lineages diverged from each other. When adjacent branches are connected to the same source node, we define these lineages—sharing a more recent common ancestor with each other than any other lineage on the tree—as **sister taxa**.

Monophyletic (clades), **paraphyletic**, and **polyphyletic** groups can be identified based on evolutionary relationships and most recent common ancestor.

- For the monophyletic group, we have ancestral species and all its descendants, including the most recent common ancestor and all descending taxa.
- For the paraphyletic group, we have ancestral species and some, but not all, of its descendants; does not include all taxa descending from the most recent common ancestor.
- For the polyphyletic group, we have taxa that do not share a most recent common ancestor; the most recent common ancestor is placed outside the group.

However, like all models, phylogenetic trees have their limitations and subsequent consequences.

- Firstly, the arrangement of branches on a phylogenetic tree does not necessarily indicate the degree of evolutionary change or phenotypic similarity among taxa. As a result, the branch lengths and the order of branch points are significant.
- Phylogenetic trees represent hypotheses about evolutionary relationships based on available (current*) evidence. Therefore, new evidence or alternative interpretations can lead to revisions of phylogenetic hypotheses.
- Different types of evidence (morphological, molecular) can sometimes yield conflicting phylogenetic trees, which can cause confusion. As a result, resolving conflicts requires careful evaluation of the evidence and consideration of potential sources of error or bias.

Evidence for Common Ancestry There are usually three forms of evidence we can rely on to make a conclusion about common ancestry for various species. These are: **molecular**, **morphological**, and **fossil** evidence.

1. Molecular evidence involves similarities in **DNA sequences** which can provide strong evidence of common ancestry. In this case, the degree of similarity reflects the degree of species relatedness, where closely related species have more similar DNA sequences than distantly related species (intuitively!)

   Dog Sequence: ACTGAGTAGGAGATC

   Sequence 1: ACTGAGTACCAGATC

   Sequence 2: ACATAGTACCAGATC

   Sequence 3: ACATATTACCAGATC

   Sequence 4: ACATAGTACGAGATC

   Sequence 5: ACATATTACCAGTAG

   The universality of the genetic code, with minor variations, suggests descent from a common ancestor that used the same genetic code. In other words, independent evolution of the same genetic code in separate lineages is highly unlikely.

2. Morphological evidence involves homologous and vestigial evidence, and **synapomorphies** (presence of shared derived characteristics). Related organisms typically exhibit similarities in basic structures, regardless of the different evolutionary pressures they have experienced over time. Such common structures are referred to as homologous. Homologous structures are derived from a common ancestor and share a similar anatomy, although they may serve different functions in different species. Meanwhile, when a species displays functionless or highly reduced organs inherited from a common ancestor. These are known as vestigial structures. Vestigial structures are crucial in understanding evolution, as they provide insights into an organism's relatedness to a common ancestor and its adaptation to the current environment over time.

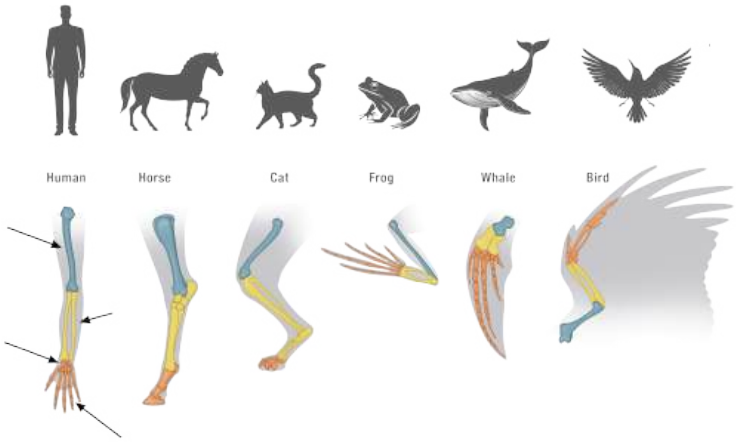


Image Credit: Monash University

3. Finally, the fossil record provides evidence of extinct species that share similarities with living species, suggesting common ancestry. **Transitional** fossils support the idea of descent with modification from a common ancestor by demonstrating intermediate stages between ancestral and descendant species. Moreover, the temporal sequence of fossils in the geological record is consistent with the predicted order of divergence based on common ancestry. In simpler terms, older fossils represent ancestral forms, while younger fossils represent more derived forms.

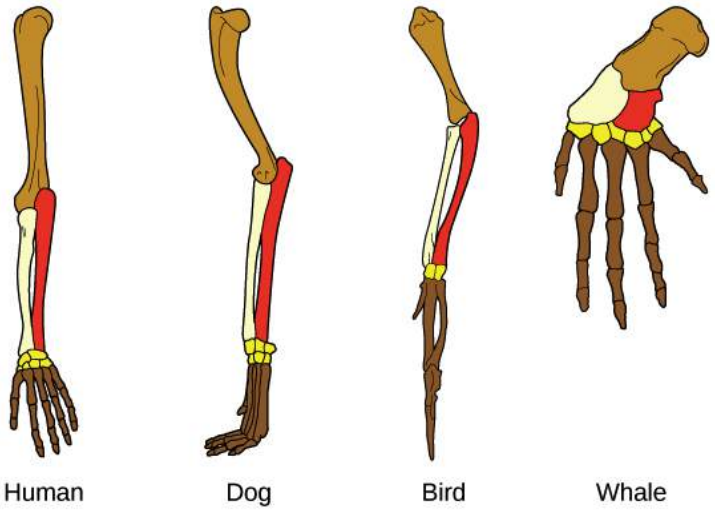


Image Credit: Khan Academy

Problem 7.7.1 — Multiple Choice Question

A student is comparing electron micrographs of cells from fungi, plants, and animals. Which structural feature would most reliably indicate their shared evolutionary history?

(A) Conserved core structure of the nuclear envelope
(B) Identical Golgi apparatus morphology
(C) Similar overall cell size and shape
(D) Identical number of mitochondria per cell

Solution: The nuclear envelope's core structure (double membrane with nuclear pores) is highly conserved across all eukaryotic lineages, providing strong evidence of common ancestry despite adaptations in other cellular features. Thus, the correct answer is $\boxed{\textbf{(A)}}$.

Problem 7.7.2 — Multiple Choice Question

A genomic analysis reveals that a particular gene in protists, fungi, plants, and animals contains introns, while the homologous gene in bacteria lacks introns. Based on this evidence and current evolutionary theory, which statement is most accurate?

(A) Eukaryotes independently evolved introns after diverging from bacteria
(B) Introns originated in each eukaryotic lineage through viral integration
(C) Bacteria lost their introns due to selection for genome streamlining
(D) The last eukaryotic common ancestor likely possessed intron-containing genes

Solution: The widespread presence of introns across diverse eukaryotic lineages but their absence in bacteria suggests that they were present in the last eukaryotic common ancestor, rather than being independently across each lineage. Thus, the correct answer is $\boxed{\textbf{(D)}}$.

§7.8 Continuing Evolution

Over time, organisms continue to evolve in order to adapt to the ever-changing world around them. If an organism fails to adapt to a significant change in its environment, the results on future generations can be devastating.

Note 7.8.1

An analogy that might be helpful is buying trendy clothes; whenever you buy the shirt or jacket that everyone is raving over, something new rises to popularity within a few days. Similarly, populations must always change to adapt to the changing world in order to survive.

Here are a few reasons as to why organisms are always evolving:

Populations are not genetic clones In the real world, there is no such thing as a genetically identical population because mutations and recombination result in genetically unique offspring. No matter how similar the organisms of a population are, mutations or recombination will force the gene pool to grow.

Natural Selection Natural selection will never stop because some form of competition will be present in all populations. No matter what, organisms with traits that provide an advantage will have a higher chance to survive the changes around them and reproduce. Over time, the traits that successful organisms have cause the population to experience genetic drift.

Changing Environment The environment is by no means static; natural disasters, diseases, and human interference often place pressure on environments, and subsequently, the organisms inhabiting these environments. To survive, organisms often evolve adaptations that help them survive and reproduce to pass on these adaptations to their offspring, and so on.

Evidence of Continuing Evolution In order to back up their claim that evolution never stops, scientists have collected evidence to validate their claims. Here are some pieces of evidence covered in the AP Biology curriculum:

Genomic changes over time Like we previously discussed, the genome of a population can be changed by many factors such as environmental pressures, natural selection, and even internal competition between organisms. When the genome of a population changes, we can infer that an event has placed pressure on the population, therefore necessitating the need for evolution.

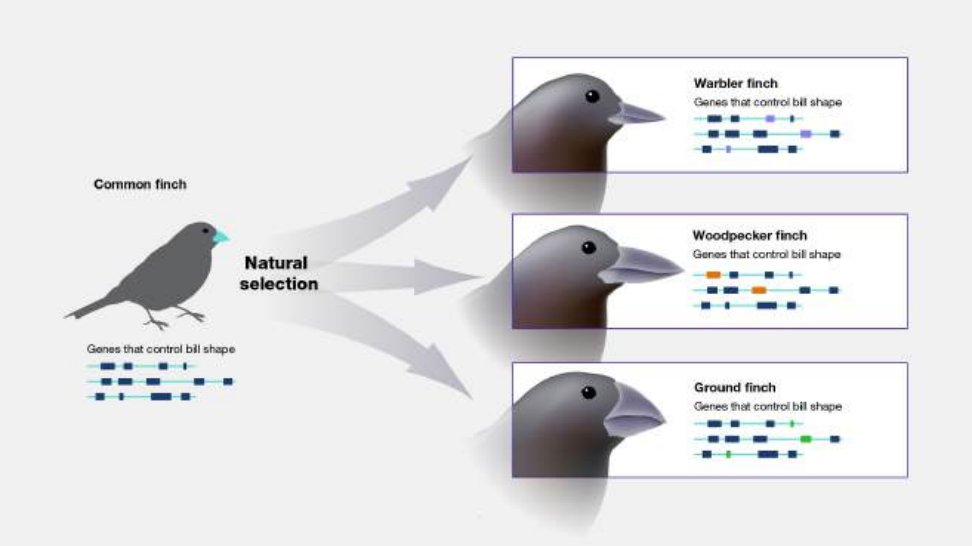
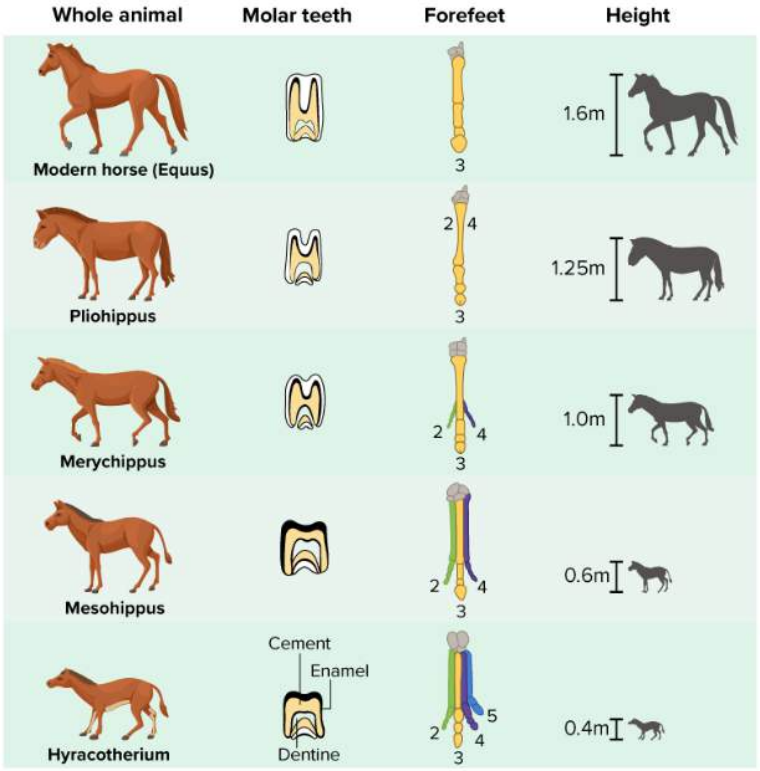


Image Credit: Sara Chandros Hull, Ph.D. (National Human Genome Research Institute)

Changes in fossil record Scientists can also support their claim with fossil records as they provide physical evidence that a species' physical characteristics, such as wings or beak size, have changed in response to environmental pressure.



Drug resistance When organisms are subjected to pressure from their environment, they can develop favorable adaptations through mutations. In the case of man-made

pressures such as antibiotics and drugs, the targets of these weapons, often organisms that are considered pests such as mice and insects, can develop resistance through random mutations and natural selection. Eventually, after enough generations, the entire population will be drug-resistant, rendering the drug or antibiotic useless.

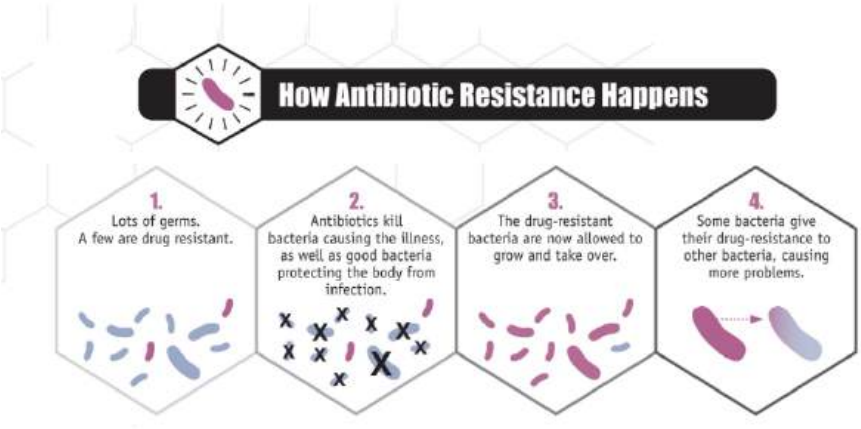


Image Credit: Melissa Brower (CDC)

Evolution of Pathogens Pathogens, just like animals and insects, can develop resistance to environmental pressures, which are almost always man-made drugs and vaccines. Similarly, the presence of resistance in a small group of the population will result in a drug-resistant population that makes the lives of scientists developing vaccines much harder. An example of pathogen evolution is the flu, which develops a new, vaccine, resistant strain every year.

Problem 7.8.2 — Multiple Choice Question

A population of lizards is introduced to a new island with different predators than their native habitat. After 20 generations, researchers observe changes in coloration patterns. This scenario illustrates which aspect of ongoing evolution?

(A) Punctuated equilibrium causes rapid speciation
(B) Founder effect establishes permanent genetic makeup
(C) Selection pressures continuously shape adaptations
(D) Genetic drift causes random fixation of neutral traits

Solution: This scenario demonstrates how selection pressures (new predators) continuously drive adaptive changes (coloration) in populations, showing evolution as an ongoing process rather than a one-time event. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

Problem 7.8.3 — Multiple Choice Question

Scientists observed that MRSA (Methicillin-resistant Staphylococcus aureus) evolved resistance to multiple antibiotics within hospital environments. This pattern of pathogen evolution is best described as:

(A) Stabilizing selection maintaining genetic homeostasis
(B) Frequency-dependent selection favoring rare genotypes
(C) Disruptive selection creating two distinct phenotypes
(D) Directional selection in response to selective pressure

Solution: MRSA evolution represents directional selection, in which antibiotic pressure selects for resistant bacteria, shifting the population toward resistance rather than maintaining existing traits or creating multiple distinct phenotypes. Thus, the correct answer is **(D)**.

§7.9 Phylogeny

Life on Earth is constantly changing. Over millions of years, living things have adapted and evolved to the world around them. This chapter will go over how scientists piece together the evolutionary history of species to understand how life has changed and continues to evolve.

Phylogenetic Trees Phylogeny is the history of evolution of a species/group and how lines of ancestry and relationships between groups of organisms. Phylogenetic trees and **cladograms** are visual representations of evolutionary relationships. Phylogenetic trees show the approximate time of evolutionary events and cladograms ancestral relationships. They are constructed using evidence from fossils and **molecular clocks**, changes in DNA and protein sequences over time.

Molecular clocks are usually considered more accurate because molecular data uses genetic code as a direct reflection of ancestry. Morphological evidence from fossils shows gained or lost traits that are used to construct phylogenetic trees.

Shared characteristics are traits that appear in more than one lineage. **Shared derived characteristics** are found specifically within a group of related organisms called a **clade** and help distinguish that clade from others. These shared derived traits suggest **homology** among organisms in the clade and serve as evidence that they share a common ancestor.

Nodes on a phylogenetic tree represent common ancestors. The more recent the common ancestor between two species, the more closely related they are. The **outgroup** in a phylogenetic tree is the species that is the least closely related to the others. The **root** of the tree represents the most recent common ancestor of all organisms included in the tree. Phylogenetic trees and cladograms can also show speciation and extinction events, which will be covered later on.

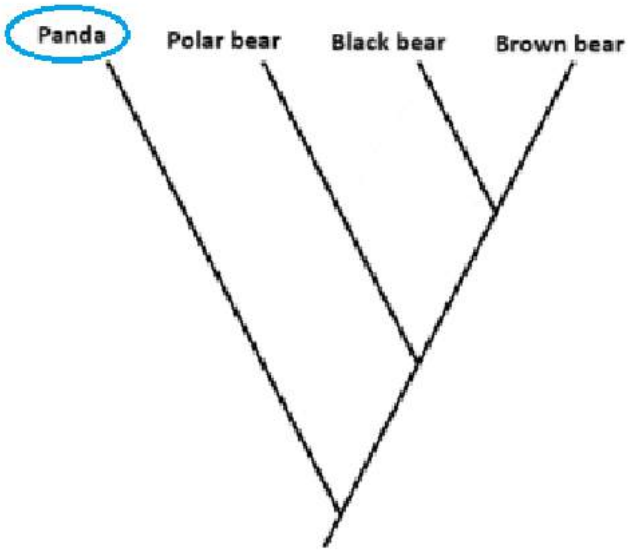
Building Phylogenetic Trees Whenever the AP test asks you to construct a phylogenetic tree, you will likely be provided with either a table that lists several organisms and their respective traits or a table that lists several organisms and how similar they are to each other genetically. Take a look at an example from FRQ #1 from the 2018 AP Bio AP test:

TABLE 1. AMINO ACID DIFFERENCES IN THE LYST PROTEIN AMONG BEAR SPECIES

	Panda	Black	Brown	Polar
Panda	–			
Black	33	–		
Brown	34	1	–	
Polar	40	7	8	–

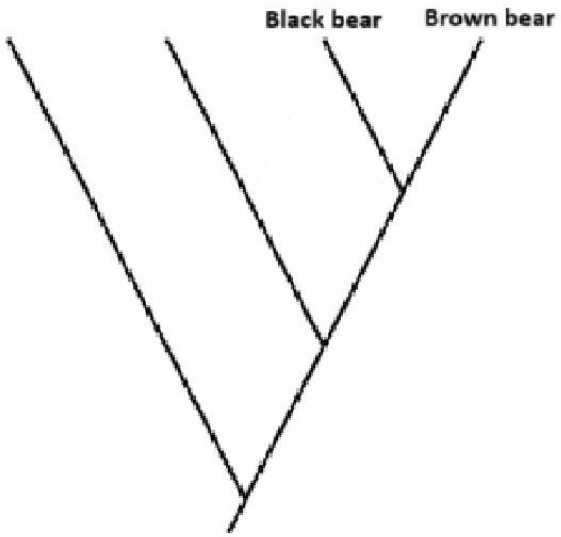
Image Credit: College Board

This table shows different types of bears and their differences in amino acids. Luckily, College Board usually provides us with a skeleton that we have to correctly label. Below is a skeleton that I labeled to match the data in the table:



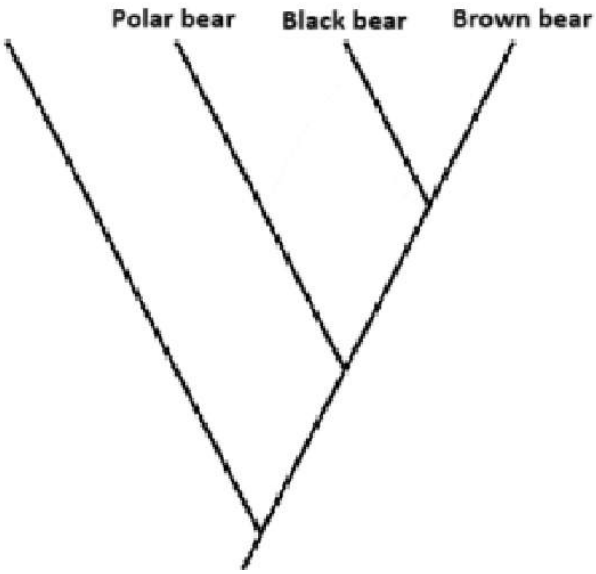
The blue circle around the Panda label indicates that the Panda is the out-group. The out-group is a species that shares a common ancestor with the other organisms being studied, but is the least related. The in-group is the set of organisms, or species, that we are investigating. But this is really the last step, so we'll go over this at the end of the problem.

But first, let's start from the beginning. To figure out the order at which to label the branches, you must consider the similarities between each species. According to the table, the two species with the least amount of amino acid difference between them is the Black bear and Brown bear with a single amino acid difference. Therefore, we can label the phylogenetic tree as the following:

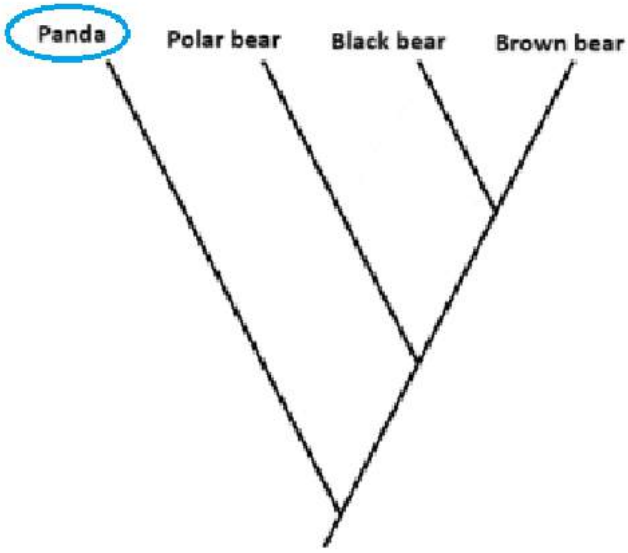


**Make note that since the Black bear and Brown bear occur at a branch point, we can switch the order at which we label them. We could have labeled Black bear to the right and Brown bear to the left.

For the next branch, we need to find the species that is most similar with Black bears and Brown bears. Based on the table, Polar bears are the next most similar species to Black bears and Brown bears because 7 and 8 amino acid differences are the next highest numbers.



Now we only have one remaining species: Pandas. But let's work through the similarities anyway. In the table, we can see that Pandas have the most amino acid differences with the three other species (33 with Black bears, 34 with Brown bears, and 40 with Polar bears). Therefore, we label the outermost branch as Panda. This question also asked us to circle the outgroup, so we should circle Panda.



The **out-group** is identified as having the most differences from other species in the table. In this case, Pandas are the out-species because they have 40 amino acid differences from Polar bears, 34 amino acid differences from Browns bears, and 33 amino acid differences from Black bears. Since 40, 34, and 33 are much larger than 1, 7, and 8, we can infer that Panda bears are the out-group!

Example 7.9.1

An example of a pair of out-group and in-group species is the lemur and humans. Although both species share a common ancient ancestor, lemurs evolved separately from humans at one point. When this separate evolving occurs, it is often referred to as branching because a new branch on the phylogenetic tree opens up.

Problem 7.9.2 — Multiple Choice Question

A researcher is constructing a phylogenetic tree for deep-sea fish species that have similar body shapes but diverged millions of years ago. Which molecular data would likely provide the most accurate evolutionary relationships?

(A) Highly conserved ribosomal RNA sequences
(B) Genes coding for body shape and fin structure
(C) Rapidly evolving surface protein genes
(D) Mitochondrial genes from hybrid zones

Solution: Out of the answer options, we know that conserved ribosomal RNA (rRNA) sequences evolve slowly and are less subject to selective pressures, making them ideal for determining evolutionary relationships between species that diverged millions of years ago. Thus, the correct answer is $\boxed{\textbf{(A)}}$.

Problem 7.9.3 — Multiple Choice Question

A researcher analyzing a phylogenetic tree notices that changing the outgroup alters the branching pattern among the ingroup taxa. This observation most directly challenges which assumption of phylogenetic analysis?

(A) Evolution occurs at a constant rate
(B) Speciation is always dichotomous
(C) Natural selection is the primary evolutionary force
(D) Character homology was correctly identified

Solution: If changing the outgroup alters ingroup relationships, it suggests that some characters thought to be homologous may actually be homoplasious, challenging the fundamental assumption that character homology was correctly identified in the analysis. Thus, the correct answer is **(D)**.

§7.10 Speciation

Speciation is the process by which new species evolve from existing ones. This can happen in several ways, but most commonly is the process of reproductive isolation, when two populations of a species become physically or biologically separated from each other, such that they can no longer interbreed and exchange genetic information. As time progresses, these populations may evolve in different forms, facilitating the development of new species.

Biological Species Concept The **biological species concept** defines a species as a group of organisms capable of interbreeding and producing *viable*, *fertile* offspring. This concept is based on the idea that species are reproductively isolated from one another, and that this isolation is the primary mechanism by which new species evolve.

Different Species When two animals can no longer breed with one another, they are classified as different species.

Example 7.10.1

A donkey and a horse can breed and create a mule, but that mule cannot breed with another mule to continue its own lineage, which is why donkeys and horses are considered to be separate species.

Evolutionary Rates The rate of evolution and speciation may also differ under different ecological conditions. For instance, punctuated equilibrium and gradualism are two different, well-known models that describe the pace of evolution.

Punctuated equilibrium is a theory of evolution that suggests that evolution occurs in fits and starts, with long periods of *stasis* (little or no change) punctuated by brief periods of rapid *evolution*. This theory was proposed by Niles Eldredge and Stephen Jay Gould in the 1970s.

Gradualism is a model that suggests evolution as a *slow, steady process* that occurs over hundreds of thousands or millions of years. The below diagram can better represent this comparison.

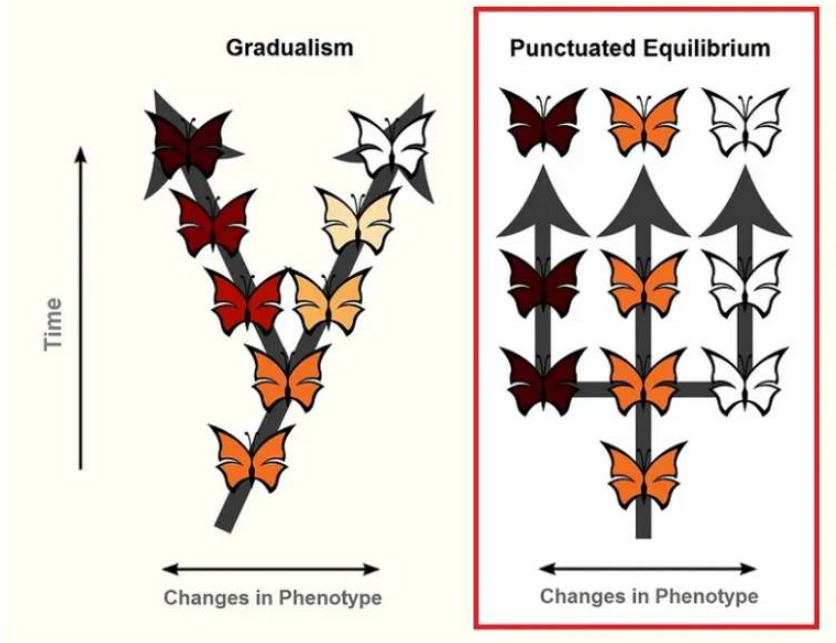
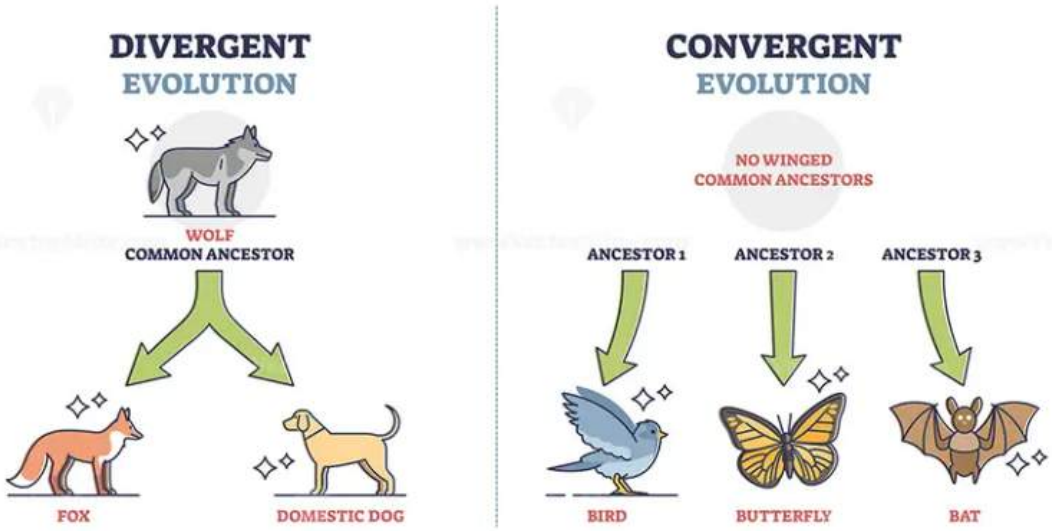


Image Credit: Biology Dictionary

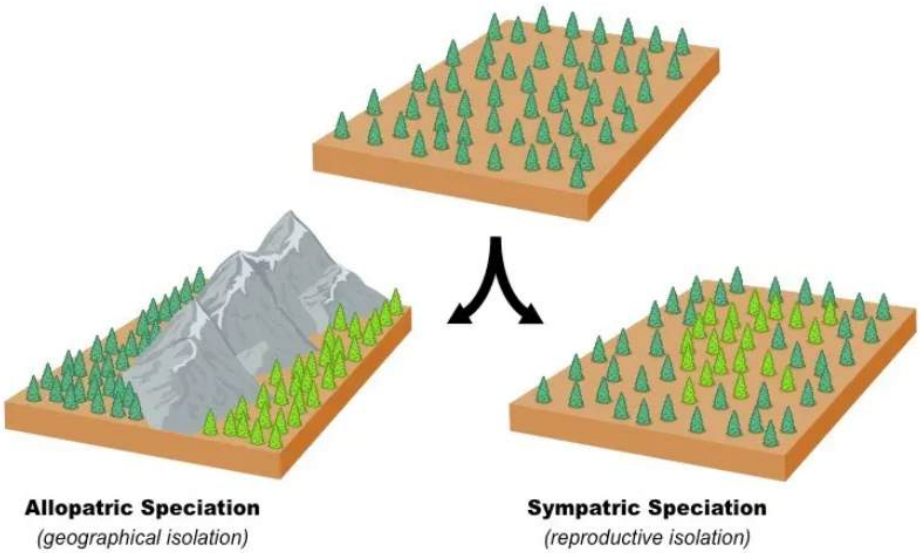
Isolating Different Populations We define **divergent evolution** as a form of evolution that occurs when different populations of a species adapt to different habitats, leading to the development of new forms. This can happen when a population becomes geographically isolated and is exposed to different selective pressures. Consequently, the isolated population may develop unique characteristics that enable them to be more fit in their new habitat.

During times of **adaptive radiation**, speciation rates can grow rapidly. This is because a lineage diversifies into many new forms as it adapts to different habitats and ecological niches. This can happen when new habitats become available or when a mass extinction event opens up new ecological niches. As new forms evolve to fill available niches, the speciation rate can be much higher than during a time of stasis.



Types of Speciation **Allopatric speciation** occurs when two populations become "reproductively isolated" from one another. For example, a *geographical barrier* could cause this, if individuals of the same species are separated. If they cannot continue to breed with each other, it is possible that the two separate populations will evolve separately until they are unable to breed with each other.

Sympatric speciation occurs when individuals within the same geographic area are influenced by either **disruptive selection** or **mating preferences**. This phenomenon can be caused when when two opposing traits are equally favored; as the population evolves separately, speciation is likely to occur.



Prezygotic vs. Postzygotic Isolation The instances we discussed above can either be classified as prezygotic or postzygotic isolation. The former prevents the fertilization of eggs when two individuals breed, thus making it impossible to reproduce. This would be

present in situations like habitat isolation, or any other external agents preventing mating or fertilization. Meanwhile, the latter does not allow the formation of a fertile offspring.

Problem 7.10.2 — Multiple Choice Question

Which scenario represents a violation of the biological species concept's definition of a species?

(A) Two populations with different mating calls are classified as separate species
(B) Two populations that cannot interbreed are classified as one species
(C) Two morphologically identical populations are classified as separate species
(D) Two populations with different ecological niches are classified as separate species

Solution: The biological species concept defines species as groups that can interbreed to produce viable, fertile offspring. Classifying non-interbreeding populations as one species directly contradicts this definition, regardless of other similarities. Thus, the correct answer is **(B)**.

Problem 7.10.3 — Multiple Choice Question

A biologist discovers that two populations of frogs can produce viable, fertile offspring in laboratory conditions, but they never interbreed in nature due to different mating seasons. According to the strict application of the biological species concept, these frogs should be classified as:

(A) The same species
(B) Separate species due to temporal isolation
(C) Incipient species
(D) A species complex

The biological species concept focuses on the potential to interbreed and produce viable, fertile offspring, which these frogs can do. Prezygotic barriers like different mating seasons don't change their biological capacity to exchange genes successfully. Thus, the correct answer is **(A)**.

§7.11 Extinction

Extinctions have occurred throughout Earth's history, and have been caused by a variety of factors including natural disasters, changes in climate, and human activities. These extinctions have had a significant impact on the diversity of life on Earth, as they have led to the loss of many species, and have created opportunities for new forms of life to evolve.

History of Extinctions Species go extinct all the time, in fact, a whopping 99.9% of all plant and animal species to ever live are now gone. The extinction of dinosaurs like the

Tyrannosaurus rex and the Triceratops approximately 65 million years ago isn't exactly noteworthy on its own, but owing to the fact that around 80% of all life at the time also died out, in what biologists term a **mass extinction**.

Mass extinctions occur when at least 70% of all species die out in a relatively short lapse of time. The most devastating event occurred approximately 251 million years ago when around 95% of all the planet's species went extinct. The following list uncovers some of the most commonly-known mass extinctions, and their impact.

1. **Ordovician-Silurian Extinction**: Small marine organisms died out approximately 442 million years ago.
2. **Devonian Extinction**: Several tropical marine species went extinct approximately 365 million years ago.
3. **Triassic-Jurassic Extinction**: Approximately 201 million years ago, the extinction of other vertebrate species allowed dinosaur species to flourish.
4. **Cretaceous-Paleogene Extinction**: Approximately 65.5 million years ago, all dinosaurs and many related species went extinct.

Causes of Extinction There are several causes of extinction, which include but are not limited to:

- Dramatic climate change (conditions that are too warm or too cold)
- Major natural disasters (e.g. volcanic eruptions and asteroid impacts)
- Sudden rises or dips in sea water and pressure levels
- New predators or competitors (think, invasive species)
- Disease outbreaks (especially devastating to populations with low genetic diversity)

In recent centuries, human activity can also be attributed to dramatic increases in extinction rates. This can be done in the form of:

- Deforestation, such as cutting down trees to develop land for urban use
- Overhunting and overfishing certain species can lead to them becoming vulnerable, endangered, and eventually extinct.
- Introducing invasive species to new areas
- Air, water, and soil pollution
- Human-induced climate change, such as greenhouse gas emissions

Example 7.11.1

The **dodo bird** (*Raphus cucullatus*) is an extinct flightless bird that was endemic to the Mauritius islands, which is located east relative to Madagascar in the Indian Ocean. It represents a classic lesson in extinction. Found by Dutch soldiers around 1600 on an island in the Indian Ocean, the Dodo became extinct less than 80 years later because of deforestation, hunting, and destruction of their nests by animals brought to the island by the Dutch. Moreover, they killed the birds for meat, and the birds couldn't run or fly away when pursued.

Source: Oxford University Museum of Natural History

Speciation vs. Extinction Rates The number of species on Earth at any particular time depends on the balance between speciation and extinction. When the former process occurs faster than the latter, there is a net increase in biodiversity, and vice versa. Throughout Earth's long history, this balance has shifted back and forth:

- After major extinction events, species tend to diversify in order to fill new niches. This is the process of **adaptive radiation**.
- During stable periods, speciation and extinction reach equilibrium with each other.
- Today, human-induced extinction is occurring at an alarming rate, faster than speciation, leading to a net loss in biodiversity.

New Niches We know that adaptive radiation occurs when a single species "splits" into many diverse species to take advantages of available opportunities once other species are removed by extinction.

Example 7.11.2

After the dinosaurs went extinct, mammals who had been mostly small and nocturnal, underwent adaptive radiation and rapidly evolved into many different forms, e.g. bats, whales, elephants, primates, etc. If it weren't for dinosaurs no longer dominating the natural landscape, this famous case of adaptive radiation would have been highly unlikely.

Problem 7.11.3 — Multiple Choice Question

Scientists have found evidence of five major mass extinction events during Earth's history. One of these, the end-Permian extinction, resulted in the extinction of roughly 96% of Earth's species. These species included many early reptiles, amphibians and the last species of trilobites.

One cause of the end-Permian extinction was extreme volcanic activity that generated huge clouds of sulfur dioxide and carbon dioxide. The presence of these gases in the atmosphere led to acid rain, ocean acidification, and global warming.

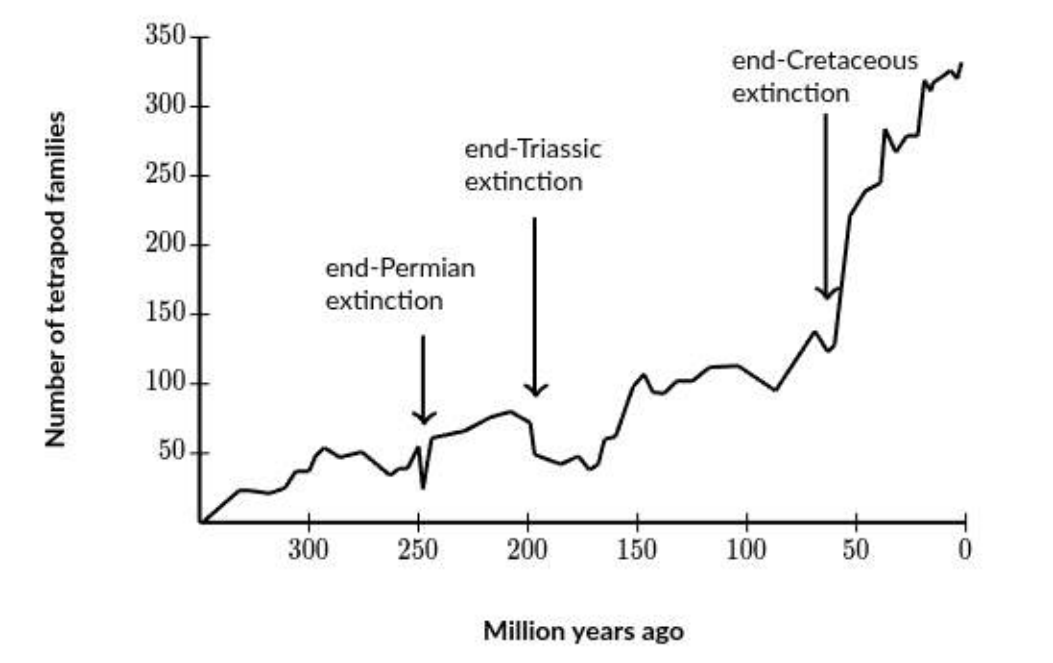
Which of the following describes how the end-Permian extinction was similar to Earth's other four major mass extinctions events?

(A) The extinction affected trilobites, amphibians, and reptiles.
(B) The extinction was due to large-scale ecological changes.
(C) The extinction was caused primarily by human activity.
(D) The extinction led to ocean acidification and global warming.

Solution: We need to know that all of Earth's mass extinction events were caused by large-scale ecological changes. These changes caused ecological stress that affected many species at once. In the case of the end-Permian extinction, the ecological stress was caused by acid rain, ocean acidification, and global warming. The correct answer is $\boxed{\textbf{(B)}}$.

Problem 7.11.4 — Multiple Choice Question

The following graph shows the number of tetrapod (four-limbed animal) families on Earth over time, as indicated by the fossil record. The arrows indicate major mass extinction events.



Which of the following statements is consistent with the information provided?

(A) Tetrapods underwent an adaptive radiation after the end-Cretaceous extinction, likely due to the use of ecological niches made available by the extinction event.
(B) Since the end-Permian extinction, the number of tetrapod families on Earth has halved roughly every 100 million years.
(C) The tetrapod families that were lost during the end-Permian extinction returned after a lag of a few million years as they re-populated previously occupied habitats.
(D) The extinction rate between the end-Permian and the end-Triassic extinctions indicates this was a time of global ecological stress.

Source: Khan Academy

Solution: According to the graph, the number of tetrapod families rapidly increased after the end-Cretaceous extinction. This increase in tetrapod diversity represents an adaptive radiation, which can occur after mass extinction events as groups of organisms adapt to newly available ecological niches. The correct answer is $\boxed{\textbf{(A)}}$.

§7.12 Variations in Populations

Variation is critical to a population's chances of survival. It is also the concept that helps us understand challenges associated with conservation, why certain species' populations are more resilient, and more. In this section, we will also dig deeper into real-world

examples of population dynamics affected by genetic diversity, evaluate the risks of populations with low genetic variation, and more.

Defining Genetic Diversity We define **genetic diversity** as the number and variety of genes within a species or population. Essentially, it encompasses the traits that can be found in all individuals. This diversity can come about via mutations, genetic recombination, and gene flow between populations.

Genetic variation is the foundation for natural selection. Without differences between individuals, there would be nothing for nature to "select" when environmental conditions change, which means the species is in big trouble! Therefore, the more genetic diversity a population has, the more likely it contains individuals with traits that might be helpful in new or changing environments.

Genetic Diversity and Resilience Populations with high genetic diversity tend to be more **resilient** when faced with challenging environmental situations. Having a variety of traits spread across the population increases the chances that at least some individuals, with desired characteristics, can survive these new challenges. Think of genetic diversity against environmental changes as having a variety of investments to withstand sudden changes in the stock market.

Some advantages of resilient populations include, but are not limited to:

- They adapt more quickly to environmental changes
- They're less vulnerable to disease outbreaks
- They recover faster after population declines
- They're more likely to thrive in varied habitats

Consequences of Minimal Genetic Diversity Species with low genetic diversity are at a heightened risk of extinction. When all individuals in a population are genetically similar, they also have virtually the same factors which make them vulnerable. This homogeneity is dangerous, as it can lead to a situation in which a single threat could wipe out the entire population.

Most endangered species today primarily struggle due to a lack of genetic diversity:

- **California condors** dropped to just 22 individuals in the 1980s, creating a genetic bottleneck that still threatens their recovery today.

Image Credit: American Bird Conservancy

- **Black-footed ferrets** went through a similar bottleneck, with all living ferrets descended from just 7 individuals.

Image Credit: Revive and Restore

- **Prairie chickens** suffered from inbreeding depression when their populations became fragmented, reducing their reproductive success.

Image Credit: All About Birds

Low genetic diversity makes these conservation efforts extra challenging. Even when population numbers increase, the limited genetic variation continues to make these species vulnerable to environmental changes and disease.

Shifts in Selective Pressures As previously discussed, traits can be both beneficial or harmful depending on the specific environmental condition. The important aspect of genetic diversity is that it provides options for different scenarios. As environments change over time, different traits may become advantageous or disadvantageous. For instance:

- Dark coloration might provide camouflage in a forest but make an animal more visible (and vulnerable to predators) in a desert.
- Thick fur is beneficial in cold environments but could cause overheating in warmer climates.
- Resistance to one disease might make an organism more susceptible to another.
- A plant's adaptation to drought might reduce its competitive ability during rainy periods.

As you probably realize, this list can go endless!

Implications on Conservation Understanding genetic diversity has proved significant for conservation efforts by humans. It is just not enough to protect a few individuals of an endangered species; preserving genetic diversity of a whole population is critical for long-term survival. Some approaches in which conservational scientists aim to maintain diversity include:

- Establishing wildlife corridors to connect fragmented populations.
- Managing breeding programs to maximize genetic diversity.
- Preserving DNA and reproductive cells in "frozen zoos."

- Reintroducing individuals to increase genetic exchange between isolated populations.

These measures help to ensure that endangered species can be supported to have enough genetic variation to adapt to future challenges, e.g. climate change, diseases, and other environmental pressures that are projected for the future.

Problem 7.12.1 — Multiple Choice Question

Researchers studying a butterfly species found that wing pattern variation is controlled by multiple alleles. After a volcanic eruption darkened the environment with ash, they observed population changes. Which graph would best represent the expected allele frequency changes over several generations?

(A) Darker wing alleles increase while lighter wing alleles decrease
(B) All allele frequencies remain constant despite environmental change
(C) All alleles decrease in frequency as population size decreases
(D) Lighter wing alleles increase while darker wing alleles decrease

Solution: The environmental change (darkening from volcanic ash) would create selection pressure favoring darker wing alleles that provide better camouflage in the new environment, while previously adaptive lighter wing alleles would lessen in frequency. Thus, the correct answer is $\boxed{\textbf{(A)}}$.

Problem 7.12.2 — Multiple Choice Question

A researcher observes that after antibiotic treatment, a bacterial population recovers with increased resistance. Which graph best represents the change in allele frequency that occurred?

(A) No change in allele frequencies after treatment
(B) Decrease in resistance allele frequency after treatment
(C) Sharp increase in resistance allele frequency after treatment
(D) Gradual linear increase in resistance allele frequency

Solution: Antibiotic treatment creates strong selection pressure that rapidly shifts allele frequencies, causing a sharp increase in the frequency of resistance alleles as susceptible bacteria die off. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

§7.13 Origin of Life on Earth

Many high school students wonder, "What is the meaning of Life?" but we propose a slightly different query: "How did Life on Earth Bring About?" In this section, we will explore various hypotheses that attempt to explain how life formed on our beautiful blue dot in a deep region of outer space. We will also explain the fostering of chemical reactions that led to life, summarize experiments that explain the formation of organic molecules, and relate the origin of life to evolutionary processes and biodiversity which we see today.

How It All Started Scientific research on the origin of life on Earth is still ongoing, and a number of theories have been put forth to explain how life first appeared on our planet. Numerous forms of scientific evidence, including geological, chemical, and biological, provide credibility to these theories.

By revealing details about the conditions on the planet in its early history, geological evidence supports theories regarding the origin of life on Earth.

Earth, for instance, is thought to have formed around 4.6 billion years ago (bya), and until roughly 3.9 bya, the environment was too harsh for life. This is supported by data from geological records, e.g. the early atmosphere's makeup, the existence of liquid water, and the strength of solar radiation. By understanding the conditions of the early Earth, scientists are able to construct models of how life could have emerged under those conditions.

Also, fossil records suggest that evidence of life on Earth date back to around 3.5 bya. This is based on the discovery of fossilized **stromatolites**, or layered structures formed by ancient microbial communities. The fossils provide strong evidence that life existed on Earth at least 3.5 bya, as well as provide insight on the quality of such life.

When combined, geological, chemical, and biological evidence provide a plausible range of dates when life could have possibly originated. Based on the geological evidence, scientists believe that life could have emerged on Earth as early as 3.9 bya and as late as 3.5 bya. However, it is important to remember that the origin of life is a complex process and is still not fully understood: the range of possible dates could be modified as new discoveries and evolutionary technology start to develop.

Modeling Life's Origins There are several models about the origin of life on Earth, each of which proposes a different explanation for how life first emerged on our planet. These models can be broadly divided into two main categories: **abiogenesis** and **panspermia**.

An abiogenesis model we know well is that "primitive Earth" model, which proposes that the formation of life was a gradual process as organic molecules were produced from inorganic precursors. According to this model, our primitive Earth provided the necessary conditions for this synthesis to occur, such as the presence of available free energy and the absence of a significant quantity of atmospheric oxygen, or O_2. This model suggests that the first living organisms were simple, self-replicating molecules that formed spontaneously through chemical reactions in the early Earth's oceans.

The panspermia model proposes that a meteorite or other celestial event "transported" the organic molecules from outer space to Earth. This model suggests that the organic molecules that make up life, such as amino acids and nucleotides, were formed in the dust clouds of other planets or in comets and meteorites. These biological macromolecules are understood as assembling living organisms.

Currently, research suggests that it is likely that multiple mechanisms were involved. Most importantly, both models have solid evidence and they are not mutually exclusive. For example, it's possible that both abiogenesis and panspermia could have contributed to the origin of life on Earth, with inorganic precursors forming on Earth and organic molecules being brought by meteorites, and the combination of these factors led to the emergence of life on Earth! We may figure out just exactly the truth in a few centuries...

Chemical Experiments Advancements in modern science and experimental chemistry tell us that it is possible to form organic molecules from inorganic precursor molecules in the absence of living entities (this process is known as abiogenesis). These experiments have been critical in shedding light on the early stages of the emergence of life on Earth.

As briefly described earlier, a key aspect of such experiments is the formation of organic biomolecules (or monomers, review this in Unit 1 if you forgot!) from inorganic precursors. These organic molecules, such as amino acids and nucleotides, served as building blocks for the formation of more complex molecules, which play a major role in living organisms. Researchers conclude that these organic molecules can be synthesized under specific conditions that are thought to be unique to Earth, such as a plentiful supply of free energy or the absence of significant levels of atmospheric oxygen, O_2.

When these monomer subunits conjoined, polymers were produced. Again, if you forgot about this, review Unit 1! These polymers have the ability to replicate, store, and transfer genetic information, which are vital to virtually all life. Nucleic acids like DNA and RNA store and transmit important information, while proteins have their own unique structure and function (e.g. enzymes speeding up crucial biochemical reactions). The formation of these polymers is an important step in the emergence of life, as they allow the replication and evolution of the first living organisms.

The Significance of RNA A widely accepted model for life's origins is the **RNA World Hypothesis**, which proposes that that RNA was potentially the earliest form of genetic material. Specifically, it was the first molecule that could store and transmit genetic information, catalyze (speed up) chemical reactions, and undergo its replication.

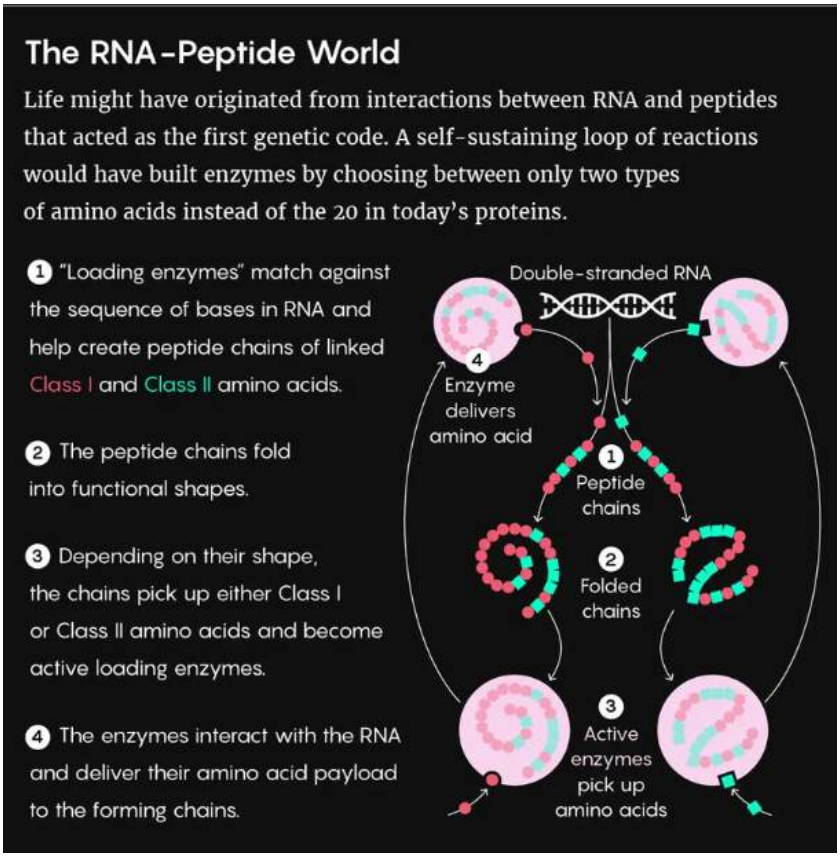


Image Credit: Quanta Magazine

This hypothesis also suggests that the presence of RNA led to the presence of DNA and proteins, which opened the door for more complex forms of life.

One of the key pieces of evidence for the RNA World Hypothesis is the ability of RNA to act as both a genetic molecule and a catalyst. Scientists have been able to demonstrate that RNA can catalyze a wide range of chemical reactions, including those that are essential for life, such as polymerizing nucleotides, forming peptide bonds, and synthesizing simple/complex carbohydrates. This is thought to have been critical for the emergence of life, as it would have allowed for the formation of more complex molecules and the replication of genetic information.

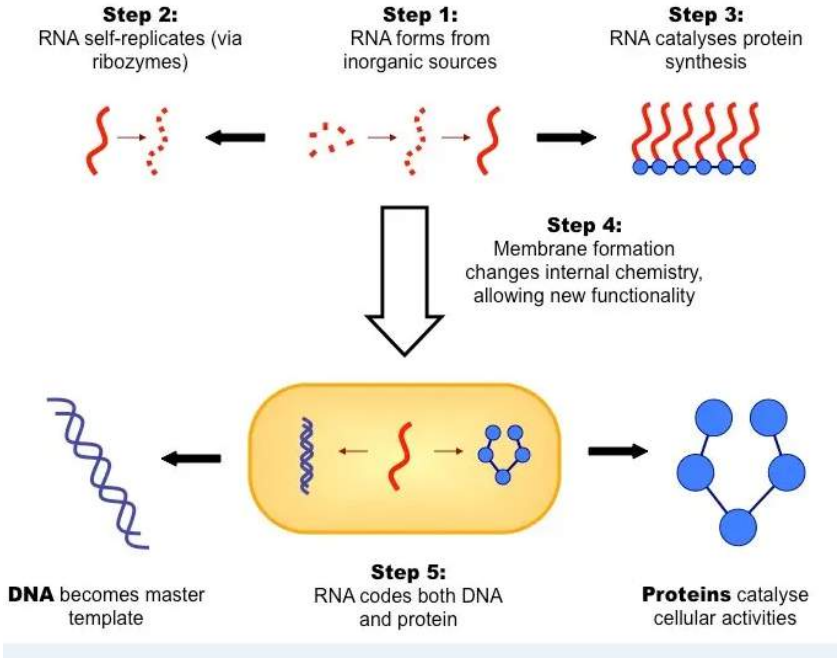


Image Credit: BioNinja

Additionally, the RNA World Hypothesis suggests that the first self-replicating RNA molecules may have been formed through the gradual polymerization of nucleotides in the presence of suitable inorganic catalysts and other minerals.

Problem 7.13.1 — Multiple Choice Question

A scientist discovers microscopic structures in 3.5-billion-year-old rocks that contain short polymers capable of template-directed synthesis. These structures most likely represent:

(A) Inorganic crystals with periodic structures
(B) Modern bacterial cells with damaged DNA
(C) Protocells with primitive information replication systems
(D) Fossilized viruses from an extraterrestrial source

Solution: Structures containing polymers capable of template-directed synthesis in ancient rocks would represent protocells - primitive cell-like entities with the fundamental property of information replication, a critical transitional stage between pre-biotic chemistry and cellular life. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

Problem 7.13.2 — Multiple Choice Question

Which experimental evidence BEST supports the RNA world hypothesis for the origin of life?

(A) Formation of amino acids in spark discharge experiments
(B) Observation of coacervates forming in primordial soup models
(C) Discovery that RNA can function as both genetic material and catalyst
(D) Detection of organic molecules in meteorites

Solution: The RNA world hypothesis is supported by the discovery that RNA can store genetic information and catalyze chemical reactions (via special proteins called ribozymes), suggesting it could have preceded DNA and proteins in early life forms. Thus, the correct answer is $\boxed{\textbf{(C)}}$.

§7.14 Unit 7 Practice Questions

Problem 7.14.1 — 2008 AP Biology FRQ (Form B)

Evolution is one of the unifying themes of biology. Evolution involves change in the frequencies of alleles in a population. For a particular genetic locus in a population, the frequency of the recessive allele (a) is 0.4 and the frequency of the dominant allele (A) is 0.6.

(a) What is the frequency of each genotype (AA, Aa, aa) in this population? What is the frequency of the dominant phenotype?

(b) How can the Hardy-Weinberg principle of genetic equilibrium be used to determine whether this population is evolving?

(c) Identify a particular environmental change and describe how it might alter allelic frequencies in this population. Explain which condition of the Hardy-Weinberg principle would not be met.

Solution to part a: Using the Hardy-Weinberg principle, $p = 0.6$ and $q = 0.4$, where p and q are the dominant and recessive allele frequencies, respectively.

AA, Aa, and aa refer to homozygous dominant, heterozygous, and homozygous recessive genotypes, respectively, for a specific trait.

- The frequency of AA is given by $p^2 = 0.6^2 = \boxed{0.36}$.
- The frequency of Aa is equal to $2pq = 2\,(0.6)\,(0.4) = \boxed{0.48}$.
- The frequency of aa is easily found as $q^2 = 0.4^2 = \boxed{0.16}$.

Finally, it follows that the frequency of the dominant phenotype is determined by adding the frequency of the homozygous dominant genotype to the frequency of the heterozygous genotype, so we get $p^2 + 2pq = (0.6)^2 + 2\,(0.6)\,(0.4) = \boxed{0.84}$.

Solution to part b: The Hardy-Weinberg principle of equilibrium states that if a population is not evolving, the allele and genotype frequencies remain about the same through generations. If this were the case with this population, then it would show that the population is not evolving.

Solution to part c: An environmental change that favors members of the population with the recessive traits. Individuals with aa are more likely to survive and reproduce, and more a alleles get passed on to the next generation. This situation goes against the natural selection condition of the Hardy-Weinberg principle. Certain traits (and alleles) are favored by the environment, meaning the population is evolving.

Problem 7.14.2 — 2013 AP Biology FRQ

Fossils of lobe-finned fishes, which are ancestors of amphibians, are found in rocks that are at least 380 million years old. Fossils of the oldest amphibian-like vertebrate animals with true legs and lungs are found in rocks that are approximately 363 million years old.

Three samples of rocks are available that might contain fossils of a transitional species between lobe-finned fishes and amphibians: one rock sample that is 350 million years old, one that is 370 million years old, and one that is 390 million years old.

(a) **Select** the most appropriate sample of rocks in which to search for a transitional species between lobe-finned fishes and amphibians. **Justify** your selection.

(b) **Describe** TWO pieces of evidence provided by fossils of a transitional species that would support a hypothesis that amphibians evolved from lobe-finned fishes.

Solution to part a: The most appropriate sample of rocks would be one from between the time of lobe-finned fishes and amphibians, specifically, the rock sample from 370 million years ago.

Solution to part b: Two pieces of evidence that could support the hypothesis that amphibians evolved from lobe-finned fishes are homologous structures and similar DNA sequences.

Problem 7.14.3 — 2014 AP Biology FRQ

A research team has genetically engineered a strain of fruit flies to eliminate errors during DNA replication. The team claims that this will eliminate genetic variation in the engineered flies. A second research team claims that eliminating errors during DNA replication will not entirely eliminate genetic variation in the engineered flies.

(a) **Provide** ONE piece of evidence that would indicate new genetic variation has occurred in the engineered flies.

(b) **Describe** ONE mechanism that could lead to genetic variation in the engineered strain of flies.

(c) **Describe** how genetic variation in a population contributes to the process of evolution in the population.

Solution to part a: Answers for this question can include different genotypes, phenotypes, genetic differences, and more.

Solution to part b: Answers for this question can include random fertilization, crossing

over, independent assortment, gene flow, meiosis, and more.

Solution to part c: Without differences in genes, members of a population would be so similar that natural selection would not be able to occur. Genetic variation enables populations to evolve by allowing some members survive and reproduce more successfully than others. Over time, helpful traits accumulate, and the population changes.

Problem 7.14.4 — 2015 AP Biology FRQ (Excerpt)

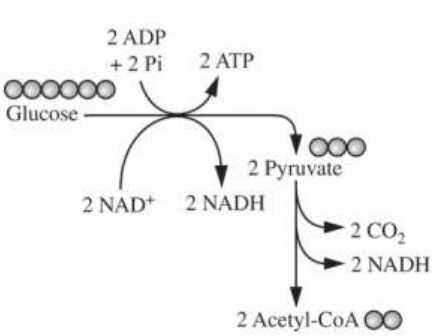


Figure 1. Glycolysis and pyruvate oxidation

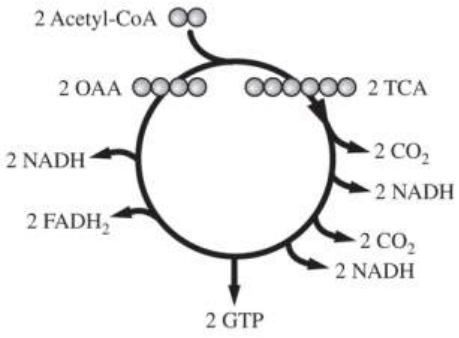


Figure 2. Krebs cycle

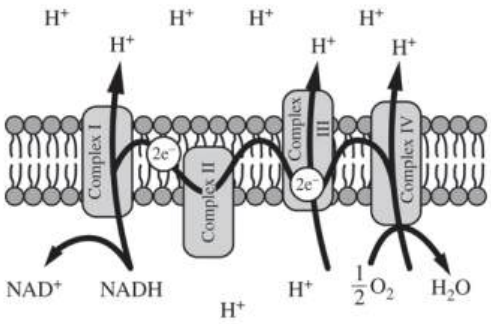


Figure 3. Electron transport chain

Cellular respiration includes the metabolic pathways of glycolysis, the Krebs cycle, and the electron transport chain, as represented in the figures. In cellular respiration, carbohydrates and other metabolites are oxidized, and the resulting energy-transfer reactions support the synthesis of ATP.

(b) Use each of the following observations to **justify** the claim that glycolysis first occurred in a common ancestor of all living organisms.

- Nearly all existing organisms perform glycolysis.
- Glycolysis occurs under anaerobic conditions.
- Glycolysis occurs only in the cytosol.

Solution to part b:

- 1st claim: Glycolysis could have been an advantageous trait, which would explain

why nearly all existing organisms perform glycolysis.

- 2nd claim: Since glycolysis occurs in anaerobic conditions, we can infer that glycolysis originated in an oxygen-free environment.
- 3rd claim: Since glycolysis occurs in the cytosol and not within a specific organelle, we can infer that glycolysis originally occurred in cells that existed prior to the cell became compartmentalized, or divided into organelles.

Problem 7.14.5 — 2019 AP Biology FRQ

TABLE 1. DIVERGENCE (IN PERCENT) OF MITOCHONDRIAL DNA SEQUENCES AMONG FIVE PRIMATE SPECIES

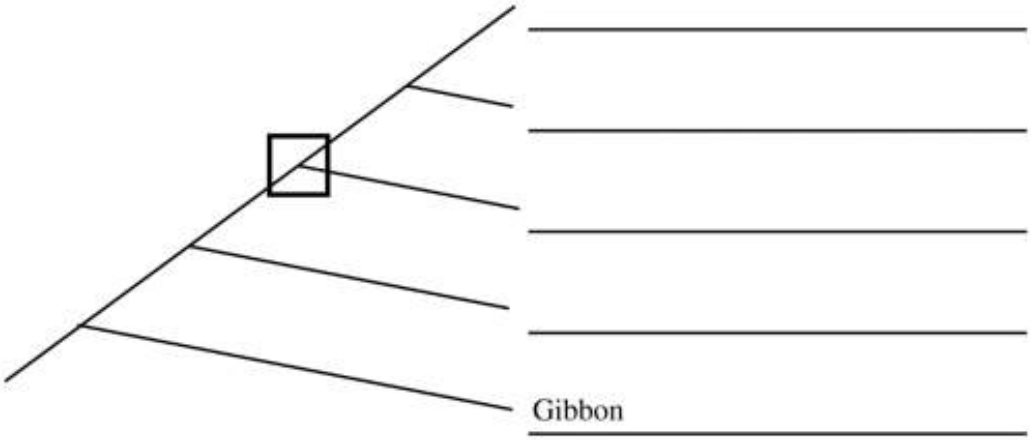
	Human	Gorilla	Orangutan	Gibbon	Chimpanzee
Human	-	10.3	16.1	18.1	8.8
Gorilla		-	16.7	18.9	10.6
Orangutan			-	18.9	17.2
Gibbon				-	18.9
Chimpanzee					-

A researcher studying the evolutionary relationship among five primate species obtained data from a sequence of mitochondrial DNA (mtDNA) from a representative individual of each species. The researcher then calculated the percent divergence in the sequences between each pair of primate species (Table 1).

(a) Based on fossil data, the researcher estimates that humans and their most closely related species in the data set diverged approximately seven million years ago. Using these data, **calculate** the rate of mtDNA percent divergence per million years between humans and their most closely related species in the data set. Round your answer to two decimal places.

(b) Using the data in the table, **construct** a cladogram on the template provided. **Provide reasoning** for the placement of gibbons as the outgroup on the cladogram.

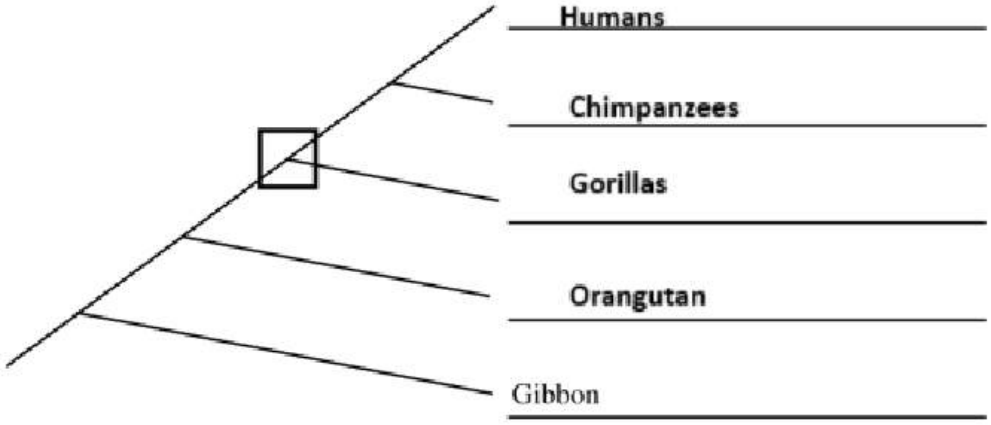
(c) On the cladogram, **draw** a circle around all of the species that are descended from the species indicated by the node within the square.



Solution to part a: Humans and their most closely related species have an 8.8% (choose the species with least percent divergence) difference. Thus, we take this quantity and divide by 7 to get the rate of mtDNA percent divergence per million years.

$$\frac{8.8}{7} \approx \boxed{1.26}$$

Solution to part b: Keep in mind that humans and chimpanzees can be switched because there is no difference between mitochondria DNA from each group (the dash means there is no difference in mitochondria DNA).



Solution to part c: Via inspection of the cladogram, we find that the mitochondrial DNA of gibbons is the least similar out of all species, followed by orangutans and gorillas (reading from farthest to closest branches).

Problem 7.14.6 — 2022 AP Biology FRQ

Existing isolated brook trout populations in Newfoundland, Canada, were once part of a larger population that was fragmented at the end of the most recent glaciation period about 10,000 to 12,000 years ago. Researchers investigated 14 naturally separated steam populations of brook trout. They found that the populations are all genetically distinct and show differences in morphology.

(a) **Describe** the prezygotic barrier that results in these genetically distinct populations.

(b) Brook trout with longer fins are able to swim faster than brook trout with shorter fins. In one of the Newfoundland streams, the main prey of the brook trout evolved to move faster. For brook trout living in this stream, **explain** the difference in fitness between longer-finned individuals and shorter-finned individuals.

(c) If two morphologically and behaviorally distinct populations of trout remain isolated for many generations, **predict** the likely impact on both populations.

(d) Researchers claim that there are more genetic differences between any two current brook trout populations than there are between any single current population and the ancestral brook trout population from which all the trout are descended. Provide reasoning to **justify** their claim.

Solution to part a: Geographic isolation prevented gene flow between the two populations and led them to evolve on their own.

Solution to part b: Fish with longer fins could swim faster, and were more likely to survive and reproduce because they were more likely to catch their prey.

Solution to part c: The two populations would continue to diverge and may become two separate species.

Solution to part d: The populations experienced genetic drift differently and became more different from the ancestral species over time. They also likely accumulated different mutations due to different selective pressures.

8 Ecology

Welcome to ecology, the most fascinating unit of AP Biology! Ecology studies the interactions between organisms and their environment, both at small and large scales. These relationships are dynamic and constantly changing. Human impact and other major issues are contributing to significant changes in global ecosystems. We will explore communities, the concept of biodiversity, energy flow, symbiotic relationships, trophic levels, population growth, and the health and resilience of ecosystems.

§8.1 Responses to the Environment

In the environment, several changes occur simultaneously. In order to survive, organisms constantly respond to their own environments. Some examples include worms crawling towards moisture, or a flower opening up in sunlight. In this section, we will explore how organisms respond to their surroundings in order to improve their chances of survival.

How Organisms Adapt to Change The manner in which organisms grow, reproduce, and maintain homeostasis is dependent upon their responses to environmental cues. **Environmental sensing** refers to the ability of organisms to detect and respond to changes in their environment. This is achieved through a variety of behavioral and physiological mechanisms that organisms have developed as they evolved over long periods of time. In turn, they can optimize changes of survival and reproduction (which leads to evolution!).

Understanding the Organism - Environment Relationship Two ways organisms respond to their environment are through behavioral and physiological mechanisms. As you read, we will unpack these two forms of environmental sensing.

- **Behavioral mechanisms** involve modifying or adopting certain habits for organisms to adapt to their environment. For example, migratory birds use the position of the sun and stars to navigate the cardinal directions during their annual migration. Additionally, several species of insects track the onset of reproduction using differences in day length.
- **Physiological mechanisms** involve changes in activity of genes, enzymes, and certain hormones in response to environmental cues, especially stresses. For example, many plants change the shape of their leaves in response to changes in light intensity, which helps them to optimize their photosynthesis and avoid overheating. Similarly, many animals change the color of their skin or fur in response to changes in temperature, which helps them to regulate their body temperature.

Likewise, several environmental factors, e.g. changing temperatures, weather patterns, an increase or decrease in the amount of food and water or availability of shelter can lead to changes within an organism.

Some examples include:

- **Photoperiodism** in plants is the ability of plants to sense changes in the length of daylight and to use this information to regulate growth and development.

Many plants use the length of daylight to time the onset of flowering. Short-day plants, such as poinsettias, will only flower when the days are shorter than a certain critical length, while long-day plants, such as wheat, will only flower when the days are longer than a certain length. This allows plants to time their reproduction to coincide with optimal conditions.

- **Phototropism** is the ability of plants to sense changes in the direction of light and to use this information to orient their growth. For example, plants will grow towards light to optimize their photosynthesis.

- **Taxis** in animals refers to their ability to move towards or away from a stimulus, such as light or a specific chemical.

Many insects, e.g. dragonflies, are attracted to light, which they use to navigate towards food sources or mates.

- **Kinesis** in animals refers to the ability to change the rate or direction of their movement in response to a stimulus, e.g. light or a specific chemical.

- **Nocturnal** and **diurnal** activity refer to the different patterns of activity that animals exhibit during the day and night. Nocturnal animals are active at night and sleep during the day, while diurnal animals are active during the day and sleep at night.

Lions are diurnal animals, while owls are nocturnal animals. These patterns of activity are usually determined by the availability of food and predators, as well as the temperature and light conditions.

- **Fight-or-flight** response is a physiological response to perceived threats or danger. This behavior is characterized by the release of adrenaline and other hormones, which prepare the body for physical activity, e.g. fighting or escaping. This response is triggered by the activation of the **sympathetic nervous system** and it increases the heart rate, blood pressure, and muscle tone.

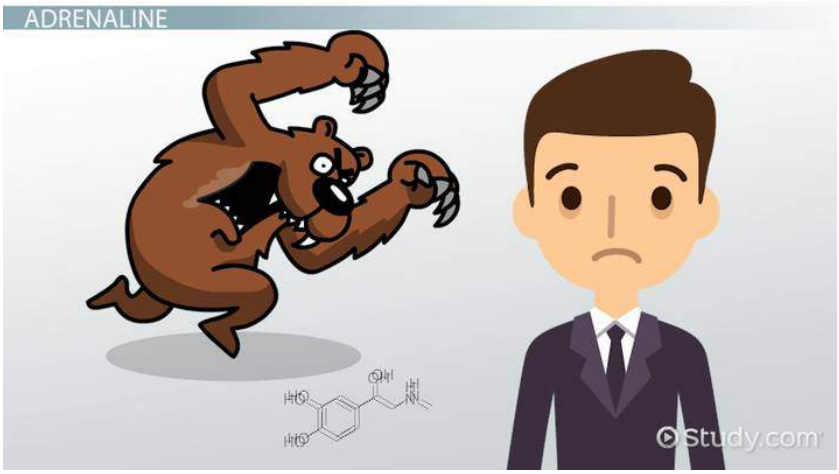


Image Credit: Study.com

- **Predator warnings** represent the communication of danger by one organism to others of the same species.

When a bird spots a predator, it emits a specific alarm call that alerts other birds in the area to the danger. This allows them to take evasive action before the predator can attack. Some plants also have mechanisms to warn other plants and release chemical signals to indicate a herbivore attack.

Understanding the Organism - Organism Relationship Organisms can, obviously enough, communicate with each other. Different species have their own unique mechanisms for communication. This can involve the release of **hormones, behavioral patterns, mating dances, warning calls**, or any other number of responses.

These forms of communications may occur via physiological responses from an organism, meaning something that occurs within themselves, e.g. hunger, or through environmental changes, e.g. the approaching of a predator. Remember that just like humans, many species communicate using **verbal** and **nonverbal** cues. This can involve audible warning signs and visible body language shifts. Some animal species have far more communication

patterns than us humans!

Many times, organisms communicate environmental changes in order to **protect** members of their species. For example, prairie dogs are known to be very visible and give loud warning calls so that their own family and community members can hear if a predator is approaching. You might think this would make them more susceptible to the predator, but this behavior still increases the chances of their genes being passed on to the family members who survive the attack.

Evolutionary Connections Responses to communication of information and the information itself are crucial to **natural selection** and evolution processes. The reason being, being able to sense and respond to environmental cues, as well exchange information with other individuals, can significantly impact organisms' survival and **reproductive fitness**.

We know that natural selection tends to favor innate and **learned behaviors** that increase fitness. Intuitively enough, animals that detect and avoid predators, find food and mates, are more likely to survive and reproduce than those who cannot. Similarly, plants that can defend themselves from herbivores, or optimize changes in light intensity, are expected to be the fittest.

Cooperative behavior, such as cooperative hunting, child-rearing, caring for elderly members of a family, and **mutualism** in plants and animals, can increase fitness odds of the individual and population survival. In particular, cooperation allows individuals to work together and achieve a common goal, such as finding food or protecting against predators, which is usually more effective than being solitary.

Image Credit: Nature

Problem 8.1.1 — Multiple Choice Question

When foraging honeybees return to their hive, they communicate information about food sources through a behavior called a waggle dance. The waggle dance allows the dancer bee to communicate the direction, distance, and quality of a food source to the bees watching the dance, which are called followers. Followers can then fly efficiently to the indicated food source, bringing more food back to the colony.

Which of the following describes the most likely evolutionary explanation for the honeybee behavior described above?

(A) The waggle dance leads to more bees leaving the hive and starting new colonies, freeing up resources for the dancer bee's colony.
(B) The waggle dance directs the behavior of the follower bees, which increases the overall fitness of the bee colony.
(C) The waggle dance points other bees away from a food source, ensuring the food source remains abundant for the dancer bee.
(D) The waggle dance recruits foragers from other hives to bring food to the dancer bee's colony.

Solution: The waggle dance helps the bees work cooperatively for the benefit of the colony, not for leaving the hive and starting new colonies, so eliminate (A). Additionally, (C) is wrong because the waggle dance points other bees *towards* a food source, benefiting all members of the colony, not only the dancer bee. Finally, the waggle dance is a method of communication with members of a bee's own colony, and not used to recruit foragers from other hives. Eliminate (D). The most likely evolutionary explanation for the honeybee waggle dance is that it directs the behavior of follower bees, which increases the overall fitness of the bee colony by allowing efficient foraging and resource gathering. The correct answer is $\boxed{\textbf{(B)}}$.

Problem 8.1.2 — Multiple Choice Question

Which of the following is an example of a behavioral adaptation that increases an animal's fitness?

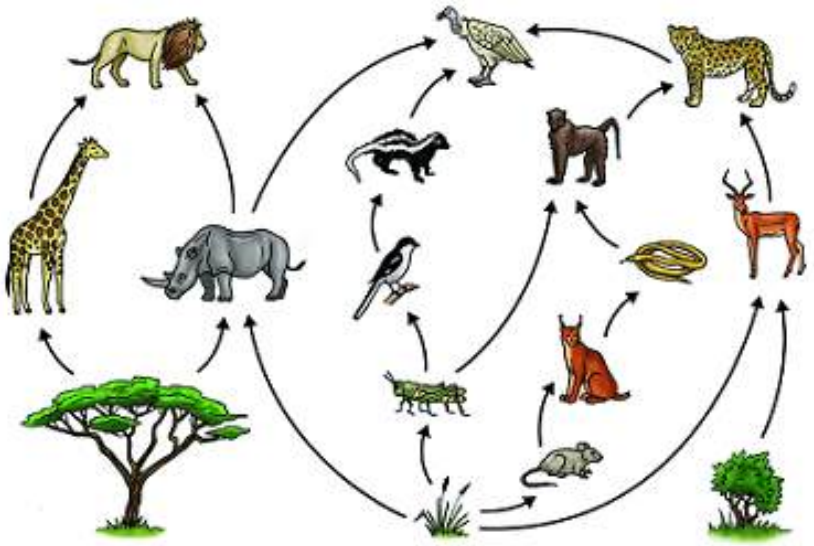
(A) Having thick fur to stay warm in winter
(B) Producing a loud call to attract a mate
(C) Being able to store water in its body
(D) Having sharp claws to catch prey

Solution: Options (A), (C), and (D) describe structural adaptations, which are based on physical traits, not behaviors. The correct answer involves the animal's behavior (the act of calling) to increase its fitness to attract a mate, which increases the chance of reproductive success. The correct answer is $\boxed{\textbf{(B)}}$.

§8.2 Energy Flow Through Ecosystems

All living organisms need **energy** to function. The energy shared by all species originates from the Sun. In an ecosystem, energy flow refers to the unidirectional movement of solar energy through producers (plants) via photosynthesis, to consumers (herbivores and carnivores) at different trophic levels, with energy being lost as heat at each step, essentially following the concept of a food chain or food web.

Understanding Trophic Levels **Trophic levels** are the pathways through which energy flows through an ecosystem. Herein, an organism exists based on what it eats. Two types of organisms we will talk about in this section are **autotrophs** and **heterotrophs**. The former produce their own energy (e.g. plants, photosynthetic bacteria, etc.) while the latter receive their energy from other organisms (e.g. mammals, birds, fish, etc.).

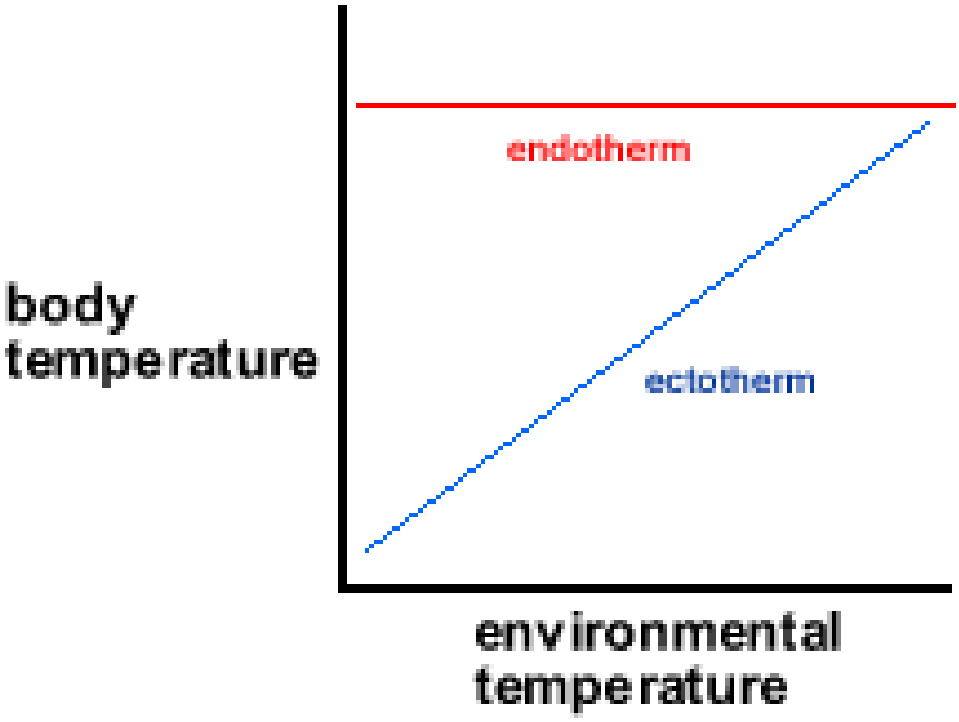


The survival of all organisms is heavily dependent on the maintenance of energy levels. An organism that uses more energy than what it gains will experience a loss of mass and may die. Meanwhile, an organism that gains more energy than it uses will experience a net positive gain in energy and will be able to grow and store energy for future use. The increase in internal energy is vital to the ability of organisms to survive and reproduce.

Maintaining Energy Maintaining the energy is just as important to organisms as storing it. There are two major strategies for organisms to maintain heat and energy within their bodies.

- **Endotherms** maintain a level temperature in their bodies. As humans, we are prime examples of endotherms, as we generally maintain a temperature ranging from 97 to 99 degrees Fahrenheit. Most of the energy that endotherms get from food is used to maintain their internal temperature.
- **Ectotherms** do not maintain a stable internal temperature. Examples of ectotherms are snakes and fish. To maintain a stable temperature, they must change their behavior. This is usually done in the form of winter hibernation or sunbathing during the summer.

Generally, the mass of an organism is correlated to the amount of energy which is metabolized. Typically, smaller organisms have an increased **metabolic rate**. Ants should metabolize energy much faster than we humans do.



More Discussion on Energy Different organisms have their own reproductive strategies to adapt to limited energy availability. For example, annual plants can reproduce quickly and produce many offspring in little time, while many trees reproduce more slowly and invest more energy into producing less offspring. The strategy of maximizing the chances of each offspring surviving to reproduce is known as *r-selected* and *K-selected*, respectively.

The *size* of multicellular organisms is inversely related to their *metabolic rate*. This is because the ratio of surface area to volume *decreases* as the size of an organism *increases*, i.e. smaller organisms need to work harder to maintain their body temperature and obtain food.

1. A net gain in energy results in the growth of an organism or having its energy stored. For example, when more food is consumed than needed for survival, the excess energy (in the form of calories) is stored as either fat or glycogen. This stored energy can come in handy when food is scarce or when the organism needs to reproduce. Moreover, a net gain in energy can be used in growth and development processes, such as new cells and tissues.

2. A net loss of energy results in reduced mass. For example, when an organism does not consume enough food, it will lose weight. If the energy deficit is prolonged, it will result in the organism's death. Cellular respiration and other metabolic processes can be responsible for a loss of energy. If organisms do not have enough energy to maintain their vital functions, they will die.

Additionally, organisms have their own mechanisms (e.g. thermoregulation, hibernation, etc.) to balance the constant transfer of energy. For example, animals will reduce their metabolic rate to conserve energy in cold weather, and in hot weather, increase their metabolic rate to release heat from their bodies. Similarly, organisms can enter *dormant*, or inactive states to survive periods of scarcity.

Potential Disturbances to Ecosystems Changes in energy availability can not only disrupt organisms' health, but also the overall ecosystem. Energy forms the basis of all life, and changes to the availability of energy resources can have a significant impact on the health and functioning of an ecosystem.

1. A **change in energy resources**, such as the presence or absence of sunlight, can affect the number and size of trophic levels in an ecosystem. A decrease in sunlight can reduce the productivity of primary producers (e.g. plants) which then affect the size and number of herbivores and carnivores that depend upon them for food. However, an increase in sunlight increases the productivity of primary producers, which means that more herbivores and carnivores will be able to benefit from them as food sources.

2. A **change in the producer level** can also affect the size and number of trophic levels present in an ecosystem. For example, a decrease in the population of producers will reduce the size and number of herbivores, which can then reduce the size and number of carnivores that depend on them for food, and vice versa.

3. Finally, **changes in energy availability** can influence biodiversity and distributions of species populations in an ecosystem. For example, some species can adapt better to new environmental conditions than others. Similarly, a variation in primary producers' productivity can change the distribution of corresponding herbivore and carnivore populations, because some species can exploit food sources better than others.

Let's conclude this section with a couple of multiple-choice questions.

Problem 8.2.1 — Multiple Choice Question

The Sundarbans are a coastal area in India and Bangladesh that contains the world's largest mangrove forest ecosystem. The dominant mangrove tree in the Sunderbans, *Heritiera fomes*, grows in salty coastal water, sending aerial roots above the water surface to help get oxygen.

The roots of the mangrove trees provide food and habitat for many species of invertebrates and fish, which provide a food source for various snakes and birds. These animals, in turn, are eaten by the main predator of the Sundarban, the Bengal tiger.

Which of the following best describes *H. fomes* in the Sundarbans mangrove forest ecosystem?

(A) *H. fomes* is an autotroph, because it uses photosynthesis to produce sugar molecules that it can use as food.
(B) *H. fomes* is a heterotroph, because it harnesses energy from dead organisms decomposing near its roots.
(C) *H. fomes* is a heterotroph, because it provides food for various species of invertebrates and fish.
(D) *H. fomes* is an autotroph, because it uses chemical energy from inorganic salts to produce its own food.

Solution: We eliminate (B) and (C). Heterotrophs are organisms that consume other organisms for energy. However, *H. fomes* harnesses energy from sunlight to produce its own food. This means that chemical energy from inorganic salts is not harnessed by the tree, so we eliminate (D). *H. fomes* actually carries out photosynthesis, making it an autotroph, harnessing energy from sunlight to produce sugar molecules it can use as food. The correct answer is $\boxed{\textbf{(A)}}$.

Problem 8.2.2 — Multiple Choice Question

The following table shows the internal body temperature of a black rat snake during activities carried out under different environmental conditions.

Black rat snake activity	Internal body temperature
Coiled on a rock in the sun	27°C
Resting inside a barn	26°C
Moving through a forest during the day	23°C
Moving through a forest at night	20°C

Which of the following statements is most likely true about the black rat snake described above?

(A) The black rat snake is ectothermic, so its body temperature changes substantially depending on the temperature of its surroundings.
(B) The black rat snake is endothermic, carrying out certain behaviors in order to maintain a constant body temperature.
(C) The body temperature of the black rat snake remains relatively stable, whether it rests in the sun or uses its muscles to move across the forest floor.
(D) The black rat snake primarily uses the thermal energy generated by its own metabolism to increase its body temperature.

Solution: Eliminate (C). The black rat snake's temperature differs by about 4 to 7 degrees Celsius when resting in the sun compared to moving in the forest, which is a substantial difference. Additionally, the substantial temperature changes in the black rat snake indicate that the organism lacks efficient internal mechanisms, such as using thermal energy from metabolism for maintaining its body temperature. Therefore, (D) is also incorrect. As the black rat snake carries out various behaviors to maintain its internal temperature in different environments, they are an *ectothermic*, not endothermic, species. We finally eliminate (B) and select $\boxed{\textbf{(A)}}$.

§8.3 Population Ecology

Population ecology is a subfield of ecology that focuses on the dynamics of species populations and how they interact with their environment. In this section, we will examine the factors that affect the size and distribution of populations, as well as their potential for survival and reproduction.

Understanding Populations A **population**, as defined by the AP Biology Course and Exam Description, is a group of the same species living in the same area. For example, people living in New York City, sparrows in a single nest, or a group of pine trees growing in a forest can each be called a *population*. Populations can vary in size, density, and distribution—characteristics subject to change when environmental changes, such as resource availability or species interactions. Different populations are also likely have a different genetic makeup, affecting their ability to adapt to and survive changing conditions.

Population ecology focuses on understanding certain population dynamics and how

different factors, such as competition, predation, and habitat availability, impact the health and growth of species in living systems.

Finally, understanding populations can help humans approach conservation and ecosystem management efforts as well as informing how species interactions affect the overall functioning of ecosystems.

Population Survival Some important factors must be fulfilled for a population to survive. These factors are divided into two categories: **biotic factors** (these have to do with interactions between members of a population and other living organisms) and **abiotic factors** (related to physical and chemical characteristics of the environment). Here are some examples of factors that are significant for population survival.

- **Access to resources**: Populations need food, water, oxygen, and shelter in order to survive and reproduce. The variation in availability for these resources is reflected in the size and distribution of various populations.
- **Habitat**: Populations require a stable habitat where they live and reproduce comfortably. Habitat loss and environmental degradation (e.g. deforestation, agriculture, urbanization, etc.) can have major negative impacts on population survival.
- **Competition**: Populations within or among species are likely to compete with each other for limited resources, e.g. food, water, and mates (for reproduction). The results of this competition can influence the survival and reproductive success of individual members of different populations.
- **Predation**: Different species can prey on each other, which can affect populations' chances of survival and reproduction.
- **Disease**: Populations can suffer from the spread of disease, which generally result in a significant decline in size.
- **Climate**: Changes in climate (e.g. temperature, precipitation, and extreme weather events) can affect the availability of resources and habitats at any moment in time for various species.

Important Equations Certain mathematical equations can be used to measure various events and interactions within a population. The following equation for population growth measures a population:

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

where:

- dN is the change in population
- dt is the change in time
- B is the birth rate
- D is the death rate

This equation is in your formula sheet, and it will come in handy for some multiple-choice questions in the AP exam.

Problem 8.3.1 — Measuring Population Growth

In a population of koalas, there were 31 births and 8 deaths during the past year. What was the change in population over the course of the year?

Solution: Set up the equation

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

We know that B and D are 31 and 8, respectively. We wish to find $\frac{dN}{dt}$, so we simply subtract, yielding

$$\frac{dN}{dt} = 31 - 8 = \boxed{23}$$

The overall change in population is +23, so the population increased by 23 koalas over the course of the year.

Exponential Growth **Exponential population growth** is a form of population growth in which the size of a population increases geometrically by a constant factor over time. For exponential population growth to be valid, three conditions must be met:

1. There are no **limiting factors**, i.e. a population with with unlimited access to resources and suitable habitats has the greatest potential for exponential growth.
2. The population has a **high reproductive rate**: as individuals in a population can produce a large number of offspring in a short period of time, exponential growth is likely to occur.
3. The population has a **low mortality rate**: when the birth rate of new individuals quickly exceeds the number of individuals who die off, the population has the potential to grow exponentially.

In the long run, exponential growth is not favorable for a population because the environment's **carrying capacity** will soon be reached. Essentially, the population can no longer continue to grow at the same rate due to limited resources and other factors. In the short term, however, exponential growth can have significant impacts on the environment and availability of resources for other species in an ecosystem.

There is another equation, also provided on the AP exam, that is used to calculate exponential growth:

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

where:

- dN is the change in population size
- dt is the change in time
- r_{max} is the maximum per capita growth rate of the population
- N is the population size

Definition 8.3.2

The **per capita growth rate** of a population is defined as the rate at which a population of a species increases or decreases for a given set of resources and conditions, such as food availability or predation.

Problem 8.3.3 — Measuring Exponential Population Growth

A population of 734 koalas has a per capita growth rate capped at 0.025. After one year, what is the new population size?

Solution: The way we will approach this problem involves two steps. First, we will calculate the change in population after one year using the exponential growth formula, and then add it to the initial population (734 koalas). We proceed with the following:

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

$$\frac{dN}{dt} = (0.025)\,(734) = 18.35$$

The population grew by 18 in one year, so the new population is $734 + 18 = \boxed{752}$.

Example 8.3.4

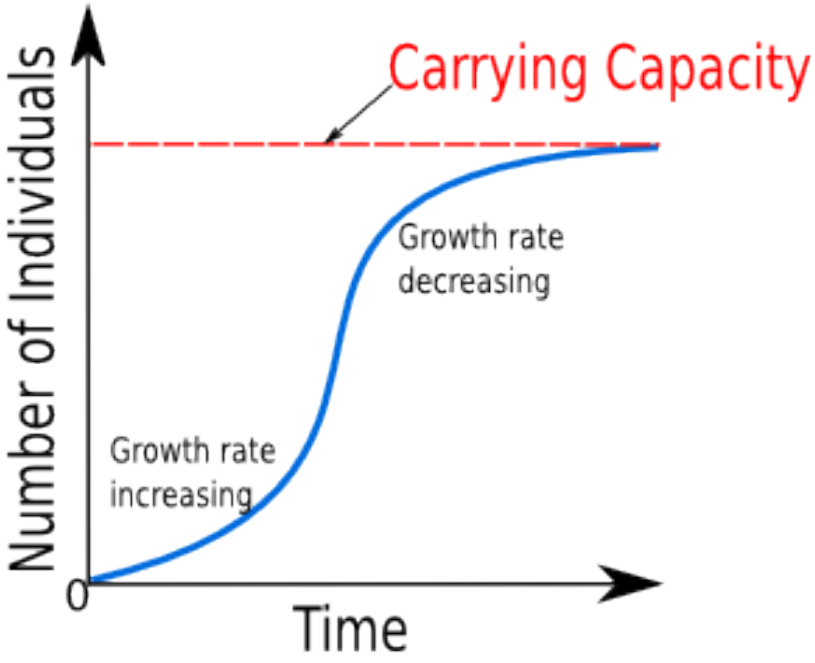
In the 19th century, European rabbits were introduced to Australia. Initially, they were brought for hunting purposes, but they quickly became an *invasive species* (a non-native organism that causes harm to the ecosystem into which it has been introduced) and spread across the content due to their rapid reproductive rate. A female European rabbit can have up to six litters per year, with each litter containing an average of four to six offspring. The exponential growth of the European rabbits had detrimental effects on Australian ecosystems, such as

- Resource competition: European rabbits competed with native species for food and habitat, which led to declines in populations of several native species.
- Habitat destruction: The rabbits caused significant damage to the landscape by burrowing and feeding on native vegetation, leading to habitat loss and degradation.
- Economic impact: As European rabbits damaged crops and pastures, farmers and ranchers suffered major losses.

Despite efforts to limit the rabbit population, exponential growth has unfortunately allowed the European rabbit to continue damaging Australia's ecosystems today.

Logistic Growth For this course, and most real-life situations, population growth is logistic. This growth model is characterized with an S-shaped curve, a rapid initial increase in population, followed by a slow rate of population growth as it approaches the environment's **carrying capacity**. Logistic growth starts with traditional exponential

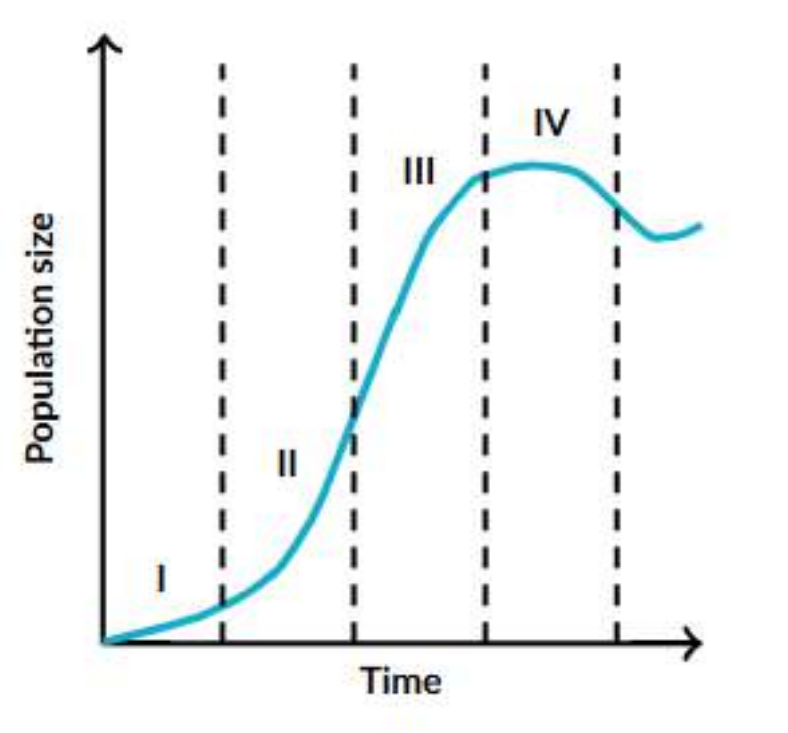
growth, but is quickly limited by factors such as resource availability, predation, and habitat. These limiting factors eventually lead to a population leveling off, or stabilizing, at or near its carrying capacity, the maximum number of individuals that an environment can support.



For example, consider the relationship between wolves and elks in the Yellowstone National Park in the mid-1990s. The primary limiting factor in their relationship is predation. Because wolves prey on elk for food, the latter's population decreased as the former species returned to Yellowstone because they experienced predation pressure to check their population size. It is important to note that this relationship works in both directions. Specifically, if the wolf population were to grow too large, there would not be enough elk to feed them all, which means that elks create a bottom-up limiting factor on wolves.

Problem 8.3.5 — Multiple Choice Question

A group of researchers measured the size of a population of mockingbirds over time. Their results are shown in the graph below.



Which of the following parts of the graph best represent when the growth of the mockingbird population was limited by the availability of resources such as food or nesting sites?

(A) I only
(B) I and II
(C) III only
(D) III and IV

Source: Khan Academy

Solution: Both Parts I and II of the graph represent a phase of near-exponential growth for the mockingbird population. The population is not significantly limited by resource availability. However, in Parts III and IV of the graph, the population curve begins to level off and slowly decline. So, these parts of the graph represent a transition from unlimited growth for the mockingbird population to growth that is limited by resource availability, and we pick $\boxed{\textbf{(D)}}$ as the answer.

§8.4 Effect of Density of Populations

Population density is the concentration of individuals within a species in a specific geographic area. Population density data can be used to quantify various types of

information and to assess relationships among ecosystems. In this section, we will use population density to explain the concept of carrying capacity, predict changes in overall health and survival in response to changes in population density, and analyze the effects of limited resources.

Importance of Population Density Ecosystems have a certain **resource availability**—the extent to which natural resources are accessible and sufficient to meet the needs of a population—and populations can produce a density of individuals that exceeds this threshold. This results in **overpopulation**.

Overpopulation generally occurs when the population exceeds the carrying capacity—the maximum number of individuals that can be supported by the available resources—of the environment. Overpopulation can deplete resources, increase resource competition, and lead to a decline in the overall health and fitness of a population.

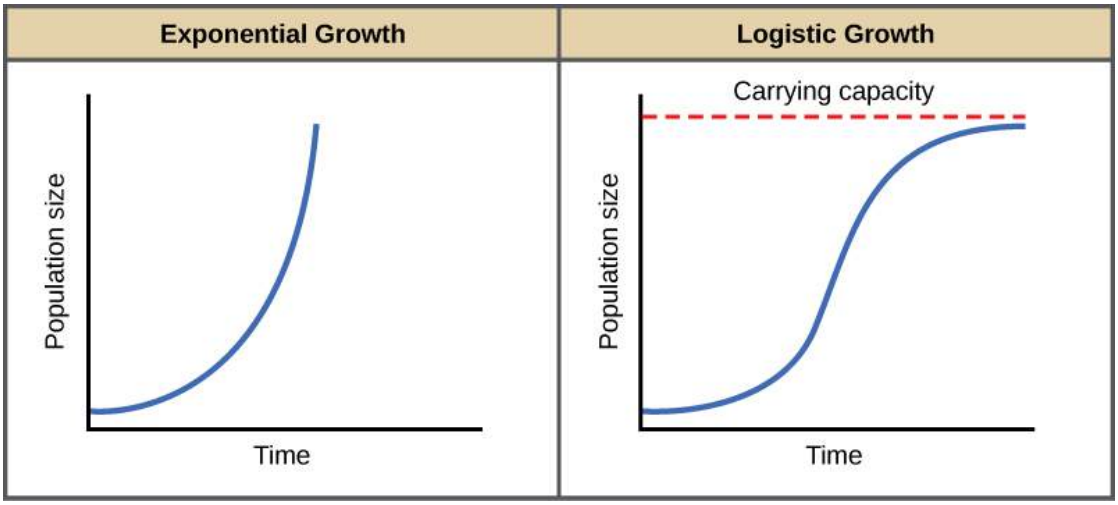
Density-Dependent Factors vs. Density-Independent Factors Populations often face circumstances that inhibit their ability to continue surviving and reproducing. These factors are broken down into two categories: density-dependent and density-independent.

1. **Density-dependent factors** are environmental factors that affect populations based on their density (depending on the size). Specifically, as the population size increases, the effects of density-dependent factors increases as well, and vice versa. Some examples of density-dependent factors are access to food, number of predators, disease, and migration. All these depend on the number of individuals in the population. Consider a small population; these individuals are less susceptible to a decrease in food as opposed to a large population that requires a lot of resources. In most cases, access to food is the density-dependent factor that has the greatest impact on populations.

2. **Density-independent factors** are environmental factors that can affect any population without regarding their sizes. The classic example of a density-independent factor is weather and climate. At the moment, climate change is affecting a variety of populations, regardless of their size. Global warming leads to habitat loss, reduced ability to adapt to changing temperatures, and loss of water sources. All of these factors can be devastating to any population.

Carrying Capacity Both density-dependent and density-independent factors impose limits on population growth. As the limits become more significant, a **logistic growth model** generally follows.

The model is based on mathematical calculations that describe how the growth rate of a population changes over time in response to the limits imposed. The logistic growth model predicts an initially high growth rate that starts to decline as the population approaches the carrying capacity of the ecosystem. Once the population reaches the carrying capacity, the growth rate stabilizes and then declines, reaching an **equilibrium population size**.



When carrying capacity is introduced in a population, exponential growth is no longer possible. Instead, ecologists measure logistic growth. The equation for logistic growth is given in your AP formula sheet, and it reads:

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

where:

- dN is the change in population size
- dt is the change in time
- r_{max} is the maximum per capita growth rate of the population
- N is the population size
- K is the carrying capacity

Problem 8.4.1 — Measuring Logistic Population Growth

A population of rabbits has a maximum per capita growth rate of 0.5 rabbits per year, a carrying capacity of 1000 rabbits, and an initial population size of 100 rabbits. Calculate the change in the rabbit population size after one year.

Solution: We wish to calculate $\frac{dN}{dt}$. The problem follows a logistic growth model. We proceed with the following:

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

In this case, we have $r_{max} = 0.5$, $N = 100$, and $K = 1000$. Substituting these values, we get the change in population size after 1 year to be

$$\frac{dN}{dt} = (0.5)\,(100) \left(\frac{1000 - 100}{1000} \right)$$
$$\implies \boxed{45 \text{ rabbits}}$$

§8.5 Community Ecology

You probably know what a community is. A community refers to any group of different populations living in the same area. For example, people, pets, and pests live together in New York City. In this section, we will explore the different types of relationships in a community, unpack the role of keystone species and their importance to the stability of an ecosystem, predict community changes based on shifts in species interactions, and analyze the impacts of rerouting certain species to and from a community.

Diversity of Species Communities can be of any size, and they can be found in various environments, e.g. terrestrial, aquatic, and even aerial. Species within a community interact through several processes, such as resource competition, predation, and mutualism, which have different effects.

When scientists and researchers study communities, they often measure the **species diversity** and **species composition** in the area, as these dynamics tell the ecosystem function, management, and methods of conservation. Species diversity reflects the number of species residing in the area and the proportion of the population represented by each species.

Both species composition and species diversity measure the structure of a community. For example, an environment with a vast quantity of unique species that is also evenly distributed is considered highly diverse. We can measure the diversity of a community by using **Simpson's Diversity Index**:

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

where:

- n is the total number of organisms of a particular species
- N is the total number of organisms of all species

Problem 8.5.1 — Multiple Choice Question

The following table lists the number of individuals of each species in a rainforest tree community.

Species	Number of individuals
A	165
B	654
C	120
D	196
Total	1135

Which of the following values represents the Simpson's Diversity Index for the rainforest tree community?

(A) 0.36
(B) 0.39
(C) 0.61
(D) 0.64

Solution: The equation we will use is

$$\text{Diversity Index} = 1 - \left[\left(\frac{n_A}{N}\right)^2 + \left(\frac{n_B}{N}\right)^2 + \left(\frac{n_C}{N}\right)^2 + \left(\frac{n_D}{N}\right)^2\right]$$

where n_A, n_B, n_C, n_D are the number of individuals in each of species A, B, C, and D, respectively, and N is the total number of individuals.

We can use the values provided in the table to calculate the Simpson's Diversity Index:

$$\begin{aligned}\text{Diversity Index} &= 1 - [\left(\frac{165}{1135}\right)^2 + \left(\frac{654}{1135}\right)^2 + \left(\frac{120}{1135}\right)^2 + \left(\frac{196}{1135}\right)^2] \\ &= 1 - 0.39 \\ &= \boxed{\textbf{(C)}\ 0.61}\end{aligned}$$

The health of a community, changes in species and populations with time, and the transfer of matter and energy are all determined by various relationships between populations. Examples include, but are not limited to, predation, competition, mutualism, commensalism, and parasitism.

Predation A relationship in which one organism eats another is called a **predator-prey relationship**. A predator in one relationship can be the prey in another.

Example 8.5.2

In a mouse-snake relationship, the snake eats the mouse. This makes the snake the predator and the mouse the prey. However, in a snake-hawk relationship, the snake becomes the prey and the hawk becomes the predator. The hawk eats the snake.

In ecosystems, predation is a top-down control on other species. Predators effectively limit prey populations, creating **trophic cascades** which affect the population sizes and behaviors at other ecosystem levels.

Interspecies competition is defined as relationships in which two species compete for the same habitat, food, water, etc. Consider two organisms that share a common food source. Competition is likely to result within this predation. For example, hawks and mongooses can compete for snakes as a food source. If one population is more fit to hunt prey, competition can lead to a decrease in the other predator population. Meanwhile, if both groups are equally fit, competition can also stabilize their populations.

Niche partitioning refers to the process by which different species divide and use resources in their own unique ways. Specifically, species adopt **ecological niches** to avoid competition between species.

Mutualism Mutualism is a relationship in which both species involved benefit or receive fitness. A classic example of mutualism is the relationship between bees and flowers, where bees collect nectar from flowers as food, while simultaneously transferring pollen from one flower to another, aiding in plant reproduction; both organisms benefit from this interaction.

Commensalism Commensalism is a relationship in which one species benefits, and the other species is neither helped nor harmed in the process. An example is epiphytic plants and large tree branches. Epiphytes are small plants that grow on large branches of trees and use them as structural support without harming or obtaining nourishment from them.

Image Credit: Britannica

Parasitism Parasitism is a relationship in which one species, the *parasite*, benefits at the expense of another species, the *host*. Parasites can be found in a variety of species, e.g. plants, animals, microorganisms, etc. Parasitic relationships are usually highly complex, involving multiple hosts and several life cycles. The relationship between a parasite and its host can range from relatively benign (only minor effects) to very harmful (resulting in serious illness or even death of the host). Some parasites are able to manipulate the behavior or physiology of their hosts in ways that increase the parasite's chances of survival and reproduction.

Parasitism and predation are similar in the way that one species experiences a benefit or increased fitness at the expense of the other. However, parasites are relatively small compared to the hosts they feed off of and usually feed on parts of other organisms rather than the entire organism, as seen in predator-prey relationships.

Consider the relationship between a tick (insect) and a dog (mammal). The former is small relative to the latter. The tick bites the dog's skin to feed on nutrients in the dog's blood. In addition, the tick carries several diseases that are likely to infect the dog. Ultimately, it is the tick that benefits and the dog that suffers in this relationship.

Image Credit: Sandia Animal Clinic

Problem 8.5.3 — Multiple Choice Question

Which of the following describes a mutualistic relationship?

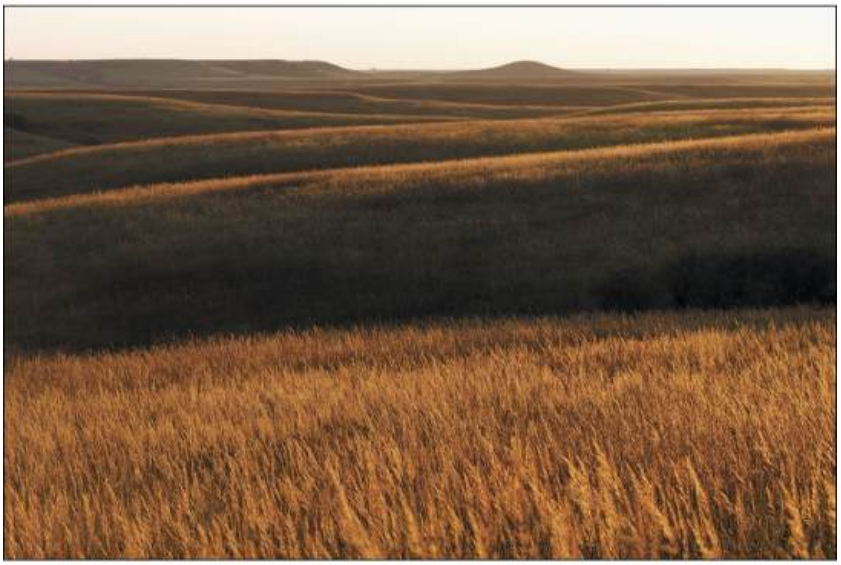
(A) A puffer fish's deadly toxin is made by Vibrio bacteria that live protected within the intestines of the fish.
(B) Ticks attach to a moose in the fall and feed on its blood throughout the winter, causing the moose to become anemic and weak.
(C) Cattle egrets have increased feeding rates when following cows because they eat the insects that fly up from the grass as the cows graze.
(D) The common spiny mouse and the golden spiny mouse are diurnal species, but in areas where they coexist, the common spiny mouse becomes nocturnal.

Solution: A mutualistic relationship between two organisms is one where both organisms benefit. In the case of option (A), the puffer fish gains a mechanism of defense against predators, and the bacteria gain a protected and nutrient-rich environment to live in. This is consistent with what we know about mutualistic relationships, but let's just make sure all the other choices are incorrect. In option (B), the tick benefits at the expense of the moose, so the relationship is parasitic. (C) is wrong because the cattle egrets benefit but the cows are unaffected. Finally, option (D) does not clearly state if either organism benefits from the relationship, so it does not make sense. We choose $\boxed{\textbf{(A)}}$ as the answer.

§8.6 Biodiversity

In this section, we will discover what biodiversity is, how it impacts an ecosystem, how it is influenced by human activity, and the relationship between biodiversity and ecosystem resilience.

(a)



(b)

The variety of ecosystems on Earth—from (a) coral reef to (b) prairie—enables a great diversity of species to exist. (credit a: modification of work by Jim Maragos, USFWS; credit b: modification of work by Jim Minnerath, USFWS)

Biodiversity and Ecosystem Impact We define biodiversity as the variety of different species of all organisms: plants, animals, etc. that exist within any particular ecosystem. It includes the diversity both *within* and *between* species. Ecosystems with a higher level of biodiversity are generally more adaptive to changes in the environment.

Genetic Diversity Genetic diversity refers to biodiversity *within* a species, and it is crucial to increase the adaptability and resilience of the species. Genetic diversity can provide the genetic variation that is needed for the species to remain fit and adapt to the ever-changing environmental conditions.

Consider the case of an infection caused by a specific pathogen. In a diverse population, it is likely that at least a few individuals possess a level of immunity or an ability to fight off the disease. On the other hand, a population with low genetic diversity would more likely be vulnerable to extinction because most individuals will respond similarly to the pathogen based on fewer genetic variations that may include resistance.

Genetic diversity is also important for maintaining the health and viability of species. Consider a species with low genetic diversity. They are more prone to inbreeding, which can reduce the fertility rate and increase susceptibility to various diseases. In contrast, a more genetically diverse species has more options to develop resistance to ecosystem challenges due to the greater availability of different alleles in the population.

Note 8.6.1

An increase in genetic diversity for a species **always** increases the protection from environmental and ecosystem challenges. No exceptions!

Species Diversity Species diversity refers to the biodiversity between different species. This form of biodiversity is equally important to the health and functioning of ecosystems. More species in a single ecosystem allow for more unique roles that contribute to its stability. Less diverse ecosystems are at greater risk of extinction if opposed to extreme events, e.g. natural disasters or food and/or water shortages. This is because they lack a larger number of species that could adapt to environmental conditions.

Keystone Species Keystone species tend to have a disproportionate effect on an ecosystem. In extreme cases, their mere presence can lead to disaster within an ecosystem.

Example 8.6.2

Sea otters compose a large part of the marine ecosystem. By preying on sea urchins, which consume seaweed (kelp), otters help protect kelp forests. Because kelp forests act as a niche for several other organisms in the marine ecosystem, otters provide an **ecosystem service**.

Although otters are beneficial to the ecosystem as a whole, a sudden change in their population can affect the population of other species. If the otter population decreases, then a habitat ripple effect occurs, putting the ecosystem at a significant risk of collapse.

There are three more types of keystone species, namely, pollinator keystone species, engineer keystone species, and predatory keystone species.

1. **Pollinator keystone species** include bees and hummingbirds, which share a mutualistic relationship with producers. Bees benefit from flower nectar, while pollination spreads plant gametes to aid reproduction and genetic diversity within the population.

2. **Engineer keystone species**, such as elephants and beavers, create habitats for other species similar to sea otters. By knocking trees and branches, elephants create a source of food and a more accessible habitat for smaller organisms.

3. **Predatory keystone species** control the population of prey species, creating a trophic cascade with top-down effects on ecosystems. Wolves in Yellowstone National Park are a predatory keystone species that control the elk population, preventing overgrazing on vegetation. Predation preserves habitats of other organisms and prevents a single primary consumer from controlling the consumption of primary producers.

Increased species diversity results in more species being present to serve as keystone species, and provide ecosystem services.

Ecosystem Resistance and Resilience This concept is related to the susceptibility of ecosystems to damage. **Ecosystem resistance** is a measure of the effect of a disturbance on the functioning of an ecosystem. The more resistant an ecosystem is, the less it will be affected by environmental changes. **Ecosystem resilience**, on the other hand, measures the speed at which an ecosystem can recover after a disturbance. Having more biodiversity in an ecosystem increases both of these factors.

Problem 8.6.3 — Multiple Choice Question

A scientist is studying the relationship between ecosystem diversity and the likelihood of destabilization after environmental change. The scientist defines **ecosystem destabilization** as a significant change in an ecosystem's biomass in response to an environmental disturbance.

Which of the following best predicts what the scientist will find regarding the relationship between ecosystem diversity and destabilization?

(A) As ecosystem diversity increases, the likelihood of destabilization remains about the same.
(B) The likelihood of destabilization will be highest at high levels of diversity.
(C) As ecosystem diversity decreases, the likelihood of destabilization increases.
(D) The likelihood of destabilization will be lowest at moderate levels of diversity.

Solution: Ecosystems that are less diverse are less resilient, or less likely to bounce back, after a change in the environment. This means that less diverse ecosystems have a higher likelihood of changing and becoming destabilized after an environmental disturbance. This trend is consistent with answer choice $\boxed{\textbf{(C)}}$.

Problem 8.6.4 — Multiple Choice Question

African elephants are herbivores distributed throughout sub-Saharan Africa. These elephants live in communities that may include cattle egrets, olive baboons, and various reptiles and amphibians. African elephants shape their habitats in many ways, including by clearing paths through dense brush and digging into the ground to create water holes.

Which of the following scientific questions would be most helpful in determining if the African elephant is a keystone species in the communities in which it lives?

(A) Is total species diversity lower in areas where African elephants have been eliminated by poaching compared to areas where African elephants are present?
(B) Are African elephants more abundant than other herbivores in the communities they inhabit?
(C) If all of the African elephants in a certain community are removed, does the total number of remaining organisms in the community decrease?
(D) When African elephants are added to a community that they previously did not inhabit, does their population increase quickly?

Solution: Keystone species are species that help maintain species diversity in an ecosystem. However, they are not necessarily more abundant than other species in their communities, so (B) doesn't have to be correct. (C) is a trap: keystone species only play a role in maintaining species diversity, not the number of organisms, in their communities. Finally, a species that is a keystone in its own community may not necessarily thrive in another community, so eliminate (D). However, we would expect species to be lower in areas where keystone species have been eliminated. Investigating the scientific question

associated with option **(A)** would be most helpful.

§8.7 Disruptions to Ecosystems

All ecosystems face challenges in maintaining their overall health. In this section, we will unpack the effects of human activities, natural events, and other factors that impact the health, resilience, and recovery of ecosystems.

Evolution When ecosystems are disrupted, this often paves the way for **evolution**. This is due to changes in the environment that can create selective advantages for some species over others, such as the continued ability to survive and reproduce.

Remember that **adaptations** are heritable, genetic variations that increase the fitness of an organism. This allows genes to be transferred to offspring. **Natural selection** occurs when different heritable variations induce unique reproductive success. Mutations can introduce new **alleles** into a population, enhancing its fitness. However, mutations are random, so they are not specifically attributed to environmental pressures on an ecosystem.

Competition and Invasive Disruption Disruptions within ecosystems can also lead to competition between species, changing the size of populations. If the disruption decreases a certain type of resource, there may be an increase in competition intra-specifically (between members of a species) and inter-specifically (between members of different species). Species that are more successful in obtaining resources will survive and reproduce more.

Invasive species, whether introduced intentionally or unintentionally, can allow some species to exploit new ecological niches without the threats of predation or resource competition. Such species can outcompete other organisms, disrupting already-established ecosystem interactions.

An example of an invasive species is the introduction of the brown tree snake to Guam. Brown tree snakes came to Guam from the South Pacific as stowaways in ship cargo. With no natural predators to control their population, the brown tree snake population expanded rapidly, allowing it to wipe out small mammal populations and much of Guam's native bird species.

Anthropogenic Disruptions The most damaging disruptions to ecosystems are anthropogenic impacts or environmental changes caused by human influence. For centuries, human activities have led to habitat loss, extinction, pollution, invasive species, and rapid climate change. The result is that organisms that cannot adapt as quickly to changing environments are more vulnerable to becoming endangered or extinct.

Natural Disruptions Ecosystems can be disturbed due to natural changes in the environment. However, most of these natural circumstances are exacerbated by human activities. From geographical to meteorological events—such as flooding, forest fires, and earthquakes—natural disasters can permanently alter habitats and disrupt ecosystems.

Problem 8.7.1 — Multiple Choice Question

Which of the following are likely impacts of a city expanding into forested areas, if that expansion occurs without attempts to mitigate its effects? Select TWO answers.

(A) Certain populations in the forested areas will get smaller due to loss of habitat, leading to a decrease in biodiversity.
(B) The city landscape will absorb more heat than it did as a forest, affecting regional temperatures and weather patterns.
(C) The population density in the city center will decrease as people spread out, resulting in less pollution generated per block of the city center.
(D) The forested areas will have fewer trees and other resources, making it more difficult for invasive species to become established.

Solution: While city expansion may cause some people to move to suburban areas, it is unlikely to significantly decrease the overall population density in the city center, and even less likely to decrease pollution per block. Therefore, (C) is not correct. (D) is wrong because it is the opposite of the truth; removing trees and other resources in forested areas can actually create more favorable conditions for the establishment of invasive species. However, not only is the natural habitat of plants and animals destroyed in this process, leading to a significant decline in biodiversity, but also deforestation causes an increase in heat, which can disrupt regional temperatures and weather patterns which are important in ecosystem stability. The correct answers are $\boxed{\textbf{(A)}}$ and $\boxed{\textbf{(B)}}$.

Problem 8.7.2 — Multiple Choice Question

The brown rat is an omnivorous mammal native to central Asia. These rats can eat a huge variety of foods including birds, fish, insects, seeds, and roots. The brown rat is currently on an international list of invasive species.

Which of the following best predicts the consequences of introducing brown rats to an island where they did not previously exist?

(A) Without its typical food sources, the rat population will not be able to become established, and the island ecosystem will remain stable.
(B) The rat population size will likely remain small, and as a result the rats will not be able to outcompete other organisms for resources.
(C) The rat population will grow rapidly, disrupting the island's community structure by feeding on native plants and animals.
(D) Without any natural predators, the rat population will become established and help increase the species diversity of the island.

Solution: This is a definition question. The brown rat is classified as an invasive species, so its population is likely to grow exponentially after being introduced to a new island. The resulting rat population will feed on the island's native plants and animals, likely reducing their populations and disrupting the island's community structure. We can confidently state that the correct answer is $\boxed{\textbf{(C)}}$.

§8.8 Unit 8 Practice Questions

Problem 8.8.1 — 2014 AP Biology FRQ

As part of a new suburban development, a sports complex consisting of athletic fields and buildings is constructed in a formerly wooded area.

(a) **Predict** ONE ecological consequence on the local plant community that is likely to result during the site preparation and construction of the sports complex. **Justify** your prediction.

(b) To maintain the playing fields, large quantities of water and chemicals are applied regularly to the grass-covered areas. **Predict** ONE effect on the local animal community that might result from regular use and maintenance of the playing fields. **Justify** your prediction.

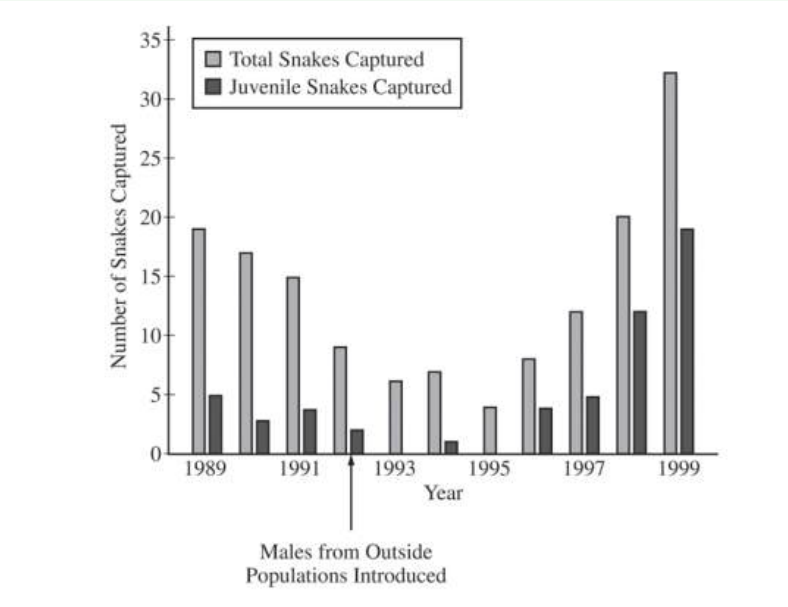
Solution to part a: A likely ecological consequence that is likely to result during the site preparation and construction of the sports complex is the destruction of plant habitats. Specifically, trees and shrubs would be removed to make way for the building, and a lack of ground cover would result in soil loss.

Solution to part b: One obvious effect on the local animal community as a result of regular use and maintenance of the playing fields is harm or death caused by exposure to toxic chemicals. Specifically, contaminated groundwater, chemicals accumulating within the ecosystem food chain, etc. can all harm animals living in the area.

Problem 8.8.2 — 2015 AP Biology FRQ

In an attempt to rescue a small isolated population of snakes from decline, a few male snakes from several larger populations of the same species were introduced into the population in 1992. The snakes reproduce sexually, and there are abundant resources in the environment.

The figure below shows the results of a study of the snake population both before and after the introduction of the outside males. In the study, the numbers of captured snakes indicate the overall population size.



(a) **Describe** ONE characteristic of the original population that may have led to the population's decline in size between 1989 and 1993.

(b) **Propose** ONE reason that the introduction of the outside males rescued the snake population from decline.

(c) **Describe** how the data support the statement that there are abundant resources in the environment.

Solution to part a: The decline in snake population which occurred between 1989 and 1993 may be attributed to a variety of factors. For example, an unfavorable sex ratio (too few males) would have inhibited sexual reproduction, causing less snakes being born. In the long run, this may have led to the decline seen in the 4 year period.

Solution to part b: If more male snakes from outside are introduced, a more favorable (balanced) sex ratio would have resulted, as there are now sufficient male-female pairs to achieve sexual reproduction. This genetic influx improved reproductive success and survival rates, as evidenced by the gradual increase in both total snakes and juvenile snakes captured after 1992. The presence of genetically diverse males reduced the negative effects of inbreeding and enhanced population growth.

Solution to part c: The data show a significant increase in both total snakes captured and juvenile snakes captured after 1992, particularly by 1999. This indicates that the population was able to grow rapidly once genetic diversity was restored, suggesting that environmental resources such as food, shelter, and breeding sites were not limiting factors for population growth. Abundant resources allowed for successful reproduction and survival of juveniles.

Problem 8.8.3 — 2016 AP Biology FRQ

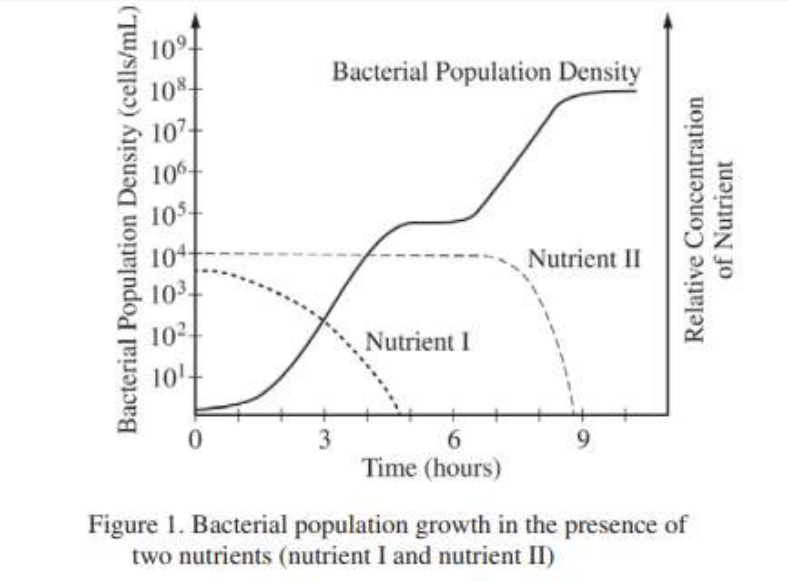


Figure 1. Bacterial population growth in the presence of two nutrients (nutrient I and nutrient II)

Bacteria can be cultured in media with a carefully controlled nutrient composition. The graph above shows the growth of a bacterial population in a medium with limiting amounts of two nutrients, I and II.

(a) **Estimate** the maximum population density in $\frac{\text{cells}}{\text{mL}}$ for the culture. Using the data, **describe** what prevents further growth of the bacterial population in the culture.

(b) Using the data, **calculate** the growth rate in $\frac{\text{cells}}{\text{mL x hour}}$ of the bacterial population between hours 2 and 4.

(c) **Identify** the preferred nutrient source of the bacteria in the culture over the course of the experiment. Use the graph to **justify** your response. **Propose** ONE advantage of the nutrient preference for an individual bacterium.

(d) **Describe** how nutrient I most likely regulates the genes for metabolism of nutrient I and the genes for metabolism of nutrient II. **Provide** TWO reasons that the population does not grow between hours 5 and 6.

Solution to part a: The solid colored curve on Figure 1 represents the population density (in $\frac{\text{cells}}{\text{mL}}$) for the bacteria culture. We observe that the highest point reached

by the solid curve is at approximately $\boxed{10^8}$. In order to identify what prevents further growth of the bacterial population, it helps to determine what causes its growth in the first place. The general trend in Figure 1 shows that in the presence of Nutrient I and Nutrient II, the population density of the culture increases. Thus, when both nutrients are depleted, further growth of bacteria in the culture is prevented.

Solution to part b: According to basic dimensional analysis, we need to determine the change in population density of the bacterial population and then divide by the elapsed time, in hours, to get a growth rate in units of $\frac{\text{cells}}{\text{mL x hour}}$. At hours 2 and 4, the bacterial population density is 10^1 and 10^4, respectively. Therefore, the growth rate of the bacterial population on this duration is

$$\text{growth rate} = \frac{10^4 - 10^1}{4 - 2} = \frac{9990 \, \frac{\text{cells}}{\text{mL}}}{2 \, \text{hour}} = \boxed{4995 \, \frac{\text{cells}}{\text{mL x hour}}}$$

Solution to part c: When both nutrients are in the growth medium, only nutrient I is used. Specifically, nutrient II is never used until after all of nutrient I is depleted. Based on this observation, we conclude that nutrient 1 is preferred. One advantage of using $\boxed{\text{nutrient I}}$ is that it provides more energy, i.e. growth medium does not have to spend energy making enzymes and proteins that the bacterial cells do not need.

Solution to part d: Because its presence in the growth medium is more favorable, nutrient I likely promotes gene expression required to metabolize itself. In the process, it represses the gene expression required to metabolize nutrient II. This happens because of two reasons; neither nutrient is being consumed (observe this on Figure 1 between hours 5 and 6) and it takes more time for nutrient I to produce proteins or enzymes required to metabolize nutrient II.

Problem 8.8.4 — 2021 AP Biology FRQ

Annual plants complete their life cycle, including germination, seed production, and death, within one year. *Ambrosia trifida* (giant ragweed) is an annual plant that readily colonizes any land that has had a disturbance such as plowing. The plant is considered an invasive species in regions outside of its native range. In a particular region, the seeds of A. *trifida* germinate from early March through the end of the summer, while the seeds of other annual plants require warmer soil temperatures and thus germinate from late April through the end of the summer.

Researchers studied the influence of A. *trifida* on the biodiversity of other annual plant species that grow in the same field. In early spring, the researchers marked off identical plots of land in a field that had been plowed the previous fall and not replanted with new crops. All plants that grew on one half of the plots were left untouched (Figure 1A), while all germinating A. *trifida* seedlings were removed from the other half of the plots throughout the spring and summer (Figure 1B). In late summer, the researchers counted and identified all plants that grew in the plots. The distribution of plants is represented by the symbols in Figures 1A and 1B.

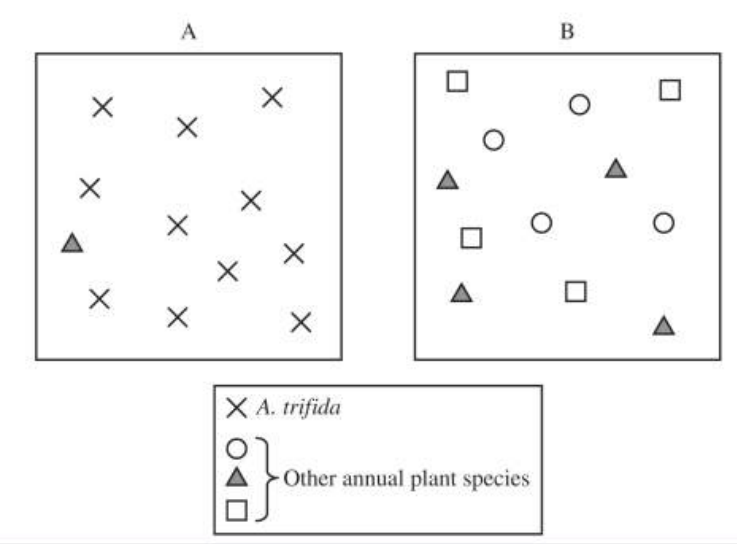


Figure 1. Representations of plant identity and distribution in experimental plots in late summer. Each box represents one typical experimental plot, and each symbol represents 10 individual plants.

(a) **Describe** a cause of logistic growth of the ragweed population.

(b) Based on the representation in Figure 1, **explain** why the scientists claim that plot B would be more resilient than plot A in response to a sudden environmental change.

Problem 8.8.5 — 2021 AP Biology FRQ (cont.)

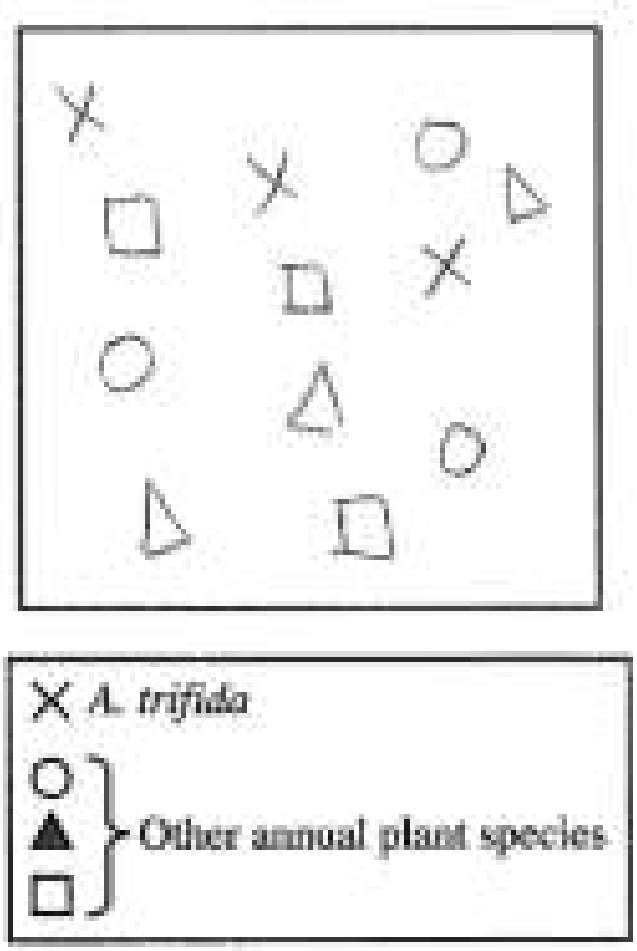
(c) In a third group of plots, the researchers removed all seedlings of all plants that germinated before June 1. All plants that germinated after June 1 were left untouched. Using the template in the space provided for your response and the symbols shown in Figure 1, **represent** the expected plant species that would be found in this third group of plots three months later. Draw no more than 12 symbols. Assume all other environmental conditions are the same as for the initial study described.

(d) **Explain** how an invasive species such as ragweed affects ecosystem biodiversity, as illustrated in Figure 1.

Solution to part a: Logistic growth is a model in which a population's growth rate initially increases, but starts to level off due to reaching its carrying capacity or the presence of limiting factors. The ragweed plant population could start to stabilize due to limiting factors in space, sunlight, nitrogen and phosphorus gases, and other density-dependent factors.

Solution to part b: Recall that the resilience of an ecosystem is directly correlated with the its species diversity. If scientists claim that plot B would be more resilient than plot A, we need to determine why the former has more species diversity than the latter. In plot A, the distribution of plants includes primarily *A. trifida*, with marginal presence of other plant species. However, plot shows an equal distribution of other annual plant species. Thus, plot B has greater species diversity than plot A, which supports the scientists' claim that it would be more resilient.

Solution to part c: Note that all four species, including *A. trifida*, must be present in the template. In addition, to maximize species diversity, we should have equal numbers of each plant species in the distribution. Since we can have a maximum of 12 symbols, we will include 3 of each plant species in the template.



Solution to part d: In this explanation, we must include a process or relationship, and state that biodiversity decreases in response to the presence of ragweed, an invasive species. There are several ways in which the ragweed could negatively impact ecosystem biodiversity. It has no predators, so it population grows faster, germinates earlier, using up resources, out-competing other plant species, all of which reduce ecosystem biodiversity.

Problem 8.8.6 — 2023 AP Biology FRQ

Sand lances of the genus *Ammodytes* are small fish that function as keystone organisms in several coastal ecosystems. These sand lances are prey fish that support organisms at higher trophic levels. Scientists performed experiments to examine how sand lance populations are likely to be affected by the rising temperatures and CO_2 levels associated with climate change.

Sand lance embryos typically develop and mature into adult fish at low temperatures (approximately 5°C) and stable, low CO_2 levels (approximately 400 μatm). Over the course of two years, the scientists measured the survival rate of sand lance embryos allowed to develop and mature in a laboratory at three different temperatures, 5°C, 7°C, and 10°C, with the level of CO_2 maintained at 400 μatm, 1,000 μatm, and 2,100 μatm for each temperature.

(a) **Describe** the effect of increased biodiversity on the resilience of an ecosystem in a changing environment.

(b) **Justify** the scientists' selecting 5°C as the lowest temperature and 400 μatm as the lowest CO_2 level in their study of sand lance embryo survival.

(c) **State** a null hypothesis for the experiment.

(d) The scientists claim that a reduction in the population size of the *Ammodytes* sand lances will affect the stability of the entire coastal ecosystem. Provide reasoning to **support** the scientists' claim.

Solution to part a: If the biodiversity in an ecosystem is increased, its resilience will increase. This is because a wider variety of species (increased species diversity) provides more options for adaptations and recovery from ecosystem disturbances, ensuring essential and overall functions continue even as some species are affected.

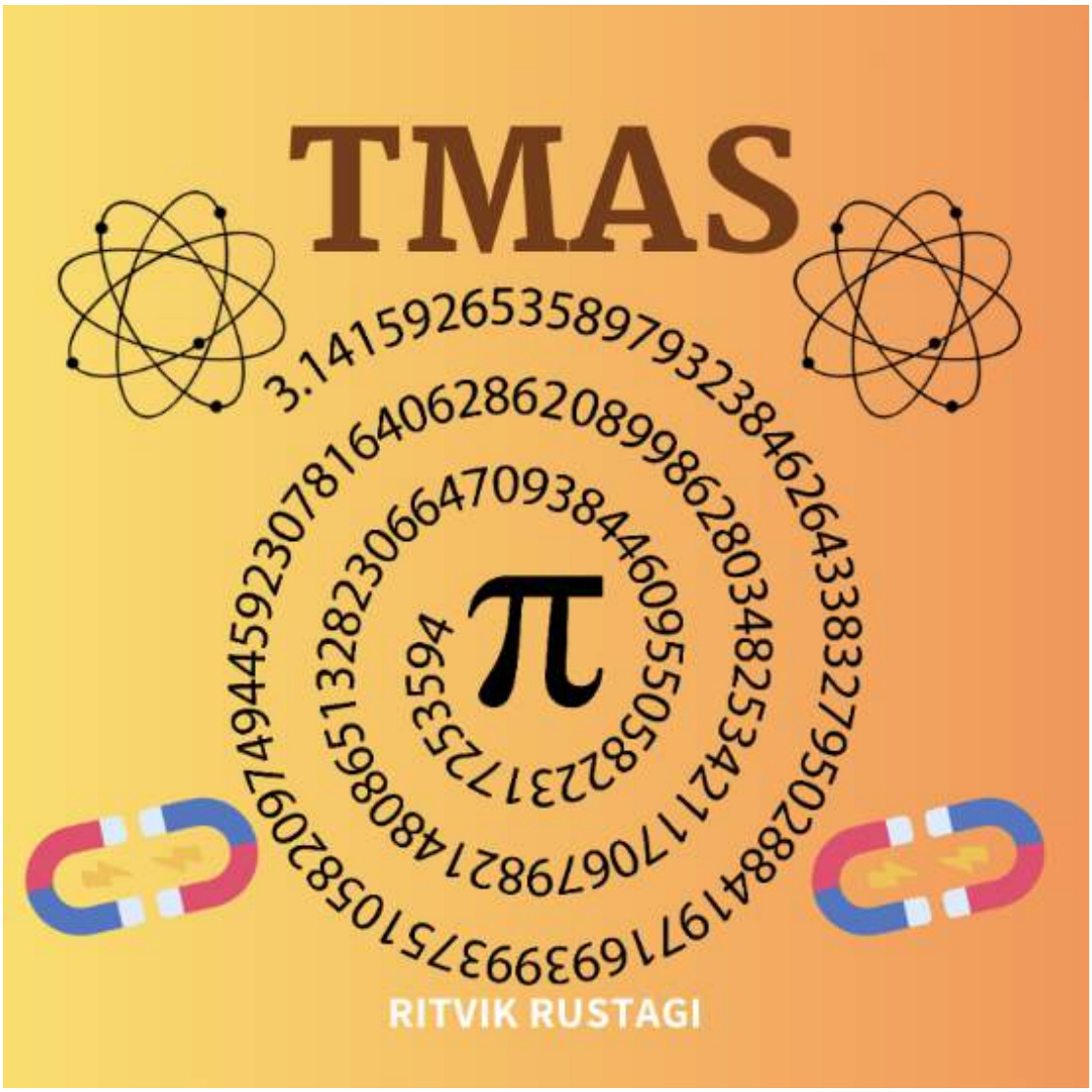
Solution to part b: The information in the problem statement states that sand lance embryos typically develop and mature at low temperatures of 5°C and stable, low CO_2 levels of 400 μatm. The scientists likely chose these normal conditions as a basis to compare the effects of changes in environmental conditions in response to increased temperatures and CO_2 levels.

Solution to part c: A null hypothesis is a hypothesis that says there is no statistical significance between the two variables. In experiments, it is usually the hypothesis that scientists aim to disprove. In these experiments, scientists want to test for a correlation between associated climate change and sand lance populations. Intuitively, the null hypothesis of the experiment is that increases in temperature and CO_2 levels will have no effect on sand lance embryos.

Solution to part d: The fact that a reduction in the population size of the *Ammodytes* sand lances will affect the stability of the entire ecosystem indicates that several

other species depends on the sand lance. There will be a negative effect on other trophic levels because the sand lance provides food for many other species. Alternatively, you could state that less energy would be transferred from lower to higher trophic levels if the population size of the *Ammodytes* sand lances were to decrease.

Thank you so much for reading this book! We are honored to have contributed to your academic journey in some way!



Thanks,

Aditya Baisakh, Amaan Shafi, and Abby Trinh