Course eBook

This course textbook was compiled from the content found in the Open Learning course created by Carnegie Mellon University: https://oli.cmu.edu/

Site:	University of the People
Course:	BIOL 1301 Introduction to Biology - Term 3, 2013-2014
Book:	Course eBook
Printed by:	Christian Thompson
Date:	Sunday, 2 February 2014, 4:12 AM

Table of contents

This eBook comprises the reading content required for this course.

Click on the Modules to the left to navigate the reading content.

The original content comes from the Introduction to Biology course, at the Carnegei Mellon University Open Learning Initiative (OLI) at this link: https://oli.cmu.edu/

The course modules at the OLI website have some interactive quizzes and 'learn by doing' activities which students may want to access directly.

Directions for accessin the original course and content at the OLI website (though all the main reading content is also copied here):

The content, interactive work, and readings for this course are found at the **CMI website** - You can log in here: https://oli.cmu.edu

Based on your academic profile you are specially invited to join the first offering of our new course Introduction to Biology (see full course description below), in partnership with world-renowned Carnegie Mellon University (CMU)!

This course will be the first offering in collaboration with CMU where you have the opportunity to utilize their innovative course materials in conjunction with our regular Moodle interface.

1. You must first test your system to ensure that you are able to access the course materials at the CMU site. If you plan on using more than one computer for your studies please test both computers.
2. Click the following to test and configure your system: https://oli.cmu.edu/configure/modern_biology-4.6_ccolibioopenfree-1.0.html
3. .If your computer is not compatible then you should not respond to this invitation at this time as you will not be able to access the required course materials.
4. Then you can log into your account and view the course reading materials at this link:
    - Access your course at: https://oli.cmu.edu/
5. The reading materials and resources for the course are hosted online, therefore a stable internet connection is required. The materials and resources are not available for offline use.

Course Introduction

To access the original content at the OLI website, click here: [Course Introduction](#)

The purpose of this course introduction is to prepare you conceptually and technically for the course. Since you may not have experienced an online course like this before, we will start with a short section describing the course and offer some learning strategies that will help you use the materials most efficiently. Finally, we will discuss what biology is all about — the "big picture" — our framework for exploring the relationship between the themes in biological research and the fundamental concepts and principles included in this course.

Information in this course is organized into units. Each unit begins with an introduction that orients you toward the major themes you'll explore in that section. The unit introduction will also show you how the content fits into the course as a whole. Each unit consists of several modules. Modules are like chapters in a book, and when you start a new module, you will see the list of learning outcomes you will achieve after completing that section of the course. Each module consists of several pages designed to help you achieve the learning outcomes. The introduction highlights what you will learn and how it relates to the big picture. The following pages make up the informational "meat" of the module. This explanatory content consists of short passages of text with information, examples, images, and explanations. As you work through the content, you will have many opportunities to practice what you are learning. The practice usually takes one of two forms:

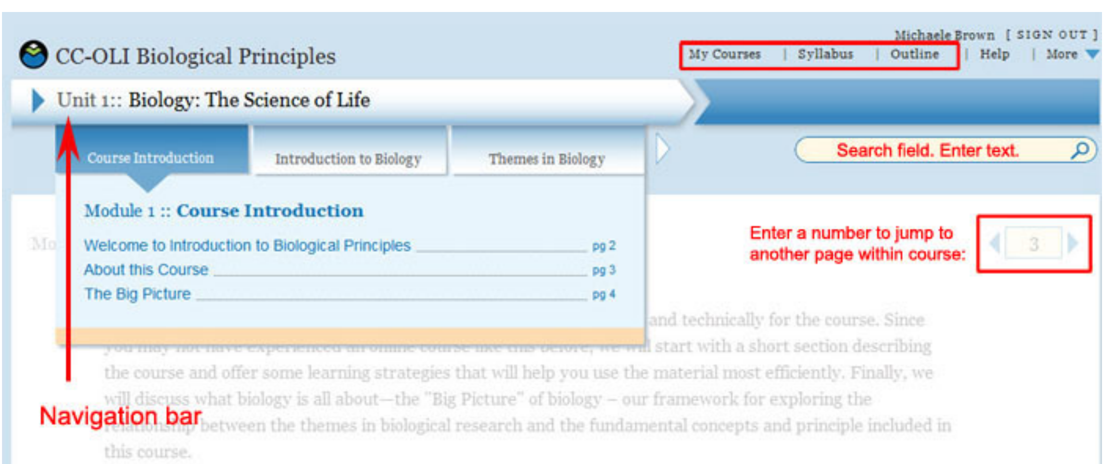
- *"Learn By Doing"* activities give you the chance to practice the concept that you are learning, with hints and targeted feedback to guide you if you struggle.
- *"Did I Get This?"* activities give you the opportunity to do a quick "self-check" to assess your own understanding of the material before completing a graded quiz.

Directed feedback during these learning activities will help you stay on track as you assimilate new information. Most modules will also include an *"Application Spotlight"* that gives you the opportunity to apply your understanding of the module's content to a specific case study or real-life example.

After completing a module, you will have a chance to demonstrate what you learned by taking a graded quiz. The module quizzes will assess and reinforce your learning as you progress through the unit. When you complete all the modules in a unit, you can participate in a *"My Response"* activity, where you will assess your own understanding of the unit content. After reflecting on your ability to achieve the learning objectives, you will have a chance to submit questions to your instructor, and then you will conclude your activities with a unit quiz.

Other Course Features

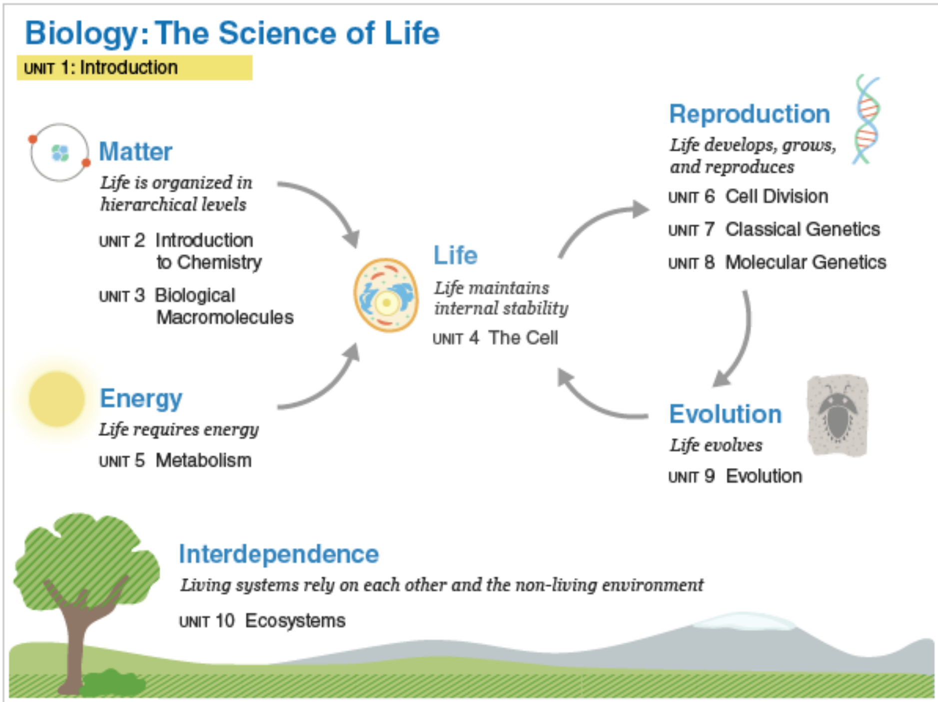
You can navigate through this course using the navigation bar at the top of the screen, the course syllabus, the course outline, and the page number box. All are accessible on any page in the course.



Also provided is an *Appendix,* which includes information such as a glossary of key terms and their definitions, a table illustrating the various ways biologists represent chemical structures, and an interactive image of the cell (the smallest unit of life).

The Big Picture

This course is divided into 10 units. This first unit, "Biology: The Science of Life," lays the foundation upon which the rest of the course is built. This unit begins by defining biology and characterizing its relationship to other fields of scientific study. It then elaborates on a few of the themes that emerge over and over throughout this course. Finally, in this unit you will explore the nature of science. This introduction represents the toolkit you'll need to understand the rest of the course, and will enable you to create context for all the new information you will learn.



The diagram above represents the "Big Picture" of biology. It illustrates how the course is organized and depicts the relationships between the main topics you will learn about as you progress through the material. You will find that as you go, the material is telling a story. It is a story based on the research and collaboration of centuries of scientific thinkers. The story begins with the smallest particles of matter: atoms. Atoms are the building blocks of all matter and they can be put together, like Legos, to form molecules. A special class of molecules called biomolecules are the "legos" used to build the structures required for life. The fundamental unit of life is the cell, and all cells are made of biomolecules. The cell is the first level of organization to display all the characteristics of life. Cells, and all living organisms, require energy to function. Organisms capture and use energy through a chain of chemical reactions called metabolic processes. The energy that cells capture through metabolism can be used to do work, including the work required for reproduction. All living organisms reproduce, passing their genetic information from generation to generation. This results in a unity and diversity of all living organisms, because we all share a common ancestor. Some organisms are more likely to survive than others, and this leads to evolutionary processes that result in the incredible diversity of life you see around you. The final chapter in the story reminds us that the diversity of life exists within a rich context of interactions, causes, and effects. Life does not take place in a vacuum; instead, living organisms rely intimately on other living organisms, as well as in the nonliving environment. All matter, living and nonliving, exists within a delicate interconnected balance, and humans are just one part of this biosphere.

This is a fascinating story and one that inspires a deep understanding and appreciation of the living world within us and around us. As we study the fundamental principles of biology, we will systematically explore the following characteristics of life.

1. Life is organized into hierarchical levels.

Atoms are tiny particles that are put together to build living organisms. While atoms do not possess life, they are required for life. The atom is the smallest organizational level that we will explore in this course, and you will learn more about atoms in *Unit 2: Introduction to Chemistry*. You will also learn how atoms can be linked together by chemical bonds to form molecules. In *Unit 3: Biological Macromolecules*, you will focus on the four classes of carbon-based macromolecules that comprise living systems: carbohydrates, fats, proteins and nucleic acids.

2. Life maintains internal stability through a process called homeostasis.

Atoms and molecules are not alive. After exploring the world of atoms and molecules, you will learn how these building blocks are put together to construct the fundamental unit of life: the cell. The cellular level of organization is the first time all the characteristics of life emerge, resulting in a structure that is able to maintain its own internal constancy. In *Unit 4: The Cell*, you will learn how the unique structures that make up a cell enable it to maintain homeostasis and carry out the varied functions of life.

3. Life requires energy.

Energy is required to sustain life and all living organisms need energy to fuel their metabolic activities. Some organisms get this energy directly from the sun through the process of photosynthesis. Other organisms harvest their energy from the food they eat. Humans are an example of organisms that obtain energy from food. In *Unit 5: Metabolism*, you will take a closer look at what energy is and explore how different cells acquire and use energy.

4. Life grows, develops, and reproduces.

All living things grow, develop and reproduce. We will focus on the ways different types of cells reproduce themselves in *Unit 6: Cell Division*. Genetic information in cells provides the instructions for carrying out life processes. In order for life to continue, organisms must pass information to the next generation. How genetic information is passed from one generation to the next is discussed in *Unit 7: Classical Genetics*. The physical traits an organism displays are ultimately determined by the DNA found within the organism's cells. In *Unit 8: Molecular Genetics*, we will connect heredity to DNA, the genetic material of the cell. We will specifically explore DNA function and figure out how DNA determines the heritable traits that individual organisms can pass to their offspring.

5. Life evolves.

Life changes and evolves over time. In *Unit 9: Evolution*, you will examine the process of evolution taking place within populations of organisms. This unit will explicitly link evolutionary change with the heritable characteristics you will learn about in *Classical Genetics* and *Molecular Genetics*.

6. Life is interdependent.

You will conclude your exploration of biology by learning about the interactions between groups of living organisms and their environments. *Unit 10: Ecology* discusses how humans are part of a living biosphere and how our actions, both intentional and inadvertent, have widespread consequences.

Introduction to Biology

To access the original content at the OLI website, click here: Introduction to Biology

Biology is the scientific study of life and is the branch of science that studies living organisms and the way organisms interact with their environments. The subject is vast and includes topics as diverse as acid rain, evolution, and genetically modified foods. In this module, you will investigate the definition of life and explore some of the characteristics of living systems.

Biologists study many varieties of living organisms. Clockwise from top left: salmonella bacteria; a koala bear; a fern plant; fly amanita, a poisonous fungus; the red-eyed tree frog; a tarantula. Source: Andrew Colvin; August, 2010; Wikipedia.

Biologists study how humans and other living organisms interact with their environment. A couple from Northern Thailand. The husband is carrying the stem of a banana plant, which will be fed to their pigs. Source: Manuel Jobi Weltenbummler, 2007, Wikipedia.

Characteristics of Life

There are five distinct qualities used to determine whether or not something is (or was) alive. A living organism is something that displays all these qualities. To be considered alive, something must:

1. Be made of materials organized in a hierarchical pattern.
2. Use energy and raw materials to survive.
3. Sense and respond to changing environments and maintain internal stability, or homeostasis.
4. Grow, develop and reproduce with the help of DNA.
5. Evolve.

The cell is the smallest unit that displays all of these characteristics. Because of this, living organisms are often identified based on whether or not they are made of cells. Nonliving things can show several of these characteristics. For example, a rock crystal can “grow” in a simple fashion. However, if even one of these conditions is not met (rock crystals do not reproduce with help from DNA), the object in question cannot be considered alive.

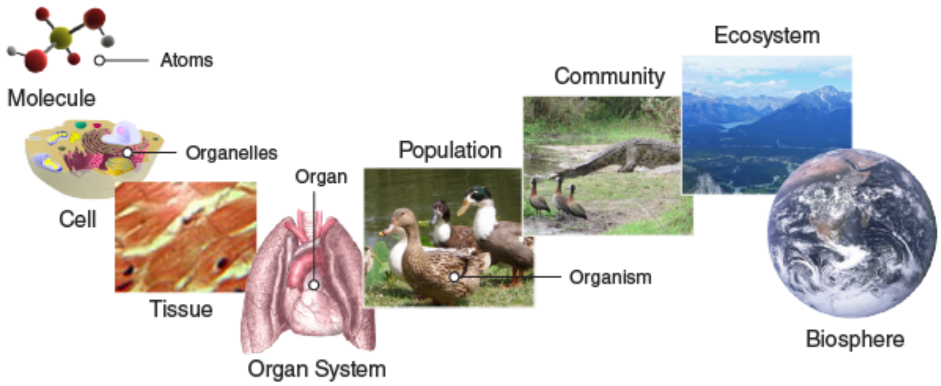
Classification of Matter

Matter is any substance that has mass and takes up space. All matter can be classified in one of two categories: biotic (living) or abiotic (nonliving). Matter is considered biotic if it was ever alive at some point in time. In this sense, a dead human buried underground in a wooden coffin is still biotic, as is the wood used to make the coffin (the wood came from a tree that was once alive). However, not everything within, or made by, a biotic organism is biotic. For example, urea, a chemical component of urine, is an abiotic substance.

To be classified as biotic, all of the required conditions for life must be met or have been met in the past. Otherwise, the matter being classified is considered to be abiotic, or nonliving.

Levels of Organization

Observe the following diagram.



All living things consist of smaller parts that are organized in a hierarchical way.

Living things are highly organized and structured, following a hierarchy that can be examined on a scale from small to large. In this course, the smallest level we will examine is the atom, which is the basic unit of matter. The atom consists of a dense nucleus surrounded by electrons. Atoms join together to form molecules. A molecule is a chemical structure consisting of at least two atoms held together by a chemical bond. Macromolecules are biologically important molecules, and they are technically polymers. Polymers are made by combining smaller units called monomers, which are simpler macromolecules. An example of a macromolecule is the genetic molecule deoxyribonucleic acid (DNA) that contains the instructions for the development of all living organisms. DNA is built of four kinds of monomers (nucleotides). They are strung together, or polymerized, in a sequence that codes for the structure of proteins and other biological molecules. The DNA in one of your microscopic cells contains a sequence of almost three billion nucleotides.

When macromolecules are used as building blocks to form a membrane-bound sphere, you have a cell, which is the fundamental unit of life. A cell is essentially a tiny droplet of water and other molecules enclosed by a fluid "skin" or membrane. The cell is the smallest and simplest entity that possesses all the characteristics of life. There are two main types of cells: prokaryotes and eukaryotes. The cells of prokaryotes are relatively small and simple; they do not have any clearly defined compartments inside of them. The cells of eukaryotes, by contrast, include membrane-bound organelles: compartments inside the cell that contain specific groups of macromolecules and carry out specific cellular functions. One of these organelles is the nucleus; it encloses the DNA within the cell.

Some organisms consist of just one cell and include unicellular organisms such as bacteria and protists. Single-celled life forms are typically referred to as microorganisms. Other organisms consist of many cells working together. These multicellular organisms include animals, land plants, and most fungi. Most multicellular organisms have cells that are specialized to carry out specific functions. Tissues are formed when many different kinds of cells work together to fulfill the same detailed function. Organs are collections of tissues that work together to carry out a common general function. Organs are present not only in higher level animals but also in plants. An organ system is a higher level of organization that consists of functionally related organs. Mammals have many organ systems. For example, the circulatory system transports blood through the body and includes organs such as the heart and blood vessels.Organisms are individual living entities that survive and reproduce as a unit. For example, each tree in a forest is usually an individual organism.

Consider this example to help clarify the nature of the levels between a cell and an organism. A human is an organism which has a circulatory system *(organ system)* that transports blood through the body. It is made up of organs such as the heart and blood vessels. Each of the organs, in turn, is made of more specific tissues. Your heart, for example, has muscle tissue for pumping and nerve tissue that helps coordinate each heartbeat.

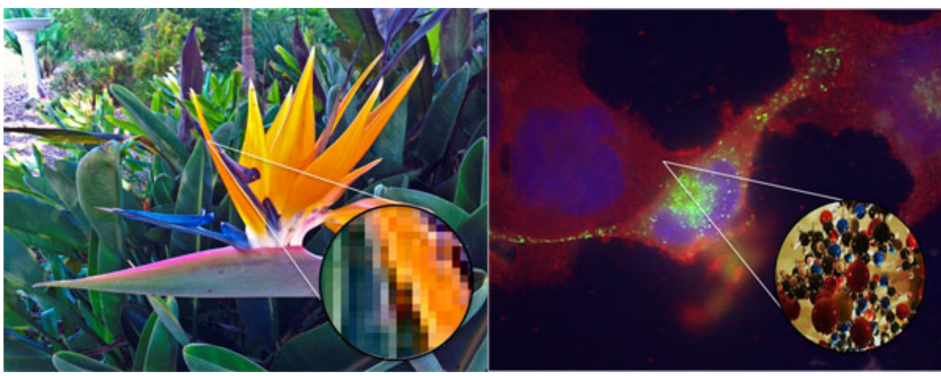
The hierarchical organization of living systems continues beyond single organisms. A population consists of all the individuals of a species living within a specific area. For example, a forest may include many pine trees. All those pine trees represent the population of pine trees in that forest. As you know, many different populations can live in any specific

area. All of these populations can interact with each other in positive and negative ways, and together they form a community. Continuing with our example, the forest with pine trees includes populations of flowers, mammals, birds, insects, fungi, and bacteria, all of which can interact. These interacting populations make up a community.
An ecosystem consists of all the living things in a particular area together with the abiotic, or nonliving, parts of that environment. The pine forest ecosystem includes not just plants, animals, and microbes but also rocks, water, temperature changes, air chemistry, and other abiotic factors that interact with living organisms in the area. Finally, the highest level of organization in living systems is the biosphere, which is the collection of all ecosystems on Earth. The biosphere includes all habitable zones on the planet, including land, soil, and rocks to a great depth in the Earth's crust; water and ice; and the atmosphere to a great height.

Life: An Emergent Property

Life is organized into hierarchical levels of increasing complexity. The study of biology involves all these levels, from single atoms or molecules up to global relationships among organisms and the environment. As we ascend through this hierarchy to more and more complex levels, emergent properties appear. These are characteristics of a system that are not present in any of its component parts. Take, for example, an automobile. The separated parts of the automobile amount to a heap of junk. Only when properly assembled, with gas, the right key, and a human driver, does the car fulfill its function, which is to transport us from place to place.

Emergent Properties



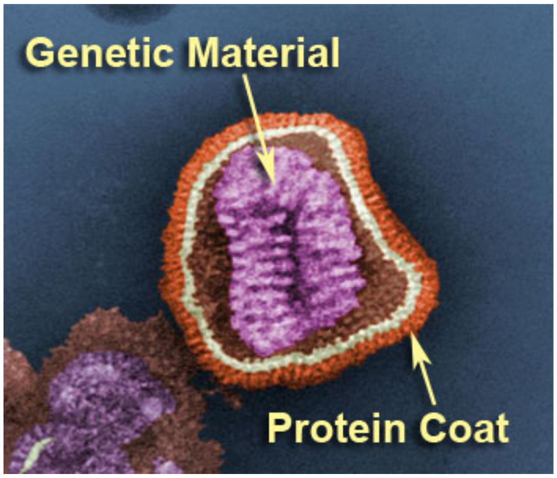
Emergent properties are visualized in this diagram. If you zoom in on the photograph, it eventually appears as a collection of individual pixels, each of one color. Only when seen in relationship to each other do these pixels make sense as an image. If you zoom in on a cell, it looks like a random mixture of molecules. Only when they are organized within a cell do these molecules work together to permit life.

Life is an emergent property, and one that appears at the cellular level of organization. Molecules are not alive, but they are the components of life. More than 2,000 years ago, Aristotle said "The whole is much greater than the sum of its parts." In biology, this is a constant theme: we can learn much about a system by looking at its details, but we also must step back and look at the big picture to truly understand the workings of life.

Application Spotlight: Viruses

Have you ever gotten sick with the flu and said something like, "I've come down with a bug," or "I've got the flu bug"? In fact, the flu (short for influenza) is not really caused by a "bug" at all. It is caused by a virus, and there is some controversy in the scientific community regarding whether or not viruses are alive. But what are viruses, really? And how would you determine whether or not they are alive? In this lesson, you'll learn more about what viruses are, so you can figure out if they are actually alive.

Components of a Virus



Viruses contain genetic material within a protein or membrane coat.

Viruses contain genetic information in the form of either DNA or RNA. The genetic information is surrounded by a protein coat called a capsid. Some viruses also have a membrane structure surrounding their genetic information. Viruses are tiny particles and they lack the machinery necessary for growth and reproduction. In order to reproduce, a virus must infect a host cell and hijack the host cell's machinery. In other words, a virus cannot reproduce without using the tools of another cell.

So are viruses alive? There is much debate on the subject. Complete the following activity and draw your own conclusions.

Virus Characteristics:

In this activity we will explore the characteristics of viruses. First, we discuss some aspect of how viruses function in relation to the conditions for life. Then, you will indicate whether or not a virus exhibits each condition for life.

Characteristic of life: Life uses energy and raw materials to grow and reproduce.

- *Fact 1:* When viruses infect cells, the viral DNA enters the cell and uses the cell's machinery to make more viruses. The newly synthesized viruses then leave the cell to infect other cells.

Characteristic of life: Life evolves.

- *Fact 2:* Viruses mutate rapidly. This is one of the reasons there is a new flu vaccine each year. The flu is caused by a virus, and the flu vaccine helps the body recognize and defend itself against the current flu virus. By next year, the virus population will have changed so much that the current immunizations will no longer work.

Characteristic of life: Living organisms grow, develop, and reproduce with the help of DNA.

- *Fact 3:* Many viruses use DNA as their genetic material. Other viruses use a related molecule called RNA. Cells also use RNA as a helper molecule to DNA.

Characteristic of life: Living organisms consist of one or more cells.

- *Fact 4:* Cells are defined by a boundary called a membrane. This membrane is made from an oily molecule (called a phospholipid) as well as proteins, carbohydrates, and other molecules. The purpose of this boundary is to define the inside and outside of the cell and to enable interactions with the environment. Cells also contain all of the machinery for growth and replication.

Themes in Biology

To access the original content at the OLI website, click here: Themes in Biology

Throughout the study of biology, several themes emerge. These recurrent concepts will continually appear as we delve deeper into the scientific study of life. As we progress through the course, we will highlight the lessons that help to illustrate these six themes:

1. Structure determines function.
2. Living organisms maintain homeostasis.
3. Energy flows through living systems; matter is recycled.
4. Life's components are interconnected and interdependent.
5. Organisms grow, develop, and reproduce.
6. Evolutionary processes explain both the unity and adaptive diversity of life.

In this module, we will explore an overview of each of these themes separately.

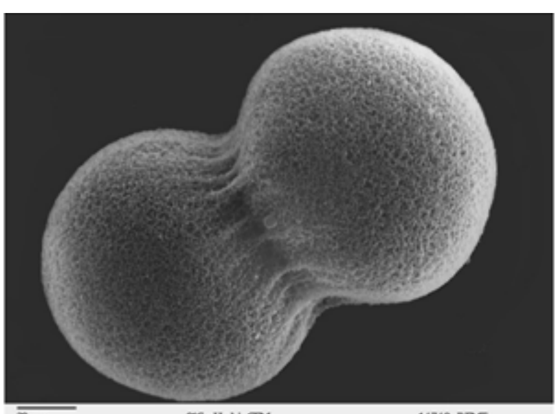
Biologists describe how organisms are put together (structure) and explain how organisms stay alive, move, grow, reproduce, and do other activities (function). In biological systems, the structure of a cell or body part is tightly linked to its function within the life of the organism.

The structure of something is determined by two factors: its three-dimensional shape, and the materials from which it is made. The structure that something takes directly influences its possible functions. Consider a piece of wood. Depending on how it is shaped, it could be used as a spear for hunting, a cup for drinking, a pipe for smoking, or even a flute for playing music. The wood also possesses unique properties that influence how it can be used. For example, the piece of wood could never function as a hot air balloon, no matter what kind of shape it took. It would always be too heavy to lift off the ground.

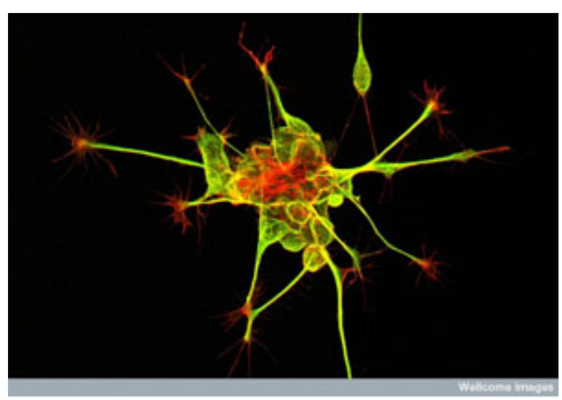
At the smallest levels of biological organization, the structure of a molecule determines its function within a cell. In this course, you might investigate the structure of a molecule and then learn what it does. It will help you to remind yourself: the structure and the function of this molecule are connected.

Enzymes are molecules found within a cell that speed up the rate of the chemical reactions necessary to support life. Enzymes break down food molecules, help build muscle proteins, can destroy toxins, and much more. An enzyme's ability to function depends directly on its three-dimensional shape. If exposed to excessive heat or harsh chemical conditions, enzymes unravel and change shape. When this occurs, the enzymes stop working and the chemical reactions of life slow down or cease.

At a larger scale, the structure of a cell is directly linked to its function within the body of a multicellular organism. Compare the following images of some different cell types and explore how structure relates to function at the cellular level.

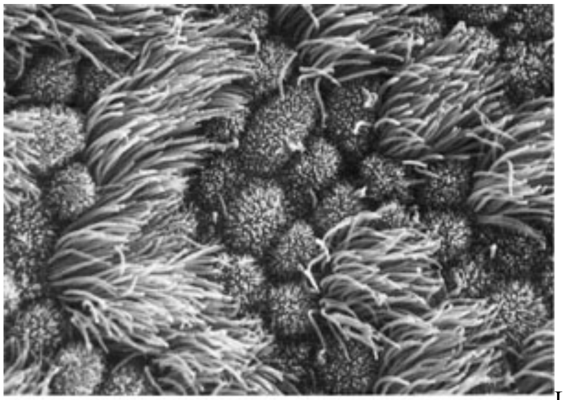


First division of a sea urchin cell just after egg and sperm join to start the life cycle. The cells are relatively large, because they are full of nutrients that will be used to feed the

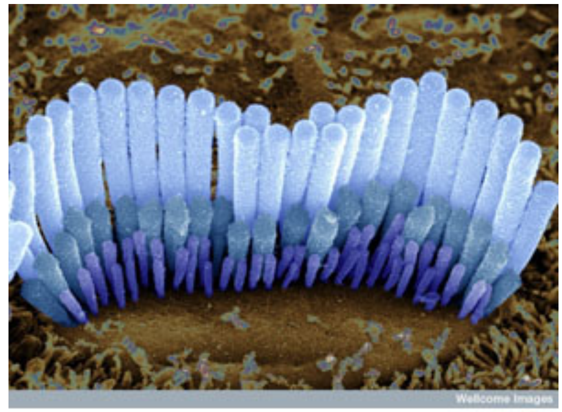


Developing nerve cells in the spinal cord of an embryo. When mature, the reddish structures will connect to other cells to relay nerve signals. Right now they are exploring the environment, responding to chemical signals, and growing developing animal. Otherwise, there is little noticeable structure to the cells. Their main function at this point is simply to divide, laying the groundwork for future more specialized generations of cells within the body. (Source: Evelyn Spiegel and Louisa Howard, The Cell Image Library)

toward their destinations. This function is supported by the branching "hand-like" structure; these cell structures are chemically "feeling their way along" through the embryo. The long thin yellow structures will act as cables, carrying signals over long distances — just as their structure suggests.



Lining of a human oviduct, or fallopian tube. This view shows several cells. Together they form a lining. They are shaped to form a sealed surface. Broom-like structures sprout from the exposed surface of each cell. These beat against the fluid in the tube, creating a gentle current that moves the egg cell toward the uterus, where it may implant to begin a pregnancy.



Hair cells in the inner ear of a guinea pig. These cells are shaped so that they are easily disturbed by vibrations. When they are flexed, a signal passes to nerve cells that take the message to the brain, where it is interpreted as sound. (Source: Dr. David Furness, Wellcome Images)

Structure also determines function at higher levels of biological organization. Your body's organs function as they do because of how tissues are put together, forming filters, pumps, levers, surfaces for gas exchange, and pipes for air and fluid flow. And, of course, the entire body of an organism is suited to its lifestyle and environment. For example, the earthworm is well-suited for burrowing: it is slimy, muscular, flexible, and cylindrical. Yet there are many surprising details in the worm's structure. The next time you get the chance,*feel* an earthworm. Pinch it carefully near the head with one hand, then rub your free forefinger against its belly. You'll notice prickly hairs on the worm's underside. And you'll find that you only feel them when you move your finger toward the worm's head: the hairs are set at an angle, enabling the worm to grip the soil to and move it forward through the earth.

You can probably imagine other ways to use different shapes and materials to build a functional body that enables Structo to overcome many different challenges. Environmental pressures have led (and continue to lead) to the evolution of organisms with a virtually infinite range of such combinations.

In fact, organisms are so well adapted to their environments that humans are now looking to them for inspiration. Today, a fast-growing field called biomimicry brings biologists together with engineers to develop new products based on solutions found in nature. One of the earliest products of this approach was the invention of Velcro (the hook and loop attachment) by Swiss engineer Georges de Mestral. He was inspired by the burrs that got stuck in his dog's fur. To learn more, visit the Biomimicry Institute.

Living organisms detect and respond to changes in the conditions of their external environment. In response to threats and opportunities, organisms may move or change their activities. For example, plant stems can grow toward a source of light. Over time, the trunks of trees strengthen when they are flexed by the wind. Animals, of course, respond to stimuli with a huge range of behaviors from the hibernation of bears to your own development of "goosebumps" on a chilly day.

In contrast to the extreme variability of the outside world, the interior of a cell is a remarkably constant environment. For example, cells typically keep their internal pH (acidity) within a narrow range. This is important because changes in pH can cause molecules like enzymes to change their shapes. As you already know, a molecule's shape (or structure) determines its function. If its shape changes, it may lose function. Because of this, many of the chemical reactions of life will not work properly if cell conditions change too much.

The ability or tendency of organisms and cells to maintain stable internal conditions is called homeostasis. The term homeostasis comes from the Greek words *homeo* (same, alike) and *stasis* (standing). It describes how life stands in one place despite many changes in the surrounding world.

Environmental conditions can also affect cellular homeostasis. If the cell's surroundings change quickly, conditions inside the cell may be temporarily disturbed. Organisms react to these changes in a corrective way: they detect changes and do something to oppose them. For example, when you get cold, your muscles start to contract in rapid bursts, causing you to shiver. The process of shivering then generates heat that warms you back up again. As a result of this and other adjustments, your temperature is maintained close to 99 degrees F *(Fahrenheit)* [37 degrees C *(Celsius)*]. At this temperature, your enzymes work very efficiently.

Homeostasis is an important theme in biology. All living systems use resources to maintain homeostasis. When cells fail to maintain homeostasis, disease results. Ultimately, if homeostasis is not restored, an organism will die.

Matter

Matter is traditionally defined as anything that has mass and takes up space. Matter is made of atoms. Matter is reused and recycled in living systems. To live and grow, organisms and cells must take in (or absorb, or ingest) certain forms of matter. Any matter an organism needs but cannot make for itself is considered a *nutrient* for that organism. Not all matter can be used by an organism, which is why all living systems release other forms of matter. When an organism or cell releases (or excretes) matter, the excreted matter is considered waste for that organism.

Wolves Fighting a Grizzly Bear

By Adolph Murie, 1944, National Park Service. Source: Wikipedia.

Both nutrients and wastes are made of atoms; they occupy space and have mass. The atoms retain their identity through the processes of life, even though they can be combined with other atoms in different ways. Consider the picture above. When a wolf is eaten by a bear, the atoms that made up the wolf become part of the bear. The matter in the wolf that is not absorbed or used for growth by the bear becomes waste. The bear excretes this waste in urine, in feces, and in its exhaled breath. Atom for atom, all the matter that was the wolf can be accounted for, and it is recycled through the ecosystem. The waste produced by one organism can provide nutrients to another.

Energy

Energy can be defined as the capacity to do work or to make a change in the location, temperature, or structure of matter. Energy does not have mass and it does not take up space, but it can be measured in terms of what it does. Energy comes in many forms, including heat, chemical potential energy, kinetic energy of motion, and light. Energy is required for all organisms to maintain homeostasis, grow, and reproduce.

Living Organisms Emit Heat


Human leaking heat energy into his environment. Photo on left was taken with a heat-sensitive camera; photo on right with a normal camera sensitive to visible light. On left, warmer regions are brighter yellow or orange. The plastic bag draped over the man's arm is transparent to heat radiation. His eyeglasses, however, tend to absorb or deflect heat.

It is important at this point to clarify the difference between *matter* and *energy* and to highlight a form of energy that is very important in biology. Food contains nutrients that are useful to humans. These nutrients take up space and can be weighed. Imagine a serving of breakfast cereal. You can weigh and measure the volume of its nutrients, and on food labels nutrient content (the amount of fat, carbohydrates, protein, etc.) is reported in grams. But the same serving of cereal also has a property called *chemical potential energy*. This is energy stored in the structure of molecules that can be converted to other forms of energy by a chemical reaction. If the cereal is burned (a chemical reaction), its molecules will react with oxygen gas. Atoms will change partners and the molecules will become much simpler. In the process, energy will be released as heat and light. We can determine the amount of energy in the cereal by burning it and measuring how much heat is released in the process.

Food Nutrition Label

Source: The U.S. Food and Drug Administration

In biology, *chemical potential energy* is a key form of energy. It is measured in units called calories. When we're talking about energy, we'll say "the calories stored in ..." or "the chemical potential energy of ..." a substance. We are talking about what the substance can do if it is put through a chemical reaction, like burning, that will release its stored energy. Returning to the breakfast cereal example, nutrition labels indicate the chemical potential energy of food by listing the calories per serving.

Interdependence and Interconnectedness of Life

Have you ever played a game of Jenga, where you try to remove one block at a time from a tower structure without causing the entire tower to collapse? In this game, each block depends on the other blocks for stability, and if you're not careful, the removal of a single block can cause the destruction of the entire structure. Life is much the same. At levels from the individual to the biosphere, the various parts of living systems are interdependent.

Jenga Game

Your trillions of cells are intimately dependent on each other for survival. Your cells are specialized, and you exist because of a massive team effort from all these different cells. If any one of your major organs were to suddenly fail, you might die very quickly. Moreover, your health also depends on trillions upon trillions of bacterial cells that live in and on your body. They provide your cells with vitamins, help keep out invaders, and may even influence your mood. So your body itself is a community of interdependent cells.

Source: Jorge Barrios, 2007; Wikipedia

An ecosystem consists of all the organisms living within a defined area along with the abiotic components of that particular environment. Within an ecosystem, organisms interact with each other in helpful and harmful ways. Some types of organisms play overlapping roles with other species (e.g., six species of oak tree may have similar, if not identical, roles in a forest). Others, however, play unique and essential roles that other organisms depend upon for their survival. For example, in a Colorado forest, researchers found that a species of sapsucker (a bird similar to a woodpecker) played a vital role in providing nesting holes and food for many other species.

To learn more: Gretchen Daily and others, 1993. Double keystone bird in a keystone species complex.

All organisms grow and develop. Growth is just an increase in size. In development, structure and function change in an orderly way as an organism passes through its life cycle. An individual's pattern of development is partly determined by genetic instructions. DNA, the molecule of inheritance, encodes proteins and other molecules that build cells and make them work. You can think of genes as "recipes" for proteins. Each cell has a huge library of thousands of recipes in its DNA. But most of the recipes don't get used in any given cell. Chemical controls tell the "cooks" whether to make a given protein, or ignore its recipe and make something else. Therefore, even though your cells share the same DNA, their activities change radically in different parts of your body and at different stages of development.

SIMULATION
Used by permission from R.O. Karlstrom and D.A. Kane. Published: *Development*, 1996, Dec;123:1-461.

In this time-lapse video, a few days of development are sped up for your viewing pleasure. In the earliest frames you can see large cells dividing. With each division the individual cells get smaller. Chemical signals in each cell are passed to its descendants and to nearby cells. As a result, DNA is turned "on" or "off" in each cell, leading to different shapes and structures. Toward the middle and end of the video, individual cells are much too tiny to see. Specialized cell types form. Cells move from place to place, grow, die to create gaps, and divide to create bulges. In this way, body structures begin to emerge.

Reproduction occurs when an individual organism passes on its genetic information to a newly independent organism, or offspring. Individual organisms have a limited life span. All are subject to extreme events that bring death, such as being eaten by a predator. Even if they avoid such a fate, most organisms decline in health and die toward the end of their typical life span. Reproduction maintains genetic information by passing it to new individuals. Offspring resemble their parent(s) and reproduction maintains the continuity of life over time.

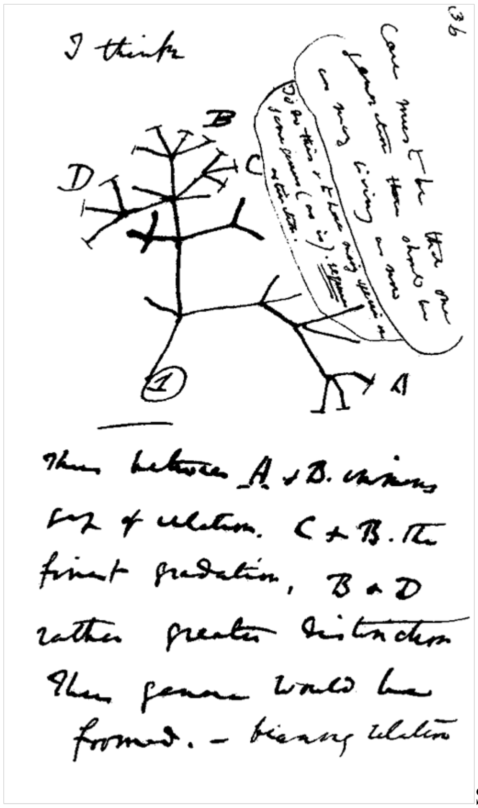
Evolution is a scientific theory that explains how and why life changes over time. Evolution provides the explanation for why all living organisms share profound similarities, and yet, the life forms on our planet are so incredibly diverse. The two fundamental tenets of evolution are shared ancestry and natural selection.

Shared Ancestry

As you learned previously in this module, reproduction results in the passing of characteristics from parents to offspring and maintains the continuity of life. You can see this in a family photograph: offspring resemble their parents and siblings resemble each other. Biologists look at all life on the planet and see the same patterns.

According to evolutionary thinking, life forms are similar because of their shared ancestry. All cells have DNA as the molecule of inheritance and they also share many other detailed features. Organisms and cells always come from parents, and this is where they get their genetic information. Trace this process back in time, and it is reasonable to suppose that all life forms inherited DNA and many other features from a long-ago common ancestor. The unity of life is very striking when we examine molecules, which can be almost identical in species as different as bacteria and whales. This unity of structure and function is also evident when we compare skeletons, kidneys, or hearts among animals.

Charles Darwin's Sketch of the Tree of Life



Sketching in his notebook in 1837, Charles Darwin created the first diagram of a phylogenetic tree. It shows several life forms related to each other by ancestry. The neighboring "twigs" in the lettered groups are similar species. Eventually Darwin would propose that ALL life forms find a place on one tree, and that it began with one or just a few very simple life forms long ago.

Scientific Inquiry

To access the original content at the OLI website, click here: Scientific Inquiry

Science is a powerful tool used to understand the natural world. It is the process that has resulted in the knowledge we are exploring in this course. However, the process of science does have limitations. In other words, there are some questions that science cannot be used to answer. For example, science cannot answer questions about supernatural things. It also cannot be used to make moral or aesthetic judgments. While questions of these types may be important for humans to explore, the process of science cannot be used to study them.

In this module, the process of science will be discussed in more detail. Then you will learn about how to design a quality scientific experiment. Finally, you will have the opportunity to practice identifying examples of science and to compare those to examples of pseudoscience, or things that claim to be scientific, but are not.

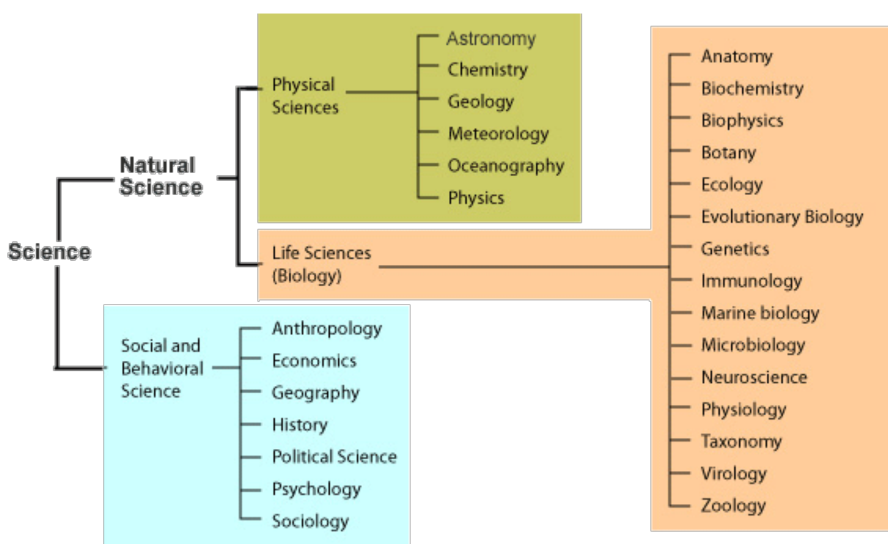
Science: What Is It?

Science is a process that helps us to understand how the natural world works. When we use the term "natural" in this context, we mean all that can be observed with our senses or with instruments that extend our senses. The "natural" world studied by science can be reliably observed and measured, from the far reaches of outer space to the man-made chemicals in our air and water. This module will examine the process of science and explore how science has led to an increased understanding of living organisms.

Biology: A Branch of Science

Biology is an example of a scientific field that deals with understanding living organisms. Chemistry is a scientific field that deals with understanding atoms and molecules. Overall, scientific fields can be broken down into two main branches: natural sciences, and social and behavioral sciences. Social and behavioral sciences focus on human cultures and the behaviors of humans in groups and as individuals. Biology is a natural science that includes many related sub-branches, such as ecology, biochemistry, and microbiology. Each sub-branch of biology examines different aspects of living organisms. Other natural sciences are physical sciences like chemistry and physics. It is important to remember that even though scientific knowledge is broken into branches and sub-branches of study, the knowledge gained from the various scientific disciplines is interconnected. For instance, to understand how a cell responds to a certain environmental signal, it is necessary to know about the chemical composition of that signal, so the science of chemistry is important to understand the science of biology. Likewise, understanding how the brain functions (neuroscience) can aid in understanding the human behaviors studied in the social and behavioral sciences.

Breakdown of Scientific Disciplines



By University of Maryland University College CC-BY-NC. This diagram shows the organization of the branches of science. Notice how biology is broken down into many sub-branches, and is closely related to physical sciences such as physics, chemistry, and geology.

Scientific Inquiry: A Method of Knowing

Science deals with testable knowledge about physical phenomena in the universe. The goal of science is to understand how the universe works. Biology focuses on understanding living things. To gain knowledge about nature and physical phenomena, scientists use a particular approach called "scientific inquiry."

Scientific inquiry is the best approach we have to understanding the natural world and predicting natural phenomena. Evidence for this claim can be found in the successes of science-based technologies. Take medicine, for example. Prior to the 1700s, most medical practices were based on folk traditions or on ideas promoted by religious leaders. Some of these prescientific remedies worked, but the process for discovering new treatments was a slow and haphazard system of trial and error. Ineffective treatments were often accepted simply because there was no clear procedure for evaluating them. Today, with science-based medicine and public health practices, we have gained unprecedented control over threats to our health. According to the Centers for Disease Control, the average life expectancy in the United States has increased by more than 30 years since 1900.

Scientific inquiry has not displaced faith, intuition, and dreams. These traditions and ways of knowing have emotional value and provide moral guidance to many people. But hunches, feelings, deep convictions, old traditions, or dreams cannot be accepted directly as scientifically valid. Instead, science limits itself to ideas that can be tested through verifiable observations. Supernatural claims that events are caused by ghosts, devils, God, or other spiritual entities cannot be tested in this way.

Scientific Methods

The rest of this module will focus on the methods of scientific inquiry. Science often involves makingobservations and developing hypotheses. Experiments and/or further observations are often used to test the hypotheses, and the data gathered are carefully interpreted. Methods and results are then communicated to other scientists within peer-reviewed scientific journals.

A scientific experiment is a carefully organized procedure in which the scientist intervenes in a system to change something, then observes the result of the change. Scientific inquiry often involves doing experiments, though not always. For example, a scientist studying the mating behaviors of ladybugs might begin with detailed observations of ladybugs mating in their natural habitats. While this research may not be experimental, it is scientific: it involves careful and verifiable observation of the natural world. The same scientist might then treat some of the ladybugs with a hormone hypothesized to trigger mating and observe whether these ladybugs mated sooner or more often than untreated ones. This would qualify as an experiment because the scientist is now making a change in the system and observing the effects.

Forming a Hypothesis

When conducting scientific experiments, researchers develop hypotheses to guide experimental design. Ahypothesis offers a testable and falsifiable explanation of observations. For example, a scientist might observe that maple trees lose their leaves in the fall. She might then propose a possible explanation for this observation: "cold weather causes maple trees to lose their leaves in the fall." This statement is testable. The scientist could grow maple trees in a warm enclosed environment such as a greenhouse and see if their leaves still dropped in the fall. The hypothesis is also falsifiable. If the leaves still dropped in the warm environment, then clearly temperature was not the main factor in causing maple leaves to drop in autumn.

In the activity below, you can practice recognizing scientific hypotheses. As you consider each statement, try to think as a scientist would: can I test this hypothesis with observations or experiments? Is the statement falsifiable? In other words, is it possible to gather evidence that clearly indicates that the statement is not true? If the answer is "no," the statement is not a valid scientific hypothesis.

Testing a vaccine

Throughout the rest of this module, we examine the scientific process by discussing an actual scientific experiment conducted by researchers at the University of Washington to investigate whether a vaccine may reduce the incidence of the human papillomavirus (HPV). The experimental process and results were published in an article titled, "A controlled trial of a human papillomavirus type 16 vaccine" [1] , available for viewing online at the National Institutes of Health's online database of publications: PubMed.gov

Preliminary observations made by the researchers who conducted the HPV experiment are listed below:

- Human papillomavirus (HPV) is the most common sexually transmitted virus in the United States.
- There are about 40 different types of HPV. A significant number of people that have HPV are unaware of it because many of these viruses cause no symptoms.
- Some types of HPV can cause cervical cancer.
- About 4,000 women a year die of cervical cancer in the United States.

- **References**

1. Koutsky, L.A., Ault, K.A., Wheeler, C.M., Brown, D.R., Barr, E., Alvarez, F.B., Chiacchierini, L.M., Jansen, K.U. (2002). "A controlled trial of a human papillomavirus type 16 vaccine." New England Journal of Medicine. Volume 347(21).

Experimental Design

You've successfully identified a hypothesis for the University of Washington's study on HPV: People who get the HPV vaccine will not get HPV.

The next step is to design an experiment that will test this hypothesis. There are several important factors to consider when designing a scientific experiment. First, scientific experiments must have an experimental group. This is the group that receives the experimental treatment necessary to address the hypothesis.

The experimental group receives the vaccine, but how can we know if the vaccine made a difference? Many things may change HPV infection rates in a group of people over time. To clearly show that the vaccine was effective in helping the experimental group, we need to include in our study an otherwise similar control group that does not get the treatment. We can then compare the two groups and determine if the vaccine made a difference. The control group shows us what happens in the absence of the factor under study.

However, the control group cannot get "nothing." Instead, the control group often receives a placebo. A*placebo* is a procedure that has no expected therapeutic effect — such as giving a person a sugar pill or a shot containing only plain saline solution with no drug. Scientific studies have shown that the "placebo effect" can alter experimental results because when individuals are told that they are or are not being treated, this knowledge can alter their actions or their emotions, which can then alter the results of the experiment.

Moreover, if the doctor knows which group a patient is in, this can also influence the results of the experiment. Without saying so directly, the doctor may show — through body language or other subtle cues — his or her views about whether the patient is likely to get well. These errors can then alter the patient's experience and change the results of the experiment. Therefore, many clinical studies are "double blind." In these studies, neither the doctor nor the patient knows which group the patient is in until all experimental results have been collected.

Both placebo treatments and double-blind procedures are designed to prevent bias. Bias is any systematic error that makes a particular experimental outcome more or less likely. Errors can happen in any experiment: people make mistakes in measurement, instruments fail, computer glitches can alter data. But most such errors are random and don't favor one outcome over another. Patients' belief in a treatment can make it more likely to appear to "work." Placebos and double-blind procedures are used to level the playing field so that both groups of study subjects are treated equally and share similar beliefs about their treatment.

Experimental Variables

A variable is a characteristic of a subject (in this case, of a person in the study) that can vary over time or among individuals. Sometimes a variable takes the form of a category, such as male or female; often a variable can be measured precisely, such as body height. Ideally, only one variable is different between the control group and the experimental group in a scientific experiment. Otherwise, the researchers will not be able to determine which variable caused any differences seen in the results. For example, imagine that the people in the control group were, on average, much more sexually active than the people in the experimental group. If, at the end of the experiment, the control group had a higher rate of HPV infection, could you confidently determine why? Maybe the experimental subjects were protected by the vaccine, but maybe they were protected by their low level of sexual contact.

To avoid this situation, experimenters make sure that their subject groups are as similar as possible in all variables except for the variable that is being tested in the experiment. This variable, or factor, will be deliberately changed in the experimental group. The one variable that is different between the two groups is called the independent variable. An independent variable is known or hypothesized to cause some outcome. Imagine an educational researcher investigating the effectiveness of a new teaching strategy in a classroom. The experimental group receives the new teaching strategy, while the control group receives the traditional strategy. It is the teaching strategy that is the independent variable in this scenario. In an experiment, the independent variable is the variable that the scientist deliberately changes or imposes on the subjects.

Dependent variables are known or hypothesized consequences; they are the effects that result from changes or differences in an independent variable. In an experiment, the dependent variables are those that the scientist measures before, during, and particularly at the end of the experiment to see if they have changed as expected. The dependent variable must be stated so that it is clear how it will be observed or measured. Rather than comparing "learning" among students (which is a vague and difficult to measure concept), an educational researcher might choose to compare test scores, which are very specific and easy to measure.

In any real-world example, many, many variables MIGHT affect the outcome of an experiment, yet only one or a few independent variables can be tested. Other variables must be kept as similar as possible between the study groups and are called *control variables*. For our educational research example, if the control group consisted only of people between the ages of 18 and 20 and the experimental group contained people between the ages of 30 and 35, we would not know if it was the teaching strategy or the students' ages that played a larger role in the results. To avoid this problem, a good study will be set up so that each group contains students with a similar age profile. In a well-designed educational research study, student age will be a controlled variable, along with other possibly-important factors like gender, past educational achievement, and pre-existing knowledge of the subject area.

Interpreting Results

Gathering Data

After the experiment is completed, results are compiled and interpreted. This involves the measurement of the dependent variable. In the case of our HPV experiment, remember, the dependent variable is the rate of HPV infection.

Significance

Although the HPV study suggests that the vaccine protects against infection by HPV, is the finding significant? In science, as in life, things can happen for many different reasons. A convincing study will rule out "luck" (random chance) as an explanation for the results. Strong results are said to be significant: very unlikely to occur by chance or random events.

Whether the outcome is significant often depends on the size of study; the larger the number of individuals enrolled, the more convincing the results are likely to be. For example, imagine only 10 women were enrolled in the study. In the control group, 2 in 5 of the women became infected. In the experimental group, 0 in 5 were infected. At first you might think this proves the vaccine's effectiveness, but it is NOT a convincing or significant result. Why not? Random events could easily explain the difference between the groups. For example, perhaps none of the five women in the experimental group were sexually active over the study period. They therefore stood no chance of acquiring HPV. The vaccine might appear to work, but a skeptical reader could account for the results by proposing many other scenarios.

However, imagine if the same study were done with 10,000 women, and the infection rates were 2,000 of 5,000 in the control group and zero of 5,000 in the experimental group. Random events would be spread out among a very large group of people in this study; on average, the two big groups should have similar sexual behavior and other factors influencing infection rates. If there is a big difference at the end of the study, it is very unlikely that *this* result occurred by random chance.

Statistical analyses did support the significance of the HPV vaccine result.

After the results are interpreted and conclusions are drawn, researchers often return to their work and begin asking further questions. In this way, scientific inquiry is a powerful tool for exploration.

Application Spotlight: Science or Pseudoscience?

Now that you have a pretty good idea about the process of science, you'll have a chance to identify examples of science and compare those to examples of *pseudoscience*.

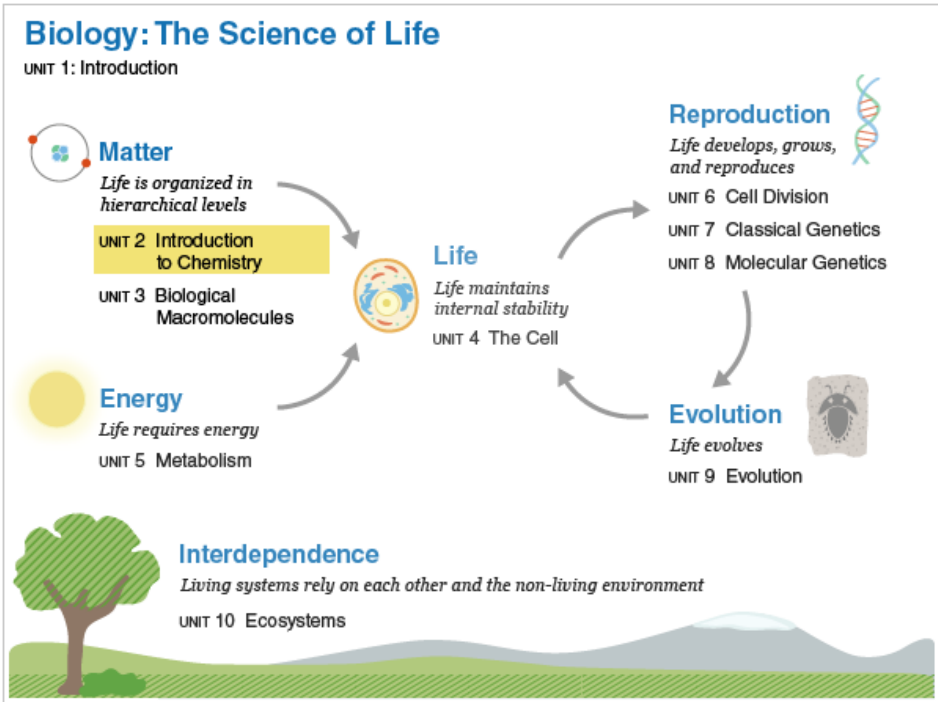
Pseudoscience is any claim that purports or pretends to be scientific in nature, but does not actually have the characteristics of true scientific inquiry. Pseudoscientific ideas often involve the supernatural. Sometimes they involve claims about forces or processes that cannot be measured using traditional tools or instruments employed by scientists. Finally, pseudoscientific claims are often quite dramatic. They are "amazing" ideas that would seem strange or unlikely to most scientists working in a related field.

The clearest line separating pseudoscience from "real" science is publication in peer-reviewed scientific journals. These are publications, usually run by scientific societies or academic publishing companies, in which scientists publish their findings according to a well-established system of oversight. Before it gets published in such a journal, a piece of research is carefully reviewed by two or more researchers in the same field of study. The methods and logic of the paper are evaluated carefully, and if it makes bold or unusual claims, the study is subject to especially close scrutiny. Reviewers and editors may demand not just rewrites, but also additional evidence if a claim is weakly supported.

Truly scientific research is published in reputable peer-reviewed journals. These journals exclude pseudoscience rigorously. If you hear that some idea is "scientifically proven," check the source to see if there's any reference to a scientific journal. Track down the article to see if it really supports the claim. Finally, double check to make sure that the publication is a respected peer-reviewed journal. One way to get this information is to ask a scientist at a research university, consult with a librarian, or do a careful Internet search. Your ability to distinguish between science and pseudoscience will help you be a scientifically literate citizen.

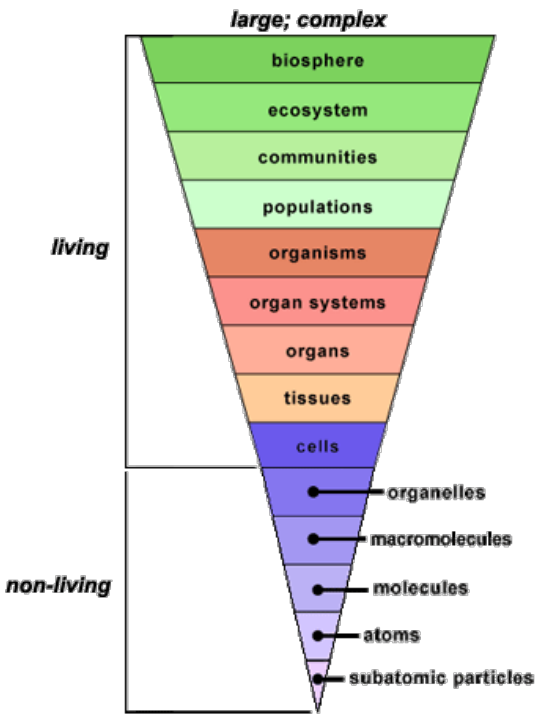
Introduction to Chemistry

Matter is anything that has mass and takes up space. The chair you are sitting in is made of atoms. The food you ate for lunch was built from atoms. Even the air you breathe is made of atoms. In this unit, we will learn more about atoms, the fundamental unit of matter.



All matter is made of atoms. There are 92 different kinds of atoms that can be put together in unique ways, resulting in all the diverse things you see around you.

The cell is the fundamental unit of life; therefore, you might think that your study of biology should begin with the cell. In fact, before you can truly understand how a cell functions, you must understand the building blocks from which cells are made. In the *Introduction to Biology* module, you learned that all life exhibits a hierarchical organization. While cells are the first level of organization that displays all the properties of life, their component parts (atoms and molecules) are not alive, as illustrated in the inverted pyramid below.



To make sense of how cells work, you must constantly return to their parts (atoms and molecules) and the interactions among them. This is why a clear understanding of some chemistry is essential to understanding how life functions. This unit will focus on the atom. You will learn how atoms combine to form different molecules, making up all the diverse matter you see around you. In this unit, you will explore only nonliving components of the hierarchy of life.

Atoms

Objectives:

- Describe the basic structure of the atom.
- Define the three subatomic particles, their charge, and where they reside in the atom.
- Distinguish between atomic number and atomic mass.
- Describe electron location.
- Define the three subatomic particles, their charge, and where they reside in the atom.
- Distinguish between atomic number and atomic mass.
- Describe electron location.
- Distinguish between atomic number and atomic mass.

In this module, you will learn about the basic structure of the atom, the fundamental unit of matter. Living things are made up of atoms arranged in a complex and nonrandom way. This is one of the common features of all living organisms. The atom is the smallest level in the hierarchy of life that we will explore in this course. Understanding the properties of atoms allows us to predict and understand how atoms interact with one another to build molecules, such as hormones and DNA. In addition, an understanding of atoms allows us to predict how cells will react to different therapeutic drugs and toxins in the environment.

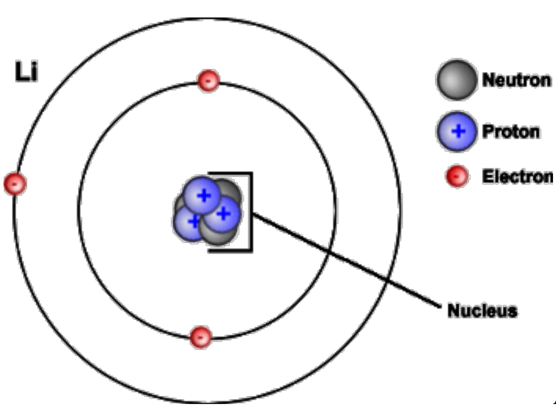
The Atom

All living and nonliving things are composed of matter. Matter can be defined as anything that occupies space and has mass. The mass of an object is a measure of how much matter it has (that is, how much "stuff" is in it). Mass is not exactly the same as weight, but here on Earth we can measure and compare the masses of different objects by weighing them.

When we explore matter scientifically, we find that it takes on many different structures as we zoom in at smaller and smaller scales. Everyday objects are mostly mixtures of molecules, which in turn are made up of atoms. Even air is a mixture of molecules. The atom is a good focal point for understanding matter; all matter is composed of atoms.

Atoms are unimaginably small. Even within a single microscopic cell, there is room for not just billions, but trillions or even hundreds of trillions of atoms. Amazingly, however, physicists now understand that most of the volume of an atom is actually made up of empty space. The atoms themselves are made of even smaller subatomic particles called *protons, neutrons,* and *electrons.* We cannot look at the parts of atoms with a microscope; they are simply too small. However, physicists have learned a great deal about atoms and subatomic particles through indirect methods. One model of the atom is shown in the diagram below.

Diagram of an Atom



Atoms contain protons and neutrons, which are found in the nucleus (center) of the atom. Atoms also contain electrons, which are found outside the nucleus. This is a model of a lithium atom.

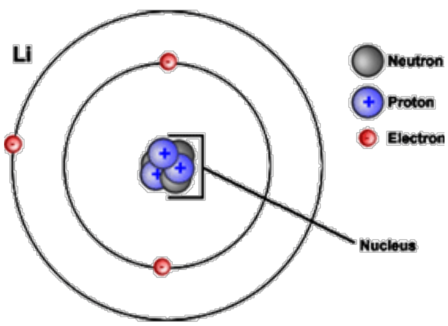
Elements

There are 92 different kinds of atoms that are naturally occurring on Earth. These different types of atoms are called *elements*. Each element has its own set of properties that are unique to atoms of its kind. Atoms differ from one another in their number of *protons, electrons,* and *neutrons*. Atoms are the smallest unit of an element that retains all of the properties of that element. So, an element is a substance that is composed of a single type of atom. For example, a hydrogen atom contains one proton and one electron. In contrast, a carbon atom contains six protons, six electrons, and six neutrons. Elements are designated by either one- or two-letter abbreviations and they can be organized into a chart called the periodic table. We will take a closer look at the periodic table (also called the periodic chart) later in this unit.

In biological systems, the major elements are *carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulfur (S)*. These elements represent more than 95% of the mass of a cell. Carbon is a major component of nearly all biological molecules. Some elements are found in relatively small amounts and are called "trace elements." Examples include sodium (Na), potassium (K), chlorine (Cl), manganese (Mn), and Zinc (Zn). Throughout the course you will see how atoms of these elements are very important to the functioning of a cell.

Elements (atoms) are characterized by their atomic structure, which is made up of subatomic particles: protons, neutrons, and electrons. Protons and neutrons reside in the nucleus (center) of the atom and have a mass of one atomic mass unit (amu) each. Electrons are found outside of the nucleus, in zones that are called "shells." Electrons have almost no mass.

Diagram of atom



Atoms contain protons and neutrons, which are found in the nucleus (center) of the atom. Atoms also contain electrons, which are found outside the nucleus. This is a model of a lithium atom.

The mass of an atom is called the *atomic mass*. When calculating atomic mass, we pay attention only to the protons and neutrons; the electrons have almost no mass. The atomic mass is the sum of the number of protons and the number of neutrons. By summing the atomic mass of all the atoms in a molecule, one can estimate the molecular mass of the molecule, which is expressed in atomic mass units *(called Daltons)*. Each of the heavy particles (neutron, proton) weighs one atomic mass unit, so a Helium (He) atom, which has two protons, two neutrons, and two electrons, weighs about four atomic mass units; that is, two protons plus two neutrons.

Particle	*Charge*	*Location in Atom*	*Relative Mass*
proton	positive	nucleus	1.0
neutron	no charge	nucleus	1.0
electron	negative	orbit outside nucleus	negligible

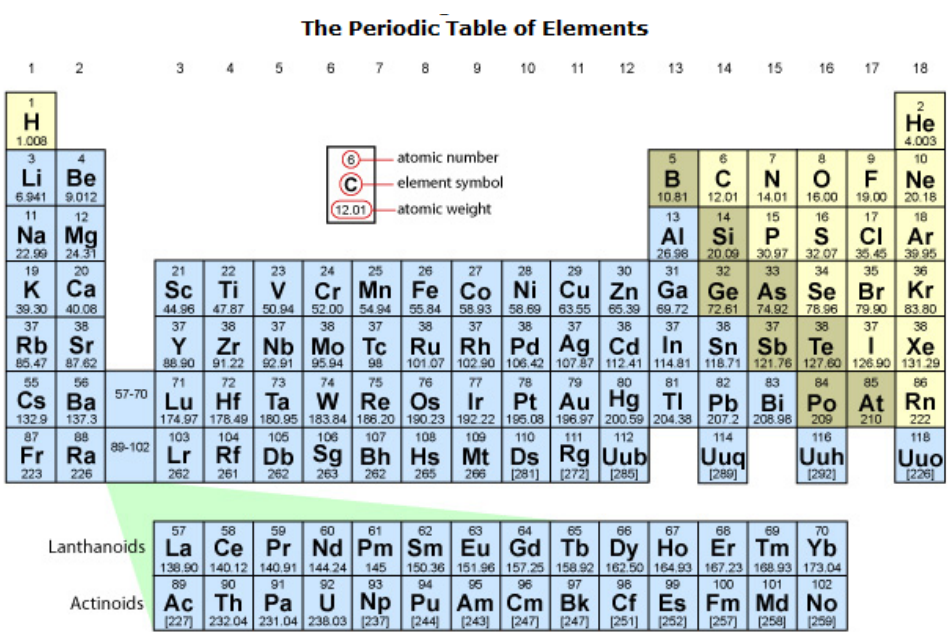
In addition to location and mass, each subatomic particle has a property called "charge." Charge can be "positive" or "negative." Items with the same charge tend to repel each other and items with opposite charges tend to attract each other. Protons have a positive charge and neutrons have no charge, giving the nucleus a positive overall charge. Each electron has a negative charge that is equal in strength to the positive charge of a proton. Electrons and the protons of the nucleus attract each other, and this is the force that keeps the atom together, much like the force of gravity keeps the moon in orbit around Earth.

Atomic Number

Atoms of different elements have many different features, including different sizes and levels of reactivity. For example, sodium is an incredibly reactive element, especially when it combines with water. Lead, on the other hand, is relatively inert. Yet all elements share some regular patterns that make it easier for us to categorize them and understand why they behave as they do.

The first key characteristic that truly identifies an element is its atomic number, which is the number of protons in each atom. The atomic number is constant and identical for all atoms of an element. For example, hydrogen (H) atoms always have only one proton and have an atomic number of one. If an atom has two protons, it has an atomic number of two, and it is helium (He). For this reason, if you started with one hydrogen atom and added a proton, the original hydrogen would now be helium. If an atom has three protons in its nucleus, it is a lithium (Li) atom. Beryllium (Be) has four protons in its nucleus, and so on. Based on their atomic numbers, elements can be organized into a periodic table of elements like the one pictured below. The number at the top of each box in the table is the *atomic number* of the element.

Periodic Table of Elements



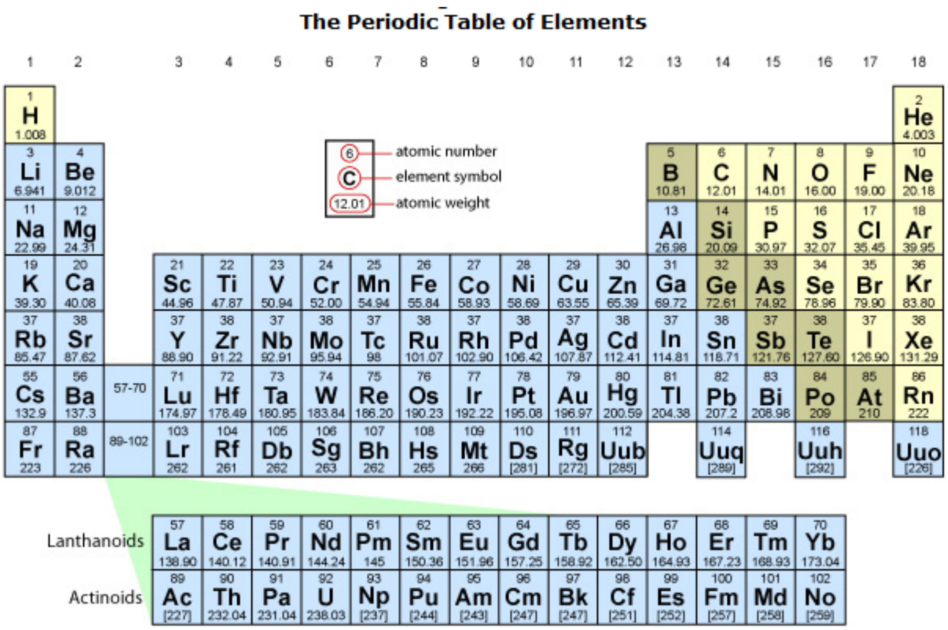
The periodic table organizes elements based on atomic number, which is the number at the top of each square. Each element has a chemical symbol, which is an abbreviation, shown in the center of each square.

Atomic Mass

In addition to providing information about each element's atomic number, most periodic tables also provide an atomic mass for each element. The atomic mass, also known as the atomic weight, reports the mass of the nucleus. The mass of the nucleus is the sum of all protons and neutrons found in the nucleus. A hydrogen atom has one proton and would therefore have an atomic mass of one. A carbon atom, which has six protons and six neutrons, would have an atomic mass of 12.

The units of atomic mass are Daltons, abbreviated *Da*, named after the British scientist John Dalton. One Da is equal to 1.66 x 10^{-27} kg, which is the mass of a single hydrogen (H) atom. Helium (He) has a mass of 4 Da or 6.67 x 10^{-27} kg. Because the mass of a single atom is so small, it is not a convenient unit for everyday use. Typically, the atomic mass is multiplied by the number of atoms in a mole to give the atomic weight in grams. A mole contains 6.022 x 10^{23} particles and is defined as the number of particles of carbon (C) that give an atomic weight of 12 grams.

Periodic Table of Elements



The atomic masses or atomic weights can also be added to the periodic table of elements. The atomic mass of an element is written below the chemical symbol.

Isotopes

Notice that the atomic mass or atomic weight on the periodic table is not generally a whole number. For example, the atomic mass of carbon (C) is 12.01. How is that possible? Atoms cannot have fractions of protons or neutrons. The reason for this is that not all atoms of an element have the same number of neutrons. For example, carbon atoms always have six protons. But some carbon atoms have six neutrons, while others have seven or even eight neutrons. A carbon atom that has six neutrons would have an atomic mass of 12; a carbon atom with eight neutrons would have an atomic mass of 14. Two atoms with the sameatomic number but a different atomic mass are called isotopes. For example, most atoms of carbon have an atomic mass of 12. There are some atoms of carbon with an atomic mass of 13 (carbon 13), and some with 14 (carbon 14). These are isotopes of the carbon atom. Carbon 12 is the most abundant or prevalent isotopic form of carbon. Because carbon 12 is the most abundant form and taking into account all of carbon's different isotopes, the average value for the atomic mass for carbon is near 12: it's listed at 12.01.

Scientists have learned that isotopes have many useful properties. Some isotopes can be used to trace chemical reactions. If a special isotope is placed in fertilizer, for instance, that same isotope will later show up in the tissues of plants, then animals and decomposers as the nutrient moves through the food web. Some isotopes break down into others at a constant rate, allowing us to determine the age of fossils or artifacts. When an isotope is radioactive, this means that it emits some energy (radiation) when it breaks down to a different isotope. Radioactive isotopes can be used to visualize certain tissues for medical diagnosis. For example, radioactive iodine tends to concentrate in the thyroid gland. It emits radiation as it breaks down to another isotope of iodine. Special cameras can pick up this radiation and use it to create an image of the thyroid gland. This can help determine if the patient’s thyroid is normally active or to detect thyroid cancer.

Electrons

The electron is the reactive part of the atom. The number and location of electrons determines the interactions between atoms. As you recall, negatively charged electrons are pulled toward the positively charged nucleus. But electrons are kept in orbit by kinetic energy. Electrons that are close to the nucleus are less energetic than those electrons farther from the nucleus.

Electrons reside in the space outside the nucleus in regions called shells. There are specific rules for filling up the shells of the atom. The first shell can hold two electrons; the second and third shells can hold up to eight electrons.

Electrons fill up lower shells before moving to the next higher shell. The electrons that occupy the outermost shell are called valence electrons and are the electrons that are involved in chemical bonding. The chemical properties of an element depend mostly on the number of valence electrons.

A key characteristic of atoms is that they are most stable when they have full outer electron shells. Helium (He) has a full outer shell with two electrons; directly below it in the periodic table is Neon. Neon (Ne) has an inner shell with two electrons and a full second shell with eight electrons. In fact, all of the elements in that column of the periodic table have full outer shells, are stable, and do not react with other elements.

Ions

Opposite charges cancel each other out when they are close together. So what would you predict about the overall charge of an atom with an equal number of protons and electrons? That's right — it is neutral. There is no charge; the atom will not be attracted to or repelled by charged objects. All atoms, in their elemental state, have equal numbers of protons and electrons, and for this reason they have no net charge.

As you recall, an atom is most stable when it has a full outer shell. Some atoms achieve this endpoint by taking on extra electrons, or giving them up. When this happens, the atom becomes an *ion* and it takes on an overall charge.

Some elements readily take on one or more extra electrons. They become anions that carry a negative charge, because they have more electrons than protons. On the periodic table, elements to the right (with the exception of the last column) are likely to take on extra electrons. For example, chlorine (Cl) has seven electrons in its valence shell. It is likely to take on one extra electron to fill its outer shell, becoming an anion with a charge of -1. The same can be said for other elements in the same column with chlorine. Conversely, elements on the left side of the periodic table tend to give up one or more electrons and become cations with a positive net charge. For example, sodium (Na) has one electron in its valence shell. It readily gives up this electron, becoming a cation with a charge of +1. The same can be said for lithium (Li) and other elements in this column.

In the next section, we will explore how these electron transfers occur, and will look at some of the other ways that atoms interact to achieve stable, full outer electron shells.

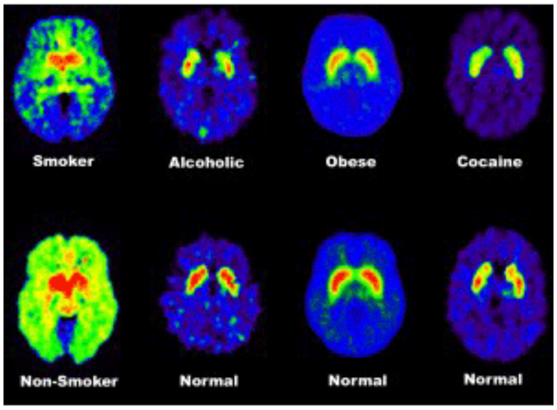
Application Spotlight: Medical Imaging

Scientists have learned to use isotopes in many different ways. For example, stable isotopes can be used to trace chemical reactions through a food web. For example, if a stable isotope is used in fertilizer, that same isotope will later show up in the tissues of plants, then in animals, and finally in decomposers as the nutrient moves through the food web. Other isotopes are unstable and they tend to decay (or break down into other isotopes) at a constant rate. Scientists have learned how to use unstable isotopes to determine the age of fossils or artifacts. Finally, some isotopes are radioactive. Radioactive isotopes emit energy in the form of radiation when they decay into different isotopes.

Radioactive isotopes can be used to visualize certain tissues for medical diagnosis. One example of this is radioactive iodine, which tends to concentrate in the thyroid gland. It emits radiation as it breaks down to another isotope of iodine. Special cameras can pick up this radiation and use it to create an image of the thyroid gland to determine if the patient's thyroid is functioning normally. If there is abnormal activity in the thyroid gland, this can indicate cancer.

Another example of radioactive isotopes is positron-emission tomography (PET). In PET, a patient ingests sugar that is marked with a radioactive isotope. Cells that are using a lot of sugar (or need a lot of energy) will absorb more of the radioactive isotope. The patient is then moved into a PET scanner, where the radioactive isotopes are visualized and the machine translates the data into an image. This can help in a variety of applications, from cancer and Alzheimer's disease diagnosis to addiction research (see image).

Positron-Emission Tomography (PET)Images



PET brain scans show chemical differences in the brain between addicts and nonaddicts. The normal images in the bottom row come from nonaddicts; the abnormal images in the top row come from patients with addiction disorders. These PET brain scans show that addicts have fewer than average dopamine receptors in their brains, so that weaker dopamine signals are sent between cells. Source: Nora Volkow, March 2001, Wikipedia.

Summary

Atoms are the building blocks for all matter. Now that you understand the structure of the atom, you can use atoms to build more complex structures, like molecules. This is what you'll learn about in the next module.

You are almost ready to take the module quiz. Before getting started on that, check your understanding by reviewing the key terms introduced in this module. When you are ready, check your understanding of this content by taking the quiz linked at the bottom of this page.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and any additional information. When you are ready, check your understanding of *atoms* by taking the quiz linked below.

- atom
- atomic mass
- atomic number
- electron
- element
- ion
- isotopes
- matter
- nucleus
- neutron
- periodic chart
- proton
- valence electrons

Chemical Bonds

Learning Objectives:

- Describe chemical bonding and the role of electrons.
- Define and describe ionic bonds.
- Define and describe covalent bonds.
- Define and describe hydrogen bonds.
- Interpret drawings (structural and skeletal formulae) of molecules and identify all atoms and covalent bonds in such drawings.
- Predict the correct partial charges on bonded atoms, given the electronegativity of the two atoms.

Chemical Bonds

Atoms are the smallest units of an element that retain all the properties of the element. Atoms combine to form a larger and more complex entity called a molecule. Molecules are composed of two or more atoms held together by covalent bonds.

Chemical bonds are attractions between atoms that hold atoms and molecules together. There are three types of chemical bonds that are important in biology: covalent bonds, ionic bonds, and hydrogen bonds.Covalent bonds are very stable, while ionic and hydrogen bonds are less stable. The relatively weaker ionic bonds and hydrogen bonds allow reversible interactions between different molecules in biological systems.

Joining atoms together builds molecules that are more complex and larger than the individual atoms that compose them. The table below illustrates some similarities and differences among ionic, covalent and hydrogen bonds.

Covalent bond	*Ionic bond*	*Hydrogen bond*
strongest	moderate strength	weak
between atoms	between ions	between different molecules or parts of molecules
sharing of electron pair, creating a strong bond between atoms	moderately strong electrostatic attraction between oppositely charged ions	weak electrostatic attraction between areas of molecules with opposite partial charges

The most stable situation for an atom is to have its outer shell completely filled with electrons. It is not easy to explain why this is true, but it is a rule of thumb that predicts how atoms will react with each other. Recall from the discussion on electrons, in the Atoms module, that the first electron shell is full with two electrons, and the second and third shells are full with eight electrons. Atoms tend to bond to other atoms in such a way that both atoms have filled outer shells as a result of the interaction.

Ionic Bonds

Ionic bonds are the interactions between ions of opposite charges. Atoms form ions when they either take up or release electrons in order to fill their outer shell. Elements in the outer columns of the periodic table often react in this manner; elements like sodium tend to lose electrons and become cations (positively charged ions), whereas elements like chlorine tend to gain electrons and become anions (negatively charged ions).

In fact, the reaction between sodium and chlorine is a great example of ionic bonding, and produces a compound you have in your kitchen — table salt. Chlorine (Cl) has an atomic number of 17, so it has 7 electrons in its outermost shell. Chlorine needs one more electron to have a full outer shell.

Sodium (Na) has an atomic number of 11, with one electron in its outermost shell. Sodium needs to get rid of an electron, and then it will have a full outer shell.

By losing an electron, sodium becomes a cation with a positive charge (+1). By gaining an electron, chlorine becomes an anion with a negative charge (-1). Now each ion has a net charge and the two charges are opposite. The ions attract one another. The electrostatic interaction between the sodium ion and the chlorine ion is an ionic bond .

Watch this animation:

Covalent Bonds

Instead of transferring their electrons completely, atoms may remain in very close contact and share electrons so that their outer shells are filled. In essence, a shared electron is counted “twice” and participates in a larger shell that joins the two atoms. A single pair of shared electrons makes a single covalent bond. Atoms can share two pairs of electrons (in a double bond), or even three pairs of electrons (in a triple bond).

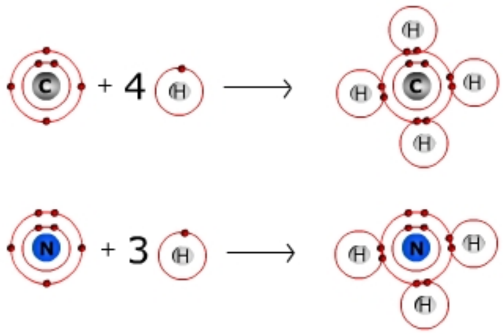
Watch this animation:

By University of Maryland University College CC-BY-NC

This sharing of electrons is called a *covalent bond*.

By University of Maryland University College CC-BY-NC

Carbon, for example, has an atomic number of 6 (see the figure below). The outer shell of carbon has 4 electrons. Carbon can share an electron with four other atoms. Hydrogen has an atomic number of 1. It has a single electron in its outermost shell, and can share this electron with one other atom. A carbon atom can form a covalent bond with four hydrogen atoms to form a molecule called methane, CH_4 . In a methane molecule, carbon effectively has a “full” second shell (8 electrons) and each hydrogen has a “full” second shell (two electrons).



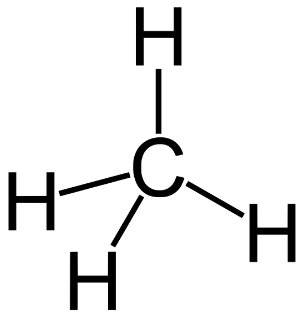
Example 1: Carbon and hydrogen react to form methane (CH_4). Each hydrogen requires one covalent bond to fill its first electron shell. Each carbon requires four bonds to fill its second shell. Exaample 2: Nitrogen and hydrogen form ammonium (NH_3). The three unpaired electrons on the nitrogen atom (N) in ammonia, represented as single dots, form bonds with three hydrogen atoms.

Nitrogen, another example, has an atomic number of 7 (see the figure above). The outer shell of carbon has 5 electrons. Nitrogen can share an electron with three other atoms. Hydrogen has an atomic number of 1. It has a single electron in its outermost shell, and can share this electron with one other atom. A nitrogen atom can form a covalent bond with three hydrogen atoms to form a molecule called ammonia, NH_3 . In an ammonia molecule, nitrogen effectively has a “full” second shell (8 electrons) and each hydrogen has a “full” second shell (two electrons).

Molecules

Molecular Formulas

When two atoms are joined by a covalent bond, the new structure that forms is called a molecule. This is in contrast to the structure formed when two atoms are joined by an ionic bond, which is called an ionic compound. When drawing a molecule on paper, covalent bonds are often drawn as lines between atoms. A single covalent bond is drawn as one line; a double covalent bond is drawn as 2 lines. Each atom is represented by its element symbol. Thus a structural formula of methane (CH_4) would be drawn like this:



Notice that the carbon in methane has formed four covalent bonds with four hydrogen atoms. Because carbon has four electrons in its outer shell, it can always form four covalent bonds with other elements.

The molecular mass or weight of a molecule is the sum of the individual atomic weights. As with atomic weights, it is convenient to use the weight of a mole of molecules. For example, the molecular mass of a single methane molecule is 16 Da (12 from the carbon, 4 from the hydrogens). The weight of a mole of methane molecules is 16 grams.

Interpreting a Molecular Formula

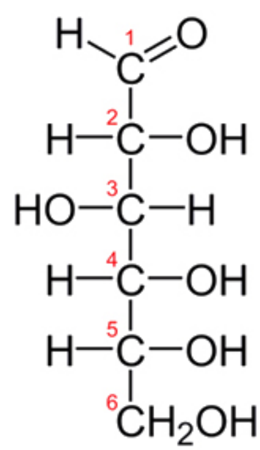
Molecules can be much more complex than methane. Carbon can form long chains as each carbon forms covalent bonds with multiple other carbons. When drawing molecules, it is important to make sure that each atom has a full outer shell. In the case of carbon, this simply means that carbon will form four covalent bonds.

Examine the activity below. Remember that the lines represent covalent bonds between atoms, but also note that the bonds between O and H are not shown. This simplifies the drawing and makes important structures easier to see.

Drawing Molecules

Structural Formulas: There are many different ways to drawmolecules. For example, look at the glucose molecule shown on the right in a structural formula. Notice that the structure consists of a carbon backbone running down the middle of the molecule. Each carbon has formed a covalent bond with four other atoms. (The first carbon actually formed two bonds with the oxygen atom; this is called a *double bond*. This carbon still formed a total of four bonds, even though two of the bonds are with the same oxygen atom.)

Skeletal Formulas: Chains of carbon atoms are very common in carbon-based molecules. Sometimes such molecules are drawn using skeletal formulas, also known as *shorthand formulas*. In these diagrams, the carbon atom, typically indicated with the letter “C,” is not shown. Instead, each C atom is drawn simply as a corner on the diagram.



Below are skeletal diagrams of glucose. In these examples, the carbons are located at each angle in the diagram.

Glucose Molecule: Linear Skeletal Diagram

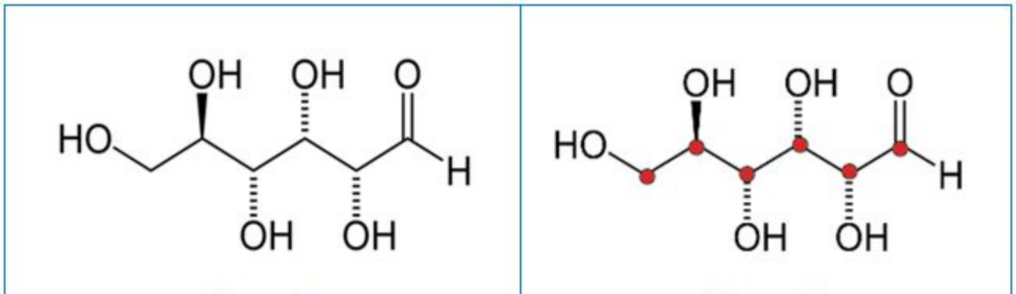


Figure 1A Figure 1B

Carbon atoms are indicated at each corner or angle, as highlighted in Figure 1B with red circles.

Glucose Molecule: Ring Structure Diagram

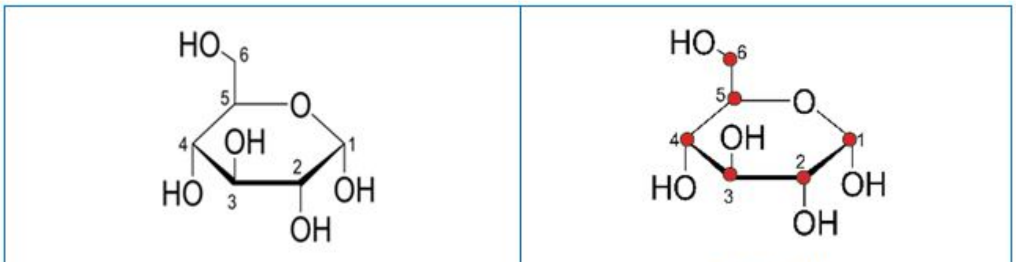
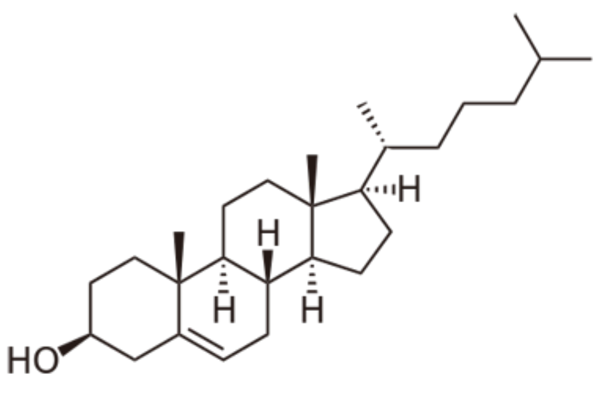


Figure 2A Figure 2B

The six carbons of glucose are numbered in the ring structure and highlighted in Figure 2B with red circles.

You may have another question about the skeletal diagrams: what happened to the hydrogen atoms attached to the carbon atoms? It looks like some of the carbons only have two or three covalent bonds! The skeletal diagrams are often drawn to be simple, not to show every atom. It is understood that carbon must have four bonds, and in any carbon-based molecule there are often one, two, or even three hydrogen atoms bonded to each carbon. To clean up the diagram, the H atoms are not drawn. It is assumed you will understand that any "missing" bond is actually provided by a hydrogen atom.

These conventions simplify diagrams of molecular structures. The cholesterol molecule, shown below, looks much cleaner than if we had to draw each carbon and hydrogen atom. You may also notice that this image has different-looking bonds. These solid and striped triangle-shaped bonds describe the three-dimensional shape of the molecule.



Electronegativity

Recall that in a covalent bond, the electrons are shared between two atoms. However, the two atoms don't necessarily share the electrons equally. Some atoms are more likely to draw the shared electrons closer to themselves. Atoms have a high electronegativity if they tend to draw the electrons towards them.Electronegativity increases as one moves from the left to the right across the periodic table. Hydrogen is moderately electronegative, with a value of 2.1, carbon is somewhat more electronegative, with a value of 2.5, and fluorine is the most electronegative atom, with a value of 4.0.

Electronegativities of Biologically Important Atoms

H 2.1						
Li 1.0	Be 1.5	B 2.0	C 2.5	N 3.0	O 3.5	F 4.0
Na 0.9	Mg 1.2	Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0

Image modified from *Chart of Each Element's Electronegativity*, UC Davis ChemWiki by University of California.

The degree of unequal electron sharing depends on the difference in electronegativity of the atoms involved in the bond. For example, in carbon-carbon bonds, both atoms have the same electronegativity, so the electrons are equally shared between the two carbons. In contrast, a carbon-oxygen bond involves two atoms that have different electronegativities. The less electronegative atom (carbon) will donate part of its electrons to the more electronegative atom (oxygen), resulting in a partial positive charge on the carbon (indicated by δ^+) and a partial negative charge on the oxygen (indicated by δ^-). The size of the partial charges is proportional to the difference between the electronegativities of the two bonded atoms. Bonds in which electrons are unequally shared between the atoms are called polar covalent bonds.

Hydrogen Bonds

Throughout this course, you will be studying many different molecules. Many of the important molecules of life, like DNA, proteins, and even ordinary water, share a key characteristic: they all form hydrogen bonds.

Hydrogen bonds are not like the covalent bonds you just learned about. They do not join atoms into molecules. Instead, they are the attraction of an electronegative atom to a hydrogen that is covalently bonded to another electronegative atom. This involves the attraction of the hydrogen with a partial positive charge to the electronegative atom with a partial negative charge. Only hydrogen covalently bonded to an electronegative atom can participate in hydrogen bonding.

Hydrogen bonding has a significant effect on the properties of molecules. For example, the structure of the DNA molecule is in part held together by hydrogen bonds. Hydrogen bonds also create coils and other structures within the complex protein molecules that are essential to life's diversity. Finally, water behaves the way it does because of the hydrogen bonds that attract water molecules to each other.

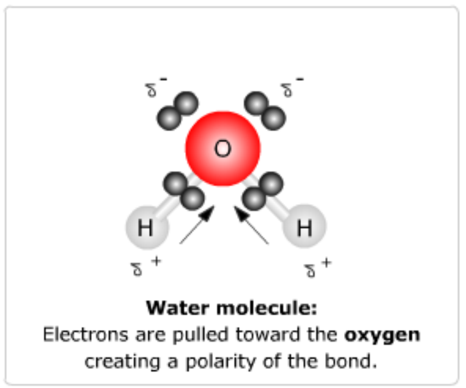
Water

The water molecule is a very important example of a molecule that can form hydrogen bonds. It is the hydrogen bonding of the water molecules that gives water many of its unique and life-sustaining properties. One water molecule consists of two hydrogen atoms covalently bonded to a oxygen atom.

Recall that in a covalent bond, the electrons are shared between two atoms. However, the two atoms don't necessarily share the electrons equally. Some atoms are more likely to draw the shared electrons closer to themselves. These atoms have a high electronegativity. Both oxygen and nitrogen are molecules with a high electronegativity.

In a water molecule, oxygen is more electronegative than hydrogen. This means that oxygen has a greater affinity or attraction for the shared electron pair than hydrogen does. Because of this, the electrons tend to spend more time close to the oxygen atom and they spend less time close to the hydrogen atom. As a result, the oxygen becomes slightly negative and each hydrogen atom develops a slightly positive charge. Whenever two atoms with different electronegativities form a covalent bond, we say that the bond between the atoms is *polar*, with each atom carrying a partial charge. Oxygen and nitrogen are the two highly electronegative elements that are often bonded to hydrogen in biological molecules. O-H and N-H bonds are strongly polar, and this sets the stage for hydrogen bonding.

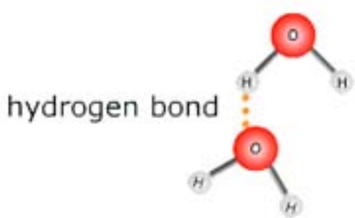
Water is polar.



The electronegative oxygen (red) draws electrons to it, creating the partial negative charge on oxygen and partial positive charge on hydrogen.

δ^- and δ^+ represent a partial negative and partial positive charge, respectively.

Hydrogen bonding is the attraction of an electronegative atom for a hydrogen that is covalently bonded to another electronegative atom. This involves the attraction of a hydrogen with a partial positive charge to an atom with a partial negative charge. However, only hydrogen covalently bonded to an electronegative atom can participate in hydrogen bonding.



In water, the partially positive hydrogen atoms are attracted to the partially negative oxygen atoms of neighboring water molecules. Hydrogen bonds are responsible for many of the unique properties of water. We'll explore this in more detail in the next module. Watch the following animation that illustrates hydrogen bonding.

Watch this animation:
Adjust the volume on your computer and click the play button.

Viewing Chemical Structures

Biologists have different ways of representing chemical structures. Each type conveys different information.

Summary

As you've seen, there are many ways that atoms interact with each other and form chemical bonds. In the next module, we'll take a closer look at water, which is one of the most biologically important molecules on the planet.

You are almost ready to take the module quiz. Before proceeding, review the key terms introduced in this module. When you are ready, check your understanding of this content by taking the quiz linked at the bottom of this page.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and any additional information. When you are ready, check your understanding of *chemical bonding* by taking the quiz linked below.

- chemical bonds
- covalent bonds
- electronegativity
- hydrogen bonds
- ionic bonds
- molecule
- molecular drawing
- molecular formula
- partial charge
- polar covalent bond

Water

Objectives:

- List the four properties of water and describe each property.
- Explain why water's properties are important for living things.
- Recognize key functional groups and predict whether compounds will be hydrophobic, hydrophilic, or amphipathic.
- Predict whether or not a substance can be used as a detergent based on its chemical structure.

Water: A Molecule Essential for Life

Have you ever wondered why scientists spend time looking for water on other planets? It is because, at least here on Earth, water is essential to life. Evidence of water on Mars, and some of the moons of Saturn and Jupiter, increases the odds that life may exist there. Here on Earth, water is one of the most abundant molecules. The water content of our bodies and our cells ranges from 70 to 95 percent. All of life's chemical reactions take place in watery fluid. Without water, life as we know it simply would not exist.

There are four properties of water that make it such a unique and important molecule:

1. Water is an excellent solvent and can dissolve a wide range of substances.
2. Water is cohesive.
3. Water's temperature tends to remain stable.
4. Solid water (ice) is less dense than liquid water.

These properties of water are due to the hydrogen bonds formed between water molecules. *Hydrogen bonds* are discussed in the *Chemical Bonds* module.

Water as a Solvent

Solutions are homogeneous mixtures. This means that you can sample any part of the solution and the composition of the solution will be the same.

Solutions have two components:

- *solvent*: the component of the solution in the greatest quantity.
- *solutes*: the component(s) present in lower quantities.

If you add some salt to water, you are making a solution. Water is the solvent and the salt is the solute. Solutions can have more than one solute. If you add sugar to your salt solution, both sugar and salt would be the solutes of the solution. Solutions in which water is the solvent are called *aqueous solutions*. The inside of our cells and our body fluids are examples of aqueous solutions. When a solute is added to a solvent and a solution is formed; the solute is described as "*dissolving*" in the solvent.

Substances that will dissolve in water are hydrophilic or *water-loving*. What kinds of molecules are hydrophilic? *Ionic* substances like table salt (NaCl) are hydrophilic. They split into positive and negative ions and dissolve in water. Polar water molecules surround the charged particles, breaking them away and pulling them into the fluid.

Polar molecules also are hydrophilic. Polar water molecules readily surround and dissolve polar molecules or molecules with polar functional groups. Examples include sugars and alcohols, which have hydroxyl groups. Molecules that do not dissolve in water are hydrophobic (from the Greek word meaning*water-fearing* or *water-hating*). Nonpolar molecules are hydrophobic. Examples include hydrocarbons and fatty acids with their abundant nonpolar C-H bonds. Have you ever tried to mix water and oil? Oils and fats are nonpolar and will not form a solution with water.

Oil Spill in San Francisco Bay

About 58,000 gallons of oil spilled from a South Korea-bound container ship when it struck a tower supporting the San Francisco-Oakland Bay Bridge in dense fog on 11/07/07. Brocken Inaglory, Nov, 2007; Wikimedia Commons.

Next we will examine *hydrophobic* molecules more closely. Substances with hydrophobic molecules will not dissolve in water and instead will tend to separate from water.

Hydrophobic and Hydrophilic Molecules

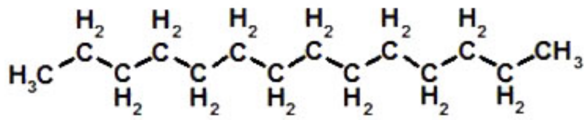
Some molecules are hydrophobic, which literally means fear (*phobia*) of water (*hydro*). These molecules do not like to dissolve in water. When *hydrophobic* molecules are mixed with water, they will tend to separate into distinct phases (or layers), one containing water and the other containing the hydrophobic molecules. This makes it very difficult, for example, to "wash" oil off of waterfowl after an oil spill.

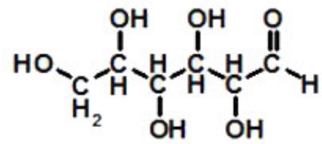
Birds killed as a result of oil from the Exxon Valdez spill. Photo in the public domain courtesy of the Exxon Valdez Oil Spill Trustee Council.

Things composed of hydrophobic molecules generally include oils, fats, and greasy substances. Materials containing hydrophobic substances are often used for removal of oil from water and management of oil spills. Other molecules are *hydrophilic*, which means love (*philic*) of water, and readily dissolve in water.

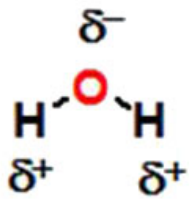
Chemical Structures

Now that you know some common hydrophobic and hydrophilic molecules, let's look at their structures to understand why they interact with water in different ways.





The additional atoms that are found only on glucose are *electronegative*, meaning that they will withdraw some of the electrons from the atoms that form bonds with them. The electronegative atom will have a slight negative charge, and the atom that it is *bonded* to it will have a slight positive charge. The unequal distribution of electrons makes the bond a *polar bond*.



Water is a *polar molecule*. The electronegative oxygen draws the electron from hydrogen toward it, causing the hydrogens to have slight positive charge and the oxygen to have a slight negative charge.

The interaction between a polar bond on water and polar bonds on hydrophilic molecules is given a special name — the hydrogen bond, because it involves a hydrogen that forms a bridge between the two molecules. Hydrogen bonds are fairly stable, so quite a bit of energy is released when they are formed. The release of energy helps hydrophilic molecules like glucose dissolve in water. Since hydrophilic molecules contain polar bonds, they are often referred to as *polar molecules*.

Nonpolar Molecules

Hydrophobic molecules lack the electronegative atoms that are required to generate a polar bond. Thus, hydrophobic molecules are also referred to as *nonpolar*.

The fact that nonpolar molecules cannot form hydrogen bonds in one reason why they have low solubility in water; however, there is another far more important force that drives nonpolar molecules from water, called the hydrophobic effect.

Hydrophobic Effect

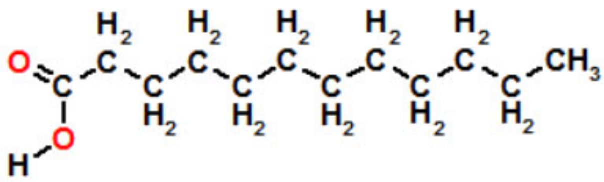
When a non-polar molecule dissolves in water it becomes completely surrounded by water molecules. The water molecules cannot form hydrogen bond with the non-polar molecule, however they do form hydrogen bonds with the other water molecules that surround the non-polar molecule, forming a layer of hydrogen bonded water molecules that cover, or form a cage, around the dissolved non-polar molecule.

The formation of the water cage is unfavorable, because it requires water molecules to become ordered. Ordering anything requires energy, whether it is a cage of water molecules surrounding a nonpolar molecule, or your messy dorm room. The energy cost of ordering water molecules around nonpolar compounds is so high that they are forced out of the water, leading to a separation of phases; oil and water don't mix because of the hydrophobic effect. Most biological molecules contain both polar and nonpolar regions. Their behavior in water depends on the relative number and type of polar groups versus nonpolar groups. For example, consider this series of simple alcohols.

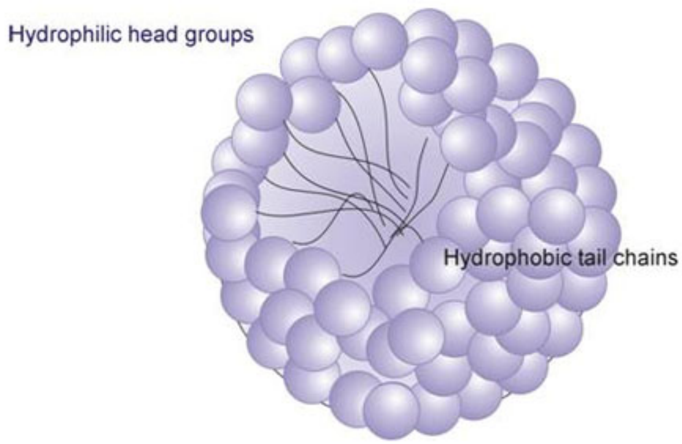
Amphipathic Molecules

Molecules that contain a very polar part and a very nonpolar part are called *amphipathic*. The polar part interacts with water, forming strong interactions, while the nonpolar part doesn't interact with water because of the hydrophobic effect. In order to accomplish this, amphipathic molecules usually undergo spontaneous self-assembly into structures that expose the polar part to water and keep the nonpolar section away from water. One example of amphipathic molecules are fatty acids.

Fatty Acids Molecule



The carboxylate group (COOH) on the left interacts strongly with water, while the remaining part of the molecule is very hydrophobic and is forced away from water. Fatty acids form structures in solution called*micelles*. These spherical structures have the *hydrophilic* part exposed to water on the surface of the sphere and bury the *hydrophobic* part in the center of the sphere.



Schematic of a spherical micelle.

You might be wondering why triglycerides are not amphipathic, given that they are similar to fatty acids, with a polar group of atoms and a nonpolar group. The reason is that the polar region of triglycerides interacts weakly with water because there is no free -OH group.

Cohesiveness

Have you ever filled up a glass of water to the very top and then slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass. This water can stay above the edges of the glass because of the property of cohesion. In cohesion, water molecules are attracted to each other (because of hydrogen bonding), keeping the molecules together. Cohesion allows surface tension, the capacity of a liquid's surface to resist being ruptured when placed under tension or stress. When water is sprinkled onto a solid surface, surface tension causes the water to remain in compact droplets instead of spreading out into a thin film.

Water drops exhibit cohesion. The water molecules attract each other strongly, and this force counteracts the force of gravity pulling water down against the leaf.

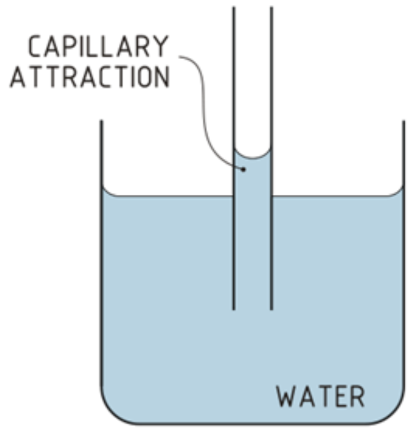
When you drop a small scrap of paper onto a droplet of water, the paper floats on top of the water droplet, even though the object is denser (heavier) than the water. This occurs because of the surface tension that is created by the water molecules. Cohesion and surface tension keep the water molecules intact and the item floating on the top. Many insects are specially adapted to exploit surface tension, which allows them to literally "walk on water."

Water Strider

The surface tension of water helps insects, such as this water strider, remain afloat.

These cohesive forces are related to water's property of adhesion, or the attraction between water molecules and other molecules. This is observed when water "climbs" up a straw placed in a glass of water. You will notice that the water appears to be higher on the sides of the straw than in the middle. This is because the water molecules are attracted to the straw and therefore adhere to it.

Capillary Action

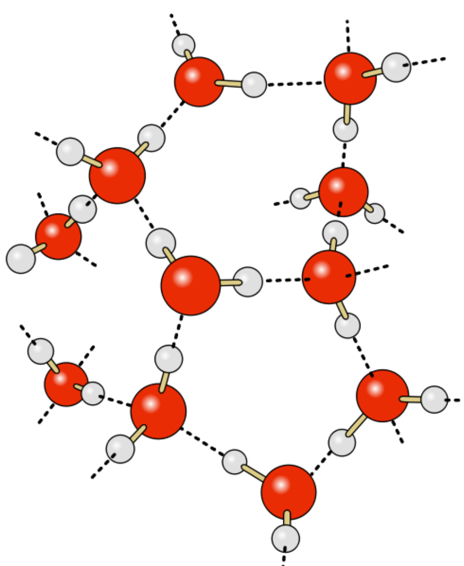


If a thin glass tube is placed in water, the water moves up the tube in a process called capillary action. Capillary action is the result of adhesion of water to the sides of a glass tube and cohesion of water molecules to each other.

Cohesive and adhesive forces are important for sustaining life. For example, because of these forces, water can flow up tubes within plants. These tubes connect the roots of plants to their leaves, and carry water to plant tissues. Adhesion helps water cling to the walls of the tubes, and cohesion keeps the water in an intact column. Without these properties of water, tall plants would be unable to receive the water and nutrients they require, and they would die.

Imagine you have placed a metal pan containing water on the stove. You transfer heat energy to the pan. If you touch the metal pan after a few minutes, it is warm or even hot to the touch, but the water does not yet feel warm. The metal's temperature changes much more quickly than that of the water, even though both substances are receiving heat from the same source. Temperature is a measure of the vibrational energy of molecules within a substance; it reflects how fast the molecules are jiggling around. If you add heat to metal, the molecules respond quickly with an increase in their "jiggling" and the temperature increases rapidly. If you add the same amount of heat to water, the molecules respond much less quickly. Why is water's temperature so resistant to change?

Hydrogen Bonds in Water



Water has many hydrogen bonds; each molecule can form hydrogen bonds with up to four other molecules. It takes a lot of energy to break all of these bonds.

When water is heated, a large part of the heat energy goes into breaking the hydrogen bonds between the water molecules. Only a small part actually increases the kinetic energy of the water molecules. Imagine a rack of billiard (pool) balls. When the cue ball strikes them, energy is transferred and the balls "break," rolling in every direction. What would happen if the balls were connected by rubber bands? They would not move nearly as much. Similarly, the hydrogen bonds among water molecules make it hard to increase their "jiggling." As heat is added, hydrogen bonds are broken and water warms up, but due to the hydrogen bonding, the water's temperature changes only slowly. When water cools down, it releases a great deal of heat as hydrogen bonds are re-established. This effect is particularly strong when water freezes; water molecules are joined in a regular crystal structure by stable hydrogen bonds. As these bonds form, heat is released to the surrounding environment. You may have noticed that snowy days are often not quite as cold as the dry clear days of winter. This is yet another example of the way that water moderates temperature.

Water Density

The Solid State of Water Is Less Dense Than Its Liquid State

When water freezes, the water molecules become arranged into a regular crystal. Each water molecule is bound by four hydrogen bonds to its neighbors. In this arrangement, the water molecules are further apart than they are in liquid water. Thus, the density of ice is less than the density of liquid water. Ice, the solid state of water, can float in the liquid state. This is important for lakes and ponds that contain fish and plants. When the temperature goes below freezing, ice is formed. The ice is less dense than the liquid, so it floats on the top of the lake or pond. The surface ice insulates the pond, helping it to retain heat, and keeps the pond from freezing solid.

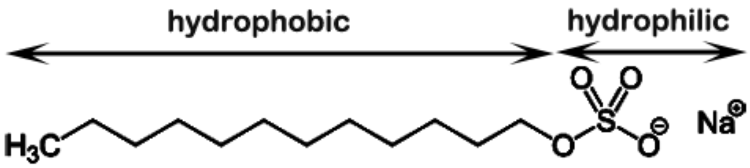
Solid water is less dense than liquid water.

Ice floats on top of a glass of water because ice is less dense than water.

Solid water is less dense than liquid water because in ice, the regular pattern of hydrogen bonds pushes the molecules further apart.

We use detergents to remove oily dirt from things. We use dish detergent to remove the grease on dishes, laundry detergent for oils on our clothes, and shampoo for oils in our hair. Detergents make the hydrophobic oils soluble so that the dirt can be rinsed away. How does this happen?

All detergents are amphipathic molecules; they have a polar, water-loving (hydrophilic) part and a nonpolar, water-hating (hydrophobic) part, which allows them to dissolve in both water and oils. The chemical structure of a common detergent, sodium dodecyl sulfate (SDS), is shown below. The hydrophilic part of DS interacts favorably with water by hydrogen bonding and electrostatic (charge-charge) interactions between the negative charge on the DS and the partial positive charges on the polar water molecules. The hydrophobic part has no polar atoms to form favorable interactions with the water.



The molecular structure of sodium dodecyl sulfate (SDS), a common detergent.

When placed in water, detergents spontaneously form organized spherical structures called *micelles*. In a micelle, the hydrophilic part of the detergent is on the surface of the sphere and interacts with the water. The center of the sphere contains the hydrophobic part of the detergent, hidden from the water. A cross section image and a three-dimensional structure of a micelle are shown below. When a micelle comes in contact with oily (hydrophobic) compounds, the oils dissolve into the interior of the micelle and can be washed away with the micelle.

Summary

You now know about some of the special properties of water, arguably the most important molecule for life on Earth. In the next module, you'll explore pH and learn about how acids and bases affect living systems.

You are almost ready to take the module quiz. Review the key terms introduced in this module. When you are ready, check your understanding of this content by taking the quiz linked at the bottom of this page.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

- adhesion
- amphipathic
- aqueous solutions
- cohesion
- hydrophilic
- hydrophobic
- micelles
- nonpolar molecules
- polar molecules
- solute
- solutions
- solvent
- surface tension

Acids and Bases

Objectives:

- Categorize a substance as acidic, basic, or neutral based on the pH of the solution.
- Use relative hydrogen ion concentrations in solutions to determine whether a solution is an acid, a base, or neutral.
- Define pH.
- Predict the pH of a substance based on its hydrogen ion concentration.
- Determine the pH of various everyday solutions.
- Interpret the results when different solutions are tested with red and blue litmus paper.
- Predict the outcome of a neutralization reaction.
- Describe the role of acids, bases, and buffers in living systems.

What Are Acids and Bases?

This course has looked closely at the water molecule because it is vital to life. Water covers 70 percent of the Earth's surface and the cell, the fundamental unit of life, consists of 70 to 95 percent water. In this module, we will examine one very small (and simple) substance that, when dissolved in water, can have an enormous impact on life: the hydrogen ion (H^+). Hydrogen ions are hydrogen atoms that have had their electrons removed. What remains is only a single proton. The simplicity of this ion, however, is quite misleading. In this module, we will investigate the dynamics of H^+ and learn more about the effects H^+ can have on solutions.

Acids and Bases

The story of acids and bases begins with water (H_2O). Water in the liquid state is highly dynamic. Not only are hydrogen bonds constantly forming and breaking between water molecules, but individual water molecules are breaking apart and then reforming again to make water. When they break apart, a hydrogen ion (H^+) is transferred to another water molecule to make a hydronium ion (H_3O^+), leaving a hydroxide ion (OH^-) from the original water molecule. This dynamic reaction can be represented by this chemical equation: $H_2O + H_2O$ [double arrow] $H_3O^+ + OH^-$. To simply things we will represent the hydronium ion as a hydrogen ion (H_3O^+=H^+) in the following discussion.

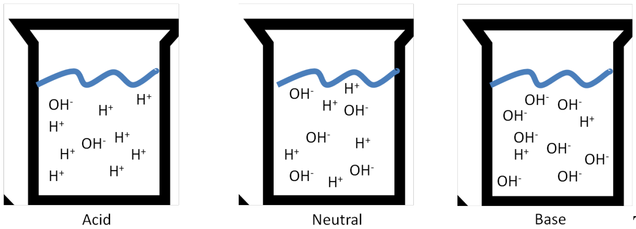
$$H_2O + H_2O \longleftrightarrow H_3O^+ + OH^-$$

To simply things we will represent the hydronium ion as a hydrogen ion ($H_3O^+ = H^+$) in the following discussion.

Notice that the two arrows point in opposite directions. This simply means that the equation can move in either direction. In other words, hydrogen ions and hydroxide ions can combine to form water, or water can break down into hydrogen ions and hydroxide ions. These two reactions are in equilibrium, so at any instant in a sample of pure water there are equal concentrations of H^+ and OH^-.

Pure water is said to be "neutral." This means it is neither acidic nor basic because it has equal concentrations of H^+ and OH^-. Some substances can dissolve in water and they will not disturb the balance between H^+ and OH^-. However, other compounds disturb this balance. Some compounds, when added to water, cause an increase of hydrogen ions (H^+) in the solution. These compounds are called acids. Other compounds, when added to water, cause a decrease in hydrogen ions (H^+) in the solution. These compounds are called bases. Some bases accept H^+ directly, but others release hydroxide ions (OH^-) that then combine with H^+ to produce water. The end result is the same. When the base is dissolved in water, the concentration of H^+ ions goes down. A compound that does not result in a net gain or loss of hydrogen ions (H^+) when in aqueous solution is said to be neutral; it does not alter the acidity of the water.

Acids and Bases in Solution



This figure shows what acids and bases look like in aqueous solution. Notice that the concentration of hydrogen ions is greater than the concentration of hydroxide ions in an acid, the concentration of the hydrogen ions equals that of the hydroxide ions in the neutral solution, and the concentration of the hydrogen ions is less than the concentration of hydroxide ions in the base.

This table compares and contrasts the features of acids and bases.

Acids	*Bases*
Readily *give* hydrogen ions (H^+) when dissolved in water	Readily *take* hydrogen ions (H^+) when dissolved in water; may donate hydroxide ions (OH^-)
Acidic foods often taste sour	Basic foods often taste bitter
Many foods and beverages are acidic	Bases often make your skin feel slimy or slippery because they release soap-like molecules from your lipids.
Strong acids can cause burns and are caustic	Strong bases can cause burns and are caustic
Acids commonly induce damage to living organisms by denaturing proteins: changing their shape so they do not function normally	Bases commonly induce damage to living organisms by breaking down fats and denaturing proteins

Understanding acids and bases is important to biology because living organisms must maintain homeostasis (balance) and cannot tolerate drastic changes in the acidity of their body fluids or cytoplasm. Cellular functions are disrupted if these fluids become too acidic or basic.

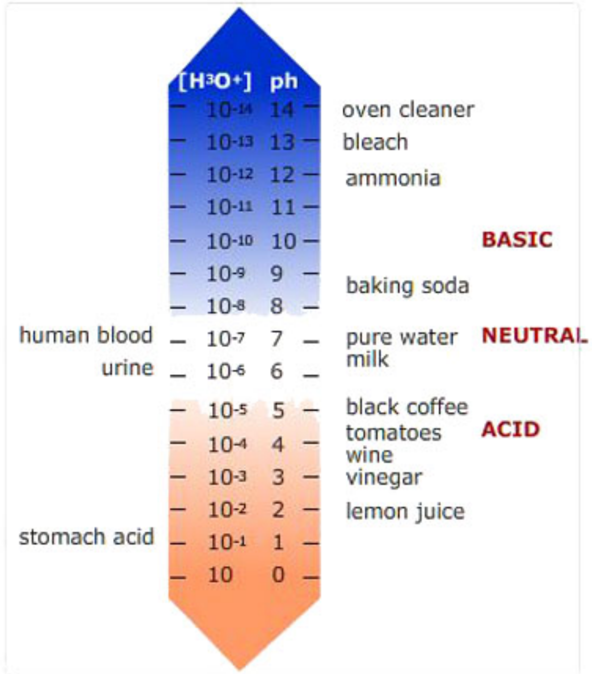
What is pH?

The pH Scale

The acidity of a solution is measured on the*pH scale*. pH is a measurement of the concentration of hydrogen ions (H^+) in a solution. You can think of pH as "*p*arts*H*ydrogen ion," but remember that the pH scale is "backwards." The *pH scale* ranges from 0 to 14, with zero being the most acidic (highest concentration of H^+) and 14 being the most basic. Neutral solutions (like pure water) have a pH of 7. Solutions with pH measurements below 7 are acidic, while solutions with pH measurement above 7 are basic. A solution at pH 7 is neutral because at that pH the number of hydrogen ions (H^+) equals the number of hydroxide ions (OH^-), just as they are balanced in pure water.

Acids and Bases in Solution

Hydrogen ion concentration can vary over many orders of magnitude. To represent very large differences in concentration levels, a logarithmic mathematical function is used to denote the pH scale.



A pH scale with annotated examples of chemicals at various pH values. On the left are biological compounds and on the right are some foods and cleaning products.

The pH scale is the -log of the *hydrogen ion* concentration; the minus sign changes the negative numbers that would be obtained from log[H^+] to positive ones:

pH = -log[H^+].

The log conversion reduces a tenfold change in hydrogen ion concentration to a one-unit change in pH. Thus, starting at pH 7, a solution at pH 6 would have 10 times more H^+ than a neutral solution. On the other hand, a solution at pH 8 would have 10 times fewer H^+ than the solution with pH 7. If you skip a few units, the differences between solutions become *very great* indeed. Lemon juice (pH 2) has one million times more H^+ ions per unit volume than seawater, which has a pH of about 8.

Measuring pH

One of the ways that scientists can measure the pH of a solution is to use indicator paper. This is special paper that is infused with dyes that change color when placed in an acid or a base. The most simple indicator paper is called litmus paper. Litmus paper comes in two colors — red and blue.

- Red litmus paper turns blue in the presence of a base (it does not change color in the presence of an acid).
- Blue litmus paper turns red in the presence of an acid (it does not change color in the presence of a base).

In the presence of a neutral solution, red litmus paper remains red, and blue litmus paper remains blue.

Acid and Base Neutralization

If an acid gives a hydrogen ion (H^+) in solution and a base accepts a hydrogen ion by giving a hydroxide ion (OH^-), you may be wondering what will happen when an acid and a base are combined. Let's consider the combination of equal amounts of hydrochloric acid (HCl), a strong acid, and sodium hydroxide (NaOH), a strong base. When the hydrogen ion (H^+) is released from hydrochloric acid, and the hydroxide ion (OH^-) is released from sodium hydroxide, the two ions combine to form water (HOH). Water, as you know, has a neutral pH, so the process of combining an acid and a base is called neutralization. Remember, in a neutral solution (like water) the number of hydrogen ions equals the number of hydroxide ions. The remaining sodium ion (Na^+) from the sodium hydroxide and the remaining chloride ion (Cl^-) from the hydrochloric acid also stay in solution as dissolved table salt (NaCl). This process can be written as it is below:

HCl + NaOH ➨ HOH + NaCl

Notice that the same four atoms (H, Cl, Na, and OH) are found on each side of the equation. Using this example we can generalize the process of neutralization as follows:

acid + base ➨ water + salt (in solution)

The process of neutralization also gives off heat, indicating that chemical potential energy is being released during the course of the reaction. Neutralization has many useful applications. One such application in the laboratory is to neutralize strong acids or bases so that they can safely be disposed of. As you will learn later in this course, the addition of acids and bases to the environment leads to ecosystem damage, so before a strong acid or base can be disposed of, it must be neutralized (to make water and salt) to prevent injuries or environmental damage. In your everyday life you may be familiar with acid and base neutralization through your lawn care and gardening activities. Grass grows best in a very mildly acidic soil (pH 6.5 to 7). So if your soil is too acidic (less than pH 6.5), you would need to add a compound like limestone (a basic mineral) to your soil to neutralize the excess acidity and correct the pH level. Likewise, if your soil is too basic (pH above 7), you would need to add sulfur, which interacts with water in the soil to form sulfuric acid, to help neutralize the excess base in the soil.

Another common application of neutralization is the standard volcano science fair project, where a mixture of vinegar (an acid) and baking soda (a base) are combined to make the volcano "erupt." In this case, the reaction releases some carbon dioxide gas, generating fizz and fun.

If you ever come into contact with a strong acid or base and receive a chemical burn, DO NOT attempt your own science experiment to try and neutralize the compound. The damage to your skin is already occurring and can be exacerbated by adding more chemicals; a vigorous neutralization reaction could cause further harm through the release of heat, causing a physical burn on top of the chemical burn already suffered. Your safest option is to wash the affected area under a heavy stream of running water, and to seek medical attention for your burn. The goal is to remove the agent causing the burn to prevent further damage.

Buffers: Why pH Matters

Living organisms are quite sensitive to even small changes in pH. The chemical reactions of life are tuned to a specific and often narrow pH range; outside this range, the reactions will not proceed normally. Therefore, organisms have mechanisms that work to maintain a constant pH level. This is true both at the cellular level and at the level of the whole organism. Maintaining a stable pH in a living organism is an important part of homeostasis. Homeostasis refers to the ability of an organism (or cell) to maintain stable internal conditions despite constantly changing environmental conditions.

Buffers

One way in which changes in pH are moderated is through the use of buffers. Buffers are aqueous solutions that can resist changes in pH. When an acid or a base is added to a solution containing a buffer, the pH of the solution will only exhibit a very minor change. Blood is a buffered solution. The liquid portion of blood contains carbonic acid (H_2CO_3). It dissociates (breaks apart) to produce bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). This reaction is easily reversible. If acid enters the blood (H^+ concentration goes up), most of the excess hydrogen ions will bond with bicarbonate, restoring carbonic acid. If a base enters the blood, the H^+ concentration will initially go down. But then carbonic acid will dissociate to replace the "missing" hydrogen ions. Thus the easily reversible reaction works to oppose any pH change in the blood. A buffered solution cannot absorb an unlimited amount of acid or base. As acid or base is added, any buffered solution will eventually reach a limit called the "buffering capacity." At this point, no additional hydrogen ions can be absorbed or produced, and the buffer stops working. The solution's pH will change rapidly if further acid or base is added.

Application Spotlight: pH and Human Health

While maintaining a pH close to neutral is usually the goal of homeostasis, there are certain conditions and parts of organisms that are maintained at a lower (more acidic) pH. For instance, the process of digestion is aided by the presence of stomach acid (pH 2). Not only does stomach acid help to break down the compounds in our food, it also helps to prevent disease by killing many of the bacteria and viruses found in food and water. Lysosomes, digestive organelles found in eukaryotic cells, have an internal pH of about 5. Again this acidic environment is used to break down cellular food, waste, and even invading bacteria. Likewise, the surface of our skin is acidic (pH of 4.5 to 6), which helps to support the growth of our normal bacterial flora, as well as to help prevent the growth of pathogenic bacteria.

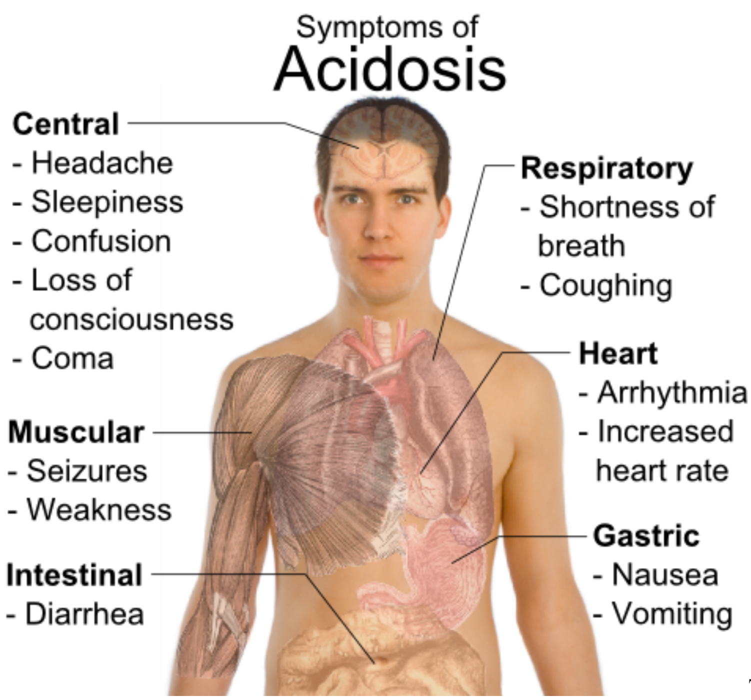
When the normal pH levels of the body are disrupted, there are detriments to the health of the organism. For instance, the female vaginal tract is moderately acidic, with a pH between 3.8 and 4.5. When the pH increases in this area of the body (becomes more basic), women are more prone to bacterial infections of the vagina. Conversely, if the pH decreases (becomes more acidic), women are more prone to yeast infections.

EXAMPLE

Diabetic Ketoacidosis

A higher-stakes example of loss of pH regulation occurs in diabetic ketoacidosis. In people with diabetes, cells cannot take up glucose (sugar) from the blood efficiently. As a result, cells switch from using glucose (sugar) as a fuel source and use fatty acids (fats) instead. When fatty acids are broken down, ketone acids are produced as a by-product. In healthy individuals, a small amount of ketone acids are released by normal metabolic processes; for example, if you are losing weight, fat breakdown will add some ketone acids to your bloodstream. This poses no problem because your blood is buffered, and your liver and kidneys are able to remove the excess acids before they cause problems. However, in people with diabetes, chronic release of ketone acids can overwhelm these systems. Ketone acids build up in the blood and urine, leading to a condition called ketoacidosis. The presence of excess ketone acids lowers the body's pH, leading to several health problems as detailed on the figure below. If the pH balance is not restored, diabetics in ketoacidosis can face serious harm and even death. Treatment consists of restoring proper insulin levels in the body (so that carbohydrates can be absorbed by cells and used as a fuel source) and ensuring proper hydration (to help the kidneys flush out the excess ketones).

Symptoms of Acidosis



This figure shows the symptoms of acidosis in the body broken down by organ system. Notice that the symptoms range from mild to severe. In the long term, these symptoms can become life threatening.

Application Spotlight: pH and the Environment

While it is clear that the regulation of pH in living organisms is crucial to their survival, the pH in the environment is just as important to maintaining life on this planet. Different environments have different pH levels, and organisms that live in those locations have adapted to those conditions. When environmental pH levels are disrupted, the health and vitality of the ecosystem becomes threatened.

EXAMPLE

Seawater

As you have learned, seawater is slightly basic at pH 8. The oceans and the organisms that live in them play a critical role in maintaining the balance of oxygen and carbon dioxide on this planet. You will learn more about this in the Photosynthesis / Cellular Respiration module in the Metabolism unit. With the increased burning of fossil fuels in the modern industrial society, more man-made carbon dioxide (CO_2) is being released into the environment than ever before. Much of this carbon dioxide is absorbed by the oceans. When carbon dioxide is absorbed into water, carbonic acid is produced. This then dissociates to produce bicarbonate ions and hydrogen ions, and the pH of the ocean is lowered. Acidification of the ocean threatens the health of the organisms that call the ocean home. Many marine life forms, including reef-building corals, are harmed or killed when ocean water is acidified. As carbon dioxide levels in the atmosphere continue to climb, there is great concern about the worsening impact of ocean acidification.

Effects of Acid on Coral Reefs

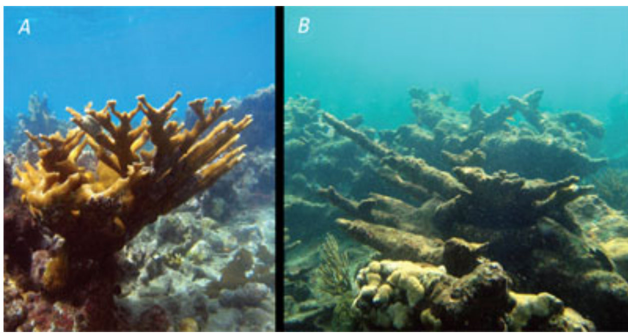


Figure A shows a healthy vibrant coral reef. Notice the bright colors and water clarity. Figure B shows a dying coral reef. Notice the dull, black color of the reef and the poor water quality. Coral reefs are made up of millions of tiny living organisms and provide shelter, food, and nesting grounds to other marine animals. The death of coral reefs due to ocean acidification and other factors is a matter of grave concern to marine biologists and to those who depend on ocean ecosystems.

EXAMPLE

Acid Rain

Another environmental problem involving pH balance is acid rain. When nitrogen oxides and sulfur dioxide, two common by-products of burning fossil fuels, combine with water in the Earth's atmosphere, acid rain is produced. In some regions, acid rain reduces the pH of fresh water sources like streams, rivers, and lakes. It also may change soil chemistry and harm plants. Some regions have rocks and soils that contain buffers, and they are less susceptible to damage from acid rain. However, when soil buffering capacity is exhausted (buffers cannot accept any more hydrogen ions), pH may decline very quickly. Tighter regulations on coal-burning power plants have helped reduce the acid rain problem in recent decades, but it remains a threat to some forest and aquatic ecosystems and the organisms living within them. We will learn more about acid rain in the Ecology unit.

Acids and Bases: Summary

Summary

The concentration of hydrogen ions in solution can have important effects on biological systems. Changes in the hydrogen ion concentration in your body can result in disease and even death. Changes in the hydrogen ion concentration of the oceans can have dramatic impacts on life in the sea, affecting all levels of the food chain. Even something as simple as soil pH can affect the kinds of plants that can live in an area.

Before proceeding with the course, review the key terms introduced in this module. When you are ready, check your understanding of this module by taking the quiz linked at the bottom of this page.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

- acids
- bases
- buffers
- neutral
- neautralization
- pH

Unit Summary: Introduction to Chemistry

Everything around you is made of atoms. After completing this unit, you should have an understanding of the different subatomic particles that make up the atom: protons, neutrons, and electrons. These particles are important in determining the properties of the atom as well as the interactions between two or more atoms.

When atoms interact, they may share electrons. This allows the atoms to connect, or form covalent chemical bonds. It is the ability of the atom to form chemical bonds with other atoms that enables the incredible diversity in forms of matter that you see around you. Ions of opposite charge can interact by electrostatic forces, making ionic bonds. In addition to ionic and covalent bonds, a particularly important chemical interaction found in biological systems is the hydrogen bond.

Water molecules form hydrogen bonds with other water molecules. The hydrogen bonds formed between water molecules give water some important properties that enable life. One such property is the *polar*nature of water, which makes it a good solvent for other polar compounds, like glucose. Hydrophobic nonpolar compounds do not interact with water because of hydrophobic effect; the ordering of water molecules around the dissolved nonpolar molecules is very unfavorable.

Another important aspect of biological solutions is pH, or the hydrogen ion concentration. You should be able to distinguish between an acid and a base and be able to discuss the importance of buffering in biological systems. *Hydrogen ions* are simple structures that have a big impact on living systems. The more hydrogen ions that are found in a substance, the more acidic the substance. As you'll learn in the next unit, hydrogen ions can affect the shape, or structure, of important biological molecules like enzymes and other proteins. As you already know, structure determines function. When the pH of a cell or organism changes, proteins can change shape, resulting in changed function.

Before you move on to learn more about *biological molecules* like proteins, take some time to assess your understanding of the learning outcomes from this unit. When you feel ready, take the unit quiz.

Learning Outcome Self-Assessment Activity:

Before you attempt the unit quiz, take some time to reflect on what you learned in this unit. To facilitate this process, we have included the following *"My Response"* self-assessment activity. In this activity, you will rate your understanding of each learning outcome covered in this unit. You will also be able to formulate questions you still have regarding the content.

Know these key terms:

atom
atomic mass
atomic number
electron
element
ion
isotopes
matter
nucleus
neutron
periodic chart
proton
valence electrons
chemical bonds
covalent bonds
electronegativity
hydrogen bonds
ionic bonds
molecule
molecular drawing
molecular formula
partial charge
polar covalent bond
adhesion

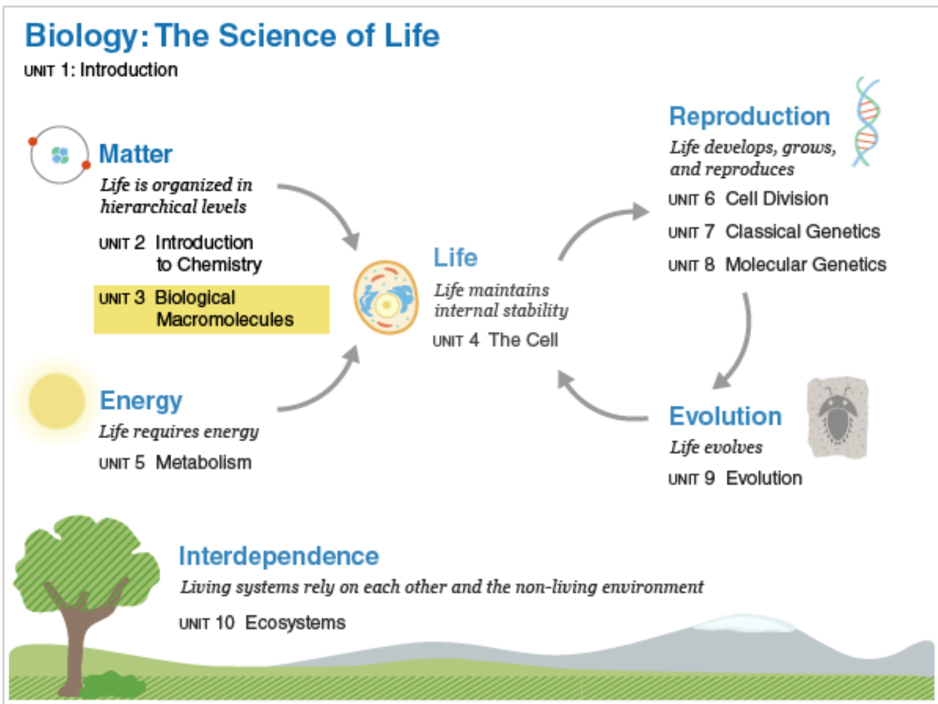
amphipathic
aqueous solutions
cohesion
hydrophilic
hydrophobic
micelles
nonpolar molecules
polar molecules
solute
solutions
solvent
surface tension
acids
bases
buffers
neutral
neautralization
pH

Intro to Biological Macromolecules

Learning Objectives:

- Identify a molecule as organic or inorganic.
- List the four major categories of organic molecules.
- Identify the reason organic molecules are diverse and durable.
- List the four major categories of biological macromolecules and their monomers.
- Identify the 3D structure of an organic molecule based on a chemical drawing.
- Select the correct chemical drawing based on the 3D structure.
- Recognize key functional groups and predict whether compounds will be hydrophobic, hydrophilic, or amphipathic.

In the Introduction to Chemistry unit, you learned that atoms are the building blocks of all matter. You also learned that atoms can be linked together with chemical bonds, to form molecules that have their own unique properties. In this unit, you will take a closer look at a special group of molecules that form the backbone of living structures: the *biological macromolecules*. Biological macromolecules are special molecules that contain carbon atoms covalently bonded with hydrogen atoms.



Atoms are the building blocks of all matter. Biological macromolecules are formed when atoms of carbon, hydrogen, oxygen, nitrogen, phosphorus, and other elements bond with each other in unique and varied ways. Biological macromolecules are the raw materials used to build living organisms.

There are four classes of biological macromolecules that we will study in this course: *carbohydrates,lipids, proteins* and *nucleic acids*. These macromolecules are probably already familiar to you, because they make up the nutrients you ingest every time you eat. In this way, you provide your cells with the building materials and energy necessary to sustain life. In the next unit, we will use these fundamental building blocks to form the cell, the first level of organization that shows all the characteristics of life.

Introduction to Organic Molecules

Learning Objectives:

- Identify a molecule as organic or inorganic.
- List the four major categories of organic molecules.
- Identify the reason organic molecules are diverse and durable.
- List the four major categories of biological macromolecules and their monomers.
- Identify the 3D structure of an organic molecule based on a chemical drawing.
- Select the correct chemical drawing based on the 3D structure.
- Recognize key functional groups and predict whether compounds will be hydrophobic, hydrophilic, or amphipathic.

Introduction to Organic Molecules

In chemistry, the word “organic” has a special meaning. It is different from the grocery-store meaning, where “organic” refers to foods that are grown in a particular way and are free of pesticides. In fact, many of the chemical pesticides that an organic farmer would never use are actually organic molecules.

An *organic molecule* is any molecule that contains a carbon to hydrogen (C-H) covalent bond. They are often complex and many store a lot of chemical potential energy. Examples of organic molecules include glucose, methane, DNA, protein, and fat.

All the molecules discussed in the "*Introduction to Chemistry*" unit were *inorganic molecules*. Molecules like water, oxygen gas, carbon dioxide, and ionic salts like sodium chloride fall into this category. Most inorganic substances are relatively stable, simple, and store little chemical potential energy. What exactly are *organic molecules*? All organic molecules have several common properties that help distinguish them from inorganic molecules:

1. All organic molecules contain carbon atoms bonded to hydrogen (C-H bonds). Organic molecules often contain oxygen, nitrogen, phosphorus, or sulfur as well.
2. Atoms within organic molecules are connected by covalent bonds.
3. Organic molecules are modular. Smaller organic molecules (*monomers*) can be linked together to make larger organic molecules (*polymers*). Larger organic molecules consist of a carbon/oxygen/nitrogen/phosphorus skeleton (backbone) with other atoms branching off from this structure.
4. Organic molecules are typically produced by living cells and are found in large amounts only in living things or in their remains. However, it is important to remember that some molecules produced by living things are inorganic. Humans have developed ways to synthesize organic chemicals artificially.

In this module, you will learn more about how to recognize organic molecules. You’ll also explore in more detail the important characteristics of organic molecules.

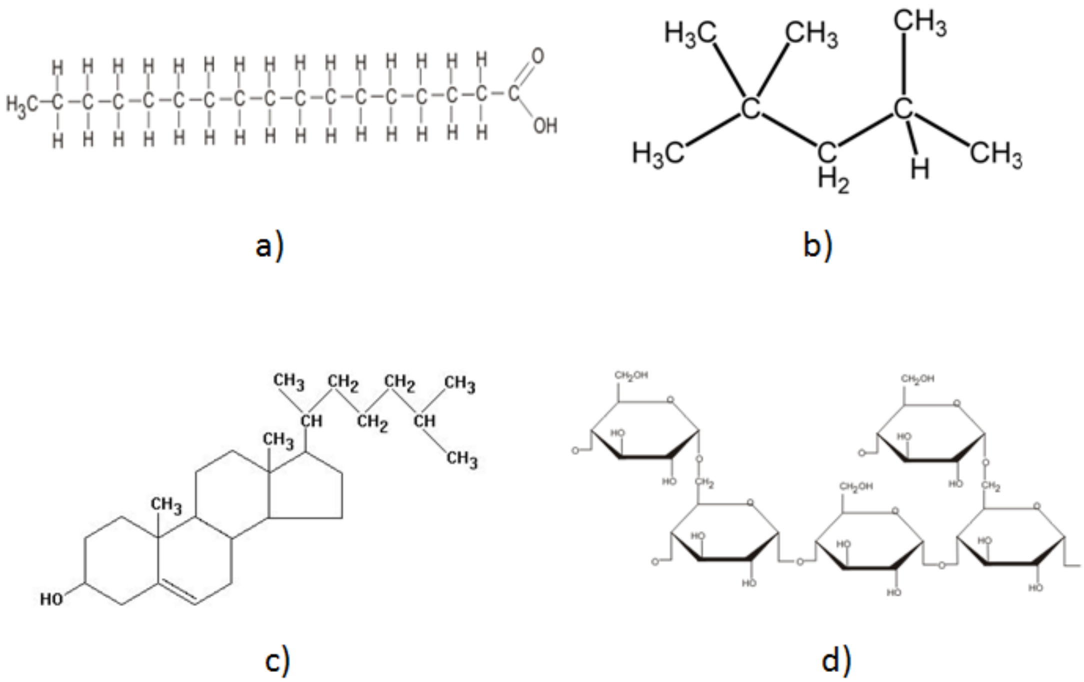
Organic Molecules Contain Carbon

All organic molecules contain carbon atoms covalently bonded to hydrogen (C-H bonds). They can also contain oxygen, nitrogen, or sulfur. In the next activity, you will practice determining whether or not a chemical structure is an organic molecule.

Carbon's Role

Why are organic molecules so diverse and flexible in their structure? The characteristics of carbon are essential for building the complex and diverse structures needed for life. A single carbon atom is able to bond with up to four other atoms, allowing the formation of chains, branched chains, and even rings.

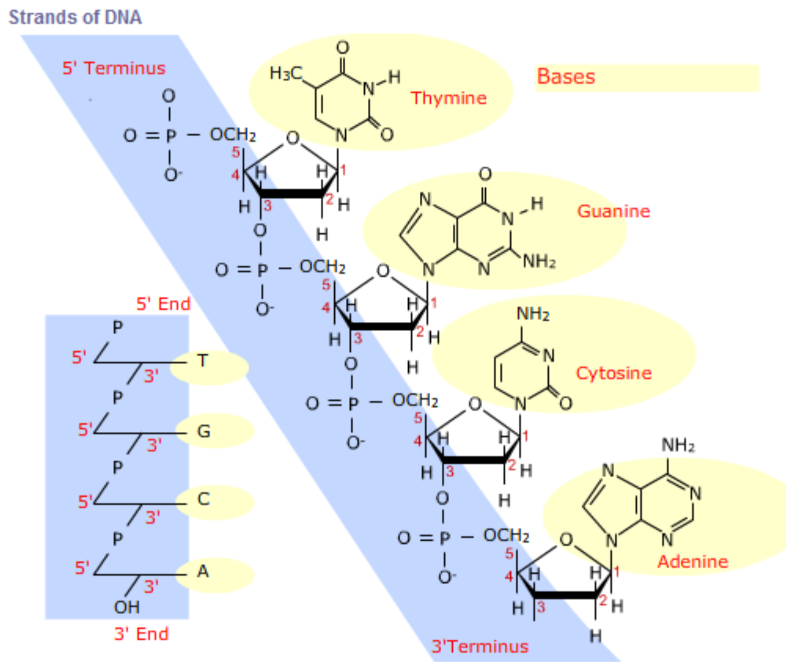
Diversity of Carbon Skeletons



Organic molecules have a diversity of shapes due to carbon's ability to form four covalent bonds. Carbon can form long chains (such as the fatty acid seen in a); branched chains (as seen in b); rings (such as the cholesterol seen in c); or even branched chains of rings (such as the glycerol seen in d).

Carbon forms covalent bonds with many other elements; these strong bonds make organic molecules durable.

DNA



The Phosphodiester Bonds between the sugars form the backbone structures of the DNA and RNA

DNA is made of a carbon skeleton that is bound to nitrogen, oxygen, and phosphorus and hydrogen.

Modularity

Organic molecules come in all shapes and sizes. One of the key features of organic molecules is their modularity: a limited set of *monomers* can be connected in different ways to form a vast array of*polymers*. It may help to consider an analogy: with a few dozen different kinds of Lego bricks, you can make an almost limitless diversity of structures. In organic molecules, monomers can be linked together by bonds between different atoms, different monomers can be used, and they can be strung together in many different arrangements. Therefore, organic molecules are virtually limitless in their diversity.

Biological Macromolecules

The four major classes of biological macromolecules are carbohydrates, proteins, nucleic acids, and lipids. These molecules carry out a diverse set of essential functions. *Carbohydrates* are essential for energy storage and cellular communication. *Nucleic acids* (such as DNA) are essential for information storage within a cell and passing on this information to the next generation. *Lipids* are essential for energy storage and maintaining a boundary between the living organism and its environment. *Proteins* are essential for carrying out most of the necessary functions of life.

Each major class of organic molecules represents a diverse assortment of *polymers* that are built from a handful of possible monomers. The *monomers*, smaller molecules bound together, are also called subunits. The table below lists the subunits for each class of organic molecule. Different carbohydrates, for example, are polymers made up of sugars (the monomers). Proteins are polymers made up of amino acids (the monomers). Nucleic acids are polymers made up of nucleotides (subunits or monomers). Even lipids are generated by combining separate fatty acid chemical components.

Macromolecules and Their Subunits

Large Macromolecule	Small Subunit Molecule
proteins	amino acids
carbohydrates	sugars
lipids	fatty acids
nucleic acids	nucleotides

There are many different types of proteins, carbohydrates, lipids, and nucleic acids. Each has a different function and purpose in living organisms. There are also many different types of subunit amino acids, sugars, fatty acids, and nucleotides. The combination of these different types of subunits is what determines the properties and function of the macromolecule. For example, the function of a particular protein is determined by the amino acids in it.

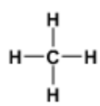
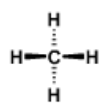
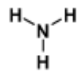
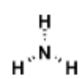
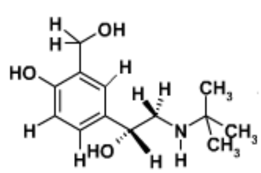
Macromolecules and Their Subunits

Perform the following activity to review the relationship between *polymers* (macromolecules) and*monomers* (smaller subunits). Indicate the macromolecule composed of each subunit.

By University of Maryland University College CC-BY-NC.

In the remainder of this unit, you will be exploring the chemical structures of the four major types of biological macromolecules. You will see molecules represented in a variety of ways. The following activity will help you practice interpreting the different ways molecules can be illustrated.

Different representations of methane, ammonia, and albuterol are shown in the table below. *Formula* gives the chemical formula, *Molecular* indicates how the atoms are bonded together, *2D-Structural* provides some information about the three-dimensional structure using a two-dimensional drawing. The solid wedges indicate that the atoms are above the plane of the page and the dashed wedges indicate that the atoms are below the page. *3D-Structural* images are seen in the Jmol images at the right of each row. You can manipulate the 3D-structures by placing the cursor in the window and moving the mouse. You should understand the relationship between the 2D-structural representation and the 3D-structural representation. You should also take note of the standard color coding in 3D representations: usually carbon is gray, hydrogen is white, oxygen is red, nitrogen is blue, and sulfur is yellow.

Name	Formula	Molecular	2D-Structural
Methane	CH_4		
Ammonium	NH_3		
Albuterol	$C_{13}H_{21}NO_3$		

See the 3D stuctures of the above molecules here (click here).

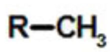
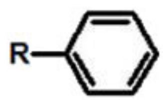
Functional groups are parts of organic molecules that have specific properties or functions. Because organic molecules can contain more than one type of functional group, a particular molecule may have multiple properties. Identifying functional groups in molecules is an important skill, because once you identify a molecule's functional groups, you can predict many aspects of its biological behavior.

Functional groups can be divided into three groups based on their physical properties. There are the nonpolar groups, the polar groups, and the charged groups.

Nonpolar Functional Groups

Functional groups in this category are also referred to as *hydrophobic* (water-hating) groups. They only contain carbon and hydrogen, and lack *electronegative atoms* such as nitrogen, oxygen, and sulfur. Nonpolar functional groups are often found on amino acid side chains of proteins, and they also make up a major part of most lipid molecules. The hydrophobic nature of nonpolar functional groups often affects the shape of molecules containing these groups. For example, proteins will fold so that nonpolar groups are clustered together and are not in contact with water. Some lipids bury the nonpolar section of the molecule by forming lipid bilayers, which shape the boundaries of all cells.

The key *nonpolar functional groups* are:

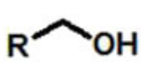
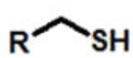
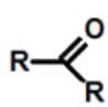
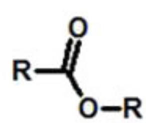
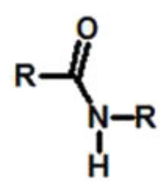
Methyl	Phenyl
	
-CH_3, found in the amino acid alanine, valine, leucine, & isoleucine	- $(CH)_6$, found in the amino acid phenylalanine

Also, long chain alkanes, $(CH_2)_n$, found in lipids, are among the nonpolar functional groups.

Polar Functional Groups

Polar functional groups contain electronegative atoms like nitrogen (N), oxygen (O), and sulfur (S). The presence of electronegative atoms in a functional group results in an unequal distribution of charges on the atoms, causing the bonds to become polar. Because polar bonds interact favorably with water, compounds with polar functional groups also interact favorably with water, making them hydrophilic, or water-loving. In addition to interacting favorably with water, the polar atoms can also participate in chemical reactions and polar functional groups are usually responsible for the catalytic properties of enzymes.

The key *polar functional groups* are:

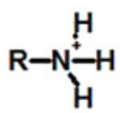
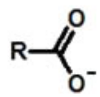
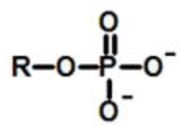
Alcohol	Thiol	Carobonyl	Ester	Amide
				
-OH, Found on Amino Acids and Carbohydrates	-SH, Found on Proteins	=O, Found on Carbohydrates	-C=O-O, Found in Lipids	-C=O-NH2, found on some amino acids. Amino acids are linked together in proteins by amide linkages -C=O-NH-C.

Some compounds contain both nonpolar and polar functional groups; molecules of this type are referred to as *amphipathic* molecules. Phospholipids and soaps are examples of amphipathic molecules.

Charged Functional Groups

Charged functional groups are *acids*, meaning that they form ions by the release of *hydrogen ions (H+)*, which are also called protons. Depending on the specific functional group, these groups of molecules lose a hydrogen ion (or *deprotonate*) and become either charged or neutral as a result. Charged functional groups play key roles in biological systems. For example, many *proteins* bind to *DNA* (or *RNA*) by utilizing the electrostatic interaction between *positive charges* on the protein and *negative charges*on the DNA or RNA. Note that when these groups are in their uncharged state, they can be considered to be polar functional groups.

The key *charged functional groups* are:

Amino	Carboxyl	Phosphate
		
Also charged at neutral pH, with a charge of +1. At high pH values, this group is deprotonated and becomes neutral.	Charged at neutral pH, with a charge of -1. At low pH, this group is protonated and becomes neutral.	This group typically has two negative charges at neutral pH.

A special case of the *phosphate group* is a phosphate diester, which links together nucleotides in DNA and RNA. The phosphate diester is always negatively charged at neutral pH.

Organic Molecules: Summary

All organic molecules contain carbon atoms that form covalent bonds with hydrogen atoms. When organic molecules combine to form proteins, carbohydrates, lipids and nucleic acids, the building blocks for life are established.

In the next modules, you will begin exploring each of these groups, starting with carbohydrates. But before you move on, make sure you understand the following key terms. Then take the module quiz when you're ready.

carbohydrates	inorganic	nucleic acids	proteins
chemical potential energy	lipids	organic molecules	

Carbohydrates

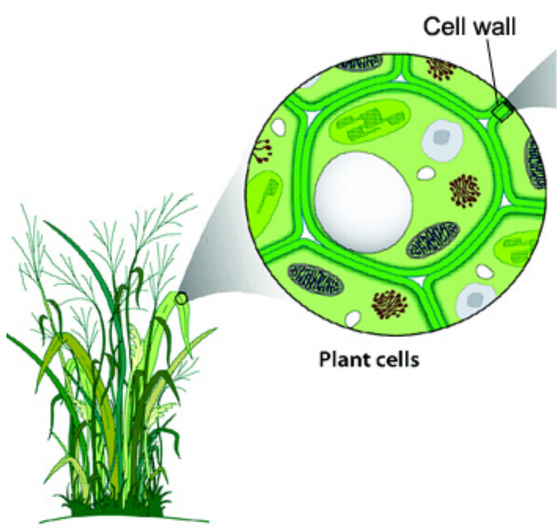
Learning Objectives:

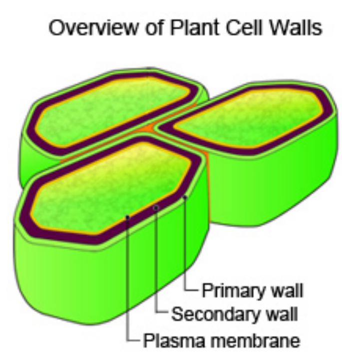
- Explain features that are characteristic of a carbohydrate.
- Compare the structures of carbohydrate molecules discussed.
- Apply your understanding of carbohydrates to address dietary issues.
- Describe how the structure of carbohydrate molecules affects function.

Carbohydrates

Carbohydrates are organic molecules that consist of carbon, hydrogen, and oxygen atoms in a 1:2:1 ratio. The most abundant class of macromolecules found in living systems, carbohydrates are the primary source of energy in living systems. Large complex carbohydrates can be used to store energy. For example, a potato is full of starch, which is a complex carbohydrate that the potato plant uses to store energy. When you eat the complex carbohydrate, your body breaks the large molecules into their smaller subunits (sugars), which you will then use to fuel your own body's energy needs.

Carbohydrates can also be used as structural building materials. Cellulose is an example of a complex carbohydrate used in plants for structural support. Within plant cell walls, cellulose molecules form chains that provide high tensile strength. In some plants, cellulose is also included in a secondary cell wall, which adds rigidity and waterproofing. This helps tree bark, plant leaf stalks, and other structures resist wind and other physical forces in the environment.





Office of Biological and Environmental Research, U.S. Department of Energy Office of Science. http://genomicscience.energy.gov

Cellulose, while indigestible to humans, is an important part of our diets because it makes up dietary fiber, which has been linked to lowered risk of diabetes and heart disease. In this module, you will take a closer look at the structure and function of these important macromolecules.

What Are Carbohydrates?

The paper you write on, the bowl of cereal you eat for breakfast, and the energy you use to walk up a flight of stairs all come from carbohydrates. Rice, wheat, and corn are some of humanity's most important crops; these foods are the primary source of energy for much of our population. All three of these foods are high in carbohydrates.

A *carbohydrate* is an *organic molecule* that contains carbon, hydrogen, and oxygen. Carbohydrates are either simple (often referred to as sugars) or complex. Simple carbohydrates (sugars) are made up of only one or two sugar monomers. Each *monomer* has the proportion of carbon to hydrogen to oxygen in the ratio of 1:2:1, or (CH_2O). You can see why these compounds are called carbohydrates; in a monomer, each carbon is “hydrated.” Complex carbohydrates are made up of more than two sugar monomers linked together. Carbohydrates can be further subclassified, again on the basis of structure, depending on the number of monomers in each molecule: *monosaccharides* and *disaccharides* (simple carbohydrates) and polysaccharides (complex carbohydrates).

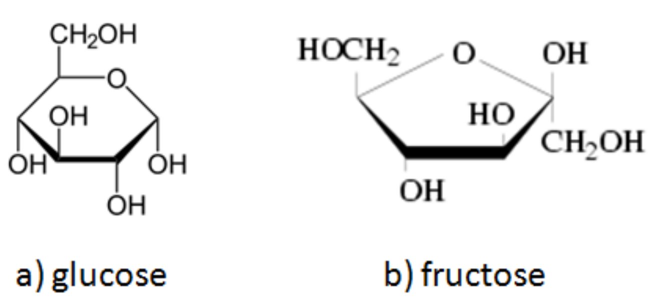
Simple carbohydrates are quickly and easily accessed to generate energy the cell can use, while complex carbohydrates are used to store energy for a longer period of time. Some *complex carbohydrates* are also used as structural components. Carbohydrates also play a role in cell signaling and recognition within multicellular organisms.

Structure of Carbohydrates

Monosaccharides

Monosaccharides are the simplest sugars. The root “mono” means "one," and “saccharide” refers to an organic molecule where the ratio of carbon:hydrogen:oxygen is 1:2:1 (i.e., $C_NH_{2N}O_N$). The more commonmonosaccharides contain six carbons and have a molecular formula of $C_6H_{12}O_6$. Glucose, fructose (fruit sugar), and galactose are examples of six-carbon monosaccharides. A common five-carbon monosaccharide is ribose (the sugar component of *RNA*), which has a molecular formula of $C_5H_{10}O_5$. *DNA* contains a modified ribose where one of the oxygen atoms has been removed, hence the name *deoxy*ribonucleic acid. Shorter monosaccharides exist as linear molecules while five- and six-carbon monosaccharides form ring-like structures.

Sample Monosaccharides



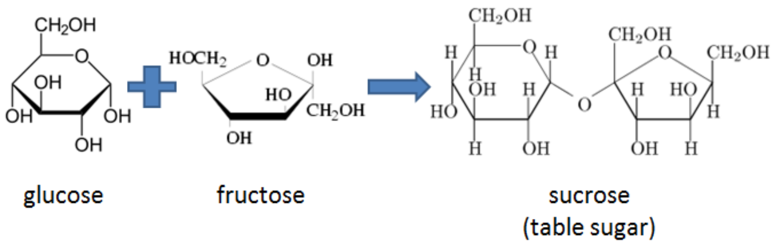
Glucose (a) and fructose (b) are monosaccharides containing six carbons. Ribose (c) is a monosaccharide containing five carbons.

Disaccharides

Disaccharides are made of two monosaccharides linked together by a covalent bond (the root “di” means "two").

- glucose + fructose = sucrose (table sugar)
- glucose + galactose = lactose (milk sugar)

Disaccharides



Sucrose is composed of one glucose and one fructose linked together.

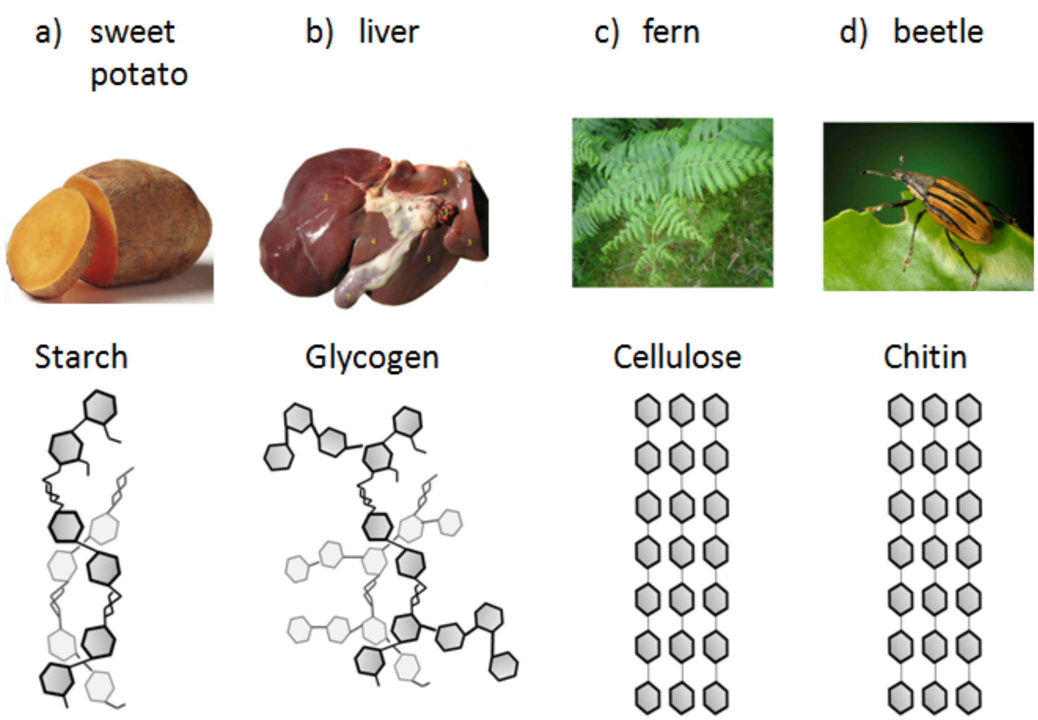
Polysaccharides

Polysaccharides are long chains of monosaccharides (“poly” means "many").

Glycogen, starch (amylose and amylopectin), and cellulose are all made of many linked glucosemonomers. Glycogen is mainly used for energy storage in animals. Starch is mainly used for energy storage in plants. Cellulose is mainly used for maintaining plant structure. These three molecules are all made of glucose, so why do they have such different functions? The main difference is how the glucose monomers are linked together. This is a prime example of one of the central themes of biology: *form affects function*.

These differences are explained in more detail below.

Chitin, a modified structural polysaccharide, is best known as a major component of the exoskeleton (hard outer shell) of arthropods (e.g., beetles, crabs, lobsters) and mollusks (e.g., snails, clams, scallops). However, chitin also plays a minor role in the cell structure of some fungi, algae, and yeasts. Chitin $(C_8H_{13}NO_5)_n$ is comprised of slightly-modified glucose monomers.



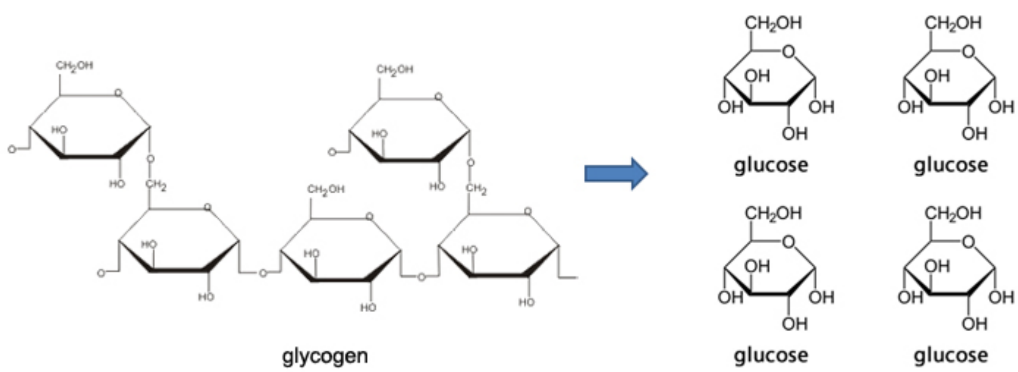
Function of Carbohydrates

Source of Stored Energy

Digestible carbohydrates provide energy in a form that is easily accessible. Glucose, with the chemical formula $C_6H_{12}O_6$, is a simple sugar and a monosaccharide. It is one of the most abundant and important energy molecules for living things. The energy stored in covalent bonds between atoms (within a glucose molecule, in this case) is released during cellular respiration, when glucose is broken down and converted to simpler, more stable molecules. This energy can be captured to make ATP, which can then be used to power cellular processes. This will be covered in greater detail in the metabolism unit.

In animals, excess glucose molecules are linked together (through an anabolic pathway) to make a long branching polysaccharide called *glycogen*. Glycogen is primarily stored in the liver, with small amounts being stored in the muscles. Once glycogen stores are filled, the body begins storing excess food calories as fat. Conversely, when food intake is insufficient to keep up with energy requirements, the body will break down its glycogen stores to release individual glucose monosaccharides.

Glycogen Can be Broken Down into Glucose

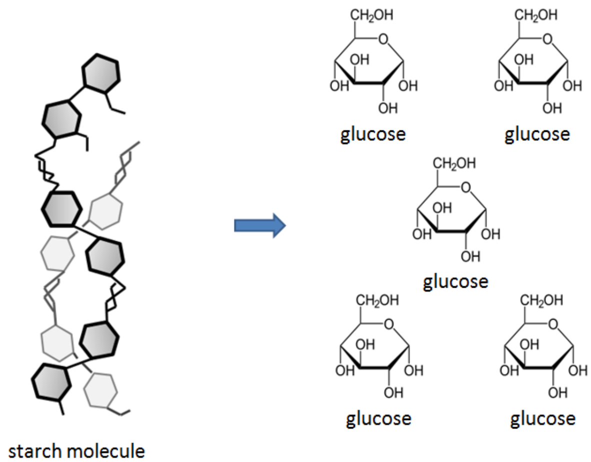


When energy is needed, glycogen stores can be broken down into individual glucose molecules. The glucose can then be used to make ATP (a usable form of energy for the cell).

Starch

Starch, another branching polysaccharide, is the primary form in which excess glucose is stored in plants (and other producers). Starch, just like glycogen, is composed of individual glucose monomers joined together. And, like glycogen, starch is broken down to release individual glucose molecules that can be used to build ATP. The difference between these two energy storage polysaccharides lies in the organization of the glucose monosaccharides.

Starch Can Be Broken Down into Glucose

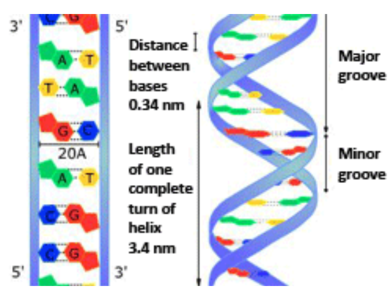


When energy is needed, starch stores can be broken down into individual glucose molecules. The glucose can then be used to make ATP (a usable form of energy for the cell).

Carbohydrates as a Structural Component

Cellulose, like glycogen and starch, is a polysaccharide that is made up of many glucose monosaccharides linked together. Cellulose is an important structural carbohydrate that provides support within plant cell walls. This carbohydrate is indigestible by humans and most animals. Some animals (e.g. cows, horses, and termites) can digest this carbohydrate. These animals have symbiotic ("living together") bacteria that inhabit their digestive tract. The bacteria produce enzymes that break down cellulose, making sugar available to their hosts.

Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) are the molecules involved with storing our genetic information (DNA) or the conversion of that information into proteins (RNA). Sugars (deoxyribose in DNA, ribose in RNA) play a part in the structure of these nucleic acid molecules. They alternate with phosphate groups to make up the long backbone of nucleic acids, as shown below.



Carbohydrates as Cell Recognition and Signaling Molecules

Although we will not delve into the specifics of this topic, carbohydrates play a variety of roles in identification and signaling. One of the ways your immune system is able to identify foreign invaders is through detection of the different carbohydrates displayed on the surface of cells. Additionally, the first step in fertilization between a sperm and egg is generally believed to involve carbohydrate-to-carbohydrate interactions. As a final example, the specific carbohydrates attached to the surface of your red blood cells determine your "blood group" (A,B,O) and predict what kind of blood you can safely receive in a transfusion.

Application Spotlight: Carbohydrates and Health

Indigestible carbohydrates, which cannot be degraded by human digestive enzymes, are referred to as*dietary fiber*. Cellulose, mentioned above as a major component of plant cell walls, is one of the largest contributors of dietary fiber. Pectin is another structural carbohydrate found in most plants, especially apples and citrus fruits, and is commonly used as a gelling agent to make jams and jellies. A diet high in fiber has several benefits. Dietary fiber plays a role in maintaining regular digestive functioning, slowing the absorption of sugar into the bloodstream, and reducing bad cholesterol. So the old saying "an apple a day keeps the doctor away" does have some truth to it, since there are proven health benefits associated with the consumption of foods that are high in fiber, like apples. Other foods that are high in fiber are oatmeal, popcorn, raspberries, black beans, lentils, and peas, to name a few.

For a quick boost of energy, simple sugars are the carbohydrate of choice; diabetics will oftentimes carry a sugary food or drink with them in case their blood sugar level drops too low. However, excessively high blood sugar levels can be equally dangerous. Accordingly, doctors routinely suggest that diabetics eat a diet high in fiber to help manage their diabetes, since fiber helps to slow the absorption of sugar into the bloodstream, which helps diabetics to prevent spikes in blood sugar. In contrast with simple sugars, complex carbohydrates are broken down by the body more slowly and energy is released in a stepwise fashion.

Summary

All living organisms contain four major classes of macromolecules, one of which is carbohydrates. Often referred to as "carbs," carbohydrate molecules consist of carbon, hydrogen, and oxygen in a 1:2:1 ratio. Complex carbohydrates are built when simple sugar molecules are covalently bonded together. The main function of carbohydrates is to store energy, which the living organism can use at a later time. Carbohydrates also function as structural materials and in cellular signaling and recognition.

You are almost ready to take the module quiz. Before starting, review the key terms introduced in this module. When you are ready, check your understanding of this content by taking the quiz linked at the bottom of this page.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

dietary fiber disaccharide glycogen monosaccharide polysaccharide starch

Lipids

Learning Objectives:

- Identify the molecular structure of a sample phospholipid.
- Identify the molecular structure of a sample steroid.
- Identify the molecular structure of a sample triglyceride.
- Identify the basic molecular structure of a wax.
- List several functions of waxes in nature.
- Identify the function of steroids.
- Compare and contrast saturated and unsaturated fatty acids.
- Describe the structure of a trans fat.
- Describe the health risk associated with trans fats.
- Identify the hydrophobic and hydrophilic parts of a phospholipid.
- Describe how phospholipids respond when immersed in water.
- Describe the importance of steroids to human nutrition.
- Identify the basic molecular structure of the four biological macromolecules.
- Identify the functions of the four biological macromolecules.
- Identify the function of phospholipids.

Introduction to Lipids

Lipids are a diverse group of macromolecules united by their hydrophobic, nonpolar nature. We are most familiar with the lipids known as fats. Fats are used to store energy for later use. They also provide structural support and cushioning for many animals. Some dietary fats are healthier than others. In this module, you will learn about the differences between saturated, unsaturated, and trans fats.

People are most familiar with fats, but there are other types of molecules that are not fats, but are lipids. Cholesterol is a familiar example of a lipid that is not actually a fat. You will learn more about cholesterol in this module as well.

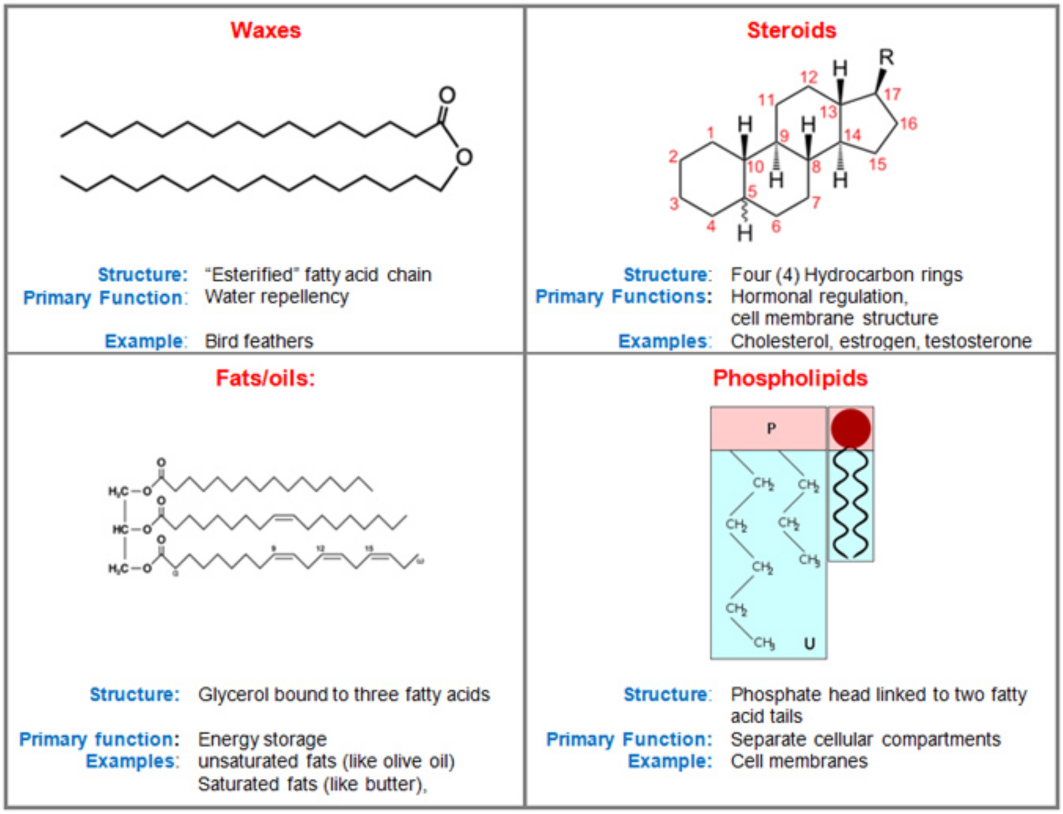
What Are Lipids?

Lipids include a diverse group of compounds that are united by two common features. First, they are largely nonpolar in nature. This is because they are hydrocarbons that include many nonpolar carbon-carbon or carbon-hydrogen bonds. Second, because lipids are nonpolar, they are also hydrophobic (water-hating), or insoluble in water.

Lipids perform many different functions in a cell. Cells store energy for long-term use in the form of fats. Lipids also provide insulation from the environment for plants and animals. For example, they help keep aquatic birds and mammals dry because of their hydrophobic nature. Lipids are also the building blocks of many hormones and are an important constituent of the cell’s plasma membrane. Lipids include fats, oils, waxes, phospholipids, and steroids.

Summary of Lipid Structures and Functions

Because lipids are such a diverse group of biomolecules, we will study them in four categories. Examine the following table for a general understanding of lipid structure and function.



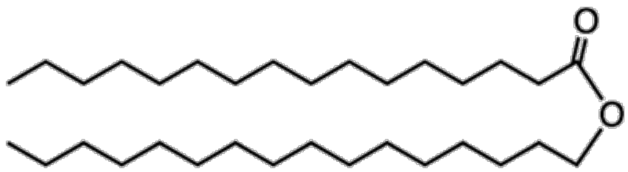
Waxes

Waxes are nonpolar lipids that form protective layers on plants and animals. For example, waxes cover the feathers of some aquatic birds to keep the feathers dry. Plants, on the other hand, often have leaves coated with waxes to prevent water from evaporating off the plant surface. Because of their hydrophobic nature, waxes prevent water from sticking on the surface of these structures.

Waxy coverings on some leaves are made of lipids.

Waxes on the feathers of ducks help keep them dry.

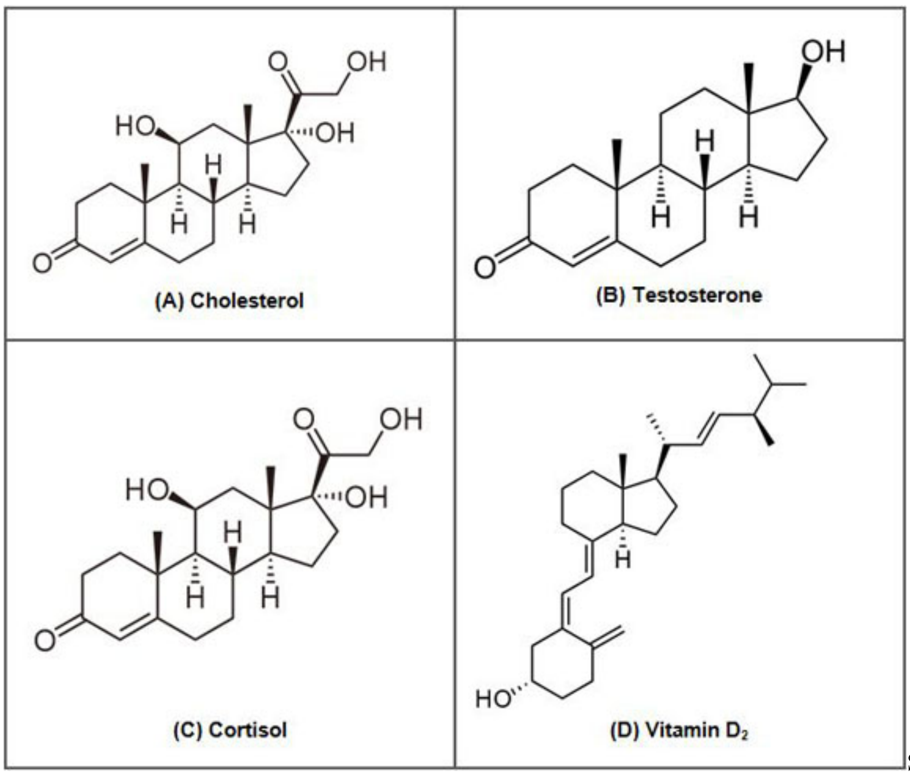
Wax: "Esterified" Fatty Acid Chain


Chemical structure of cetyl palmitate, a typical wax ester.

The chemical structure of a wax is linked to its function. Waxes are the simplest lipids in nature, consisting of two long hydrocarbon chains linked in the middle by an ester group. It is this structure that enables waxes to function the way they do in living systems.

Steroids

Steroids are a family of lipids based on a molecular structure with four fused carbon rings. This family of lipids includes many hormones and cholesterol. Hormones (such as estrogen and testosterone) are used by some animals as long-distance messengers. This means that they are produced by cells in one part of the body and affect cells in a different part of the body.



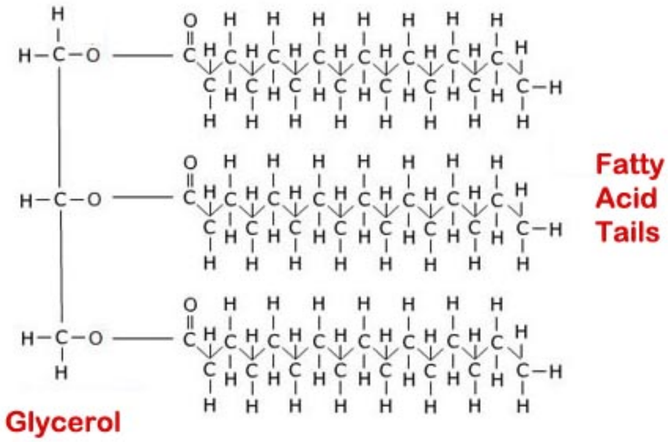
Steroids — including cholesterol, testosterone, vitamin D_2, and cortisol — are characterized by four fused hydrocarbon rings. The chemical groups attached to these carbon rings are what distinguishes different types of steroids: (A) shows a molecule of cholesterol; (B) shows a molecule of testosterone; (C) shows cortisol; and (D) shows vitamin D_2.

Cholesterol is an example of a familiar steroid that plays many important roles in your body. While most people are familiar with cholesterol, they often don’t realize how important it is for healthy function. In fact, most of the cholesterol in your body is synthesized by your liver. Cholesterol has many functions. Cholesterol is used to build steroid hormones, including testosterone and estradiol, which are secreted by the sex organs. Cholesterol is also the precursor to vitamins D and K. Some cholesterol is converted to bile salts, which help in the absorption of fats from the digestive system into the body. Cholesterol is also used by animals to maintain the proper consistency of the cell membrane, which is the structure that surrounds every cell. Other organisms use different steroids for this function. For example, plants use a steroid called stigmasterol, while fungi use ergosterol.

Triglycerides

Structure and Function of Triglycerides

Fats and oils are called triglycerides because they are made of three (“tri”) fatty acids attached to one glycerol. A fatty acid is a carboxylic acid that contains a long hydrocarbon chain. The fatty acids are usually 16 to 22 carbons long, but can range from 4 to 36 carbons in length.



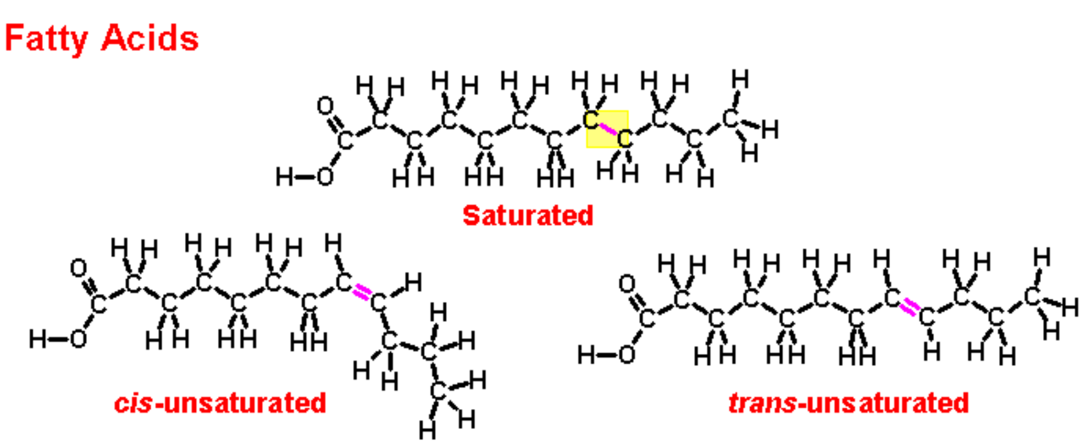
In one triglyceride there are three fatty acid tails (shown on the right). Each is connected by a covalent bond to one of the three oxygen atoms of a glycerol group.

Fats are mainly energy storage and insulating molecules. Per gram, fats contain twice as much energy as carbohydrates. Layers of fat also surround the vital organs of animals to help cushion and protect them. In some animals, layers of fat under the skin provide insulation. This is particularly true of marine*endotherms* (i.e., organisms that maintain internal body temperature using their own metabolism) that live in cold polar regions, like penguins, whales, and seals. These are all examples of animals with thick insulating “blubber” beneath the skin.

Saturated and Unsaturated Fats

In one triglyceride there are three fatty acids. All of these can be the same, or there can be two or three different types of fatty acids in a single triglyceride. The fat’s properties depend on the types of fatty acids that are present.

In saturated fatty acids, all of the carbon-carbon bonds are single bonds and each carbon is bonded to two or three H atoms; each carbon is “saturated” with hydrogen. Because all the bonds are single, the entire fatty acid can adopt a linear shape. Unsaturated fatty acids have one, two, or even three double bonds along the carbon “backbone.” Notice in the diagram below that at each double bond, the carbons involved are bonded to only one instead of two hydrogen atoms. Thus these fatty acids have less hydrogen; they are “unsaturated” with respect to hydrogen. The double bonds found in the unsaturated fatty acids have an effect on the overall shape of a triglyceride: unsaturated fatty acids are normally “kinked,” because the double bond prevents free rotation between the two carbons involved.



Three 12-carbon

fatty acids are shown. The top structure, lauric acid, is fully saturated. The two lower structures are unsaturated fatty acids, each with a double bond. The *cis* (left) form is typically found in biological lipids. In cis unsaturated fatty acids, the hydrocarbon chain is kinked at each double bond. The *trans* (right) form is generated artificially by a process that is used to convert liquid vegetable oil to solid margarine. In trans fatty acids, the double bond is rotated so that the fatty acid is relatively straight.

Saturated fats have three saturated fatty acid “tails” — all of which are linear in shape. With their compact shape, saturated fat molecules pack together efficiently and form a solid at room temperature. These are usually produced by animals; everyday examples of saturated fats include lard and real butter. Unsaturated fats have at least one unsaturated fatty acid. With their “kinky” fatty acid(s), unsaturated fats will not pack into a regular structure and thus remain fluid at room temperature. They are called oils, and are commonly produced by plants; everyday examples include olive oil, corn oil, and canola oil.

Trans Fats

A diet rich in saturated fats may contribute to formation of plaques in the arteries (atherosclerosis) and increase your risk of heart disease. To reduce this risk, it is recommended that you replace some foods rich in saturated fats (e.g. fatty cuts of pork, beef, and high-fat dairy products like butter) with foods that provide unsaturated fats (available in foods like olive oil, canola oil, seafood, and walnuts). Such a shift is believed to help improve blood cholesterol levels and may reduce your risk of cardiovascular disease.

Physical Properties of Saturated and Unsaturated Fats

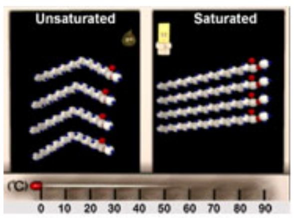


Fig. 1

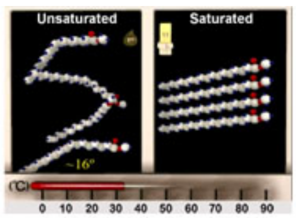


Fig. 2

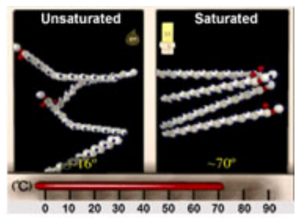


Fig. 3

In the diagram above, you see the physical behavior of two different triglycerides (with saturated and unsaturated fatty acids) at three distinct temperatures. Figure 1 shows that at a temperature of 0^{o}C (freezing), both types of fatty acids stack neatly. At 16^{o}C (Fig. 2), the unsaturated fatty acids lose the tightly stacked formation and become more mobile. At 70^{o}C, the saturated fatty acids also become mobile (Fig.3). At 27^{o}C (room temperature) and at 37^{o}C (body temperature), triglycerides with unsaturated fatty acids are liquid oils, whereas saturated fats remain solid.

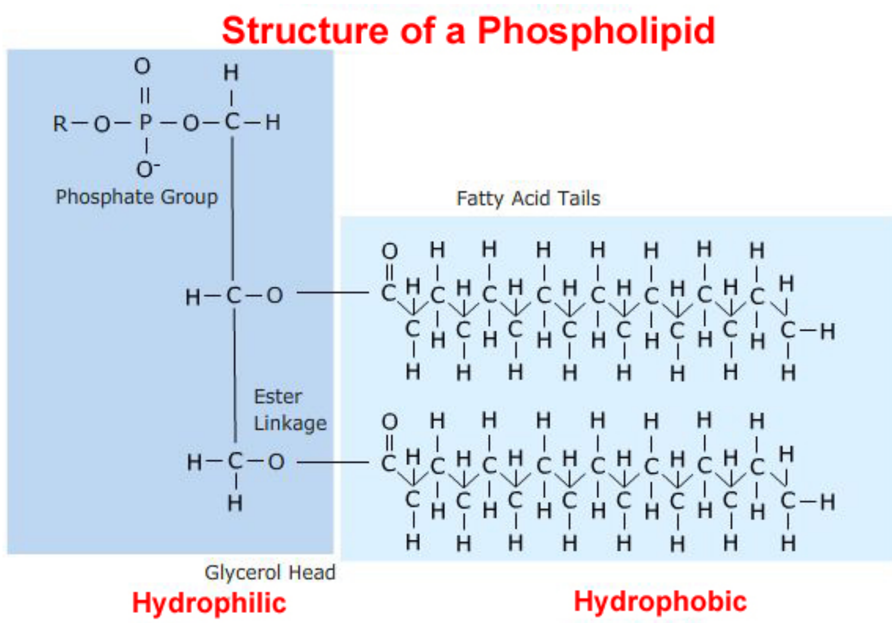
Trans Fats

Since the early 20th century, modified vegetable oils have been produced that are solid at room temperature. Examples include margarine and vegetable shortening. To make these products, a chemical process is used to add hydrogen to vegetable oil. Many of the double bonds in the fatty acids are replaced by single bonds (and hydrogen atoms), but some double bonds remain in the partially hydrogenated oils that result. This process increases shelf-life and produces flaky rather than crumbly crusts when used for baking. As a side effect of the chemical transformation, the orientation of some of the remaining double bonds is shifted. The naturally occurring double bonds are converted to *trans* double bonds, making "*trans* fats."

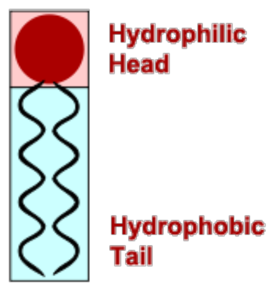
Historically, it was believed that synthetic *trans* unsaturated fats would be as “good for you” as natural unsaturated fats. However, recent studies have shown that consumption of trans fat may pose a significant health risk. Consuming a lot of trans fat can lead to an increase in levels of low-density lipoproteins (LDL). This in turn is associated with a higher risk of heart disease. Many fast food restaurants have recently banned the use of trans fats, and many products have been reformulated so that they are much lower in trans fats. However, trans fats are still a common ingredient in many processed foods; close reading of ingredient and nutrition labels is recommended.

Phospholipids

Phospholipids are an important class of lipids found in the membranes of all cells and organelles. A phospholipid contains only two fatty acids attached to a glycerol, which in turn is bound to a phosphate group. Together, the phosphate and the glycerol make up the "head" of the phospholipid. The fatty acids make up the molecule's "tail." The phosphate group carries a negative charge and is therefore hydrophilic. The tail, on the other hand, is made up of nonpolar fatty acids and, like other lipids, is hydrophobic. Thus phospholipids, like fatty acids, are amphipathic. An amphipathic molecule has both a hydrophilic end and a hydrophobic end.



A phospholipid is made of two fatty acids and a phosphate group attached to glycerol.



For simplicity, phospholipids are often drawn as a circle to indicate the phosphate group and 2 chains to indicate the fatty acids.

Phospholipids in Water

Remember that hydrophilic molecules dissolve in water and hydrophobic ones do not. But phospholipids have a "split personality" in this regard. How do they behave in water? When small numbers of phospholipids are in an aqueous solution they will self-assemble into micelles, structures that exclude water molecules from the hydrophobic tails while keeping the hydrophilic head in contact with the aqueous solution. If enough phospholipids are present, they will form a bilayer. This is the favored formation because it is the most stable orientation for phospholipids in a water solution. View the animation that demonstrates the formation of micelles and bilayers.

Click the green arrow to play the animation.

With their "split personality," phospholipids are able to play a very important role in biology. Phospholipids, together with other molecules in smaller quantities, form membranes that surround the cell and intracellular organelles such as mitochondria. The cell membrane is a fluid, semipermeable bilayer that separates the cell's contents from the environment. See animation below.

A closer view of a Lipid Bilayer forming a membrane

Application Spotlight: Cholesterol in the Human Body

Although some cholesterol is essential for healthy physiological functioning, excess cholesterol can lead to health problems. Because cholesterol is hydrophobic, it cannot be easily transported through the body in the blood stream. A carrier is required to transport cholesterol around the body to the cells that need it. These carriers are called *lipoproteins*. You can think of lipoproteins as cholesterol boats that carry cholesterol to the body's cells (where it can be used to build or repair cell membranes or synthesize steroid hormones). Lipoproteins that carry cholesterol *to the cell* for use are called *low-density lipoproteins (or LDL)*. LDL is often referred to as "bad" cholesterol, because excess LDL levels have been linked to plaque deposition in the arteries, which can result in heart disease. Another type of lipoprotein, known as high-density lipoprotein (or HDL) transports cholesterol *to the liver*, where it is often turned into bile salts and excreted. HDL is often referred to as "good" cholesterol, because high blood concentrations of HDL have been linked to a decreased risk of heart disease. Exercise and proper diet can increase HDL levels. Increasing intake of unsaturated fats and decreasing intake of saturated fats is also a good strategy for increasing HDL levels.

learn by doing

Cholesterol by the Numbers

Given what you know about the function and structure of cholesterol, why would deposits within the arteries be bad? Examine the table below providing interpretation of cholesterol numbers including LDL and HDL.

Recommended Lipoprotein Levels for the USA

TOTAL Cholesterol Levels	
Below 200 mg/dL	Desirable
200-239 mg/dL	Borderline high
240 mg/dL and above	High
LDL	
Below 70 mg/dL	Ideal for people at very high risk of heart disease
Below 100 mg/dL	Ideal for people at risk of heart disease
100-129 mg/dL	Near ideal
130-159 mg/dL	Borderline high
160-189 mg/dL	High
190 mg/dL and above	Very high
HDL	
Below 40 mg/dL (men) or below 50 mg/dL (women)	Poor
50-59 mg/dL	Better
60 mg/dL and above	Best

Cholesterol numbers measured in milligrams (mg) per deciliter (dL) of blood. Table modified from "Cholesterol levels: What numbers should you aim for?" June 1, 2011; Mayo Clinic.

Lipids: Summary

Summary

Lipids are a diverse group. These molecules function in energy storage, cell communication, and protection. They vary in shape from multiple carbon rings to long carbon chains. However, they are united as a group because they are mostly made of hydrocarbons.

Lipids are essential to life. Phospholipids form the bulk of cell membranes, which define the cell. Steroids can be used to help maintain proper membrane fluidity and are used as long-distance messenger molecules in some animals. Triglycerides are an excellent source of energy storage for organisms. Maintaining proper lipid levels is also essential to human health. A deeper understanding of the chemistry and physiology of these molecules can help us develop a better understanding of ourselves.

Key Terms

Take some time to review the main concepts in this module. When you are ready, check your understanding of proteins by taking the quiz linked below.

cholesterol	endotherms	fatty acids	lipids	lipoproteins
phospholipids	saturated fats	steroids	trans fats	triglycerides
unsaturated fats	waxes			

Proteins & Enzymes

Learning Objectives:

- Distinguish between proteins and enzymes.
- Associate biological functions with proteins.
- Recognize the common chemical structure of amino acids.
- Predict whether an amino acid is hydrophobic or hydrophilic based on its side chain.
- Describe chemical changes during peptide bond formation.
- Identify the peptide bonds in strings of amino acids.
- Using the relationship between sequence and structure, predict how a protein will fold, based on the hydrophobic effect.
- Describe structural changes during protein denaturation.
- Predict the substrate that will bind to a ligand, based on complementarity between the binding site and ligand.
- Predict the effect of changing the activation energy on the rate of a reaction.
- Predict the effect of the environment on the activity of enzymes.
- Determine the consequences of an enzyme malfunction.

Introduction to Proteins

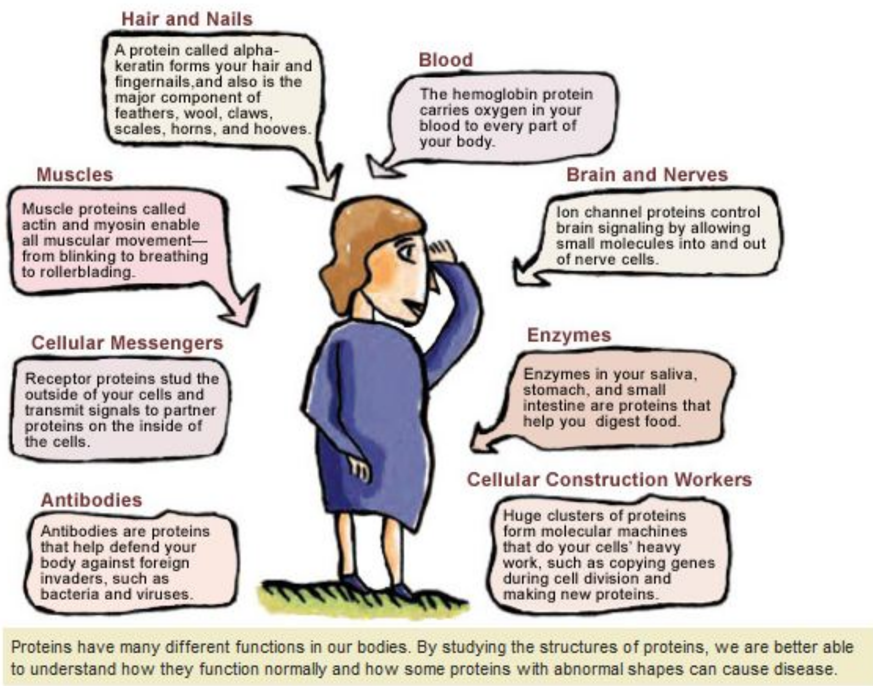
Proteins are the most functionally diverse group of biomolecules we will examine in this unit. Critical to our diet, protein can be found in animal products like meats and cheeses, as well as in plant products like beans and grains. Kwashiorkor, which causes a distinct swelling of the abdomen, is often seen in malnourished children who lack sufficient protein in their diets. Proteins are also found in many toxins, such as the incredibly poisonous toxin produced by the bacterial species *Clostridium botulinum*. Studies have shown that just one teaspoon of this poison, which is a protein, would be enough to kill 20 percent of the world's population! This module will take a closer look at the structure of a protein and examine how protein structure enables such a wide range of diverse functions.

What Are Proteins?

Proteins are macromolecules built from amino acids. There are 20 different amino acids that can be joined in a myriad of ways to produce molecules with an enormous variety of possible structures that can perform a huge number of critical cellular functions. The following list represents just a sampling of the many things proteins can do in living systems.

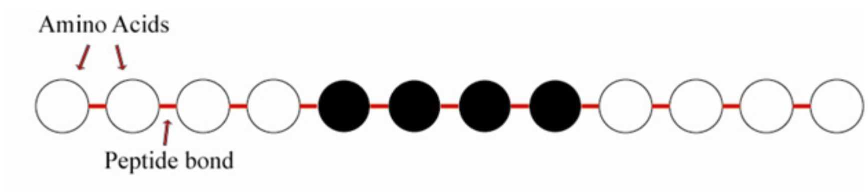
1. Proteins can catalyze chemical reactions by accelerating the rate at which chemical reactions take place in the cell. Proteins that catalyze reactions are called enzymes.
2. Proteins play a role in the storage, replication, transmission, and regulation of genetic information (DNA). Some proteins bind to DNA and either reduce the expression of a gene, or activate the expression of a gene.
3. Proteins can help move substances in and out of the cell. These proteins can be embedded in the cell membrane, where they act as transporters.
4. Some soluble proteins can transport materials throughout the body. Hemoglobin is a protein that is found in high concentrations in red blood cells. Hemoglobin carries oxygen from our lungs to our tissues.
5. Proteins can recognize specific molecules. Protein receptors found in the lining of your nose recognize and bind to chemicals in the air, which triggers a message to the brain indicating the presence of a certain smell.
6. Proteins can facilitate mechanical movement. Special proteins found in muscle cells use the energy in ATP to flex your muscles.
7. Proteins can help maintain structure in an organism. The cellular cytoskeleton consists of proteins that form long fibrous scaffolding in cells that helps the cell maintain its shape.

Take a look at this diagram to see even more ways that proteins are used in your body.



Source: *The Structures of Life,* National Institute of General Medical Sciences.

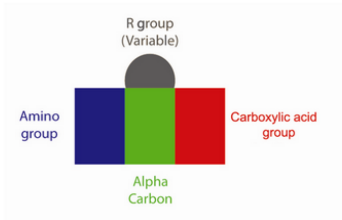
Amino acids are the building blocks of proteins. A protein is composed of a series of amino acids attached end-to-end via covalent bonds. Consequently, a protein looks like a string of beads, with each bead representing an amino acid. The bond between the amino acids is referred to as the peptide bond.



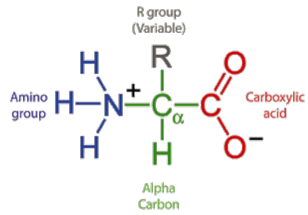
Amino acids, represented here by circles, are the building blocks of proteins. When amino acids are attached to each other via peptide bonds, they form a protein. Proteins can be made up of a number of different amino acids, represented in this figure by the open and filled circles.

An amino acid is a small organic chemical that is made up of four parts. There is a nitrogen-containing amino group on one end of an amino acid. The other end of an amino acid has a carboxylic acid group. These two groups (the amino group and the carboxylic acid group) are the reason for the name "amino acid." The amino and carboxylic acid groups are linked by a single carbon atom called the alpha carbon. Finally, there is a variable "R group" also attached to the alpha carbon. The amino acids differ in the nature of the R group that is attached to the central alpha carbon. There are 20 different R groups commonly found in nature. In this way, all amino acids are identical except for the different R groups (also called side chains) attached to the alpha carbon. The properties of different proteins depend entirely on the sequence, or arrangement, of the amino acids.

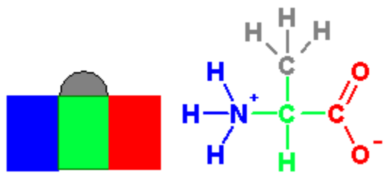
There are many ways to represent an amino acid. Take a look at some of the representations below.



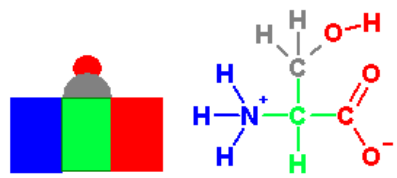
This is a building block diagram.



This image reminds you that the blocks are representing chemical structures.



Alanine



Serine

Two amino acids are shown: alanine and serine. The building block diagram for each amino acid is on the left and the chemical structure is on the right. Note that only the side chain (R group) differs between the two: in alanine, it consists of a nonpolar CH3 group; in serine, one of the hydrogens has been replaced by a polar -OH group

learn by doing

Common Amino Acids

Instructions: You should become familiar with the functional groups associated with the side-chain atoms of each amino acid. You should be able to infer the properties of the side chain from the 2D chemical diagram and the 3D structure. For example, which amino acids have polar side chains? Which have planar aromatic groups? You can explore the basic functional groups by clicking on this link.

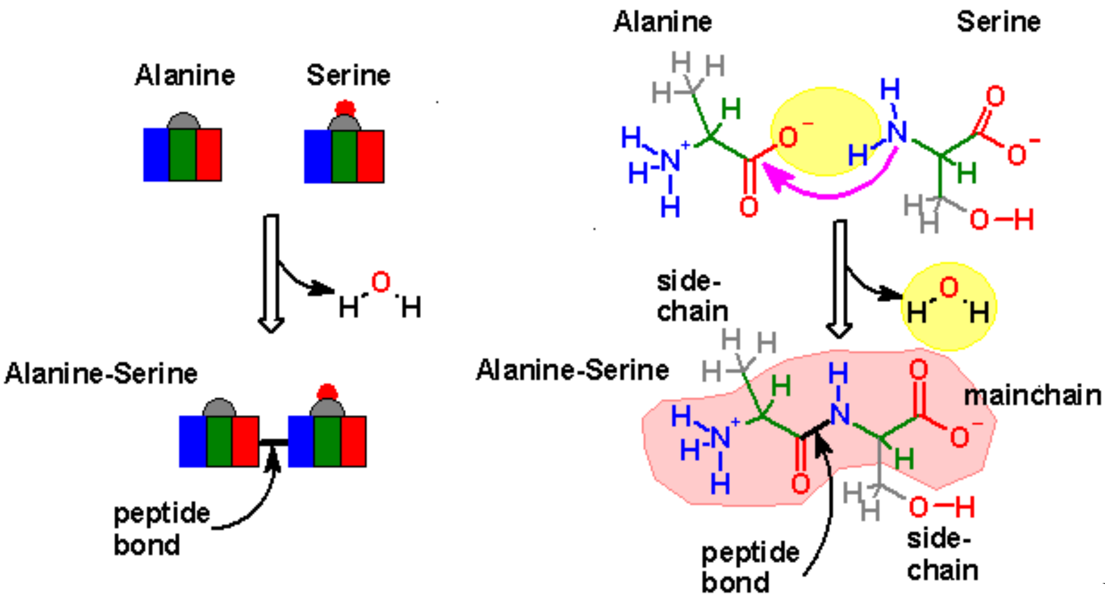
- The main-chain atoms of glycine are highlighted in yellow and its side chain (H) is highlighted in green. All amino acids have the same main-chain atoms, but differ in the side chains. For clarity, the hydrogen is omitted in the remaining drawings.
- Nonpolar amino acids are highlighted in gray,
- Aromatic amino acids are highlighted in cyan,
- Polar amino acids are highlighted in purple,
- Amino acids with acidic side chains are highlighted in red, and
- Amino acids with basic side chains are highlighted in blue.
- The amino acids cysteine and proline, which are shown at the bottom of the page, have unique properties. Cysteine can form covalent S-S disulfide bonds, stabilizing the protein structure. In the case of proline, the side chain attaches to its own nitrogen, making proline an amino acid.

The structure of the 20 common amino acids is shown in the table. *Click on any of the 2D drawings of an amino acid below* and the 3D structure will be presented in the Jmol window on the right. (Note: you may need to click twice the first time you use this tool.) Initially, a 2D drawing of the simplest amino acid, glycine, is shown in the upper left and its 3D structure is shown at this link (click here).

Connecting Amino Acids

Proteins are built when amino acids are linked end-to-end by covalent bonds. The covalent bonds that link amino acids are called peptide bonds. A peptide bond is formed when the amino group of one amino acid reacts with the carboxylic acid of another amino acid. After a peptide bond forms, the three conserved parts of the two amino acids (the nitrogen group, the alpha carbon and the carboxylic acid) are all linked, forming the main chain, or backbone, of the protein. The variable side chains of each amino acid (the R groups) project out from the main chain.

Two amino acids join to form a dipeptide. Longer chains of connected amino acids are often called polypeptides. When polypeptides are synthesized, new amino acids are added only to the carboxylic acid end of the existing chain. A completed polypeptide is directional; it has two different ends. One end has a free amino group, while the other end has a free carboxylic acid group. When amino acids in a protein are counted, the numbering starts with the amino acid that has the free amino group. The last amino acid is also the last one that was added when the chain was built: it has a free carboxylic acid group.



Peptide bond formation. The left side shows a building block representation; the right side shows chemical structures. Note that the serine is flipped upside down in the right diagram for ease of presentation. The amino group of the second amino acid (serine) forms a peptide bond with the carbon that is part of the carboxylic acid group of the first amino acid (alanine), releasing a water molecule. The atoms that become the water molecule are highlighted in yellow. There is now a dipeptide ("di" means "two"). The resultant dipeptide consists of a continuous chain of main-chain atoms (pink highlight), from which the side chains project. When building a dipeptide, any pair of amino acids can be linked together in any order. This variability and the different chemical properties of each amino acid result in a vast number of very different proteins with very different functions.

Protein Structure

The order of the amino acids in a particular protein is determined by information encoded in the cell's genes, and the order of amino acids is referred to as the sequence of the protein. An example of a protein sequence is shown below where the one-letter abbreviations are used for each of the 20 amino acids used in cellular protein synthesis. By convention, the first amino acid is at the end with the free amino group and the last amino acid is at the end with the carboxylic acid group.

EXAMPLE

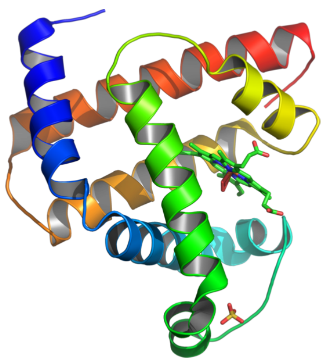
Human Myoglobin

Amino acid sequence of Human Myoglobin (a protein found in muscle cells).

```
        10         20         30         40         50         60
MGLSDGEWQL VLNVWGKVEA DIPGHGQEVL IRLFKGHPET LEKFDKFKHL KSEDEMKASE
        70         80         90        100        110        120
DLKKHGATVL TALGGILKKK GHHEAEIKPL AQSHATKHKI PVKYLEFISE CIIQVLQSKH
       130        140        150
PGDFGADAQG AMNKALELFR KDMASNYKEL GFQG
```

Human myoglobin is a polypeptide chain made up of 154 amino acids. Amino acids are indicated using the single letter code. For example, the amino acid alanine is abbreviated with the letter A, and the amino acid serine is abbreviated with the letter S.

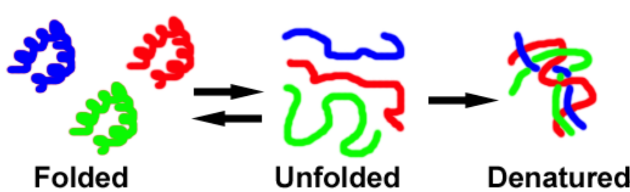
The linear chain of amino acids will spontaneously fold into a three-dimensional shape, which is usually the active form of the protein. For example, look at the drawing of the three-dimensional structure of myoglobin (shown on the left). You can manipulate the 3D structure using the Jmol image on the right.



Many folded proteins bind small organic molecules that assist the protein in performing its function. For example, the heme group in myoglobin (colored gray in the right image) is not part of the protein chain, but fits within a pocket in the myoglobin protein. Myoglobin is responsible for binding oxygen in muscles. Heme groups also are present in the oxygen transport protein, hemoglobin.

Protein Folding

Proteins spontaneously fold to form their functional three-dimensional shape, reaching the lowest energy state, because this is the most stable state. The folding process can be reversible, meaning that a folded protein can unfold and then refold. However, unfolding can also be irreversible, where the unfolded protein chains tangle with each other, forming an aggregate and precipitating out of solution. This is often referred to as a denatured state. Conditions that cause proteins to unfold and denature are extremes of temperature and pH. Cooking denatures proteins by heating so they unfold and denature. The same effect occurs when proteins are exposed to the low pH in your stomach. This helps your body digest the proteins found in your food, and it helps kill ingested bacteria and viruses.



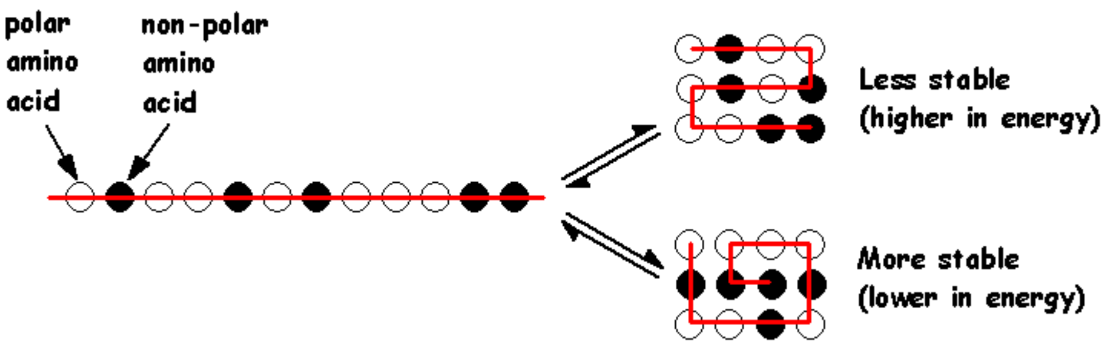
The folded structure of one particular protein is similar for all molecules in solution. Heating the sample can cause the protein to unfold. In the unfolded state, each molecule has a different shape. The unfolded protein can either refold, or the chains can aggregate or tangle, forming the insoluble denatured form. The polypeptide sequence is the same for all three forms of the protein.

The Hydrophobic Effect on Folding

Although many factors stabilize the final shape of a protein, the most important factor is the hydrophobic effect. Amino acids with nonpolar (hydrophobic) side chains are driven into the central core of the protein because they are repelled by the water. This is known as the hydrophobic effect, and it results in proteins that have amino acids with hydrophilic side chains on the surface of the protein. The folded protein reaches the lowest energy state, which is the most stable, by folding in a way that will optimize the burial of nonpolar amino acid side chains while still leaving the polar groups on the surface. Therefore, the shape of the folded form of the protein depends on the order of the hydrophobic amino acids in the protein.

EXAMPLE

Consider a short 12 amino acid protein consisting of polar (white) and nonpolar (black) amino acids. This polypeptide will fold to bury most of the nonpolar amino acids, removing them from contact with water, giving the lowest energy state. Other structures are possible, but these will be higher energy (and consequently less stable) because they expose more nonpolar amino acid side chains to water.

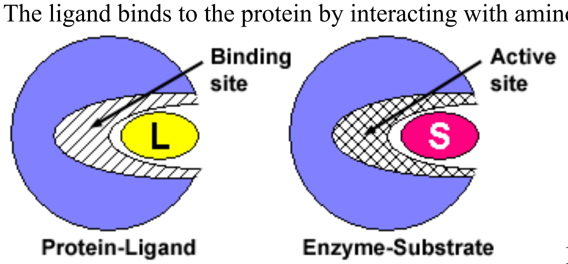


The unfolded form of a 12 amino acid peptide is shown on the left. Notice that the first amino acid is polar, followed by a nonpolar one, and then two polar ones. Two possible folded structures are shown on the right. The top structure exposes four nonpolar side chains to the water, while the lower structure only exposes three nonpolar side chains to the water. This indicates that the lower structure would be the most stable folded structure. The red line shows the path of the main-chain atoms.

Protein Function

The biological function of most proteins involves binding to something else. The binding event may be the first step in transport, signaling, regulation, or an enzyme-catalyzed reaction. Molecules that bind to proteins without being modified are called ligands. Although ligands are usually small molecules, they can also be larger than the protein to which they are binding. For example, when proteins bind to DNA, it is the DNA that is the ligand. Oxygen is a ligand when it binds to hemoglobin (a protein) during oxygen transport to the tissues. Molecules found on the surface of bacterial cells are ligands when antibodies (proteins) in your blood bind to them during an immune response. Sometimes ligands are given special names to remind us of their function. For example: enzyme inhibitors are ligands that bind to and inhibit enzymes; antigens are ligands that are recognized by antibodies (which are proteins).

The ligand binds to the protein by interacting with amino acids in the protein's binding site.



Binding proteins have binding sites for their ligand (L).

Binding proteins have amino acids in their binding site that are complementary to the ligand. Generally, a higher degree of complementarity leads to tighter binding and a more specific interaction. The molecules can be complementary in these different ways:

- The shape of the ligand matches the shape of the ligand binding pocket on the protein. The better the match, the stronger the bond between the ligand and the protein.
- Any charges on the ligand molecule can be aligned close to opposite charges on the protein's binding site. Remember, opposite charges attract each other.
- Hydrogen bonds often form between the ligand and the protein binding site.
- Nonpolar ligands bind more favorably to nonpolar surfaces on the protein.

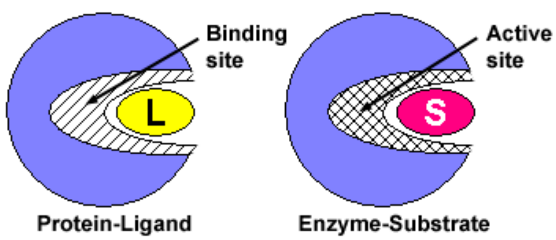
The interactions between proteins and their ligands are incredibly diverse, but they all share some basic ground rules. Protein-ligand binding is:

- Reversible — bound ligands can be released by the protein.
- Concentration dependent — the level of binding depends on the ligand concentration. As the ligand concentration increases, so does the amount of protein bound.
- Limited — once all of the proteins are ligand bound, no additional ligand can bind and the protein is said to be *saturated*.

Enzymes

Enzymes are proteins that have the ability to bind substrate in their active site and then chemically modify the bound substrate, converting it to a different molecule — the *product* of the reaction.*Substrates* bind to enzymes just like ligands bind to proteins. However, when substrates bind to enzymes, they undergo an enzyme-induced chemical change, and are converted to products.

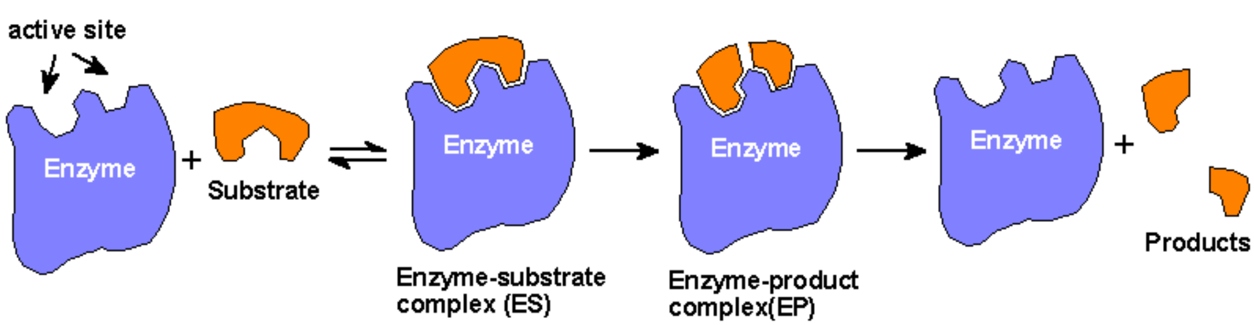
The substrate binds to the enzyme by interacting with amino acids in the *binding site*. The binding site on enzymes is often referred to as the *active site* because it contains amino acids that both bind the substrate and aid in its conversion to product.



Compare the protein-ligand interaction to the enzyme-substrate interaction. Notice that both binding proteins and enzymes have binding sites for their ligands (L) and substrates (S), respectively. This area of the enzyme is called the active site because it also contains amino acids that are important for the conversion of substrate to product.

You can often recognize that a protein is an enzyme by its name. Many enzyme names end with "-ase." For example, the enzyme lactase is used to break down the sugar lactose, found in mammalian milk. Other enzymes are known by a common name, such as pepsin, which is an enzyme that aids in the digestion of proteins in your stomach by breaking the peptide bonds in the proteins.

Enzymes are catalysts, meaning that they make a reaction go faster, but the enzymes themselves are not altered by the overall reaction. Examine this image to see how enzymes work.



Simplified enzymatic reaction. The substrate reversibly binds to the active site of the enzyme, forming the enzyme-substrate (ES) complex. The bound substrate is converted to product by catalytic groups in the active site, forming the enzyme-product complex (EP). The bound products are released, returning the enzyme to its unbound form, ready to catalyze another round of converting substrate to product.

The amino acids in the active site of enzymes play two roles, and sometimes those roles overlap. Some of the amino acids in the active site are responsible for binding of the substrate and others are responsible for facilitating the chemical reaction. Enzymes are generally quite specific for their substrates. Although lactase and pepsin both catalyze the same type of reaction, breaking a bond using water (hydrolysis: "hydro" means "water" and "lysis" means "to break"), lactase only functions when lactose is its substrate and pepsin can only break peptide bonds.

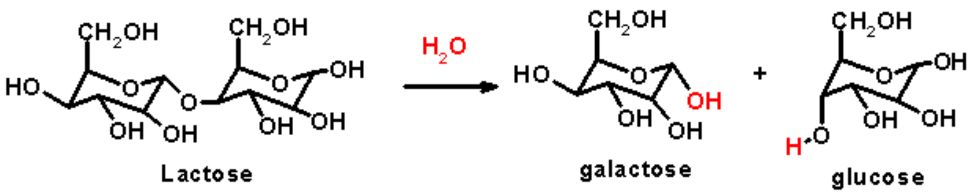
Enzymes in Anabolic and Catabolic Pathways

Enzymes catalyze many different types of chemical reactions. Some of the reactions are synthetic and result in products that are more complex than the original substrates. This is often done by binding two substrates together. Synthetic metabolic pathways like this are called anabolic pathways.

Other enzymes catalyze reactions that reduce the substrate to simpler products. These enzymes catalyze reactions in catabolic pathways.

EXAMPLE

An example of an enzyme that is involved in catabolism is lactase. Lactase is produced in the intestinal tract of mammals and breaks the sugar in milk, lactose, down into the monosaccharides glucose and galactose so that they can be metabolized to produce energy.



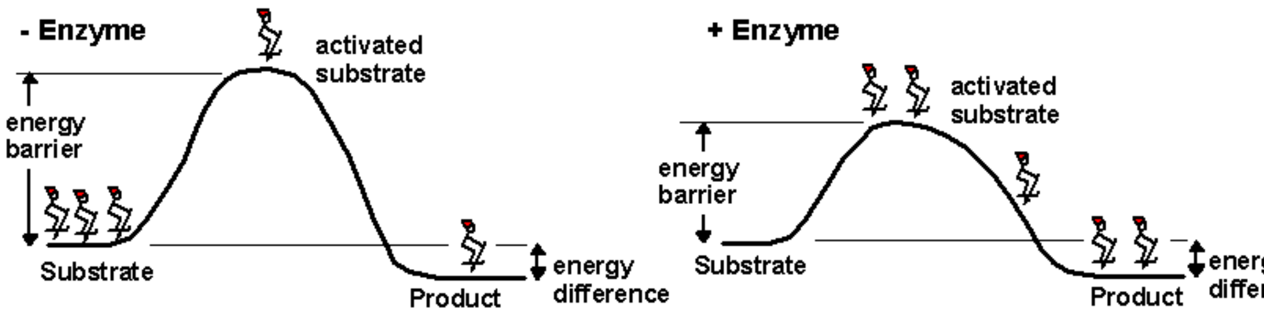
The enzyme lactase breaks lactose into the monosaccharides galactose and glucose by adding a water molecule to the bond between the two sugars.

Unfortunately, in many adults the ability to produce lactase is diminished. Without adequate lactase, ingested lactose from milk and cheese is not broken down and absorbed in the small intestine. Instead, the lactose goes to the large intestine, where it is converted into large volumes of carbon dioxide (CO_2) gas by the bacteria in the large intestine. These individuals are lactose intolerant and should avoid eating foods with high milk content.

How Enzymes Work

In all chemical reactions, there is an initial input of energy that is required before the reaction can occur. If this initial energy requirement (called the activation energy or energy barrier) is small, then the reaction will happen quickly and easily. If the activation energy is large, then the reaction will take longer to occur. Enzymes function to reduce the activation energy required for a chemical reaction to occur.

First, the enzyme binds to the substrate and slightly distorts its shape. The change in shape activates the substrate molecule and decreases the total activation energy required for the substrate to be turned into product. As the number of activated substrate molecules increases, so does the conversion of substrate to product. An analogy for this effect is a ski hill, with skiers at the bottom of one side of the hill representing substrates, skiers on the top of the hill representing activated substrates, and the products being the number of skiers that ski down the other side. If the height of the hill is lowered (due to the presence of the enzyme), then more skiers can make it to the top, increasing the number that ski down to become products.



A noncatalyzed reaction is shown on the left and an enzyme-catalyzed reaction is shown on the right. The enzyme reduces the energy barrier required to activate the substrate, allowing more substrates to become activated, which increases the rate of product formation. Note that the energy difference between the substrate and the product is not changed by the enzyme.

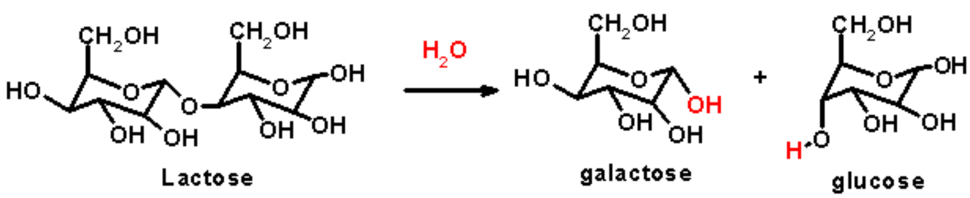
Influencing Enzyme Function

The activity of an enzyme (its ability to convert substrate to product), depends on a number of parameters that are listed below. Many of these parameters can help control the activities of enzymes to optimize the utilization of cellular resources.

- *Temperature:* As the temperature increases, the kinetic energy of the substrate molecules increases, allowing more substrate molecules to become activated and increasing the reaction rate. This is equivalent to more skiers having the energy to surmount the activation energy and reach the top of the hill. Many enzymes have optimal activity at the temperature of the organism. However, there *is* a limit to how much you can increase the rate of the reaction by changing the temperature. If the temperature is too high, the enzyme unfolds, denatures, and becomes inactive.
- *pH:* Protein structure can be affected by the pH of the solution surrounding it. If a protein group that is important for substrate binding or catalysis can be protonated or deprotonated, then changing the pH is likely to affect the enzyme activity. Different enzymes are functional at different pH levels. Pepsin is a digestive enzyme secreted by the stomach lining that is activated by the low pH in the stomach. Salivary amylase, on the other hand, is denatured and nonfunctional in the stomach environment.
- *Substrate concentration:* As the substrate concentration increases, the number of substrate molecules that bind to the enzyme also increases. This leads to increased substrate activation.
- *Presence of inhibitors:* Inhibitors can reduce the activity of enzymes through two different mechanisms. Competitive inhibitors bind to the active site and prevent the substrate from attaching to the binding site. Since less substrate can bind to the enzyme, the activity is reduced.Noncompetitive inhibitors (also called mixed-type) do not bind to the active site, but bind elsewhere on the enzyme. However, the bound inhibitor changes the shape of the active site, reducing the activity of the enzyme. Drugs to treat disease often inhibit enzyme activity. For example, one of the drugs used to treat HIV is a competitive inhibitor of a specific viral enzyme, while another anti-HIV drug is a noncompetitive inhibitor of a different viral enzyme.
- *Presence of activators:* Activators, like noncompetitive inhibitors, also change the shape of the active site by binding elsewhere on the enzyme, but in this case the enzyme is converted from an inactive form to an active form. In this way, activators increase enzyme activity.

Application Spotlight: Lactose Intolerance

Lactase is an example of an enzyme that breaks large molecules down into smaller ones. Lactase is produced in the intestinal tract of mammals and breaks the sugar in milk, lactose, into the monosaccharides glucose and galactose. The monosaccharides can then be metabolized to produce energy.



Lactase breaks lactose into galactose and glucose by adding a water molecule to the bond between the two sugars. Without adequate lactase, ingested lactose from milk and cheese is not broken down, and therefore cannot be absorbed in the small intestine. Instead, the lactose goes to the large intestine, where it is eaten by bacteria that live there. After metabolizing the lactose, the bacteria produce large volumes of carbon dioxide (CO_2) gas, which results in significant discomfort for the individual lacking lactase.

Unfortunately, as many individuals age, their ability to produce lactase is diminished. This is especially true for individuals from Asian, African, Native American, or Mediterranean descent. The incidence of lactose intolerance is lower for those of European descent. Approximately one in seven American adults suffer from lactose intolerance, and African Americans can show signs of lactose intolerance as early as two years of age.

These individuals are lactose intolerant and should avoid eating foods with high lactose content, such as milk. Milk products, such as buttermilk, yogurt, and cheese, cause less of a problem because the amount of lactose in these products is reduced by the microorganisms that are used to make them. Lactose intolerant individuals can consume milk under certain conditions.

Proteins: Summary

Summary

Proteins are the most functionally diverse group of biological macromolecules. Simply by stringing together amino acid building blocks in different combinations, structures are built that can function as enzymes to catalyze chemical reactions, provide structural support, transport substances in and out of the cell, and even transport substances around the body. Proteins can carry out this wide array of different functions because they can assume very different structures.

Key Terms

Take some time to review the main concepts in this module. When you are ready, check your understanding of proteins by taking the quiz linked below.

active site	activation energy	amino acid	amino acids with acidic side chains	amino acids with basic side chains
aromatic amino acid	catalyst	denatured state	enzyme	ligand
nonpolar amino acid	peptide bond	polar amino acid	protein	substrate

-

Nucleic Acids (DNA, RNA)

Learning Objectives:

- Describe the structure of a generic nucleotide.
- Distinguish between purines and pyrimidines.
- Identify the 5' and 3' ends of a nucleic acid.
- Describe the key features of molecular structure of DNA.
- Relate molecular interactions between the components of nucleic acids to the stability of the double helix structure of DNA.
- Distinguish RNA from DNA based on the molecular structure.
- Describe the structure and function of ATP.
- Calculate the mass of ATP needed to fuel a single day's activities.

Introduction to Nucleic Acids

In 1953, a group of scientists contributed to one of the most significant scientific discoveries in history when they determined the structure of DNA, a nucleic acid that is the hereditary material in a cell.

Nucleic acids are macromolecules that carry out two main functions in the cell: storage of genetic information and synthesis of proteins. Two types of nucleic acids specialize in these functions: deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA is the genetic material that stores information for making proteins in all living organisms. Some viruses store their genetic information in RNA instead of DNA. This may seem like an exception to the universal use of DNA as genetic material; however, recall that viruses are not cellular, and are not considered living organisms.

A nucleic acid consists of a chain of nucleotides. There are different kinds of nucleotides that can be linked to build the different nucleic acids. DNA is probably the most familiar nucleic acid, but in this module, you will also learn about RNA. The nucleotides that are used to build RNA molecules are different from the nucleotides that are used to build DNA. You'll also take a look at a very special nucleotide — ATP, which acts as the energy currency of the cell.

Nucleotides

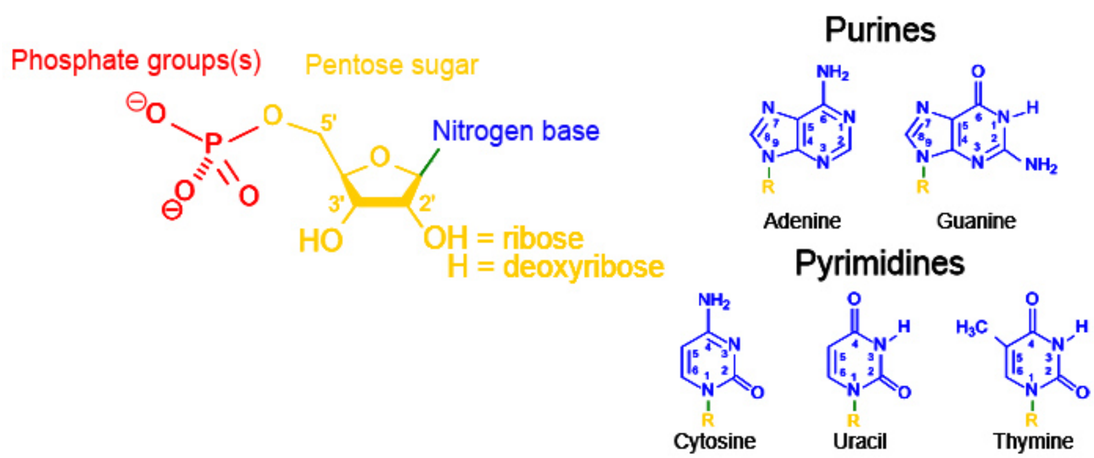
Nucleic Acid Building Blocks

Like any polymer, nucleic acids are made up of repeating subunits or monomers. The subunits of nucleic acids are called *nucleotides*. Each nucleotide contains three building blocks: a phosphate, a sugar, and a*nitrogenous base*. The nitrogenous base is a type of organic molecule that consists of one or two ring structures. Note that the term "*base*" is used here to refer to a specific part of the nucleic acid structure; the meaning is very different from the use of the term "base" in the discussion of pH and acid-base chemistry.

There are five different nitrogenous bases that can be found in various nucleotides. In DNA, you will find these nitrogenous bases: *adenine (A)*, *guanine (G)*, *cytosine (C)*, and *thymine (T)*. In RNA, thymine is replaced by *uracil (U)*.

learn by doing

Nucleic Acid Structures



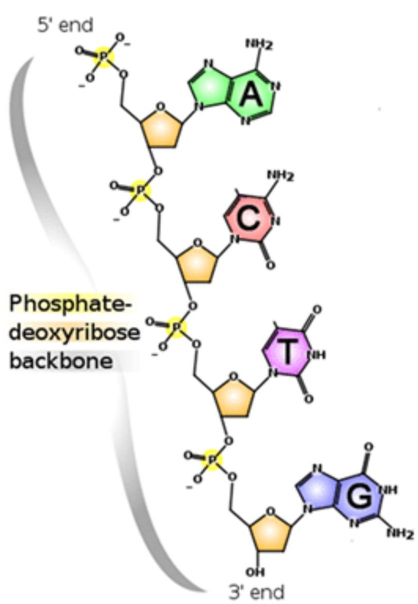
Nucleotides can also differ in the type of sugar they contain. All sugars found in nucleotides are pentose sugars, which means they have five carbons; however, they can be different pentose sugars. For example,DNA contains the sugar deoxyribose. RNA, on the other hand, contains ribose.

Finally, nucleotides can differ in the number of phosphate groups they contain. DNA and RNA nucleotides contain just one phosphate. But a very common nucleotide used for energy (adenosine triphosphate) contains three phosphates. We will look at this molecule in greater detail in the *Metabolism* unit.

Connecting Nucleotides

Nucleic Acid Polymers

Let’s examine the structure of a nucleic acid polymer. How are nucleotide building blocks connected to each other? The alternating "phosphate - sugar - phosphate" building blocks form a backbone of the linear polymer. Bases are attached to the backbone via the sugars and are equivalent to the “side chains” of amino acids in proteins.



When nucleotides are linked end to end, they form a sugar-phosphate backbone. The nitrogenous bases are attached to the backbone via the sugar.

Just as with proteins, a DNA (or RNA) strand has directionality: one end is different than the other. In the case of proteins, an amino group is found on one end and a carboxylate group is found on the other end. Since it is the order of bases that carries out the function of DNA (information storage), we often represent DNA as just a sequence of bases (GAGGCT) and do not bother representing the backbone. By convention, the first letter is the base at the 5' (five prime) end of the DNA strand. Thus, the sequence GAGGCT is shorthand for 5'-GAGGCT-3'. Determine how this directionally occurs in DNA in the following learn by

DNA Structure: Double Helix

All DNA found in living organisms comes in sets of two polymers or strands, usually referred to as double-stranded DNA. Some viruses are an exception to this rule and contain single-stranded DNA as their genetic material. The discovery that DNA structure is a double helix (two strands wound around each other) is considered one of the greatest discoveries in science. Understanding of the structure of DNA opened up a whole new realm of biological and biomedical research (molecular biology) and led to the development of new technologies in science and medicine.

DNA structure is an antiparallel double helix: the two DNA strands run in opposite directions. The sugar-phosphate backbone is on the outside, and the bases are on the inside of the helix. The two strands are held together by base pairing: hydrogen bonding between specific bases. Adenine (a purine) always pairs with thymine (a pyrimidine); guanine (a purine) always pairs with cytosine (a pyrimidine). These base pairing rules (A-T, G-C) are very important to the structure and function of DNA.

RNA vs. DNA Structure

Two of the most important nucleic acids are DNA and RNA. DNA contains the instructions for building proteins. RNA, on the other hand, is involved in actually building the proteins. Because of these different functions, the structures of the two molecules are very different.

Compare DNA and RNA and answer the questions about these structures.

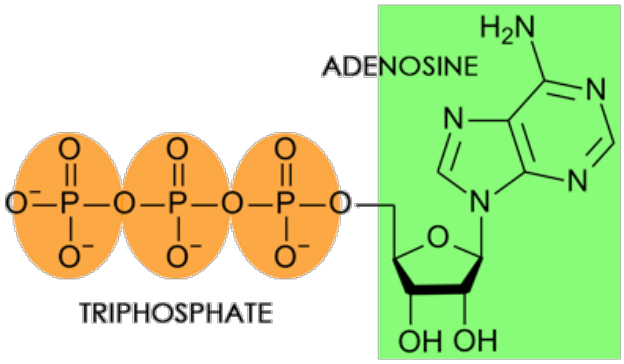
Features of DNA and RNA

	DNA	RNA
Function	Stores genetic information	Involved in protein synthesis
Location	Remains in the nucleus	Leaves the nucleus
Structure	Double helix	Usually single-stranded
Sugar	Deoxyribose	Ribose
Pyrimidines	Cytosine, thymine	Cytosine, uracil
Purines	Adenine, guanine	Adenine, guanine

Application Spotlight: ATP

In this module you learned that nucleotides are the monomers that make up the nucleic acid polymers. Adenosine triphosphate (ATP) is a nucleotide. It consists of a single adenosine (the base adenine and the sugar ribose), linked to three phosphate ions. However, ATP has another essential function: it acts as a general energy source for most cellular activities. You will learn in detail about ATP in the unit dedicated to metabolism.

ATP is a relatively unstable molecule; consequently, it is never used for the long-term storage of energy in the cell. This job goes to other more stable compounds, like fats and sugars. However, ATP is specialized for direct and rapid transfers of energy. The bond between the second and the third phosphates can be broken in a reaction producing ADP (adenosine *di*phosphate). The energy released in this reaction can be used for chemical reactions or cellular work. Conversely, if there is a surplus of energy, specialized reactions can produce ATP from ADP and phosphate, storing the energy temporarily before being used for other processes.



The ADP generated when energy is released is recycled back to ATP using energy gained from the metabolic process. Large amounts of ATP are consumed while providing energy for biological functions.

Nucleic Acids: Summary

Summary

Nucleic acids are molecules made up of repeating units of nucleotides that direct cellular activities such as cell division and protein synthesis. Each nucleotide is made up of a pentose sugar, a nitrogenous base, and a phosphate group. There are two types of nucleic acids: DNA and RNA. DNA carries the genetic blueprint of the cell and is passed on from parents to offspring. It has a double-helix structure with the two strands running in opposite directions and complementary to each other. RNA is composed of a single strand and it is involved in protein synthesis. RNA is composed of a pentose sugar (ribose), a nitrogenous base, and a phosphate group. ATP is a nucleotide composed of an adenine base, ribose sugar, and three phosphate groups; it provides energy for cellular activities.

Key Terms

Take some time to review the main concepts in this module. When you are ready, check your understanding of nucleic acids by taking the quiz linked below.

Chloroplasts	DNA: deoxyribonucleic acid	DNA Replication	Gene
Gene expression	messenger RNA (mRNA)	mitochondria	nitrogenous bases
nucleic acid	nucleotide	Nucleus	RNA: ribonucleic acid
Ribosomal RNA (rRNA)	Transfer RNA (tRNA)	Transcription	

Unit Summary: Biological Macromolecules

Biological systems use only a small part of the total chemical repertoire. This is due to the number of chemical reactions that can occur under physiological conditions, and to the small number of chemical or*functional groups* compatible in biological systems. The physical properties of these groups define how molecules behave in biological systems at physiological *pH* and temperature. By learning the properties of these groups, you will be able to predict how various molecules will function, as well as which functional groups can be converted to others during metabolism.

In this unit, you learned about the four classes of *biological macromolecules* that form the building blocks of the *cell* — the cell from a molecular point of view. Chemistry is fundamental to life's unity; it helps us grasp how all cells maintain a stable internal environment, grow, reproduce, and process energy. Chemistry also helps to explain the incredible diversity of life. In particular, an understanding of protein structure helps us see how life takes on such endless variety.

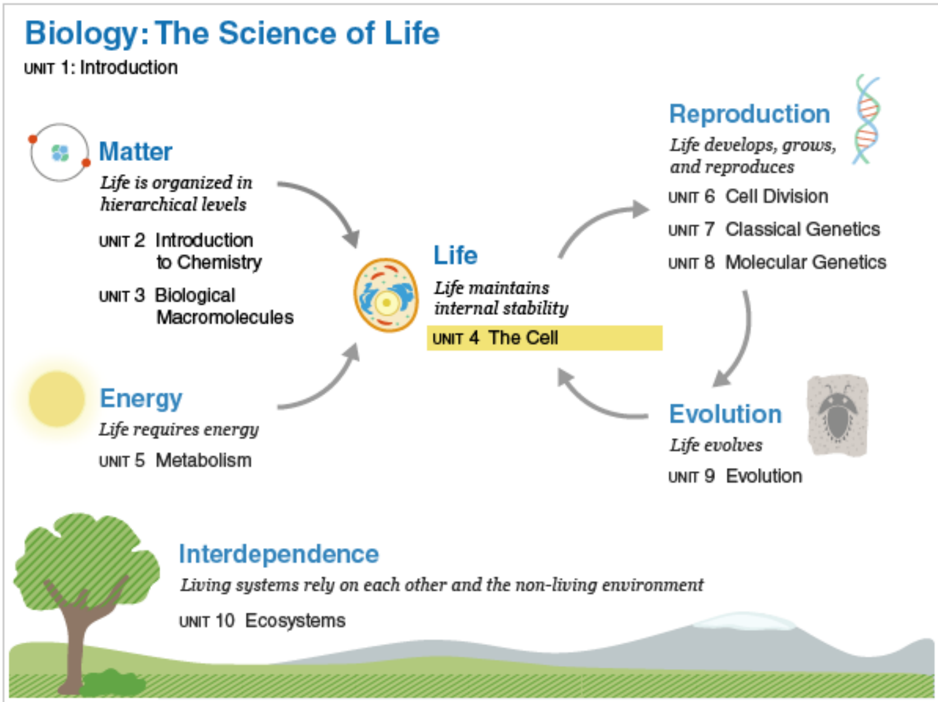
Carbohydrates, lipids, proteins, and *nucleic acids* each have distinct properties that emerge due to their chemical structure and formation of large assemblies. You should be able to relate the structure ofmacromolecules to their function. Two important small organic molecules that you should be familiar with are the carbohydrate glucose and ATP. Can you describe the role of ATP and glucose in biology?

Learning Outcome Self-Assessment Activity

Stop for a moment and reflect on what you learned in this unit. To facilitate this process, we have included the following *"My Response"* self-assessment activity. In this activity, you will rate your understanding of each learning outcome covered in this unit. Formulate questions you still have regarding the content, and submit them in the My Response text box.

Unit Introduction: The Cell

The *cell* is the first level of organization that exhibits all the properties of life. Made up of *biological macromolecules*, the cell's unique structure enables it to carry out the functions of life.



In the "*Biological Macromolecules*" unit, you explored matter and learned how atoms can be combined to form molecules that, through their own unique structures, are able to carry out specific functions. You learned that *proteins*, such as *enzymes*, are able to function like little molecular machines. However, enzymes and other *biological macromolecules* made of matter do not possess the properties of life. In fact, it is only after we combine these molecular building blocks to form a cell that we finally see the emergent property of life. Take a moment to review examples of each level of organization forming these building blocks using the activity below.

One of the hallmarks of living systems is the ability to maintain *homeostasis*, or a relatively constant internal state. The cell is the first level of complexity able to maintain homeostasis, and it is the unique structure of the cell that enables this critical function.

In this unit, you will learn about the *cell* and all the parts that make it functional. You will also focus on the cell membrane, which is the structure that surrounds the cell and separates its internal environment from the external environment. This separation enables the cell to maintain homeostasis and exhibit the emergent property of life.

Cell Structures

Learning Objective:

- Describe the functions of cellular structures possessed by all cells.
- Compare and contrast the main characteristics of prokaryotic and eukaryotic cells.
- Describe the main components of the eukaryotic cell and their functions.
- Compare and contrast the main characteristics of animal and plant cells.
- Recognize that antibiotics are only effective against bacteria and do not affect human body cells or viruses.
- Predict and explain the consequences of misuse or overuse of antibiotics.
- Identify examples of improper use of antibiotics.

Cell Theory

The microscopes we use today are far more advanced than those used in the 1600s by Antony van Leeuwenhoek, a Dutch shopkeeper who had great skill in crafting lenses. Despite the limitations of his now-ancient lenses, van Leeuwenhoek observed the movements of bacteria, other single-celled organisms, and sperm. He labeled these moving microbes "animalcules."

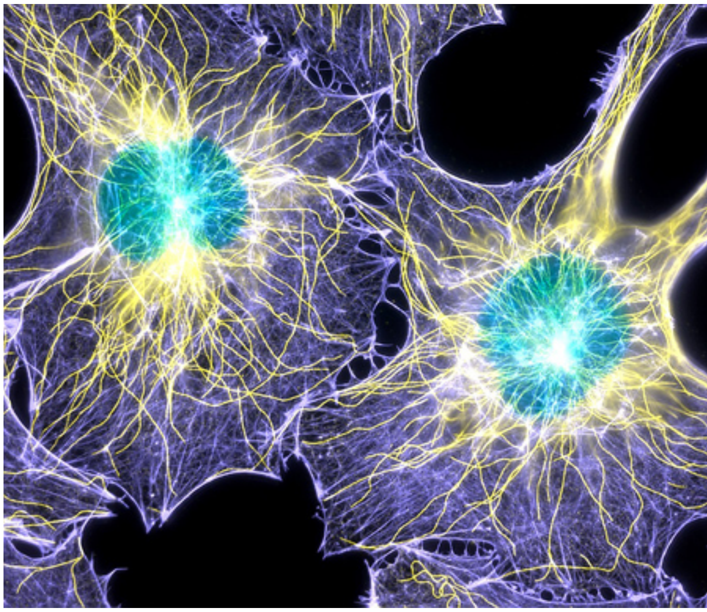
In a 1665 publication called *Micrographia*, experimental scientist Robert Hooke coined the term "cell" for the box-like structures he observed when viewing cork tissue through a lens. Later, he confirmed van Leeuwenhoek's 1678 discovery of bacteria and protozoa. Later advances in lenses and microscope construction enabled other scientists to see some components inside cells.

By the late 1830s, scientists had closely examined many plant and animal tissues under the microscope. Comparing notes, botanist Matthias Schleiden and zoologist Theodor Schwann realized that cells were found in every tissue they had studied. They proposed the *Unified Cell Theory*, which states that all living things are composed of one or more cells, and that the cell is the basic unit of life. You, for instance, are made of approximately 60 trillion cells, all of which originated from one single cell, the fertilized cell produced when an egg from your mother was fertilized by the sperm cell from your father.

However, there were still controversies between those who believed in the existence of a vital force able to "create" life (spontaneous generation) and those who supported biogenesis, which claims that living cells can arise only from pre-existing cells. A series of experiments by Louis Pasteur and Rudolf Virchow showed that living organisms could only come from other living organisms. The currently accepted tenets of *Cell Theory* are:

1. All known living things are composed of one or more cells.
2. All new cells are created by pre-existing cells dividing in two and reproducing.
3. The cell is the most basic unit of structure and function in all living organisms.

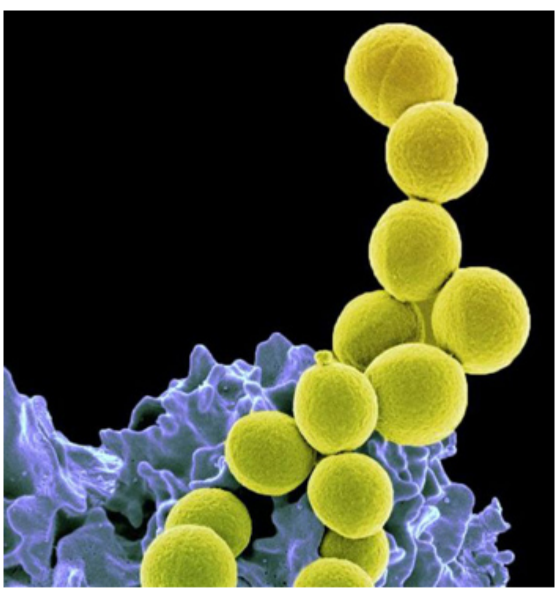
Modern cell theorists assert that all functions essential to life occur within the cell and that during cell division the cell contains and transmits to the next generation the information necessary to conduct and regulate cell functioning.

Using special technology, biologists can capture images of living cells. The yellow and blue fibers in these cells are made of proteins and the green circles in the middle are nuclei (singular: nucleus), which hold the cell's DNA. Image by: Torsten Wittmann, NIGMS Image Gallery.

Cell Structures

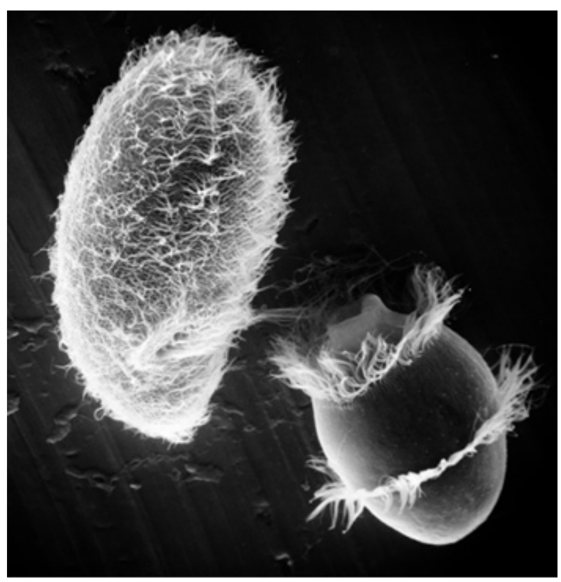
In spite of the fact that all cells share certain characteristics, there is incredible diversity in structure and function among different cells. The human body alone contains trillions of cells of more than 200 different types, each with a unique structure and function. Cells are categorized into two types: *Prokaryotes* are small, simple, single-cell organisms; bacteria are the most prevalent kind. *Eukaryotes* are larger, and most often they are multicellular organisms, including plants, animals, and fungi. Eukaryotic cells are about 15 times wider than the typical prokaryotic cell, and up to 1,000 times greater in volume. The images below show examples of a prokaryote and single-celled eukaryotic organisms.

Prokaryotic MRSA Bacteria Cells



Methicillin-resistant Staphylococcus aureus (commonly

Eukaryotic Single-Celled Organisms



These two cells are both single-celled organisms, also known as MRSA) is an antibiotic-resistant of bacteria, shown here in yellow. These bacteria are being ingested by a white blood cell, shown here in purplish blue. Source: National Institute of Allergy and Infectious Diseases /National Institutes of Health (NIAID/NIH)

known as protists. The Didinium (bottom right) is stalking the Paramecium (top left), and will eventually catch and eat the larger cell. Image by: Gregory Antipa (San Francisco State University).

You have already learned that cells are made up of organelles, molecules, atoms, and subatomic particles. These parts assemble into various structures to perform specific functions within the cell. *Organelles* are specialized structures formed when a specific set of molecules bonds, providing a subunit within a membrane-like enclosure that performs particular functions within the cell. Some structures are the same for both *prokaryotic* and *eukaryotic* cell types and some structures are different. The remainder of this page will focus on a handful of structures that all cells have in common. Then, later in this module, you will learn about the structures and characteristics of each cell type in more detail.

Structures Common to All Cells

There are several parts (referred to as *structures*) common to all cells regardless of the cell type. All cells are surrounded by a cell membrane. The *cell membrane* provides a barrier between the interior and exterior of the cell and it regulates the flow of substances in and out of the cell. All cells also have*cytoplasm*, which is the fluid that occupies the space inside the cell. Cytoplasm is the space in which the chemical reactions that enable life take place. All cells also contain *DNA*, which is often called the “master molecule” of the cell because it contains the instructions for synthesizing all of the cell’s proteins. As you already know, *proteins* are the raw materials used to build many important structures in living systems. Finally, both prokaryotes and eukaryotes contain *ribosomes*. Ribosomes are the molecular machines that use the instructions contained in the DNA to build all the proteins needed by the cell.

The following table summarizes the major structures found in cells and the primary function of each structure. In addition, it lists the types of cells in which each structure is found. (There are many other important structures and features of cells. The table below shows only the most important structures.)

The Most Important Structures Found in Prokaryotic and Eukaryotic Cells

Structure	Function	Prokaryotic Cells	Eukaryotic	
			Animal Cells	Plant Cells
Outside Structures				
plasma membrane cell membrane	Protection; control of substances moving into and out of cells	yes	yes	yes
cell wall	Protection; support	yes	no	yes
flagella/cilia	Movement from one place to another (locomotion)	some	some	some
Inside Structures				
cytoplasm	The site of metabolic activity; internal cushioning for the cell	yes	yes	yes
cytoskeleton	Cell shape, movement, locomotion, and internal organization	some	yes	yes
chromosomes/DNA	Storage of genetic hereditary information	yes	yes	yes
ribosome	The site where proteins are made	yes	yes	Yes
Organelles				
chloroplast	The site of photosynthesis; conversion of light energy into chemical energy	no	no	Yes
lysosome	The site of digestion	no	yes	yes
mitochondria	Generates energy in the form of ATP molecules	no	yes	yes
nucleus	The control center; where chromosomes/DNA are located	no	yes	yes

The essential differences and similarities among prokaryotic and eukaryotic cells are:

- All cells contain DNA (chromosomes), membranes, cytoplasm, and ribosomes.
- Prokaryotes do NOT contain a nucleus or any other organelle.
- Chloroplasts exist only in eukaryotic plant cells.

Check your understanding of cell structures with the following activity and then learn more about the structures and characteristics of each cell type on the next page.

Prokaryotes and Eukaryotes

Every cell on Earth belongs to one of two categories:

1. Prokaryotic cells
2. Eukaryotic cells

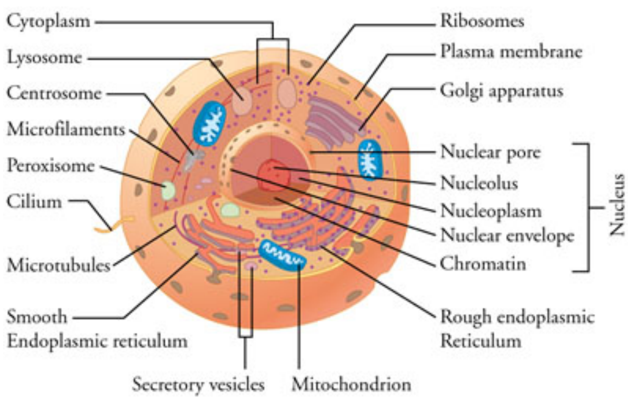
Prokaryotic cells were the first cells to appear on our planet. All prokaryotes alive today are unicellular (one-celled), and include bacteria (singular form is "bacterium") and archaea (singular form is "archaean"). Prokaryotes are small cells that don't have a nucleus or membrane-bound organelles.

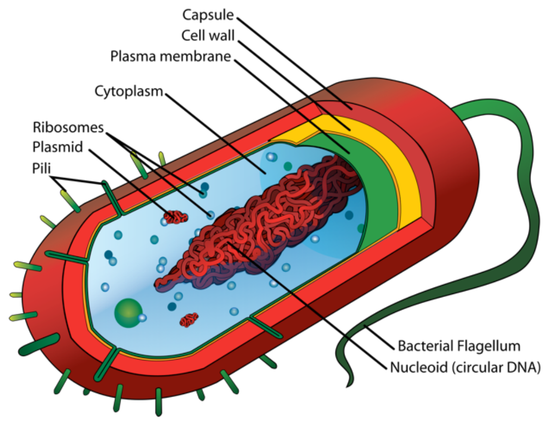
Eukaryotic cells appeared 1.5 billion years after prokaryotes. The main difference between the two is that eukaryotes have a central control structure, called the nucleus (plural form is "nuclei"), where DNA is housed. In prokaryotes, the main DNA molecule (bacterial chromosome) is present in a region called thenucleoid, but the nucleoid lacks a surrounding membrane. Smaller DNA molecules called plasmids can be also found in prokaryotes. Prokaryotic DNA is circular, in contrast to the linear structure of eukaryotic DNA.

Both eukaryotic and prokaryotic cells have a cell or plasma membrane, which surrounds and defines the inner environment of the cell. The cell membrane is made of a phospholipid bilayer containing a variety of proteins and additional components. The cell membrane is responsible for mediating interactions between the cell and its environment. The Cell Membrane module contains a more detailed discussion of the structure and function of the cell membrane.

Bacteria Cell (Prokaryotic)

Typical Animal Cell (Eukaryotic)

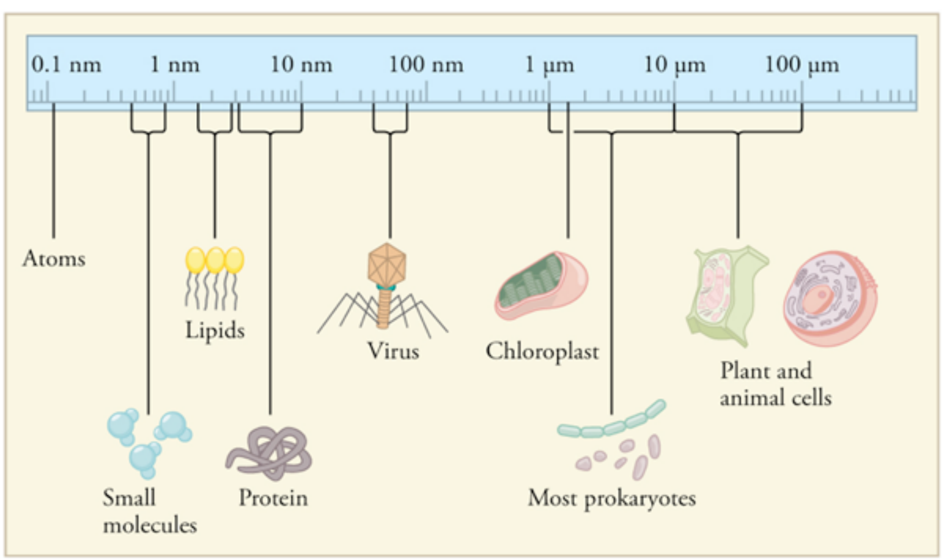




Note: these images are not drawn to scale. A typical eukaryotic cell is 10 times bigger than the typical prokaryotic cell.

Prokaryotic cells have a simpler structure than eukaryotic cells, and they range in diameter from 0.1 to 5.0 µm (micrometers). Most prokaryotes have a protective layer called the *cell wall* that is made of peptidoglycan, which is a combination of polysaccharides and amino acids. Prokaryotes also have a cell membrane and cytoplasm. Many prokaryotes also have external appendages such as a *flagellum*. The cytoplasm contains the DNA and the *ribosomes*, where protein synthesis takes place. Several types of RNA are involved in the process of protein synthesis, and ribosomal RNA (rRNA) is the main component of ribosomes. Both prokaryotes and eukaryotes have ribosomes, but they are different. Prokaryotic ribosomes are smaller and lighter than their eukaryotic counterparts.

Comparison of cell sizes



Relative sizes of cells and their contents. Notice that the scale shown is logarithmic.

Feature	Prokaryotic cell	Eukaryotic cell
Size	variable, 0.1-5 μm	variable, 2-100 μm
Location of DNA	Nucleoid region	Nucleus
Internal Structures	No compartments	Organized into membrane-bound compartments called organelles
Examples	Bacteria	Plants, Animals

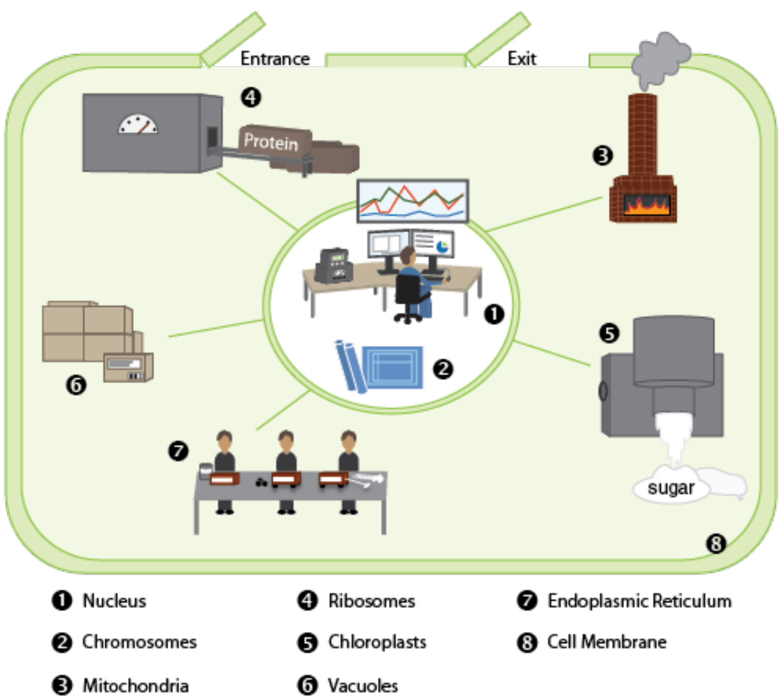
Note that certain abiotic entities such as viruses and prions (infectious proteins causing diseases such as mad cow disease) are also studied in biology. However, *they are not cells,* and while they may exhibit certain characteristics of life, they do so only in certain conditions.

Eukaryotic Cell Components

All *eukaryotes* contain a nucleus. Animals and plants are familiar eukaryotes; in fact, all large complex organisms are eukaryotes. *Fungi* (the singular form is "fungus"), which include molds and mushrooms, are also eukaryotes. There are even single-celled eukaryotes, called *protists*. All eukaryotes have a nucleus, but they can also have other cell structures in common.

One simplified but useful analogy of a cell is that of a factory. Just as in a factory, cells have a wall or membrane providing a protective enclosure, a planning center where the product blueprints are stored, a source of energy, an assembly line for production, packaging and shipping facilities, storage facilities, etc.

The Plant Cell as a Factory



In this visual, a plant cell is compared to a factory. Each functional unit of the factory is compared to a cellular organelle. Even though cells can have many different functions, the function often relies on the production of different types of proteins. In this way, a cell is like a protein-producing factory. We will refer back to this analogy as we discuss the functions of different cellular organelles.

Organelles

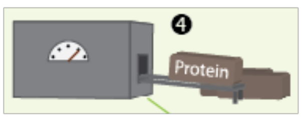
Eukaryotic cells contain compartments with specialized functions called organelles. *Organelles* are surrounded by membranes. Organelles are similar to the specialized work areas in the factory above. Because a cell is a protein-producing factory, we can take a closer look at the different organelles and see how they function toward this goal.

Nucleus: Control Center

The *nucleus* is the control center of the cell and it stores the *DNA*, which contains the instructions for how to build all the protein products required by the cell. The nucleus is like the factory command center, which stores the instructions needed to build its product. A single molecule of DNA is called a *chromosome*. The chromosomes are like the different books in the factory's control center.

The nucleus is surrounded by a double-layered membrane called the*nuclear envelope*. The nuclear envelope is studded with pores that allow information from inside the nucleus to enter the *cytoplasm*. You can imagine that a factory command center would not be very effective if it did not have doors or windows through which to pass information to the rest of the factory.

Ribosome: Protein Production



There are several important structures found within the nucleus. The most visible of these is the *nucleolus*. In contrast to other organelles, the nucleolus is not bound by a membrane. Instead, it is an aggregate of molecules where *ribosomes*, another type of nonmembranous organelle, are assembled.

Most organelles, including *ribosomes* (after they are built in the nucleus), are found in the *cytoplasm*, which is the substance found between the nucleus and the cell membrane (number eight in the cell factory diagram). The cytoplasm is analogous to the factory floor, where all the work takes place.

Mitochondria: Power Plant

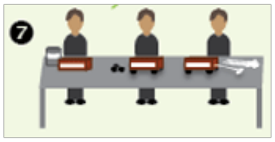
All this work requires energy. Most factories need some sort of power plant that converts fuel into a form of energy that can be captured to do work. In the cell, this job is accomplished by organelles called*mitochondria* (singular form is "*mitochondrion*"), which take fuel in the form of sugar (glucose) and convert it to usable energy — *ATP*.

Chloroplasts: Sugar Production

Plant cells have an additional type of organelle — *chloroplasts*, which exist only in plant cells — involved in energy transfer. The chloroplasts provide sugar. Chloroplasts capture energy from the sun and use that energy to build sugar molecules. *Mitochondria* then harvest the energy stored in the sugar molecules and use it to do work. The chloroplasts and mitochondria are the organelles responsible for providing energy for all cellular functions.

Endoplasmic Reticulum: Product Assembly

Factories often have assembly lines that put together the company's product. In the cell, *proteins* and other cellular components are put together, or assembled, by the *endoplasmic reticulum (ER)*, a series of sacs and tubes. In eukaryotes, *ribosomes* are associated with the "rough ER," which gets its name from the beaded appearance that the ribosomes give it. The smooth ER (without ribosomes) can have different functions



depending on the cell type, but it is often the site for the synthesis of *lipids*.

Vacuoles: Storage

The *Golgi apparatus* is the packaging and shipping center of the cell, where the proteins that were built by the *ER* assembly line are delivered to different parts of the cell, or in multicellular organisms, to different parts of the body. Often the Golgi apparatus packages proteins in *vesicles* and *vacuoles*, which are membrane-bound sacs that function in storage and transport. Vesicles are specialized for transport and some other functions. Their membranes can fuse with the plasma membrane, allowing them to empty their contents into the extracellular space. Vesicles also may fuse with the membranes of the endoplasmic reticulum and Golgi apparatus, allowing them to empty their contents into those organelles. *Lysosomes* are specialized vesicles found only in animal cells. Lysosomes contain powerful digestive enzymes that can recycle cellular parts or destroy external invaders. Vacuoles are specialized mainly for storage. Their membranes do not fuse with the membranes of other cellular components.

Other Structures in Eukaryotes

Eukaryotic cells include other important structures not illustrated in our factory diagram; they are the cytoskeleton, actin, centrioles, microtubules, flagellum, and cilia.

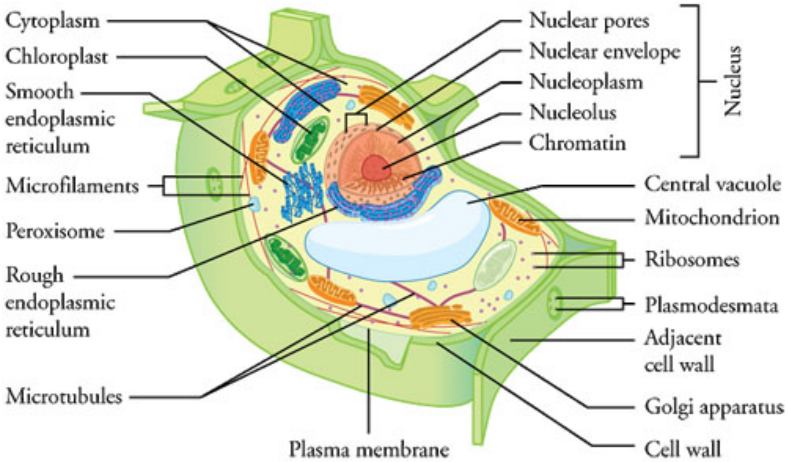
The *cytoskeleton* is formed by a series of protein filaments, and is both a scaffold for the cell structure and a framework for many cellular activities, including movement and cell division. In our factory analogy, the cytoskeleton is represented by structural beams, as well as any transport infrastructure, like hallways, elevator tracks, or even small railroads. In the cell, the cytoskeleton is made up of many different protein filaments. One important filament is *actin*, which has a prominent role in cell movement, maintaining cell shape, and connection to other cells, as well as intracellular transport. A barrel-shaped structure only present in animal cells is the *centriole*, which plays a role in the spatial organization of the cell and cell division. Centrioles are formed by *microtubules*, another filament type of the cytoskeleton. Microtubules also form appendages such as the *flagellum* of the sperm cell and the *cilia* of the cells of the respiratory system.

Plant and Animal Cells

Both animal and plant cells are eukaryotic cells. However, they both contain some specialized structures. Plants have *chloroplasts* and a rigid *cell wall*. Chloroplasts are unique organelles able to harvest solar energy to make sugars from carbon dioxide. This process, called photosynthesis, is the basis of life as we know it on our planet. This process is possible due to the presence of special pigments, called chlorophylls, which are found in the chloroplasts.

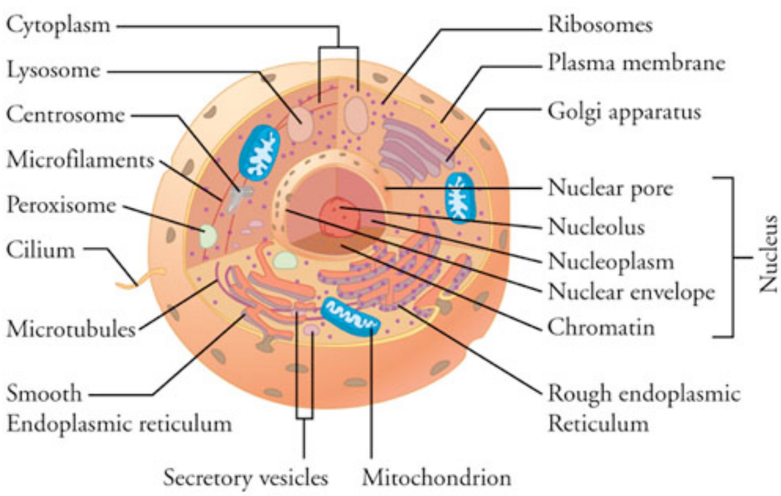
The *cell wall* is a porous structure that protects, supports, and gives shape to the cell. The plant cell wall is different from that of prokaryotes, and it is mainly formed by *polysaccharides*, particularly cellulose. Plant cells can also have a *central vacuole*, which can be a place of storage, degradation, defense, and even physical support for the cell. Even though plants have a cell wall, this does not mean they don't have a cell membrane. All cells have a *cell membrane*. Some, like plant cells, just have a cell wall as well.

Eukaryotic Plant Cell



A typical eukaryotic plant cell. Compare this to the image of the animal cell. Notice that each plant cell has a cell wall, chloroplasts, and a central vacuole, but lacks cilia, lysosomes, and a centrosome.

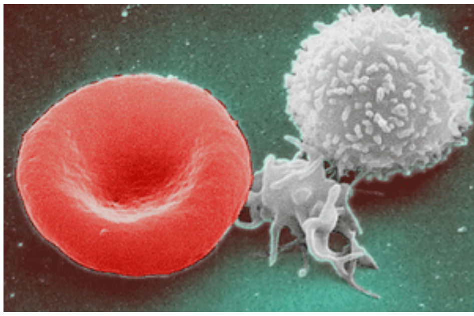
Eukaryotic Animal Cell

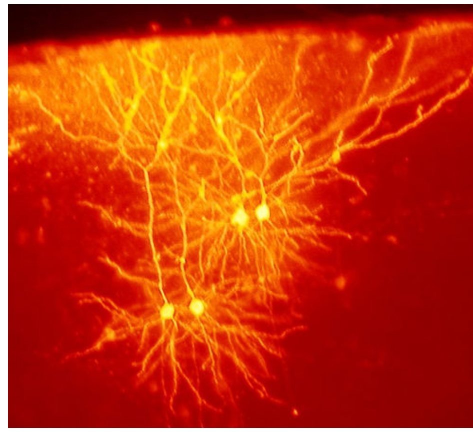


A typical eukaryotic animal cell. No cell looks exactly like this one, but this figure orients you to the organelles and other components discussed. Cilia are not present in all animal cells, but are in some.

The structures shown above are parts of a “generic” eukaryotic cell. While most eukaryotic cells will present these structures, variations occur depending on the function of the cell. Think about cars — while most cars have the same parts, there will be differences between a sedan and an off-road vehicle. Among animal cells, extreme examples of specialization include red blood cells (containers of hemoglobin to transport oxygen; see picture on the left) and nerve cells (dedicated to transmission and integration of signals; picture on the right).

Blood Cells **Nerve Cell**


Human red blood cell, platelet, and white blood cell. Observe the flattened disk shape of the red blood cell, which allows it to easily pass through small blood vessels.


Mouse neurons (nerve cells). Observe the many projections connecting cells with each other, allowing communication and transmission of signals.

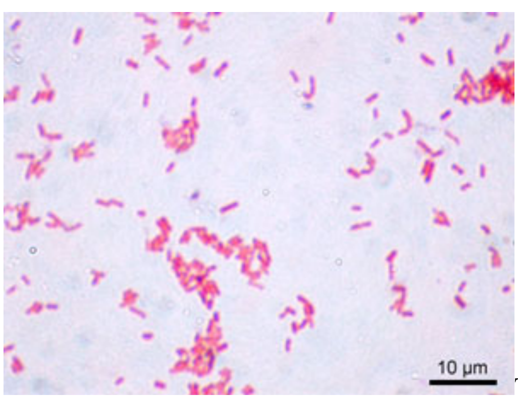
Application Spotlight: Antibiotics

Bacteria

Until the late 1600s, only large life forms such as plants and animals were known to science. Humans were completely ignorant of the teeming masses of microscopic life forms that inhabit our world. In fact, they didn't even know that plants and animals are composed of cells.

The invention and refinement of the microscope changed all that. Today we are aware of a vast diversity of single-celled, microscopic life forms that interact with us every day. In fact, in and on your body, bacterial cells outnumber your own human cells 10 to one. The bacteria that live on and in you are often critically important to your own health and well being. Bacteria have mutually beneficial relationships with every large organism on Earth and they also cleanse the water we drink and renew the air we breathe. While bacteria can be invaluable partners in the quest for healthy living, it is also well known that bacteria cause disease. Interestingly, this fact was not fully demonstrated until the late 1800s. The earliest measures taken to control bacterial diseases involved improving sanitation using procedures such as sterile surgical techniques, water purification, and sewage treatment. While these strategies helped reduce infections caused by bacteria, it didn't change the fact that once bacterial infections took hold, they were often fatal.

***E. coli* Under a Microscope**

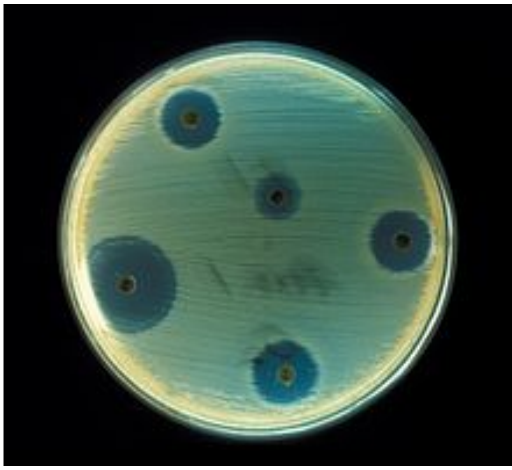


These *Escherichia coli (E. coli)* are seen under a light microscope at a magnification of 1,000x (at this level, a grain of rice would appear to be the size of a bus). Microscopic organisms such as *E. coli* are essential for keeping us healthy. *E. coli* and other microbes living in our gut help with proper digestive health. Although some *E. coli* can be harmful, most are not.

Antibiotics

In 1928, Alexander Fleming serendipitously discovered the first antibiotic, Penicillin. Fleming was studying bacteria in his lab and was growing different cultures on Petri dishes. He wasn't very tidy and had accidentally forgotten to clean some Petri dishes before leaving his lab for a monthlong vacation. When Fleming returned to the lab, he noticed that a mold had grown on one of the plates. Looking closely, Fleming saw that his bacteria had not grown well in a zone surrounding the moldy spots. Following up on a hunch, he deliberately added mold to some Petri dishes seeded with bacteria and found that all bacteria were killed near the mold colonies. By the mid-1940s, just in time to help wounded soldiers in World War II, scientists were able to mass-produce a drug derived from the mold discovered by Fleming.

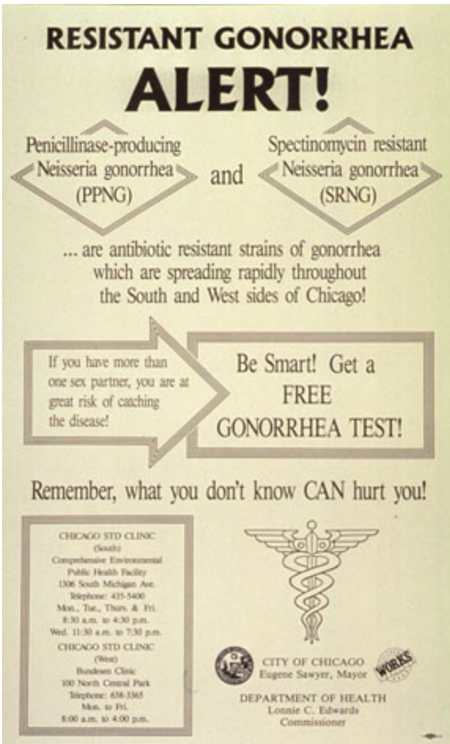
Testing Antibiotics


Examine this image of a petri dish filled with a light-colored bacterial culture. Each black dot is a spot of antibiotic. Notice the area surrounding the antibiotic in which the bacteria are unable to grow.

Fleming had discovered the first antibiotic. *Antibiotics* are substances that are produced by one type of organism (usually bacteria or mold) and used to kill or suppress other organisms (usually bacteria). Antibiotics have a very specific way of working, which is called their "mode of action." Penicillin works by interfering with cell wall construction in bacterial cells. The cell wall is a somewhat rigid "shell" that encloses a bacterial cell. In the presence of penicillin, a bacterium's cell wall cannot be built (or rebuilt) and the cell wall eventually collapses, killing the cell. Cell walls are not present around human cells, or those of any other animal. Therefore, penicillin does not harm our cells — only those of bacteria. This is a general feature of antibiotics. When taken in prescribed doses, antibiotics are usually harmless to humans.

During and just after World War II, penicillin was touted as a wonder drug, and many believed the battle against pathogenic (harmful) bacteria would be won in a matter of years. However, the initial success of this antibiotic was relatively short-lived, as bacteria began to evolve resistance to the drug. In any group of bacteria, individuals can have variations in their genetic makeup that help them survive in the presence of specific antibiotic compounds. Over time, if the antibiotic is used, vulnerable types of bacteria die out and the "resistant" types of bacteria reproduce much better than average. Eventually most or all bacteria in the environment are resistant, making the antibiotic useless.

Antibiotic Resistance



A poster produced by the Chicago Department of Health warning about antibiotic resistant gonorrhea. Chicago, Il

Presently, we are facing a growing threat to human health; the overuse and misuse of antibiotics has led to the evolution of "superbugs" — bacterial strains that are resistant to many different types of antibiotics. Such infections are very hard to treat, and can be deadly. Perhaps you have heard about methycillin-resistant *Staphylococcus aureus (MRSA*), which can be picked up in hospitals and places of close body contact (locker rooms, retirement homes). It has evolved a resistance to the antibiotic methycillin. If it penetrates the body, it may dissolve the skin and underlying muscle.

One way to reduce the development of antibiotic resistance is to use antibiotics only when necessary, so that there are many antibiotic-free people and places in the environment. This makes it easier for vulnerable strains of bacteria to reproduce, and keeps these strains more common. Within a sick patient, however, the goal of antibiotic therapy is to keep reducing the numbers of harmful bacteria until your immune system can kill off the last (and probably most resistant) holdouts. Therefore it is important to take antibiotics at full dosage and to complete the round of treatment as directed, continuing until it is certain that your bacterial foes have been eliminated.

We are not helpless against the rising tide of antibiotic resistance. Today, with our great knowledge of microscopic life and nonliving — but equally dangerous — viruses, we have an unprecedented ability to understand and address health challenges.

What Is a Cell? Summary

Summary

In this module, you learned about the characteristics that all *cells* have in common, like the cell membrane. You also learned about some of the different kinds of cells. You learned about eukaryotic cells, which have*DNA* contained in the *nucleus*, and prokaryotic cells which lack a nucleus altogether (though they do not lack DNA).

In the next module, you'll take a closer look at the cell membrane, which is the structure that defines a cell by separating its internal environment from the external environment. Take some time to review these key terms. When you're ready, take the module quiz.

Key Terms

Review the following key terms discussed in this module.

chloroplast	chromatin	chromosome	cilium	cytoplasm
eukaryotic cells	flagellum	golgi apparatus	mitochondrion	nucleoid
nucleus	prokaryotic cells	ribosome	vesicle	

The Cell Membrane

Learning Objectives:

- Describe two properties of phospholipid membranes.
- Explain why fluidity is an essential property of biological membranes.
- Identify the components of cellular membranes and discuss the function(s) of each.
- Discuss the functions of the plasma membrane.
- List the functions of membrane proteins.
- Compare and contrast the cell membranes of archaeans and other cells.
- Describe the functional significance of the unique cell membrane found in archaeans.

Membrane Structure: Phospholipid Bilayer

Plasma Membrane

The cell membrane, also called the plasma membrane, is the boundary of the cell; it determines what enters and exits the cell, and it is how the cell interacts with its environment. Have you ever looked closely at the colors swirling in a soap bubble? This may give you a feel for the fluid nature of a cell's membrane. A membrane's components are in constant motion, as if they were flowing in a river. A variety of different proteins, carbohydrates, sterols, and other molecules are embedded in the *phospholipid bilayer*. This gives the impression of a tile mosaic, which has variously shaped and colored tiles embedded in grout. Because of its fluidity and its variety, biologists currently describe the *cell membrane* as a fluid mosaic.

The *phospholipid bilayer* is the main fabric of the membrane. The bilayer's structure causes the membrane to be semipermeable. The hydrophobic core blocks the diffusion of *hydrophilic ions* and*polar molecules*.
Small *hydrophobic* molecules and gases, which can dissolve in the membrane's core, cross it with ease.

Other *molecules* require proteins to transport them across the membrane. *Proteins* determine most of the membrane's specific functions. The *plasma membrane* and the membranes of the various organelles each have unique collections of proteins. For example, to date more than 50 kinds of proteins have been found in the plasma membrane of red blood cells.

Importance of Phospholipid Membrane Structure

What is important about the structure of a phospholipid membrane? First, it is fluid. This allows cells to change shape, permitting growth and movement. The fluidity of the membrane is regulated by the types of phospholipids and the presence of cholesterol. Second, the phospholipid membrane is selectively permeable.

The ability of a *molecule* to pass through the membrane depends on its polarity and to some extent its size. Many *nonpolar molecules* such as oxygen, carbon dioxide, and small hydrocarbons can flow easily through cell membranes. This feature of membranes is very important because hemoglobin, the protein that carries oxygen in your blood, is contained within red blood cells. Oxygen must be able to freely cross the membrane so that hemoglobin can get fully loaded with oxygen in your lungs, and deliver it effectively to your tissues. Most polar substances are stopped by a cell membrane, except perhaps for *small polar compounds* like one-carbon alcohol, methanol, and water. Glucose is too large to pass through the membrane unassisted and a special transporter protein ferries it across. Certain types of diabetes are caused by misregulation of the glucose transporter. *Charged ions*, such as sodium (Na+) or potassium (K+) ions seldom go through a membrane; consequently, they also need special transporter molecules to pass through the membrane. The inability of Na+ and K+ to pass through the membrane allows the cell to regulate the concentrations of these ions on the inside or outside of the cell. The conduction of electrical signals in your nerves is based on the ability of cells to control Na+ and K+ levels.

Selectively permeable membranes allow cells to keep the chemistry of the *cytoplasm* different from that of the external environment. It also allows them to maintain chemically unique conditions inside their*organelles*.

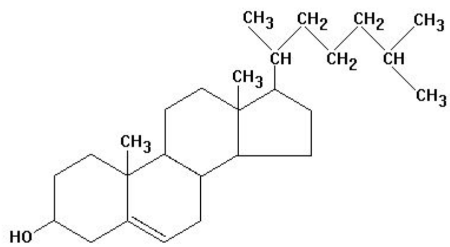
Fluidity of Cell Membranes

The cell membrane must be a dynamic structure if the cell is to grow and respond to environmental changes.

Maintaining Proper Fluidity of the Membrane

To keep their membranes fluid across a range of temperatures, cells alter the composition of their membranes. *Phospholipids* with differing fatty acid tails have different levels of mobility in the membrane. The right ratio of *saturated* to *unsaturated fatty acids* keeps the membrane fluid at any temperature conducive to life. For example, winter wheat responds to decreasing temperatures by increasing the amount of unsaturated fatty acids in cell membranes. The unsaturated fatty acid tails keep membranes fluid because they are kinked and resistant to packing. In animal cells, the membrane is made up of mostly saturated fatty acids, so it is relatively stable (not too fluid). *Cholesterol* plays a key role in keeping animal cell membranes fluid across a range of temperatures. At high temperatures, cholesterol molecules interfere with phospholipid movement and reduce membrane fluidity. At low temperatures, cholesterol keeps the saturated fatty acid tails from packing and maintains adequate fluidity. Other *sterols*play a similar role in the cell membranes of plants, fungi, and even some prokaryotes. Fungi, for example, use ergosterol.

Structure of Cholesterol

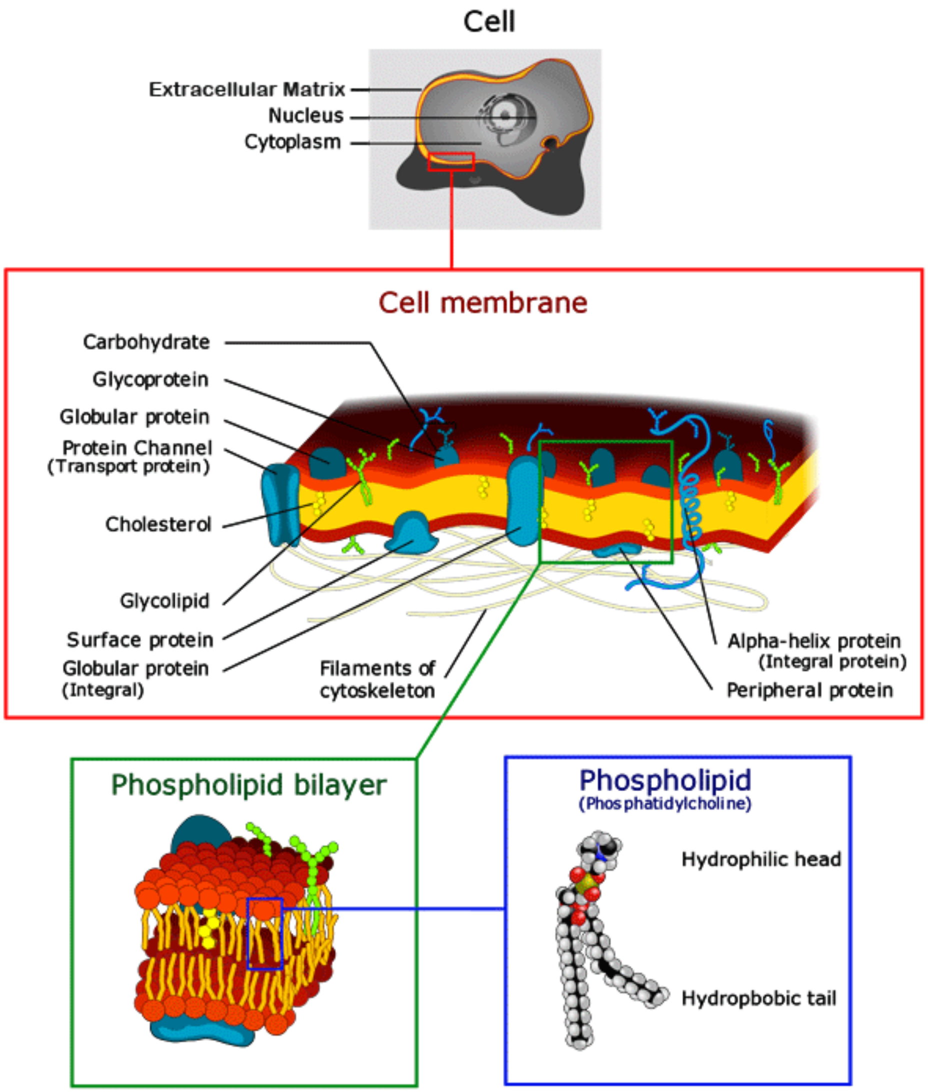


Cholesterol in the membrane maintains the correct fluidity.

Components of the Membrane

The cellular or plasma membrane is a lipid bilayer composed of *phospholipids* and associated *proteins*, specialized *lipids*, and *carbohydrates*. The composition of the plasma membrane varies according to the type and function of the cell.

Components of the Membrane



The plasma membrane is a complex structure containing many different macromolecules. [Wikicommons]

Sterols

Sterols are used by some cells to maintain proper membrane fluidity.

Carbohydrates

The extracellular surface of the cell membrane is decorated with carbohydrate groups attached to lipids and proteins. These short carbohydrates play a role in giving a cell its identity (i.e., distinguishing self from nonself) and are the distinguishing factor in human blood types.

Proteins

Membranes also contain proteins, which carry out many of the functions of the membrane. Some functions of membrane proteins are:

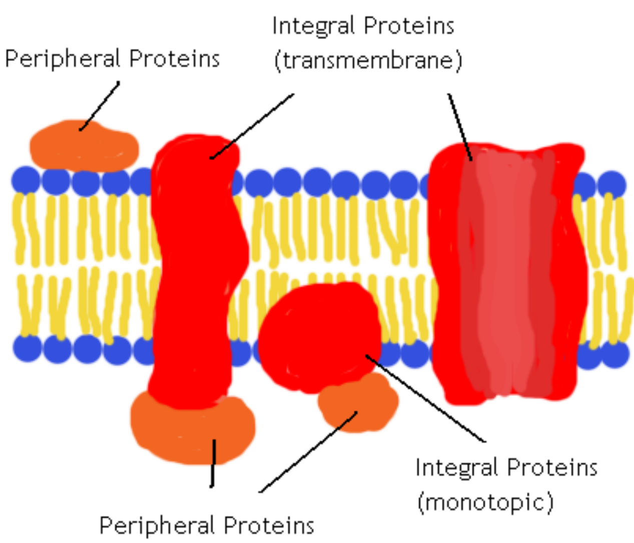
- *Transport.* Because the plasma membrane is only semipermeable, the cell needs a way to transport larger materials into and out of the cell.
- *Communication.* Because the plasma membrane is the border of the cell, this is where the cell communicates with its

environment. Membrane proteins are able to receive signals from outside the cell and begin a chain of events that cause the cell to respond to these signals.

- *Metabolism.* Membrane proteins can be enzymes that are involved in the chemical reactions of metabolism. These are the processes that allow the cell to grow, obtain energy, and eliminate wastes.
- *Adhesion.* Membrane proteins help cells bind to each other and form tissues. One example of this is skin cells, which must form a tight surface if the skin is to maintain proper integrity. Membrane proteins also bind to molecules inside and outside the cell, which helps the cell maintain its structure.

In order to carry out their functions, some proteins need to be embedded in the membrane. These proteins are called *integral proteins* ("integral" because they are "integrated" into the membrane). For example, a membrane protein that transports materials into or out of the cell needs to completely span the membrane. On the other hand, a protein that binds the cell to another can simply be attached to the outer surface of the membrane. Proteins that are attached to the inner or outer surface of a membrane are called*peripheral proteins*.

Membrane Proteins



Application Spotlight: Archaea

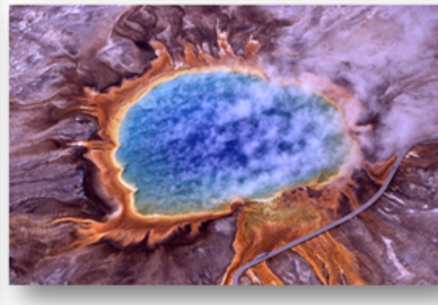
Prokaryotes are an enormously diverse group of organisms. However, they can be organized into two primary groups: *bacteria* and *archaea*. While both bacteria and archaea are prokaryotes (both groups lack nuclei), the archaeans have some interesting structural characteristics in the cell membrane that have unique functional significance.

The cell membranes found in both *eukaryotic* and bacterial cells consist of a *phospholipid bilayer*that separates the internal environment of the cell from its external environment and regulates the materials that pass in and out of the cell. This enables the cell to maintain internal *homeostasis*, regardless of changing external conditions. You already know that cell membranes can be structurally different, to enable different functions. For example, some bacteria live in the frozen Arctic Circle. They are able to maintain membrane fluidity because of an increased concentration of unsaturated fatty acid tails found within the membrane phospholipids.

The Archaean Cell Membrane

Archaeans are often found living in extreme environments such as high temperature, pH, or salinity, and as such, are often called "extremophiles" (loving extreme conditions). How can their cell membranes stay intact in such conditions? The cell membrane must have a unique structure to withstand these conditions.

Grand Prismatic Spring, Yellowstone National Park

Archaea were first found in extreme environments, such as volcanic hot springs like Grand Prismatic Spring, Hot Springs, Midway and Lower Geyser Basin, Yellowstone National Park. The picture on the right shows an aerial view of the spring. Photo by Jim Peaco, National Park Service, July, 2001, Public Domain.

You will explore characteristics of the archaean cell membrane in the following activities. First, you need to orient yourself to the phospholipid found in a bacterial cell. You might want to review the structure ofphospholipids.

You figured out that the structure of the archaean phospholipid is significantly different from the structure of the bacterial phospholipid. These structural differences lead to functional differences that enable archaeans to survive in extreme environments. This is an excellent example of how structure determines function at the cellular level of organization.

Cell Membrane: Summary

Summary

Membranes are the defining characteristic of a cell in the same way that your skin distinguishes what is "you" from what is "not you." Like your skin, the membrane interacts with the environment and controls what gets in and what gets out. However, additional features (such as eyes and a mouth) are necessary for more complex interactions with the environment. Similarly, proteins in the membrane further help the membrane control what enters and exits and regulate environmental interactions. We'll explore transport of things in and out of the cell in more detail in the next module.

Review the following key terms and when you're ready, take the module quiz.

Key Terms

The following key terms were introduced in this module.

adhesion	cell membrane	cell wall	endomembrane system	integral proteins
peripheral proteins	phospholipid bilayer	plasma membrane	sterols	

Membrane Transport

Learning Objectives:

- Define diffusion.
- Discuss the functions of the plasma membrane.
- Predict whether molecules and ions will pass easily through biological membranes based on their size, polarity, and formal charge.
- Define facilitated diffusion and describe the role of channels or pores in facilitated diffusion.
- Compare and contrast active and passive transport proteins.
- List the functions of membrane proteins.
- Describe endocytosis and exocytosis as a means of moving materials across the membrane.
- Define osmosis.
- Identify and discuss cellular responses to hypertonic, hypotonic, and isotonic solutions.
- Explain how a malfunctioning membrane transporter can result in the disruption of normal bodily function.

What Is Diffusion?

How Molecules Enter and Exit Cells

The *cell membrane* determines what enters and exits the cell, and it is how the cell interacts with its environment. As you have already learned, the cell membrane is a *phospholipid bilayer* structure that provides a semipermeable barrier between the inside and the outside of the cell. In this module, you will explore the following three ways molecular substances enter and exit the cell:

- Molecules can pass across the membrane (diffusion and active transport).
- Molecules can be transported into the cell without passing across the membrane (endocytosis).
- Molecules can send signals for actions within the cell without actually passing across the membrane themselves (signal transduction).

This module will discuss how the cell membrane controls the transport of nutrients, ions and signals between the highly variable outside environment and the relatively well-defined interior of the cell.

Passive/Simple Diffusion

Molecular substances enter and exit the cell so that: nutrients and waste can be exchanged; the cell can perform its function; and, when required, the cell can send appropriate signals to other cells. Transporting some substances may require the cell to exert energy and other *molecules* may cross through the membrane passively, requiring no use of energy by the cell. One way molecules passively move through the cell membrane is a process called simple diffusion.

In *simple diffusion*, both large and small molecules spontaneously move from areas of high concentration to areas of low concentration following random movements, referred to as Brownian motion. The classic example is the diffusion of a drop of ink placed in a beaker of water. The concentrated drop of color slowly disperses (diffuses) until at some point equilibrium is reached and the water in the beaker appears to have a uniform color. The following animation depicts this simple diffusion process. Add ink to the beaker and watch the diffusion process. After a period of time, how has the distribution of the ink changed in the beaker? Follow the yellow ink for some time. Does its behavior change as time passes?

Selective Permeability of Membranes

The *cell membrane* provides a semipermeable barrier between the inside and the outside of the cell. The*phospholipid bilayer* structure of the membrane allows selected *ions* and *organic molecules* to pass through the plasma membrane and regulates the movement of molecular substances. This characteristic of the membrane, known as *selective permeability*, acts as a filter that allows only selected substances that are needed for the survival and functioning of the cell in and out. The movement of molecular substances across the membrane can occur passively without the cell exerting energy or it can occur through the cell's use of energy to transport substances. Selective permeability affects the energy required to transport substances in and out of the cell. This page will explore the conditions under which molecules can pass across the membrane passively through diffusion.

Diffusion Across the Membrane

Molecules can be divided into four categories with regard to their ability to cross the *plasma membrane*. The first category is *nonpolar molecules*. These *hydrophobic molecules* can easily cross the membrane because they interact favorably with the nonpolar lipids. Note that these molecules can accumulate in the membrane because they interact so well with the *lipids*. The second category is *small polar molecules*. Although they don't interact with the lipids, their small size allows them to pass through small temporary holes in the membrane. The third category is *large polar molecules*. These have difficulty crossing the membrane because of their size and poor interaction with the lipids. The last category is *ionic compounds*. Their charge interacts very unfavorably with the lipids, making it very difficult for them to cross the membrane.

The size, polarity, and charge of a substance will determine whether or not the substance can cross the cell membrane by diffusion. The cholesterol was an example of a lipid, and is highly soluble in the nonpolar environment of the lipid bilayer. You saw, in the animation above, the cholesterol freely passing into the hydrophobic environment of the membrane. Cholesterol distributes freely in the membrane and then some fraction will dissolve in the aqueous environment of the cytoplasm. Water, on the other hand, while polar, is small enough to cross the membrane at a slow rate. Note that specialized transport proteins in certain cell membranes can provide a channel for the water, greatly increasing its rate of crossing the membrane. The lipid bilayer is much less permeable to the ion, because of its charge and larger size. As a general rule, charged molecules are much less permeable to the lipid bilayer.

Facilitated Diffusion

Cells must be able to move *large polar* and *charged molecules* across the lipid bilayer of the membrane in order to carry out life processes. To allow these molecules, which are not soluble in the *lipid bilayer*, to pass across the *hydrophobic* barrier, it is necessary to provide ports, channels, or holes through the membrane. The molecules will still move spontaneously down a concentration gradient from high to low concentration. These channels can either remain open at all times, allowing the molecules to move freely according to the concentration gradient, or they can be gated channels that open and close in response to the needs of the cell. In most cases these channels are very discriminatory and will only allow specific molecules to pass. The process of moving impermeable molecules across a membrane (down their concentration gradients) using channels or pores is referred to as *facilitated diffusion*. Because the molecules are moving down a concentration gradient, the process is driven by *simple diffusion* and does not require the input of additional energy from the cell. The following simulation depicts the facilitated diffusion of glucose across the membrane using the glucose permease transporter.

Active Transport

In some cases it is necessary to move molecules against their concentration gradient. The *eukaryotic cell*has many compartments within it, each surrounded by a membrane. In most cases, the environment within the compartment is different from the environment in the *cytoplasm*. An example is the *lysosome*, an*organelle* whose function is to digest *macromolecules* delivered either from outside the cell or from other compartments within the cell. To carry out this function, the lysosome maintains a very low internal*pH* compared to that of the cytoplasm. Thus, there is a steep pH gradient across the lysosome's membrane. This contrasts with the equilibrium state, in which the concentration of *hydrogen ions* would be the same inside and outside the lysosome.

To decrease the pH inside the lysosome, the concentration of protons will need to be greater inside the lysosome than in the cytoplasm. To accomplish this, *protons* will need to move from a low concentration to a high concentration. This is a nonspontaneous process and requires the cell to do work to move the ions "uphill" against the concentration gradient. To do work, the cell must expend energy and actively move (pump) the ions. This process is referred to as *active transport*. The source of energy for this process in most biological systems is the *hydrolysis* of ATP.

The animation that follows illustrates an example of an *active transporter* that uses energy from the molecule *ATP* to transport sodium (Na^+) ions out of the cell and potassium (K^+) ions into the cell. Both ions are moved against their *concentration gradients*. The main stages of the process are:

1. Three Na^+ ions from inside the cell bind to the transporter.
2. A molecule of ATP binds to the transporter, providing the energy needed to change the shape of the transporter. This allows the Na^+ to cross the membrane and exit the cell, against its concentration gradient.
3. Two K^+ ions from outside the cell bind to the transporter.
4. The transporter changes shape again, bringing the K^+ into the cell.

Observe the active transport of sodium and potassium molecules using ATP.

Transport Proteins

Facilitated diffusion and *active transport* both require *transport proteins* that act as channels or ports in the membrane. Transport proteins are classified both by structure and by function. The structure (shape) of each channel helps determine what materials can pass through. Even within classes of transport proteins that carry out similar functions (e.g. ion channels) there are many different structures that can discriminate between specific substances. Dozens of different transporters swirl around within the fluid membranes that enclose your cells and organelles, contributing greatly to their *"mosaic"* quality.

Molecules can also be moved across the membrane in bulk. Additionally, larger items (such as entire cells) can also be taken into a given cell. These processes are types of *endocytosis* and *exoctyosis* and will be discussed next.

Endocytosis and Exocytosis

Facilitated diffusion and active transport are not the only ways that materials can enter or leave cells. Through the processes of endocytosis and exocytosis, materials can be taken up or ejected in bulk, without passing through the cell's plasma membrane.

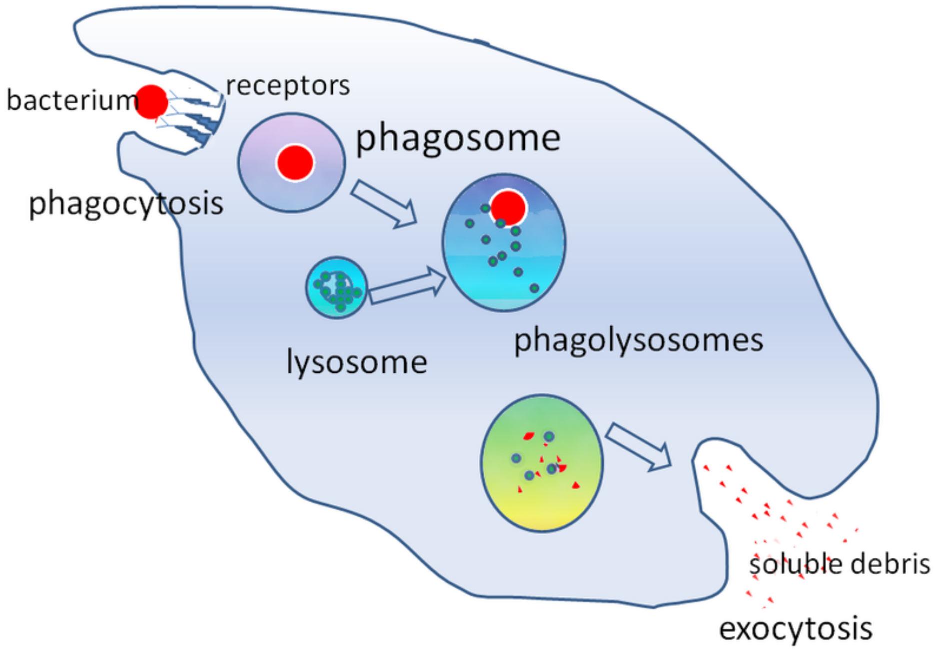
In *endocytosis*, material is engulfed within an infolding of the plasma membrane and then brought into the cell within a cytoplasmic vesicle. To begin endocytosis, a particle encounters the cell surface and produces a dimple or pit in the membrane. The pit deepens, invaginates further, and finally pinches off to form a vesicle in the cytoplasm of the cell. Note that during the process the inside surface of the newly formed vesicle is the same as the exterior surface of the cell. Thus the integrity of the cytoplasm and the orientation of the plasma membrane are preserved. Once internalized, a new vesicle containing solid materials may fuse with a lysosome so that its solid contents are digested. The resulting molecules may be released to the cytoplasm for use within the cell.

There are two general forms of endocytosis: phagocytosis and pinocytosis. *Phagocytosis* is the uptake of large solid particles such as bacteria or cellular debris. *Pinocytosis* is the uptake of fluid and any small molecules dissolved within it. Cells are also capable of recognizing specific particles and engulfing them in a more targeted way, a process called receptor-mediated endocytosis. In this case, the particle first binds to a membrane protein receptor on the surface of the cell. Binding of the target particle induces the cell to engulf it.

Exocytosis is just the reverse of endocytosis. In exocytosis, an internal vesicle fuses with the plasma membrane and releases its contents to the outside. The balance of exocytosis and endocytosis preserves the size of the plasma membrane and keeps the cell's size constant. The following animation depicts endocytosis.

How are endocytosis and exocytosis important to everyday life? Immune cells protect animals by recognizing and destroying foreign objects such as bacteria. Disease-causing bacteria are recognized by proteins called receptors on the surface of the immune cell. The phagocytic immune cell will then engulf the bacterial cells (phagocytosis). The vesicle that contains these bacterial cells is called a phagosome ("phago" means "eating" and "-some" refers to "body"). The phagosome next fuses with lysosomes. Finally, the digested bacterial products are excreted through the process of exocytosis.

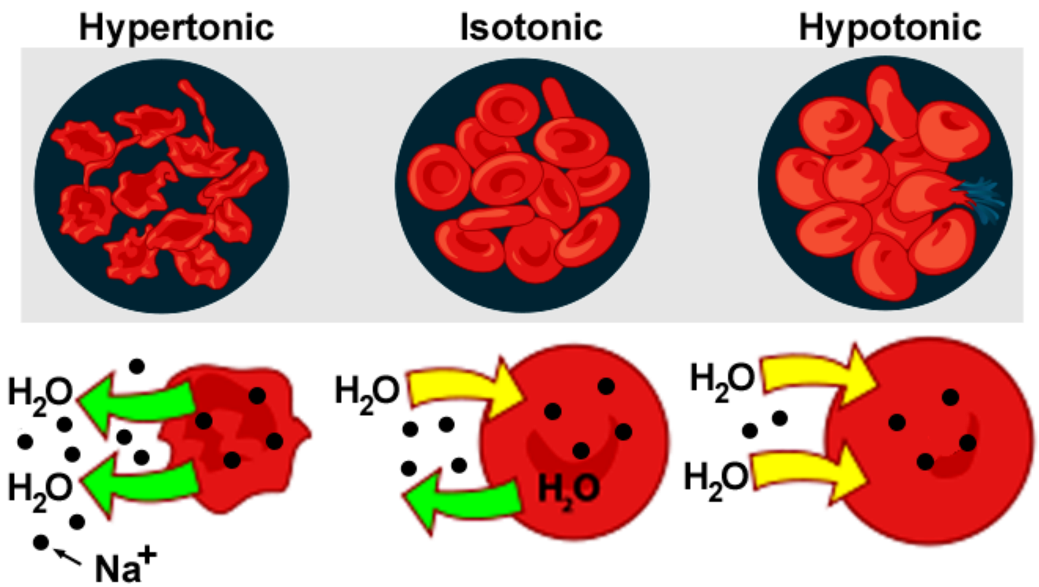
Phagocytosis of a Bacterium



Membranes — Osmosis

Cells continually encounter changes in their external environment. Most cells have a similar blend of solutes within them, but external fluids can vary dramatically, from pure water to brine or syrup. What will happen if there is a strong concentration gradient between a cell's interior and the fluid outside? As you know, molecules will tend to move down their concentration gradients until equilibrium is reached. You might think that solutes will flow into our out of the cell until the solute concentrations are equal across the membrane. However, not all molecules can pass through the cell membrane. The plasma membrane (lipid bilayer) is significantly less permeable to most solutes than it is to water. Therefore the WATER tends to flow in a way that establishes an equal concentration of solutes on either side of the membrane. The water flows down its own concentration gradient, with a net movement toward the region that has a higher concentration of solutes. This movement of water across a semipermeable membrane in response to an imbalance of solute is called osmosis.

Osmosis in an Animal Cell



The figure shows red blood cells immersed in three different solutions. The black dots represent sodium ions. Inside the red blood cell, the concentration of sodium is equal under all three conditions (shown as four dots). In the hypertonic solution, the concentration of sodium is higher outside (8 dots) than inside the cell. Water tends to leave the cell, flowing down its own concentration gradient. In the isotonic solution, the sodium concentration is the same inside and outside the cell. Water molecules enter and leave the cell at the same rate and the system is in equilibrium. In the hypotonic solution, there is a relatively low concentration of sodium (two dots) on the outside of the cell. Water is more concentrated outside the cell and tends to flow in. As water enters, sodium is diluted inside the cell, bringing the cytoplasm's sodium concentration closer to that of the external solution. But if too much water enters, the cell can burst (lyse).

Cells may find themselves in three different sorts of solutions. The terms isotonic, hypertonic, and hypotonic refer to the concentration of solutes outside the cell relative to the solute concentration inside the cell. In an isotonic solution, solutes and water are equally concentrated within and outside the cell. The cell is bathed in a solution with a solute concentration that is similar to its own cytoplasm. Many medical preparations (saline solutions for nasal sprays, eye drops, and intravenous drugs) are designed to be isotonic to our cells. A hypotonic solution has a low solute concentration and a high concentration of water compared to the cell's cytoplasm. Distilled (pure) water is the ultimate hypotonic solution. If a cell is placed in a hypotonic solution, it will tend to gain water. The solutes will "stay put" within the cell, but water molecules will diffuse such that their net flow is toward the area with a higher concentration of solutes. A hypertonic solution has a high solute concentration (lower water concentration) compared to the cell cytoplasm. Very salty or sugary solutions (brines or syrups) are hypertonic to living cells. If a cell is placed in such a solution, water tends to flow spontaneously out of the cell.

Application Spotlight: Cystic Fibrosis

Cystic fibrosis is an inherited condition that affects the respiratory and digestive systems in children and adults. While there is no cure for the condition, in the 1950's, people diagnosed with cystic fibrosis were lucky if they lived long enough to go to elementary school. Medical research has made an enormous difference in the life expectancy of people with cystic fibrosis, and today, they routinely live into their thirties and forties.

A diagnosis of cystic fibrosis (CF) is suspected if a patient has chronic weight loss accompanied by problems with the respiratory system. Most people with the condition are diagnosed by the time they are two years old. A century ago, cystic fibrosis was diagnosed when a doctor licked the forehead of a patient and found it to be unusually salty. While the medical equipment used to diagnose the condition today is much more professional, the same symptoms are identified. People with CF exhibit a variety of symptoms [1] that may include:

- persistent coughing often heavy with mucous;
- frequent respiratory infections;
- wheezing and shortness of breath;
- excessive appetite but poor weight gain;
- unusually salty-tasting skin; and

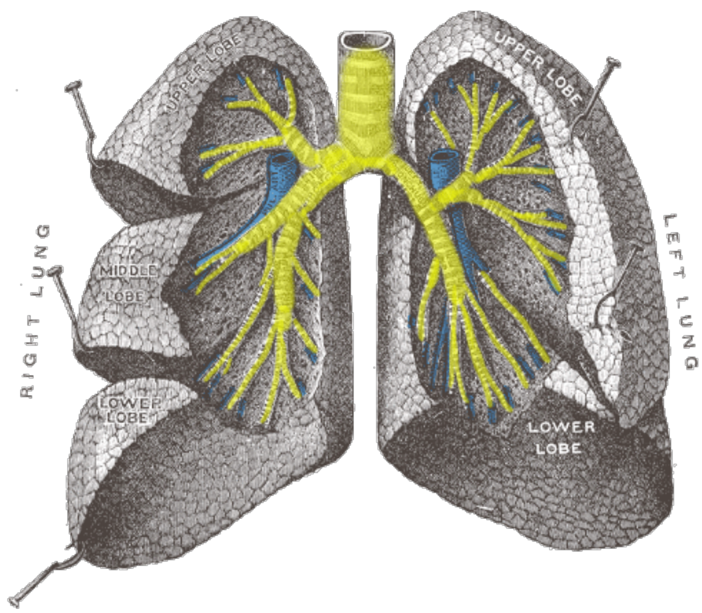
- greasy, bulky stools.

Cystic fibrosis is caused by a malfunctioning transport protein called *Cystic Fibrosis Transmembrane Conductance Regulator (CFTR)*. CFTR is a channel that allows for the passage of chloride ions (Cl-)into and out of the cell. CFTR is located in the cells that line the respiratory tract, the pancreas, and sweat glands. It allows for the movement of Cl- into or out of a cell. CFTR is an *active transporter* and requires *energy* in the form of ATP to function.

Effect of Malfunctioning Membrane Transporters

People with cystic fibrosis have respiratory difficulties, usually caused by unusually thick mucus in the respiratory tubes in the lungs. In the lungs, CFTR transporters secrete chloride ions into the center of the respiratory tubes. This increases the concentration of solutes in the mucus lining the tubes, which in turn causes water to flow into the space inside the tubes (yellow). Under normal conditions, this process allows for a runny mucus to line the tubes.

Human Lungs



The lungs function by allowing air to flow through a series of tubes (yellow) that culminate in tiny sacs where gas exchange occurs. The yellow tubes are lined with special cells that have CFTR transporters in them that secrete chloride ions into the air tubes.

Treatments for Cystic Fibrosis

Most of the treatments for cystic fibrosis involve making sure the lungs remain clear of the thick, sticky mucus. This can be done using drugs that thin the respiratory mucus, like Pulmozyme. A more recently discovered treatment involves the inhalation of hypertonic saline solution. This salty solution causes water to move from the cells and into the airways (via osmosis), making the mucus more watery and easier to cough up.

References

1. *Cystic Fibrosis: Symptoms, Diagnosis and Treatment.* American Lung Association, http://www.lung.org/lung-disease /cystic-fibrosis/symptoms-diagnosis-and.html .
2. Frank E. Beddard (1902). *The Cambridge Natural History, Volume X—Mammalia.* Project Gutenberg.

Membrane Transport: Summary

Summary

The ability to carefully regulate substances moving in and out of the cell is crucial for maintaining cellular homeostasis. There are many ways items can get in and out of the cell. Some substances can move through simple diffusion. Others require a transport protein. Sometimes energy is needed and sometimes it is not. Membrane transport proteins are so important that serious diseases can result when they malfunction.

Review these key terms and when you're ready, take the module quiz.

Key Terms

The following terms were introduced in this module.

active transport	concentration gradients	diffusion	endocytosis	exoctyosis
facilitated diffusion	hypertonic	hypotonic	isotonic	osmosis
passive transport	selective permeability	simple diffusion	transport proteins	

Unit Summary: The Cell

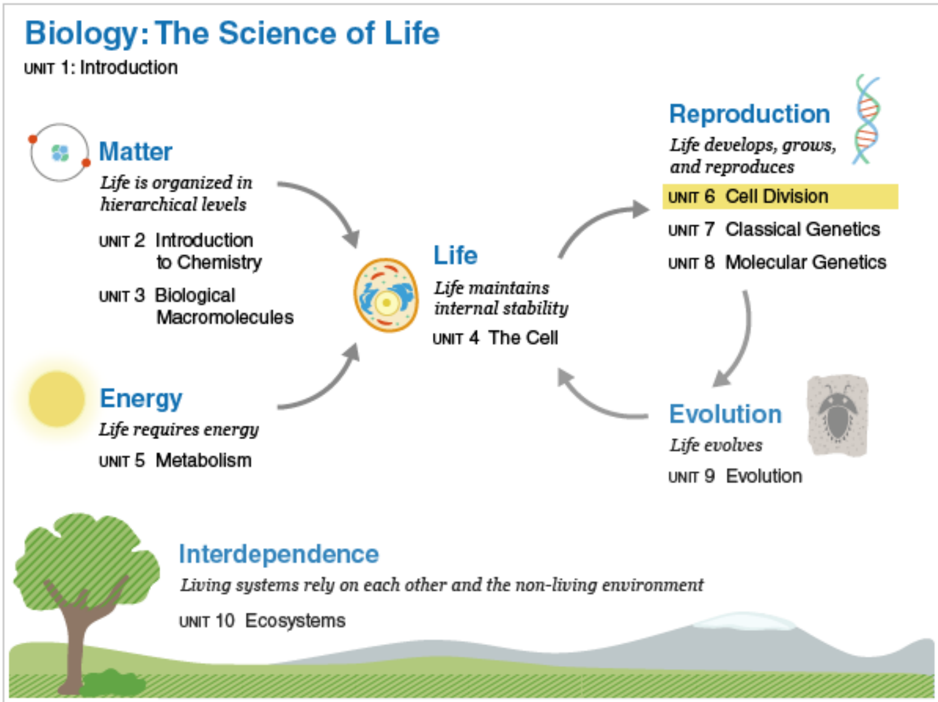
In this unit, we learned about the cell, which is the fundamental unit of all living systems. Cells can be divided into two major groups: *prokaryotes* (cells without a *nucleus*) and *eukaryotes* (cells containing a nucleus). Eukaryotic cells are larger and contain organelles that are specifically related to different cellular functions.

Two types of eukaryotic cells are *plant cells* and *animal cells*. Because they are both eukaryotes, both cell types have *nuclei*. However, there are several structures that distinguish the two types of cells. For example, plant cells have *chloroplasts* and a *cell wall*. Animal cells lack both of these structures.

All cells have a *cell membrane* that defines the boundary between the cell's interior and the external environment. The membrane mediates communication to the external environment. The cell membrane has a unique chemical structure that enables the passage of particles into and out of the cell. Some particles are able to simply diffuse across the membrane. In other situations, special *proteins* are required to help facilitate the movement. When particles move against a concentration gradient, energy is required. In the*Metabolism* unit, you'll explore energy and learn about out how cells generate and use this energy.

Review the learning objectives for this unit. Do you think you could demonstrate your knowledge of each of these objectives? If so, you will be ready for the assessment. If not, consider reviewing content related to these objectives before attempting the assessment.

In this *unit* [1] , you will learn about another major cell process — cell division, or cell reproduction. The word "reproduction" is used in many different scientific and nonscientific settings. Regardless of the setting, though, reproduction has the same basic meaning. Reproduction is defined as "the act of making a copy of the original." With this in mind, the word reproduction can be applied to many different situations. Some of these include parents having a baby, you photocopying a page in your textbook, and a museum staff member making print copies of a famous oil painting.



In each case, a relatively close copy of the original has been made. The same principle applies in cell reproduction —making new cells that closely resemble the original cell. Cell reproduction is a complex process that involves many intricate, highly regulated steps. Like *metabolism*, each of these steps must occur in a particular order.

Cell reproduction is important for three reasons:

1. It provides new cells for growth, the replacement of dead cells, and healing.
2. In cells, it ensures the inheritance of genetic information from parent cell to offspring cell.
3. In organisms, it ensures the inheritance of genetic information from one generation to the next.

In this unit, you will learn about how cells carry out these critical processes. Your understanding of the information this unit will lay the foundation for understanding heredity and molecular genetics.

References

1. . Course materials for the "Cell Division" unit provided courtesy of the University of Maryland University College under the CC-BY-NC license.

Cells and Chromosomes

Objectives

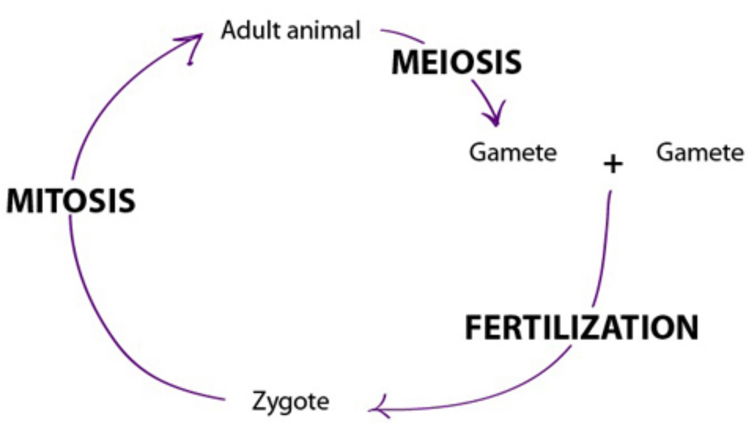
- Explain the functional differences between somatic cells and gametes.
- Describe the structure of a chromosome in different stages of the cell cycle.
- Relate the phases of the cell cycle to the corresponding cellular events.
- Identify the chromatids and centromere of a chromosome and describe their role in cell replication.

Types of Cells

Somatic Cells, Germ Cells, and Gametes

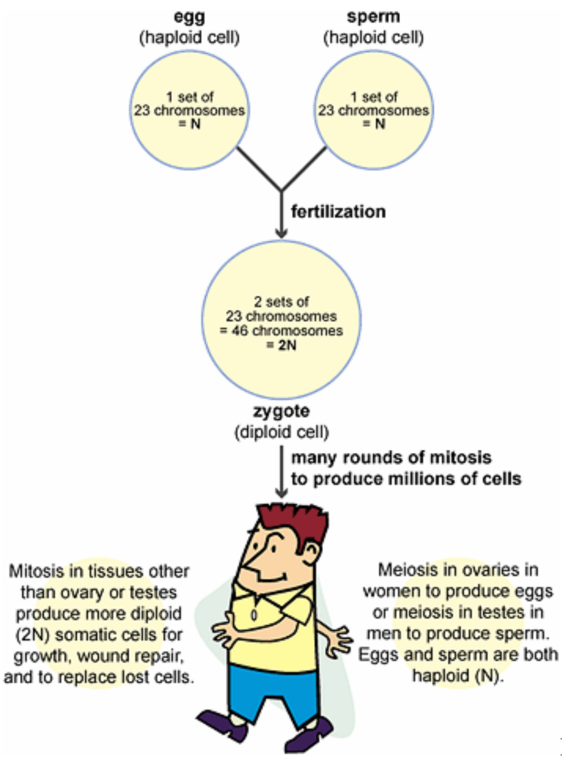
Why do cells divide? Cells undergo different phases, during which they grow, duplicate their genetic material, and then divide. In single-celled organisms, cell division results in two new individuals. Cell division in multicellular organisms is more complex. Most cells in multicellular organisms are *somatic cells*. Somatic cells consist of all the nonreproductive cells in an organism; for example, tissue cells, nerve cells, and blood cells. When somatic cells divide, they go through the process of *mitosis*, which is a type of cell division that results in two identical daughter cells.

Meiosis, on the other hand, is a type of cell division that prepares an organism for sexual reproduction. Meiosis begins with *germ cells*. Be careful not to confuse “germ cells” with the common use of the word “germ,” which refers to any infectious microorganism. In humans, germ cells are found in the ovaries and testes. These germ cells go through the process of meiosis to produce *gametes*, which in animals are sperm and egg cells. When two gametes from different individuals combine, a unique new cell is produced, called a *zygote*. This single cell then goes through the process of mitosis to grow into a new individual.



You might be wondering how a single cell can grow into a complex adult organism containing many different cell types simply by mitosis. This happens through a process known as *differentiation*, in which certain genes found in a cell’s nucleus are turned on or off. Even though every single somatic cell in your body contains identical DNA, these cells were able to differentiate into specific cell types (such as blood cell, liver cells, etc.) simply by turning certain genes on or off. Throughout our lives, we continue to produce more genetically identical cells through the process of mitosis. These somatic cells are essential for growth and replacement of worn-out cells and tissues.

Mitosis and Meiosis: Role in Human Growth

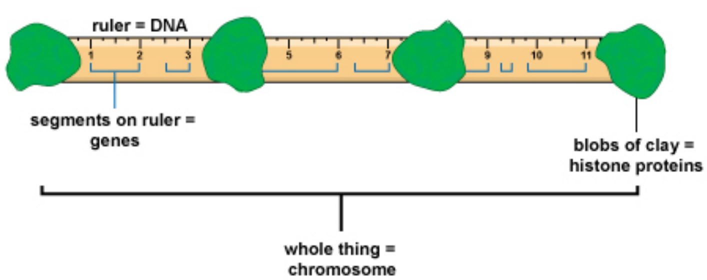


By [University of Maryland University College](#) [CC-BY-NC](#).

Mitosis and meiosis are the processes by which cells divide and grow; their role in human growth is summarized in the diagram above.

Basic Chromosome Structure

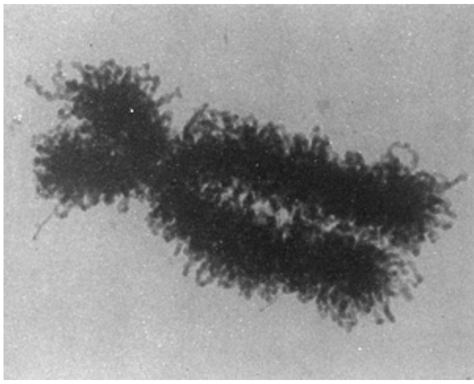
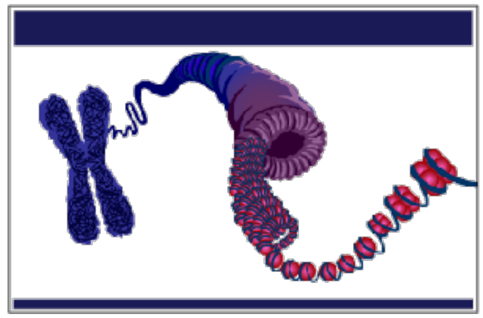
Chromosomes are thread-like structures located inside cells. In *eukaryotic cells*, the chromosomes are contained inside an organelle called a [nucleus](#) . In *prokaryotic cells*, they are located in a particular area of the *cytoplasm*. Chromosomes are made up of two major parts: *DNA* and [proteins](#). Both DNA and proteins are *large molecules*. Envision the general makeup of a *chromosome*, as shown in the following diagram.



By [University of Maryland University College](#) [CC-BY-NC](#).

DNA is the molecule that stores and transmits inherited genetic information. This information includes the directions that tell a cell how to make proteins. Information is stored in DNA in segments called *genes*. In the diagram above, the ruler represents the entire DNA molecule. The genes are represented as short segments of the ruler. You will learn more about the structure and function of genes in the *Molecular Genetics* unit.

The blobs of clay in the diagram above represent *histone protein molecules*. These proteins associate with DNA in a very precise way. First, they couple with DNA at regularly spaced intervals. Notice in the diagram above that the blobs of clay (histones) are located at equally spaced intervals along the ruler. Second, they help to wind the DNA molecule into an organized and compact structure. The following diagram shows how histones wind DNA into a compact structure called a *chromosome*.

By University of Maryland University College CC-BY-NC.

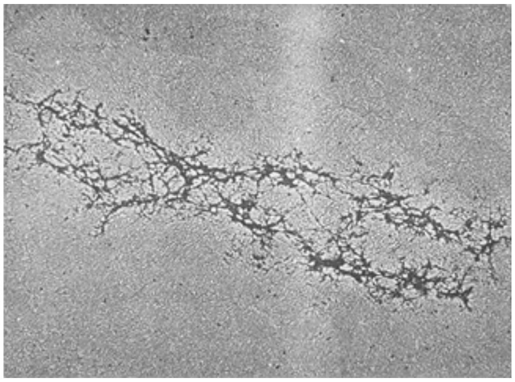
The winding function of histones plays a very important role in cells. It allows the DNA to be condensed into organized bundles (chromosomes) that can easily be moved around the cell. Because the DNA is wound around the histones in such an organized way, the DNA can be easily wound up and unwound at various points during the cell cycle. For example, chromosomes must unwind slightly when a new copy of DNA is made. Then, the chromosomes become very tightly wound as the cell gets ready to divide during mitosis or meiosis. Without an organized compaction system, the long pieces of DNA in chromosomes could easily become "knotted" and tangled. Think of a long piece of string. Knots can easily form in the string if it is not carefully wound up into a ball. Keeping the DNA organized is critical, especially when you consider that the DNA in one human cell is three feet long when it is stretched out straight. This is quite amazing when you realize that this must fit into a cell so small that it cannot be seen with the naked eye. This feat is achieved by two different winding processes. One of these is the winding of DNA around histone molecules. As a result of this winding, the DNA molecule becomes shorter than before it was wound around the histone molecules.

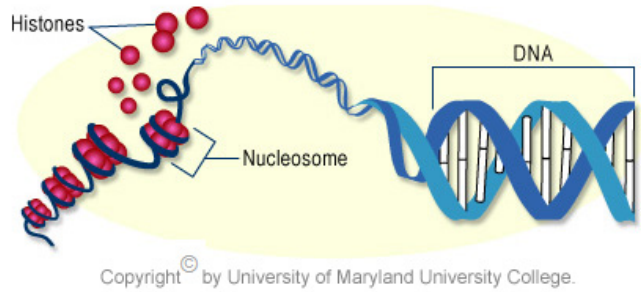
Winding DNA into Condensed Chromosomes

The videos below are two illustrations of the winding of DNA around histones. The left video shows the DNA strand coiling and condensing to form chromosomes; on the right, a model depicts the structure of DNA.

By University of Maryland University College CC-BY-NC.

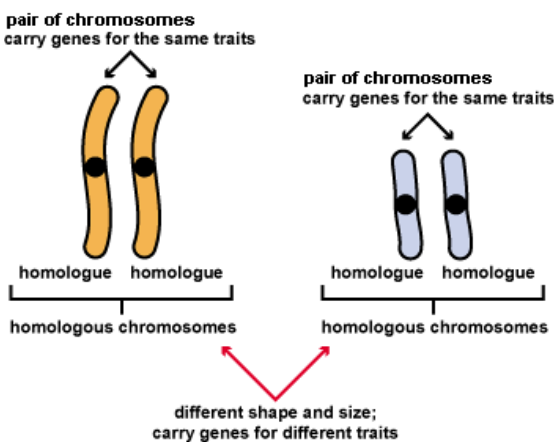
Now look at an image of the relationship between *DNA* and histones in chromosomes that is more realistic than what is shown in our ruler-and-clay diagram above. When the DNA becomes tightly wound around the*histone proteins*, imagine that the chromosome looks as illustrated below.





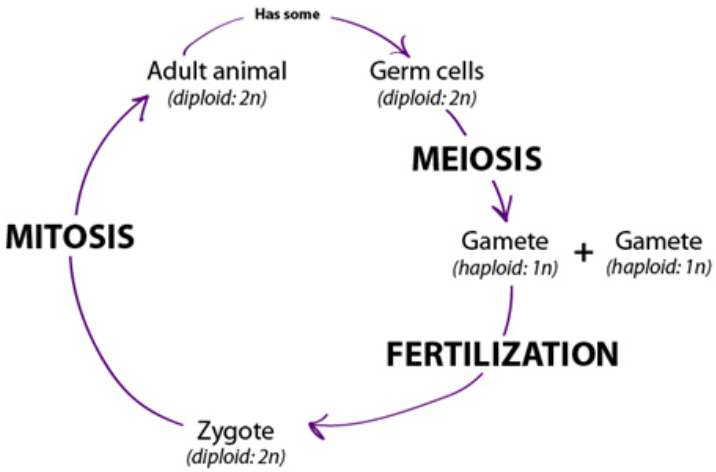
Counting Chromosomes

The chromosomes in *somatic cells* and *germ cells* are present in pairs. One chromosome in each pair is descended from the organism's father. The other chromosome in the pair is descended from the organism's mother. Each member of a chromosome pair is called a *homologue*. Together, these two chromosomes make up a pair of *homologous* chromosomes. The words homologue and homologous both begin with the prefix "homo-," which means "the same or similar." So the two chromosomes in each pair contain the same set of instructions. The following diagram shows the relationship between homologues and homologous chromosomes.



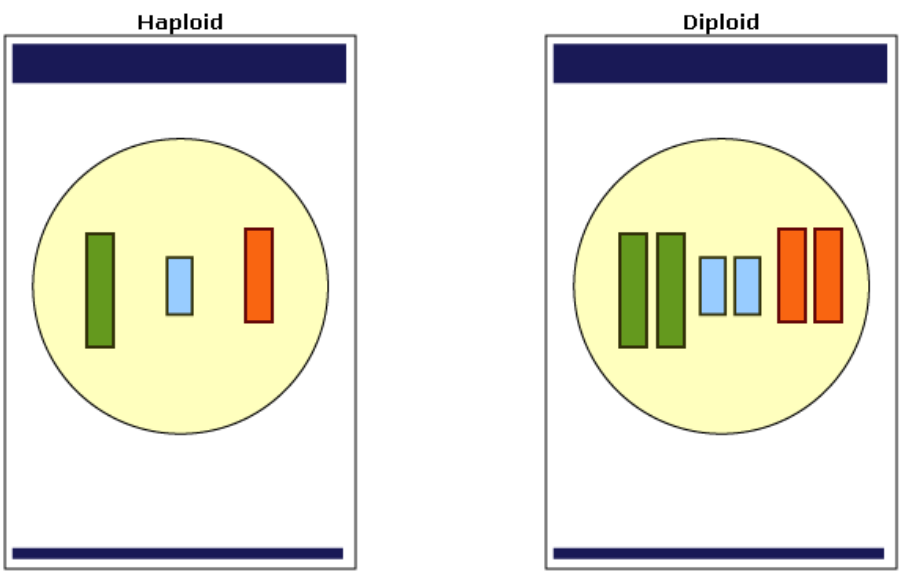
Somatic cells produced through *mitosis* are *diploid*. “Di-” means “two,” and diploid cells contain two copies of every chromosome. *Chromosomes* are the condensed form of *chromatin*, the combination of DNA and proteins that fill the eukaryotic nucleus. Humans have a total of 46 chromosomes in their diploid cells. One way to write this is *"2n = 46."* Humans who have more or less than 46 chromosomes sometimes survive, but usually have life-altering conditions, such as Down syndrome. Down syndrome is caused by having three copies of chromosome 21, instead of the usual two copies.

Gametes are *haploid* cells. They contain only one copy of each chromosome. In human haploid gametes, there are 23 chromosomes. One way to write this is "*1n = 23*." As you learned in the previous activity, two haploid cells can combine, through the process of fertilization, to form a diploid zygote. The diploid zygote then goes through mitosis to form the diploid somatic cells of the organism.



Remember that *germ* cells, found in the ovaries and testes, give rise to gametes. In other words, germ cells go through meiosis to produce gametes. Germ cells are diploid cells. When they go through meiosis, the end result is four unique haploid daughter cells. These haploid cells can be fertilized by other haploid cells to produce diploid cells again.

Number of Chromosomes in Diploid and Haploid Cells



By University of Maryland University College CC-BY-NC.

The table below summarizes the characteristics of somatic cells, germ cells, and gametes.

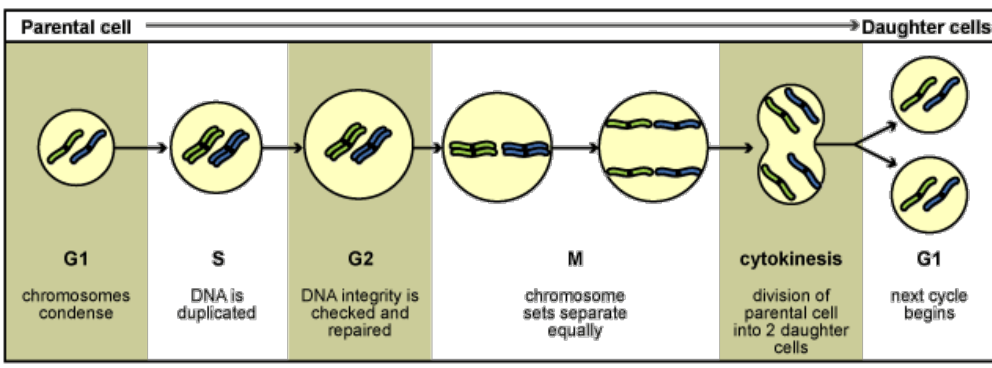
Type of Cell	Number of Chromosome Sets	Scientific Term	Scientific Abbreviation	Examples
Somatic Cell	2 sets	Diploid	2N or 2n	Non-reproductive cells. All cells not germ or gamete, for example: Blood cells, brain cells, kidney cells, liver cells, lung cells, nerve cells, skin cells, etc.
Germ Cell	2 sets	Diploid	2N or 2n	Immature reproductive cells. Cells in the ovaries and testis.
Gamete	1 set	Haploid	N or n	Mature reproductive cells. Eggs and sperm cells.

Overview of the Cell Cycle

Every living organism goes through various stages of development. For example, human beings go through these stages of development: fetus, infant, child, youth, teenager, young adult, adult. Remember from earlier that cells are living things. They, too, go through a set of programmed stages.

The cell cycle is the "life cycle" of a cell. It is the set of stages that a cell goes through during its lifetime. Cells go through five major stages of development: G1, S, G2, M, and cytokinesis. The events that occur during stages G1, S, and G2 are nearly the same in all types of cells. Together, these three stages of the cell cycle are called "interphase." The events that occur during stages M and cytokinesis are different, depending upon the type of cell. The diagram below shows an overview of the stages in a cell's life cycle:

Overview of the Cell Cycle



By University of Maryland University College .

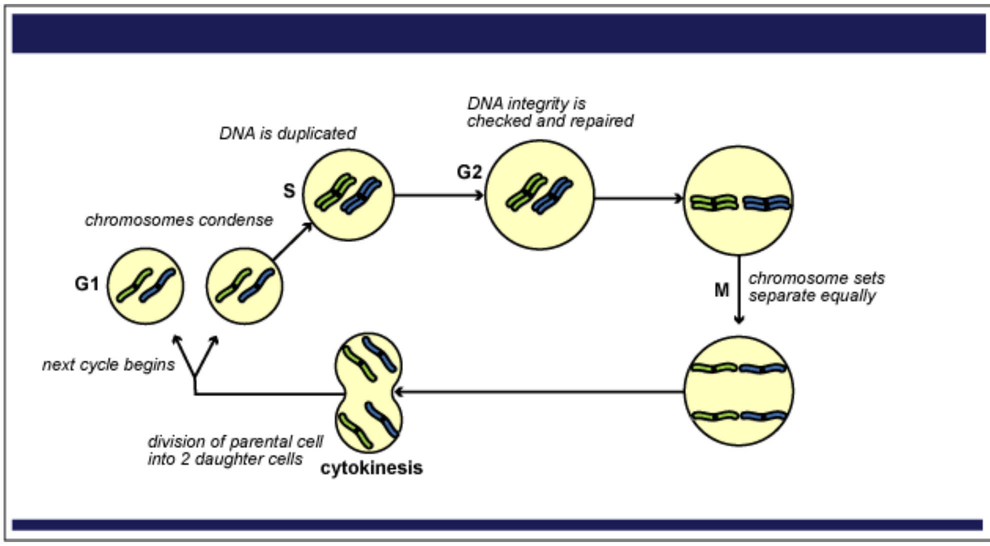
Notice in the diagram above that we start with one cell on the left side. This is called the parent cell. It is called this because, like a human parent, it reproduces—it makes new cells that are copies of itself. The parent cell goes through the five stages of development in this order—G1, S, G2, M, and cytokinesis.

At the end of the development process, two new cells are produced. These cells represent the next generation of cells in this lineage (just as your parents represent one generation and you represent the next generation). Each of the new cells is called a daughter cell. Do not be confused by the use of the word daughter—it does not mean that these are female cells. Regardless of whether they are male or female cells, the newly produced cells are called daughter cells.

Notice that the parent cell no longer exists—but the parent cell did not die. Rather, the contents of the parent cell have been split into two new cells. Each of the new cells contains a portion of the original parent cell. Previously, we compared the cell cycle to the phases of human development. Notice here a very important difference between the two: The far end of human development is marked by the death of the individual. The end of the cell cycle, however, results in the formation of new cells.

In the diagram "Overview of the Cell Cycle" above, look closely at the parent cell and the two daughter cells. Notice that they look the same. Once again, we revisit the theme of cycles in nature that we discussed above. The cycle generates cells that resemble the cells we started with. In addition, the new cells undergo the same development-and-division process that their parental cell did. For these two reasons, we call this the cell cycle, and draw it like a circle. Similarly, human beings have children, who then have children themselves. (You may have heard this called the circle of life.) Cells do the same thing through the cell cycle. The following diagram shows the cell cycle in circular form.

Overview of the Cell Cycle



By University of Maryland University College CC-BY-NC.

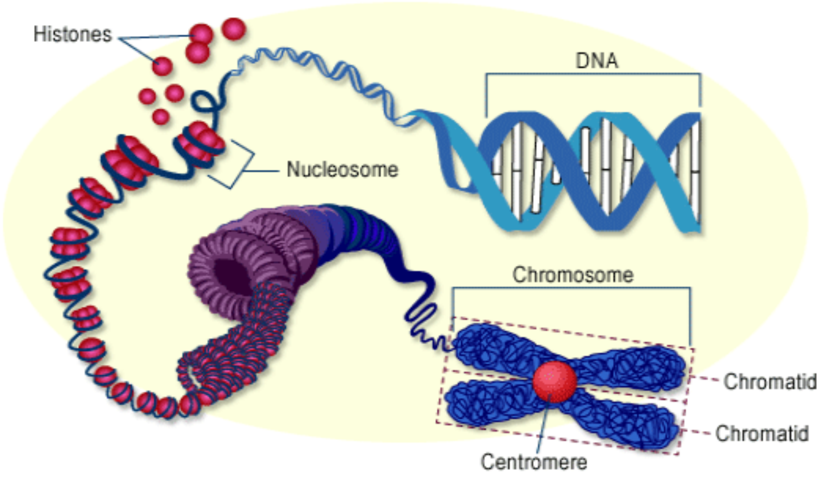
Preparing for Cell Replication

In cell replication, chromosomes are moved to new locations. Like packing household materials into a box before moving, condensing the chromosomes helps with this process. Chromosomes are condensed by wrapping them more tightly around *histones* (proteins found in the nucleus).

If a cell is going to reproduce, more *DNA* is needed. During *mitosis*, one cell divides into two cells containing identical genetic material. This requires twice as much DNA, because there must be one complete set for each daughter cell. *Meiosis* also requires the DNA to be replicated. DNA replication (or DNA synthesis) occurs in the synthesis (*S*) stage of the cell cycle.

After a *chromosome* has replicated, the two copies remain attached at a point called the *centromere*. Each copy of the chromosome is called a chromatid.

Before cell division, DNA is copied and condensed.

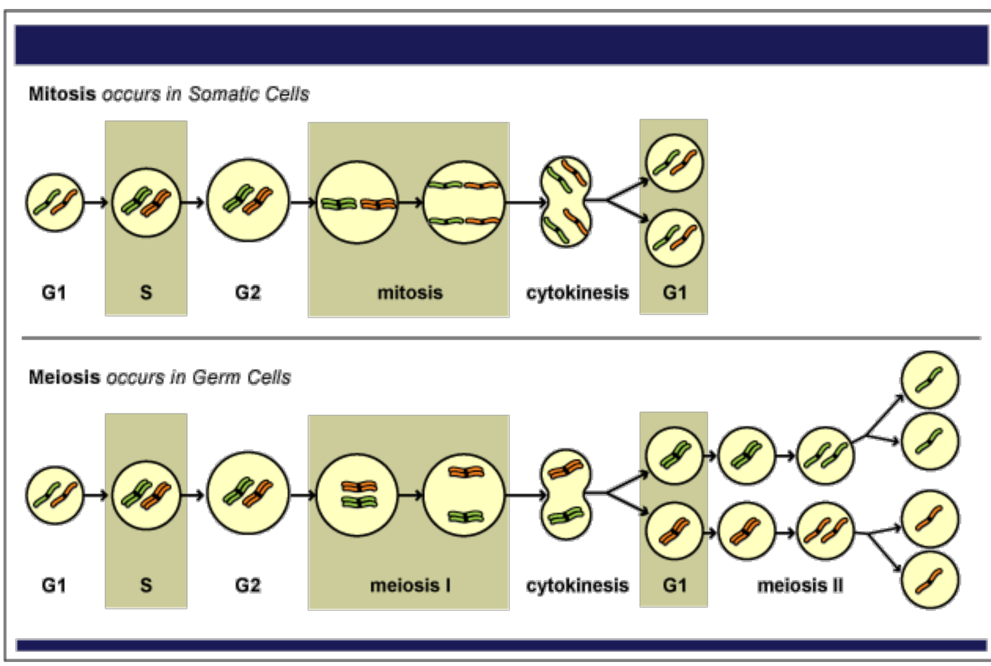


Copyright (c) by University of Maryland University College

During cell division, each *chromatid* moves to one of the two daughter cells. Keeping the two copies of a single chromosome attached helps the sorting process. In human cells, there are a total of 46 chromosomes. After the *S* stage of the cell cycle, these chromosomes have replicated and there are now 92 total pieces of DNA. The process of mitosis must sort these into 2 identical piles of 46 chromosomes. The cell keeps the matching pairs attached to keep track of which chromosomes need to be sent to opposite poles.

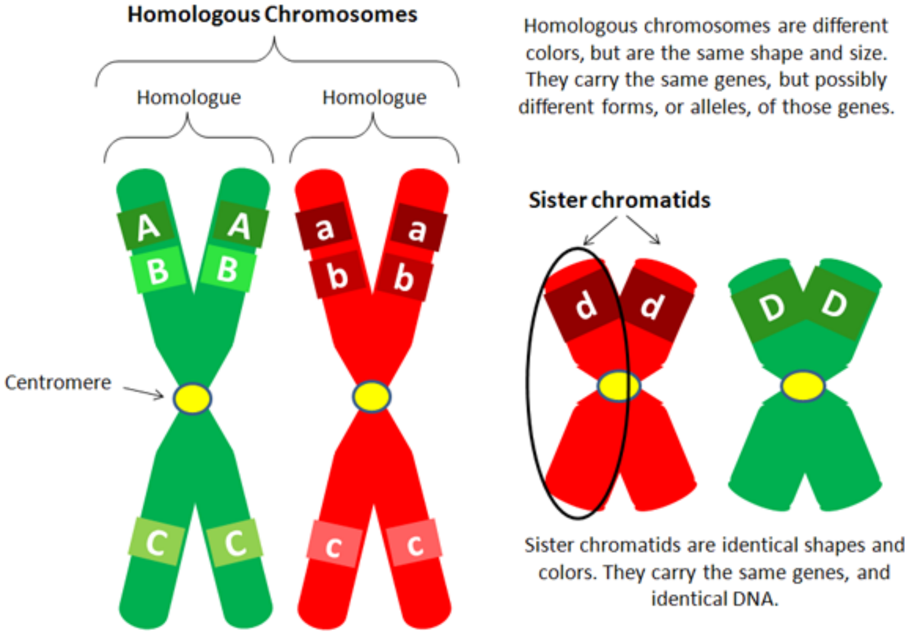
This is rather like sorting a sock drawer. If all the socks are loose in the drawer, it can be challenging to find the identical mate to a sock. But if the sock mates are folded together, each bundle contains both mates in the set.

Overview of Mitosis



By [University of Maryland University College](#) [CC-BY-NC](#).

Both *mitosis* and *meiosis* must keep track of the chromatids on a chromosome. In the Meiosis module, you will learn that meiosis must also keep track of homologous chromosomes. A *diploid* cell has two copies of each chromosome — one copy from each parent. These chromosome pairs are called*homologous* because they have the same genes, but may have different versions of that gene. For example, a homologous pair of chromosomes may have a gene for hair color. One chromosome in this homologue may contain a “blond” version of that gene and the other homologue may contain the “brown” version. Each gamete that is produced will get either the homologue with the brown version or the homologue with the blond version.



Cells and Chromosomes: Summary

Summary

Multicelled organisms are made of two main types of cells.

- *Somatic cells* are all the nonreproductive cells. Somatic cells are *diploid* and reproduce using mitosis. Diploid cells (2N) have two copies of each chromosome.
- *Germ cells* are immature reproductive cells. Germ cells are diploid and divide using meiosis to produce gametes. *Gametes* are haploid reproductive cells (sperm and eggs). Haploid cells (1N) have one copy of each chromosome.

Cell division (mitosis and meiosis) sorts the genetic material (DNA) of a cell. This sorting of genetic material is essential, because most of the essential information for life is stored in the DNA. Each newly formed daughter cell must receive identical information; therefore the DNA in a cell must be copied before cell division begins. The copied DNA strands remain attached near their centers in a region called the centromere. Each copy of the DNA is called a chromatid, and both copies are called a chromosome. The cell packages the DNA so that it can be sorted between the new cells. The DNA is packaged by wrapping it tightly around proteins called histones.

In *diploid cells* (cells with two copies of each *chromosome*) each chromosome has a homologue.*Homologous* chromosomes have the same genes, but they can have different versions of those genes.

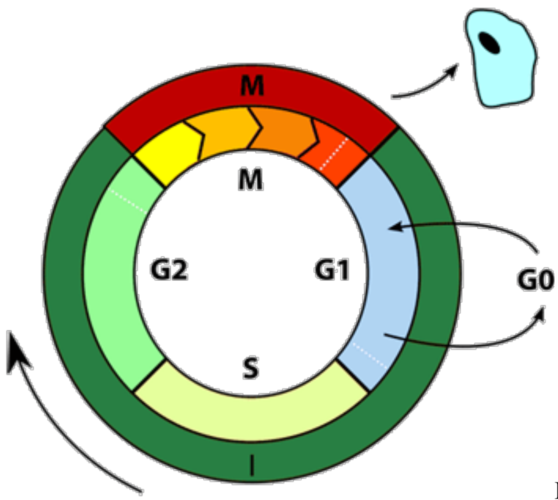


Diagram depicting the cell cycle phases G1, S, and G2, collectively referred to as the Interphase (I). G0 corresponds to cells that do not divide further, such as some nerve cells. *M* (red) corresponds to *mitosis*, with the four phases of mitosis designated below in colors yellow, gold, tan, and orange.

In the next module, you will examine the details of *mitosis*. But before you move on, review these key terms and prepare for the module quiz.

Key Terms

Review the following key terms introduced in this module. When you are ready, check your understanding of cells and chromosomes by taking the quiz linked below.

diploid	gametes	genes	germ cells	haploid
homologous	homologue	karyotype	meiosis	mitosis
sister chromatids	somatic cells	zygote		

Mitosis

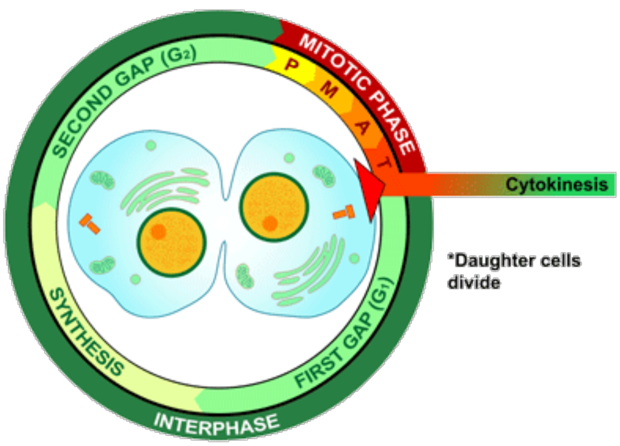
Objectives:

- Describe the function of mitosis.
- Predict the number of genes/gene pairs of the progeny cells based on the number of genes of the parental cell.
- List the stages of mitosis and describe what happens at each stage.
- Match a picture of a cell with the stage of mitosis it is in.
- Relate the regulation of the cell cycle to cancer.

What Is Mitosis?

Growing from a single fertilized egg to an adult organism requires many rounds of cell division. Before cell division, a cell must copy its *genome* so that each new daughter cell receives a full set of DNA. This *DNA*replication occurs in the *synthesis (S)* stage of the cell cycle just prior to *mitosis*. The process of mitosis sorts the DNA equally into two separate nuclei. The process of mitosis is divided into the following steps or phases:

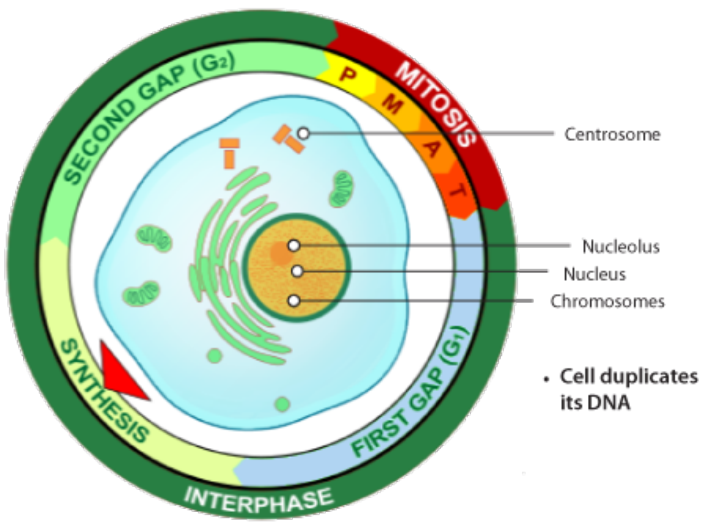
1. *Prophase* and *Prometaphase*: The cell prepares to sort the chromosomes.
2. *Metaphase*: Chromosomes are moved to the center of the cell.
3. *Anaphase*: Chromosomes are sorted.
4. *Telophase*: The new nuclei are formed.



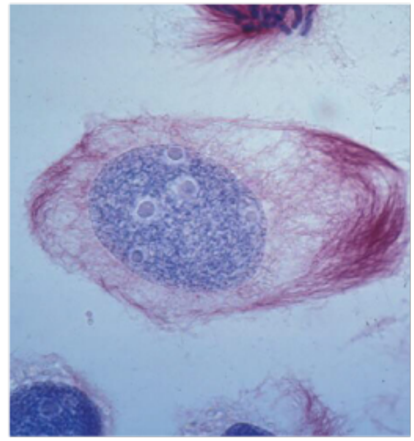
Each new cell gets one of these nuclei during the process of *cytokinesis*. At the end of mitosis and*cytokinesis*, each new daughter cell should have the identical genetic makeup of the parent cell. Mitosis of a single *diploid* cell will result in two diploid cells with identical genomes, unless a mutation or other error occurred. Mitosis of a *haploid* cell will result in two identical haploid cells. These cells can go through the process again to reproduce.

Interphase: Duplicates DNA

Let's begin with a diploid cell that is 2N = 4. This cell has two copies of each of its two chromosomes. During the *S* phase of interphase, the cell replicates its DNA. This results in two sister chromatids that are attached to each other at the centromere. The chromosomes have not condensed enough at this point to be visible with a microscope.



The synthesis (S) stage of the cell cycle

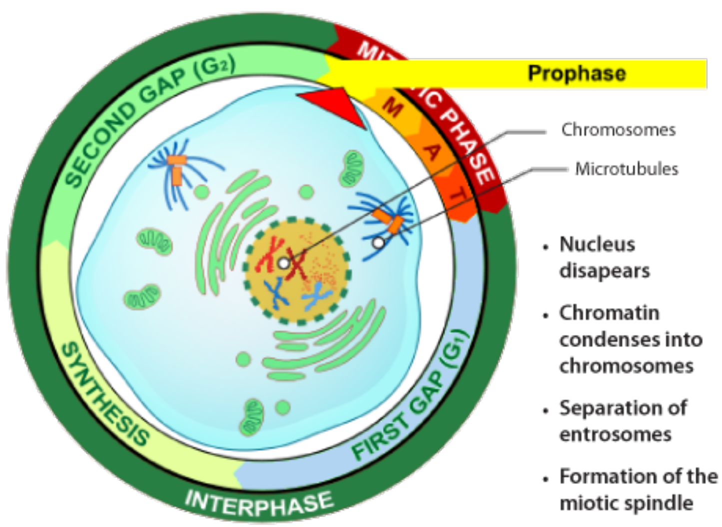

Cell in interphase. Notice that individual chromosomes are not visible in the nucleus.

Centrosomes are also formed during interphase. Centrosomes are used to identify the poles of the cell during the division process; these poles determine where the chromosomes will be sent.

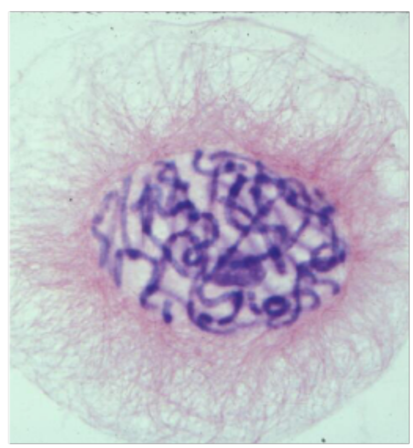
The Phases of Mitosis

Prophase

Mitosis begins when DNA condenses into chromosomes visible under a light microscope. This packaging of the chromosomes into condensed bundles makes them easier to sort, but it inhibits protein synthesis. Therefore, it is essential that the cell has produced all necessary proteins prior to the start of this process.



Prophase


Cell in the prophase. Notice that individual chromosomes are visible in the nucleus.

The *nucleoli* disappear and the nuclear envelope begins to disintegrate. This allows cellular components to act upon the chromosomes (the chromosomes are no longer tucked away inside the nucleus).

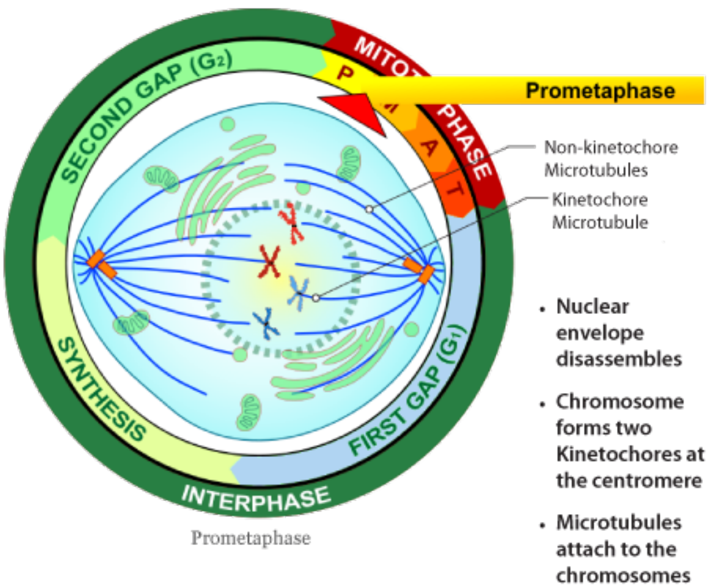
Centrioles, contained in the centrosomes formed during interphase, are areas where microtubules originate in order to help sort and organize the sister chromatids. The centrioles begin to move to the opposite poles of the cell. This will determine where the chromosomes go when they are sorted.

Microtubules are disassembled from the cytoplasm and reassembled into the mitotic spindle. This structure will move the chromosomes to the proper location.

This stage is called “prophase,” because it is a preparatory stage. “Pro-” means "before;" “phase” means “stage.” So, this is the stage before the process gets into full swing.

Prometaphase

Prometaphase is the stage between prophase and metaphase. During this stage, the nuclear envelope is fully broken down. This allows the microtubules to attach to the centromeres of the chromosomes.



Prometaphase

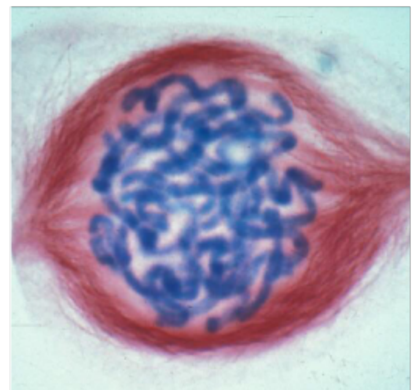
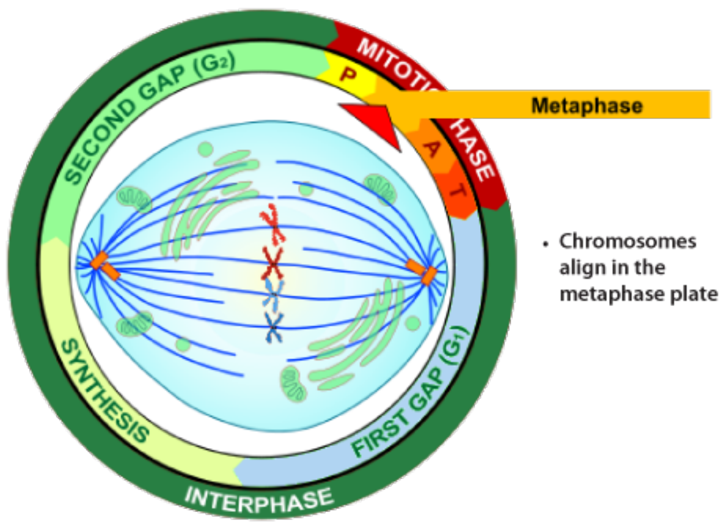


Photo of cell in prometaphase.

The centromere is the region in the center of the X-shaped chromosomes. Each half of the X is a copy of the same DNA strand. The centromere contains proteins that hold together these two copies and can bind to the microtubules. The proteins on the centromere are called the kinetochore, and the microtubules that attach to them are called kinetochore microtubules. The microtubules that are not attached to the kinetochores are called nonkinetochore microtubules.

Metaphase

Metaphase is so named because the chromosomes line up in the middle of the cell. The root “meta-” means “middle.”



Metaphase

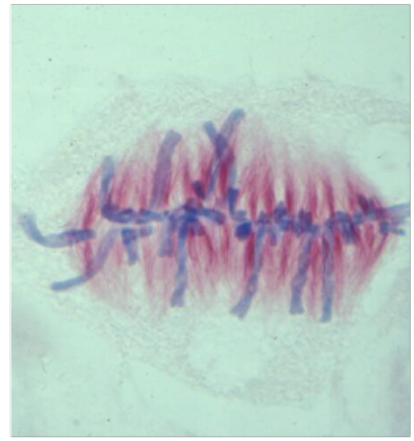
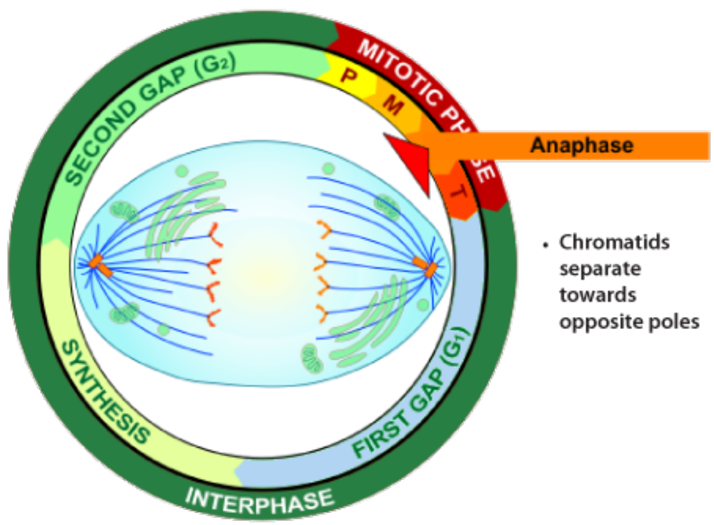


Photo of cell in metaphase. Notice the chromosomes in the center of the cell.

The kinetochore microtubules are used to orient the chromosomes in the center of the cell. Each chromosome will be attached to two kinetochore microtubules. Each of these kinetochore microtubules will be attached to one of the two centrioles.

Anaphase

During anaphase, the kinetochore proteins break down the microtubules attached to them and the connections between each copy of the chromosome will be broken down. This causes the individual chromosomes to move to opposite poles of the cell. The root “ana-” refers to “apart”; the chromosomes are moving apart from each other.



Anaphase

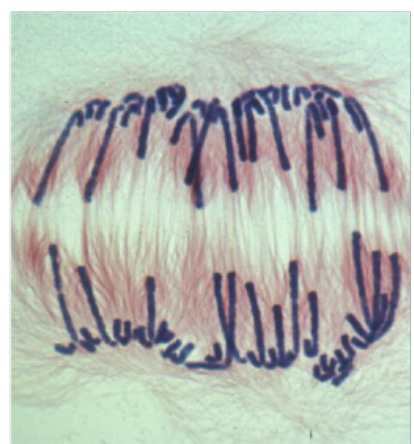
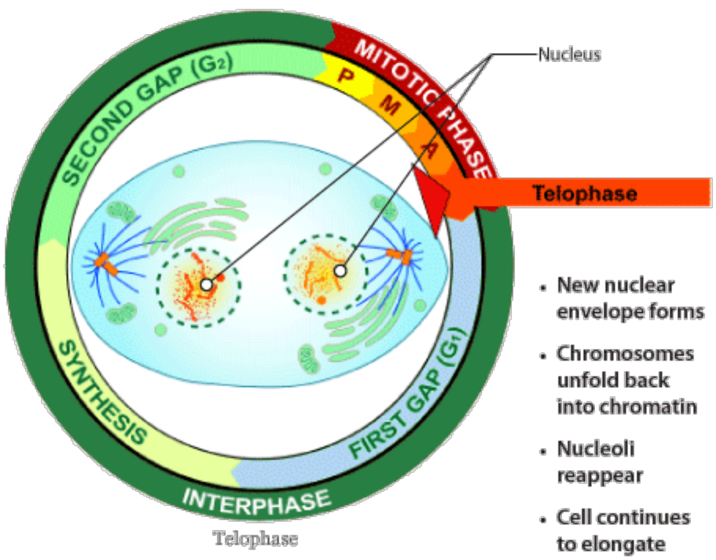


Photo of cell in anaphase. Notice the chromosomes being pulled to the opposite poles of the cell.

The nonkinetochore microtubules from one pole also push on the nonkinetochore microtubules from the other pole. This causes the cell to elongate. By the end of anaphase, each pole of the cell contains an identical set of chromosomes.

Telophase

In telophase, the nuclei at each pole form again. The chromosomes are now separated into two identical nuclei. This is the end of mitosis.



Telophase

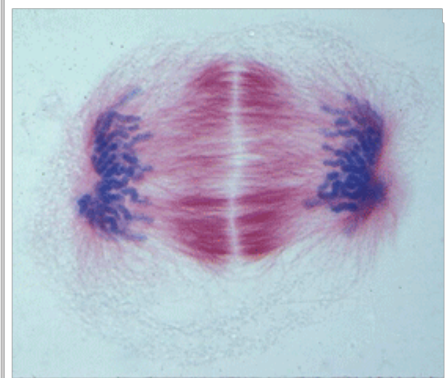
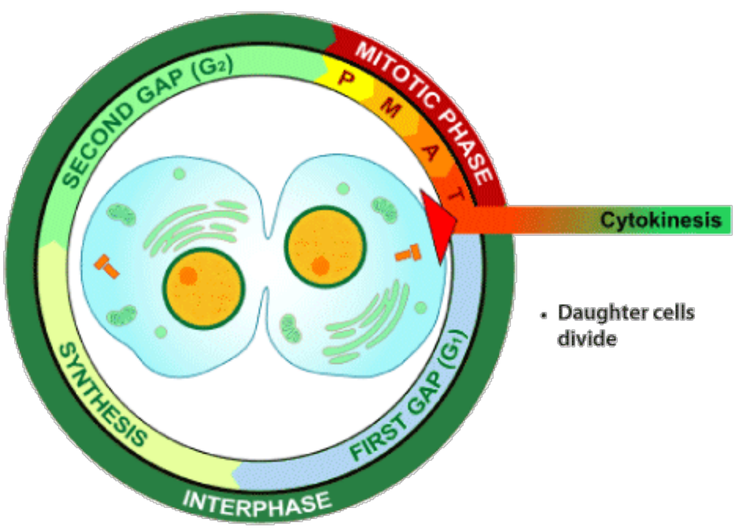


Photo of cell in telophase. Notice the chromosomes clustering at the opposite poles of the cell.

However, the two nuclei are still in a single cell. The next step will separate the cytoplasm into two cells. “Telo” comes from the Greek word for “end.”

Cytokinesis

Cytokinesis is the separation of the cytoplasm into two new daughter cells. Animal cells divide when proteins pinch in the center of the cell until it separates into two. This region is called the cleavage furrow.



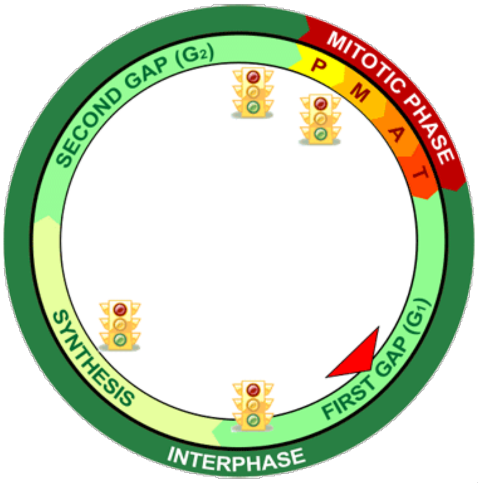
Cytokinesis

Photo of cell in cytokinesis. Notice the cell dividing in half.

Plant cells divide when new cell wall components are laid down in the center of the cell. This is called the cell plate.

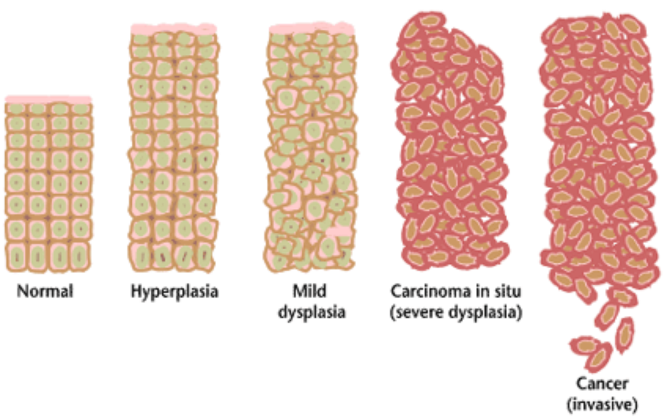
Application Spotlight: Cancer

The cell cycle is highly regulated. There are many checkpoints that are used to determine if the cell should or should not continue through the stages of the cell cycle. Many different environmental and internal signals are involved in determining whether or not a cell will complete division.



Checkpoints occur throughout the cell cycle. These checkpoints control whether or not a cell will continue dividing. Image adapted from a diagram by [LadyofHats: Mariana Ruiz Villarreal](#) in the public domain.

A healthy cell has many genes that produce proteins involved in the process of regulating cell division. Some of these genes produce proteins that encourage cell division. These proteins would be produced under circumstances where the cell should divide. For example, if you scrape your knee, the cells in that area need to be replaced. Other genes produce proteins that inhibit cell division. For example, healthy human cells grown on a petri dish would stop growing when they filled the dish. This is also an essential component of regulation. Cells that continue dividing when they should not can cause cancer.

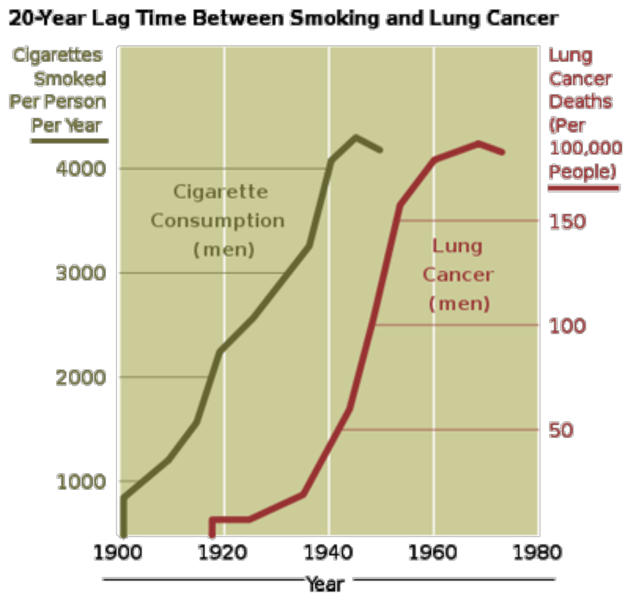


Cancer cells do not respond to proper regulatory signals and divide when they should not divide. Image from the [National Cancer Institute in the public domain](#).

Numerous research projects in the past and present are investigating cell cycle genes. Some of these research projects are focused on cancer treatments and cures and others are focused on understanding the biology of this process. Because much of this research is focused on cancer, the terminology used is generally focused on relationship to the disease.

For example, genes that inhibit cell division are classified as tumor suppressor genes. If these genes are working properly, a cell will not divide uncontrollably because these genes will stop the process. Genes that encourage cell division are called proto-oncogenes. If these genes are working properly, a cell will not receive the message to divide unless it should be dividing.

Mutations could cause these genes to stop working properly. Mutations are errors in DNA that can result from genetic predisposition or environmental factors. Mutagens are chemicals in the environment that produce mutations. Carcinogens are specifically those mutagens that have shown that they can cause cancer. Cigarettes, for example, contain carcinogens that can alter the DNA and disrupt proper regulation of the cell cycle.



Current efforts to decrease the use of cigarettes are correlated with a decrease in lung cancer. Image from the [National Cancer Institute in the public domain.]() Chart illustrates a correlation between smoking and lung cancer in US males, showing a 20-year time lag between increased smoking rates and increased incidence of lung cancer.

The development of cancer requires mutations in BOTH proto-oncogenes and tumor suppressor genes. A malfunctioning proto-oncogene is called an oncogene because it promotes the development of cancer. The root “proto-” refers to "before" and the root “onco-” refers to "cancer." A defective tumor suppressor gene can no longer suppress tumors. Cancer is the result of numerous mutations in multiple genes involved in regulating the cell cycle.

Mitosis: Summary

Mitosis is the process by which eukaryotic cells divide into two identical daughter cells. The process ensures identical DNA is present in both daughter cells. Organisms use mitosis to grow and replace old or malfunctioning cells. There are checkpoints during the cell cycle that regulate whether or not a cell goes through mitosis. When this regulation goes awry, cells can begin to divide uncontrollably, possibly resulting in cancerous tumors.

Mitosis results in identical daughter cells. However, sexually-reproducing organisms need a way to produce gametes, which are unique haploid cells that combine to form new organisms. In the next module, you'll learn more about meiosis, which is the process used to produce gametes.

Before you move into the next module, review these key terms and take the module quiz.

Key Terms

Review the following key terms that were introduced in this module.

alleles	anaphase	centrioles	cytokinesis
interphase	kinetochore	metaphase	microtubules
prophase	telophase		

Meiosis

Objectives:

- Describe the function of meiosis as it relates to sexual reproduction.
- List the stages of meiosis and describe what happens at each stage.
- Predict the number of genes/gene pairs of the progeny cells based on the number of genes of the parental cell.
- Compare and contrast mitosis and meiosis in regards to their overall functions, steps of the processes, number of progeny cells, and number of genes (haploid vs. diploid).
- Explain how an incorrect separation of homologues or sister chromatids can result in defective gametes.

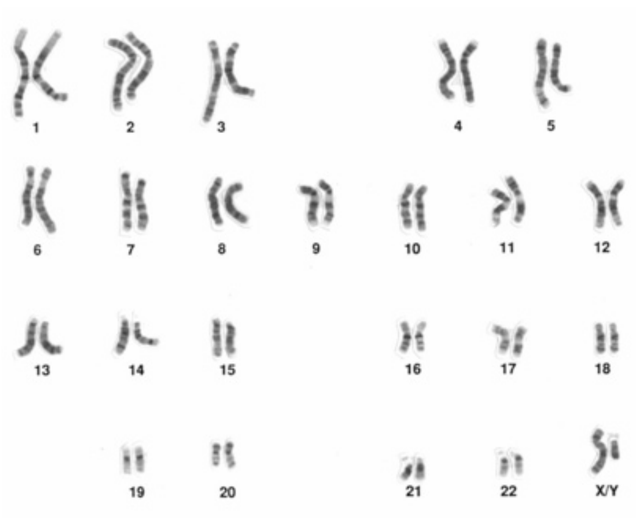
Asexual and Sexual Reproduction

There are two ways for organisms to reproduce: asexual and sexual. Many organisms, such as bacteria, fungi, and even some plants and animals reproduce asexually. During asexual reproduction, all of the genes in a cell are passed to its daughter cells. This means that the resulting cells are *clones*, or identical copies of the parental cell.

Asexual reproduction is efficient and fast. However, it only provides one set of genes to adapt to the environment. Think about trying to guess a number. Do you have a better chance of guessing the number if you get one guess or if you get two guesses? *Sexual reproduction*, in which the genes of two parents are combined, results in more genetic variability. This enables offspring to deal more successfully with environmental change. However, sexual reproduction is a more complex process and results in a smaller number of offspring. Interestingly, certain organisms that can reproduce both asexually and sexually will choose sexual reproduction only when environmental conditions are not optimal. That way, a smaller number of more variable, and thus more adaptable, offspring is produced. In optimal conditions, however, asexual reproduction is the favored mechanism.

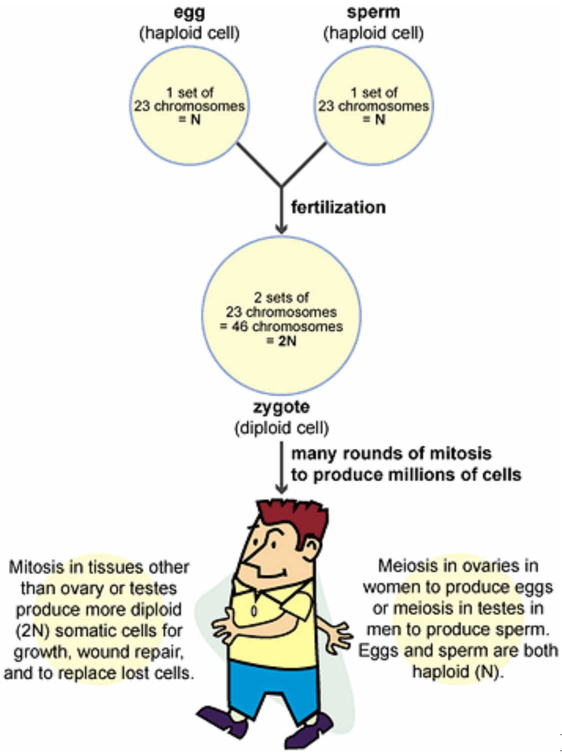
As you learned, genetic information is contained in *DNA*, which in eukaryotic cells is bound to special proteins called histones. The combination of DNA and histone proteins is called *chromatin*. During the S phase of the cell cycle, the chromatin is loose, to facilitate DNA replication. Chromatin can condense to form *chromosomes* during nuclear division. Chromosomes have a typical appearance and can be organized in a *karyotype*.

Human Karyotype of a Male



Humans have 23 pairs of chromosomes (2n = 46). Of those 23 pairs, 22 are autosomes, and the 23rd pair are sex chromosomes. *Sex chromosomes* can be of two types: X and Y. Males have one X and one Y chromosome (XY), while women have two copies of the X chromosome (XX).

In sexual reproduction, two reproductive cells called *gametes* fuse in the process of *fertilization*. In order to avoid the duplication of the chromosome number, gametes are formed through a special form of cell division, *meiosis*, which halves the number of chromosomes. Cells with a single set of chromosomes are *haploid (n)*, in contrast to the somatic (body) cells, which are *diploid (2n)*. The fusion of the gametes during fertilization restores the diploid chromosome number in the first cell of the new individual, the *zygote*.



By University of Maryland University College CC-BY-NC

In the human life cycle, haploid gametes produced during meiosis fuse to form a diploid zygote, which goes through the process of mitosis to grow into an adult human. When the adult human produces haploid gametes, the process can be repeated.

Meiosis I

What Is Meiosis?

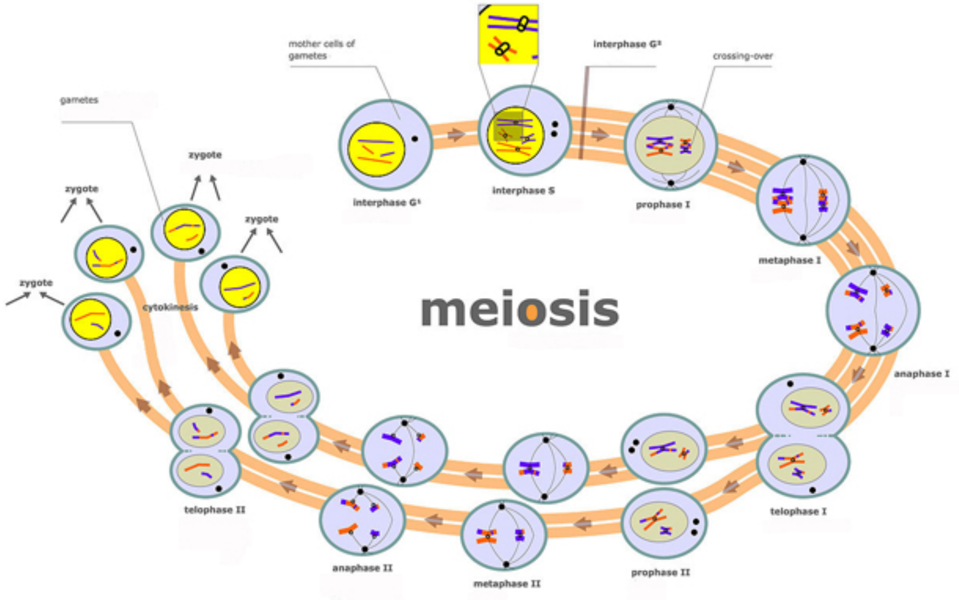
Germ cells are diploid cells that go through the process of meiosis to form haploid gametes. This process can happen at different times, depending on the organism. For example, in humans, the male gametes (sperm cells) are formed continuously from germ cells in the testes, starting in puberty. Female gametes (eggs or oocytes), on the other hand, are formed in the ovaries during fetal life. They remain in the ovaries, "stuck" in the final stages of meiosis, which is not completed unless fertilization occurs.

Meiosis achieves more than just halving the chromosome number. It also introduces variability in the way the genes are distributed in the gametes. In diploid cells, there are 23 pairs of homologous chromosomes. Each pair of homologues has the same set of genes, though they can have different *alleles* (or forms) of each gene. One homologue comes from your mother and the other comes from your father. You may have inherited an allele for straight hair from your mother and an allele for wavy hair from your father. When meiosis takes place, the homologous chromosomes will separate, so one gamete will carry the allele for wavy hair and the other for straight hair. Each trait on each chromosome will segregate its two alleles in a completely random way. There are also other additional ways of "shuffling the cards" of genes, which explains why siblings from the same parents can be so different.

The Process of Meiosis

Let's learn more about meiosis. Meiosis consists of two consecutive cell divisions, called meiosis I and meiosis II. Both stages of meiosis consist of prophase, metaphase, anaphase and telophase, just like mitosis. The phases are labeled I in meiosis I, and II in meiosis II.

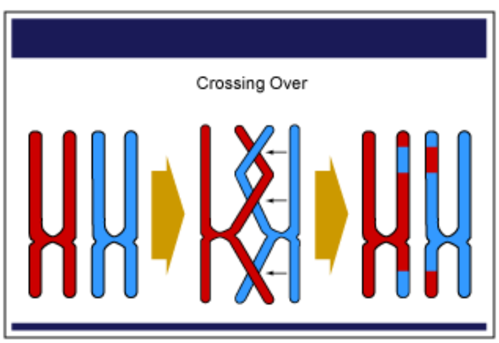
Meiosis I is often referred to as the reduction division, because it is during this stage that the number of chromosomes in the parent cell are divided in half. Meiosis II is extremely similar to mitosis, except that there are half as many chromosomes.



Meiosis I: Crossing Over

An important feature of meiosis is the process called *crossing over*. Crossing over is responsible for generating much of the diversity that exists within a species. Remember that diversity in a species is one of the hallmark characteristics of living organisms. In future modules, you will see that this diversity allows species to survive in changing environmental conditions. So, crossing over is another process that brings variability in the offspring.

Crossing over is a process in which genes swap positions on matching chromosomes. The result is a new combination of genes on each chromosome.

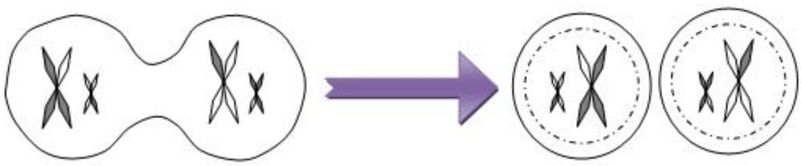


By University of Maryland University College CC-BY-NC

During metaphase I, homologous pairs of chromosomes line up on the metaphase plate. This is very different from mitosis, when sister chromatids line up, completely independent of their homologues.

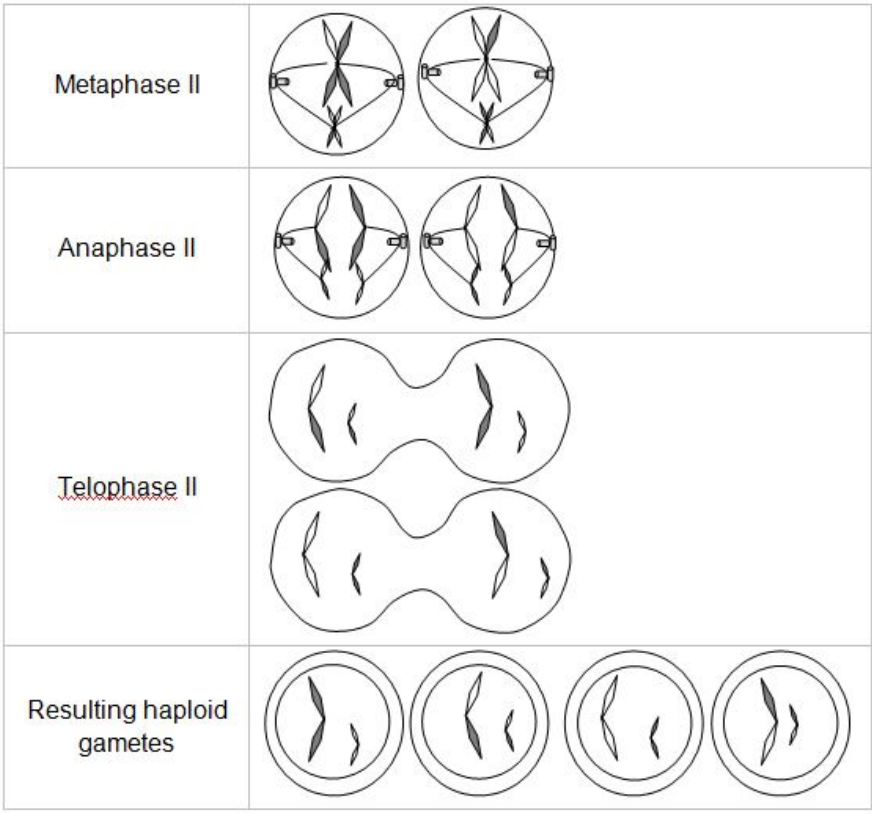
During anaphase I, homologous pairs are pulled apart, and they move toward the poles of the cell.

In telophase I, cytokinesis occurs and two new daughter cells are formed.



Meiosis II

Meiosis II begins with two haploid cells, each containing too much DNA. The events in meiosis II are almost identical to the events of mitosis.



In *Meiosis II* (which is essentially like mitosis), the sister chromatids separate from each other. Thus, as the result of meiosis, four haploid cells are produced. Note that those four cells are not always viable. In humans, male germ cells will produce four viable sperm cells. However, in the case of females, only one of the four will survive as an egg.

The end result of meiosis is four unique haploid daughter cells. Genetic variability is introduced in various ways during meiosis:

1. Crossing over during prophase 1: crossing over introduces novel combinations of traits among offspring.
2. Segregation of chromosomes into gametes: the maternal and the paternal copy of each chromosome pair will segregate to different gametes. However, which goes to which cell is a random process. Thus, the possible number of combinations is astounding: in the case of humans, with 23 chromosomes, it is 2^{23} (8,388,608).

When you add that fertilization is also a random process, you can get an idea of the incredible number of combinations of possible offspring showing up even in one family.

Mitosis and Meiosis Compared

Comparing Mitosis and Meiosis

	Mitosis	***Meiosis***
Overall purpose	The purpose of mitosis is to produce newsomatic cells and germ cells. These new cells are needed to: (1) increase the number of cells in an organism during growth and development; (2) replace damaged cells during wound healing; and (3) produce replacement cells as other cells undergo naturally preprogrammed death. Mitosis must *preserve the same chromosome number* in the parent and daughter cells. This is necessary for the parent and daughter cells to be identical to one another.	The purpose of meiosis is to produce new *gametes* (eggs and sperm). These cells are needed for reproduction. Meiosis must *reduce the chromosome number* in the daughter cells to half that in the parent cell. This is necessary for reproduction. when an egg and sperm (each with half the full chromosome set) fuse during fertilization, they create a single new cell with the full chromosome set.

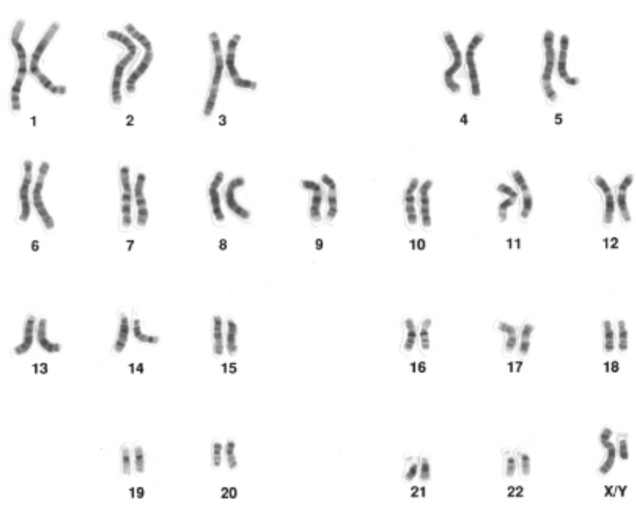
	Mitosis	*Meiosis*
Starting cells (parental cells)	Somatic cells	Germ Cells
New cells made (daughter cells)	Somatic cells	Gametes (eggs in female; sperm in male)
Chromosome content of the parent cells	Diploid (2n)	Diploid (2n)
Chromosome content of the daughter cells	Diploid (2n)	Haploid (1n)
Effect on the chromosome number of the daughter cells	Preserves the chromosome number from parent to daughter cells	Cuts the chromosome number in half from parent to daughter cell
Number of cell divisions that occur	1	2
Number of daughter cells made	2	4

Application Spotlight: Aneuploidy

When the Chromosome Number is Not Right

Aneuploidy is a chromosomal abnormality characterized by an abnormal number of chromosomes in a cell. It is caused by *nondisjunction*, which occurs when chromosomes fail to separate properly during anaphase. Genetic problems caused by nondisjunction can be diagnosed prenatally by studying the fetus'*karyotype*. A karyotype is a visual representation of the chromosomes of an individual, obtained from a small sample of cells. In fetuses, this is usually obtained from sampling either the amniotic liquid (amniocentesis) or the placenta.

Karyotype of a Normal Human Male



Courtesy of the National Human Genome Research Institute

In *nondisjunction*, chromosomes are not separated correctly during metaphase I or II, resulting in gametes with too few or too many chromosomes. There are many genetic disorders associated with incorrect chromosome numbers. One of the most well known condition caused by nondisjunction is *Down syndrome*. Down syndrome results from nondisjunction of chromosome 21, resulting in a child with 3 copies of this chromosome (trisomy 21). Down syndrome appears in approximately 1 of every 1,000 children, and older women are at a higher risk of having babies with the condition. Chromosomal abnormalities can include sex chromosomes also. For example, males with Klinefelter syndrome have an extra X chromosome (XXY), and females with Turner syndrome have only one X chromosome (X_). Both these conditions are relatively benign and can be corrected with hormone treatment. Note that nondisjunction due to lack of separation of sister chromatids can occur also during mitosis.

Meiosis: Summary

Summary

Meiosis is a process of reductive cell division that produces haploid (1N) cells from diploid (2N) cells. In animals, gametes are haploid reproductive cells that are produced using the process of meiosis. The gametes from two individuals fuse in the processes of fertilization to produce a diploid zygote. The diploid zygote divides using the process of mitosis to become an adult organism.

Meiosis is divided into two phases. In meiosis I, homologous pairs of chromosomes bind together and exchange pieces. This process is called "crossing over" and is essential for generating diversity within a species. By the end of meiosis I the homologous pairs of chromosomes have been sorted into separate cells. In meiosis II, the individual chromatids of a chromosome are sorted into separate cells. By the end of meiosis, a single diploid cell has divided into four haploid cells.

When you are ready, review the key terms in this module and take the module quiz.

Key Terms

The following key terms were introduced in this module.

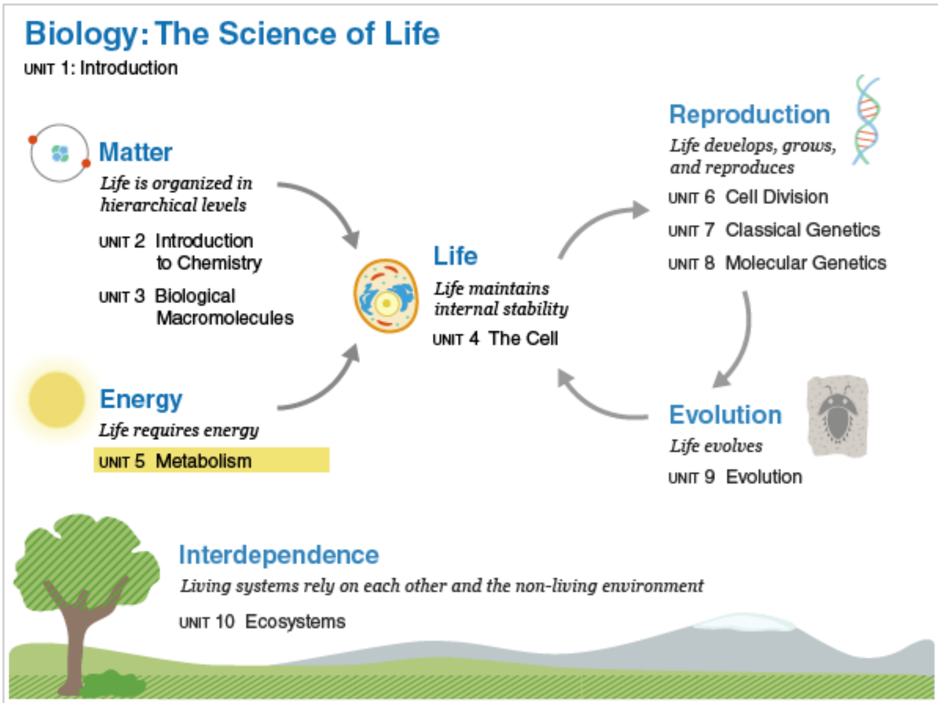
asexual reproduction	clones	karyotype	meiosis II
nondisjunction	sexual reproduction		

quiz

Cell division is an essential life process that ensures the passage of genetic information from one generation to the next. Mitosis results in two identical diploid cells and occurs in somatic cells. Meiosis results in four unique haploid cells and takes place in the gonads. Two different processes are necessary because they serve two different functions. Mitosis allows for growth of an organism and replacement of cells. Meiosis allows for sexual reproduction.

Take some time to reflect on what you learned in this unit. Consider whether you could demonstrate your knowledge of each of the learning objectives. To facilitate this process, we have included the following “My Response” self-assessment activity.

The cell is the fundamental unit of life. It is the first level of organization that presents all the properties of life. In "The Cell" unit, you learned about the different structures that make up a cell. Implicit in that knowledge was the notion of cells as continuously changing and dynamic entities; cells: *grow, rebuild, repair, reproduce*, and *react to the external environment*. All of these functions require *energy*.



Energy provides the fuel needed to sustain living systems. This energy enables organisms to carry out complex processes, including the maintenance of homeostasis. Life captures, stores and uses energy through the process of metabolism, which is the sum of all the chemical reactions that take place in an organism.

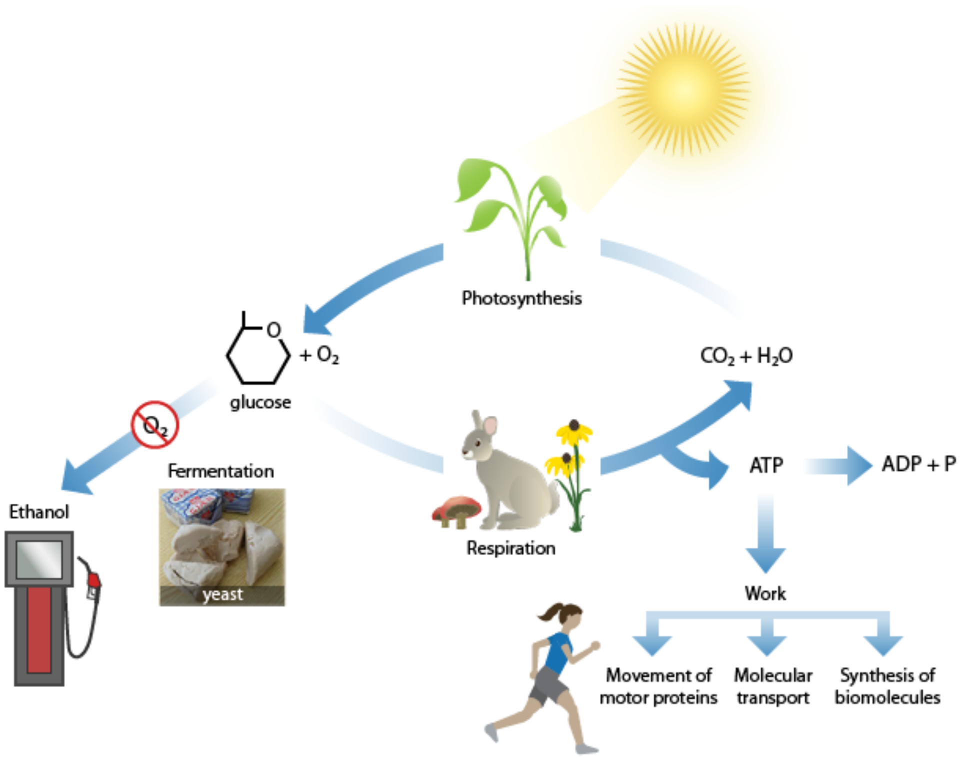
All living organisms — from bacteria to trees to humans — are composed of molecules. To make a cell, many molecules must be combined, and it takes energy to build these complex structures. Covalent bondshold these molecules together, and the chemical bonds contain energy associated with the force that holds two atoms together. As you know, some bonds are relatively weak and unstable. When they are replaced by stronger, more stable bonds, *chemical potential energy* is released that can be captured by the cell and used to do work. In cells, certain high-energy molecules contain many unstable bonds and are used for fuel. When these molecules are broken down into simpler molecules with more stable bonds, chemical potential energy is released. In this unit, you will learn how cells manage to capture this *energy* and use it to do work (e.g., power movement or build new macromolecules).

Energy and carbon flow through the biosphere in a tightly coupled manner. The coupling between energy and carbon is accomplished within an organism through the process known as metabolism. *Metabolism* is the sum of all of the metabolic pathways within an organism. A *metabolic pathway* is a series of chemical conversions, each of which are catalyzed by an enzyme (protein catalyst). The compounds that are internal to the pathway are referred to as *intermediates* in the pathway. A number of pathways, such as those related to energy production, are essential to life and are found in all cells. Although specialized cells may possess different pathways, there are common characteristics that apply to most pathways. These will be covered in the discussion on "*Common Characteristics of Metabolic Pathways*." In the *Energy* module, you will learn about *ATP*, *the universal energy carrier in cells*, and about how energy is transformed and transferred during metabolic reactions.

Metabolic pathways are either anabolic or catabolic. *Anabolic* pathways involve the use of energy and simple organic building blocks to create more complex molecules. *Catabolic* pathways convert complex molecules to simpler ones, releasing energy for use by the organism. In the *Pathways and Regulation*module, you will learn the differences between catabolic and anabolic pathways.

The Common Pathway: Photosynthesis / Cell Respiration

The principle source of energy for all organisms on earth is the sun. This energy is absorbed by photosynthetic organisms such as plants and algae and used to convert carbon dioxide (CO_2) to glucose and oxygen during *photosynthesis*. The end result is that the energy from the sun has been stored in glucose, a small six-carbon carbohydrate. The oxygen and glucose are then available to other living organisms. Humans (and all other organisms, including plants) use glucose as food, and release the energy in glucose through a process called *respiration*. The figure below illustrates this process of photosynthesis and respiration. During this process, the carbon atoms in glucose combine with oxygen to produce CO_2; the glucose is oxidized, releasing energy. The energy from the oxidation of glucose is stored in a small chemical called *ATP (adenosine triphosphate)* for immediate use by the cell. *ATP* is used for almost all of the energy needs of the cell, from the synthesis of other complex molecules to doing mechanical work, such as running. You will learn more about these two pathways in the section about "*Anabolic and Catabolic Reactions*."



The source of almost all energy on the planet is the sun. This energy is harvested by plants and certain microbes and is stored in the simple sugar glucose, in a process called photosynthesis. All living organisms consume glucose and combine it with oxygen to produce energy and carbon dioxide. The energy released is temporarily stored by the synthesis of the high-energy compound ATP. The energy released when ATP is broken down to ADP can be used to power many biological functions, such as muscle contraction. Many organisms, such as yeast, can utilize the energy stored in glucose without using oxygen. Fermentation produces less ATP then cellular respiration and can produce a variety of other end products. Yeasts, for example, produce ethanol (a useful biofuel) when they ferment.

Many microorganisms, such as yeast, can utilize the energy stored in glucose in the absence of oxygen (anaerobic growth); the most common form of this process is *fermentation*. In the absence of oxygen, yeasts still produce ATP by the partial oxidation of glucose, releasing smaller amounts of CO_2. The remaining carbon atoms in the glucose are converted to ethanol. The energy stored in ethanol can be used as fuel for our internal combustion engines. Humans also undergo anaerobic metabolism during vigorous exercise, but in humans, lactic acid is produced instead of ethanol. When sufficient oxygen becomes available, the carbon atoms in lactate are converted to CO_2. Other organisms that perform fermentation produce a variety of other end products. *Alternative pathways* such as fermentation are addressed in a separate module.

Regulation of Pathways

All metabolic pathways are regulated such that they are only active when the products of the pathway are required by the cell. In this way, the organism is able to optimize the use of its carbon and energy resources.

EXAMPLE

The Glycolysis Pathway

The first part of the process of respiration is called glycolysis. It consists basically of the breakdown of glucose into a smaller compound called pyruvate. Pyruvate can then go on to either respiration or fermentation, depending on the availability of oxygen. Glycolysis will occur if the cell requires energy.

The glycolysis pathway is regulated to turn glycolysis on or off, depending on the energy needs of the cell. There would be two dire consequences if the energy that is stored in food were to be released immediately after consumption.

First, the organism would run out of energy quickly and would therefore have to consume food all the time, which isn't possible for most organisms, especially mammals, which need to sleep.

Secondly, the heat that would be released by the production of energy would raise the temperature of the organism to intolerable levels. Misregulation of metabolic pathways can cause disease. For example, in diabetes, the metabolism of glucose is incorrectly regulated.

Energy

Objectives

- Define energy and describe the different types of energy.
- Describe the flow of energy in biological systems.
- Identify heat as a form of energy released during all energy transformations.
- Recognize and predict the difference between ATP and ADP, in terms of both structure and energy.
- Explain why the hydrolysis of ATP releases energy to accomplish cellular work.
- Describe the flow of energy from the sun to stored chemical energy.
- Distinguish between catabolic and anabolic pathways and recognize specific examples of each.
- Identify ATP as a central molecule shuttling energy between catabolic and anabolic pathways.

What Is Energy?

All living things need energy to run the processes required for life. Energy is defined as the capacity to do work. You can think of “work” as any change that won’t happen on its own. Work can involve movement, building larger molecules, increasing the concentration of chemicals, increasing the temperature of an object, making a sound, or even glowing (bioluminescence).

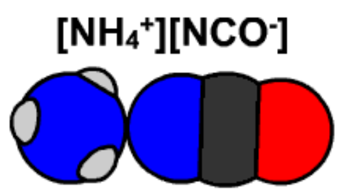
Energy is recognized by what it DOES: it makes “work” happen. It makes things change. Energy exists in many forms. Some biologically important forms of energy are light energy, electrical energy, sound energy, and thermal or heat energy. *Kinetic energy* is the energy of motion. *Potential energy* is stored energy. Energy can change forms and often transforms from potential to kinetic energy, and back. In biology, a key form of potential energy is *chemical energy*: the energy stored in chemical bonds. It can be released when certain bonds are broken. Chemical energy is released when wood is burned: the bonds in the wood are broken, releasing light and heat energy.

EXAMPLE

Types of Work

The first example below shows a single-celled organism — an amoeba — using energy to move. The second example illustrates the chemical reaction resulting in urea, a molecule found in urine. The third example shows bioluminescence — the emission of light by living organisms; in this case, the aurelia aurita jelly fish.

Example 1: Cell movement. Double-click on the above image to observe an amoeba using energy to move.

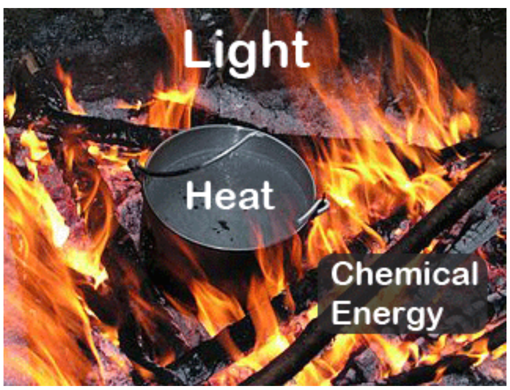


Example 2: Chemical Reaction. This chemical reaction is building urea (a molecule found in urine).

Example 3: Light Emission. Double-click on the image to observe the jellyfish (*Aurelia aurita*) showing bioluminescence.

Energy Conversion

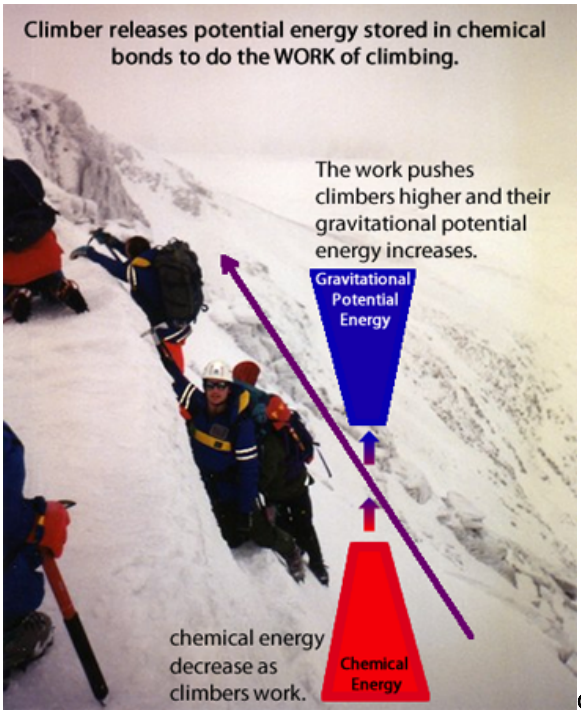
Energy can be converted from one form to another. In the image below, the chemical energy in the wood is converted to light and heat. After the fire dies, the heat and light have dissipated and are no longer available for living organisms. Energy in our biosphere is a one-way system: It comes from the sun, is captured by living organisms, and eventually is released back out as heat.



Biological Energy Transformations

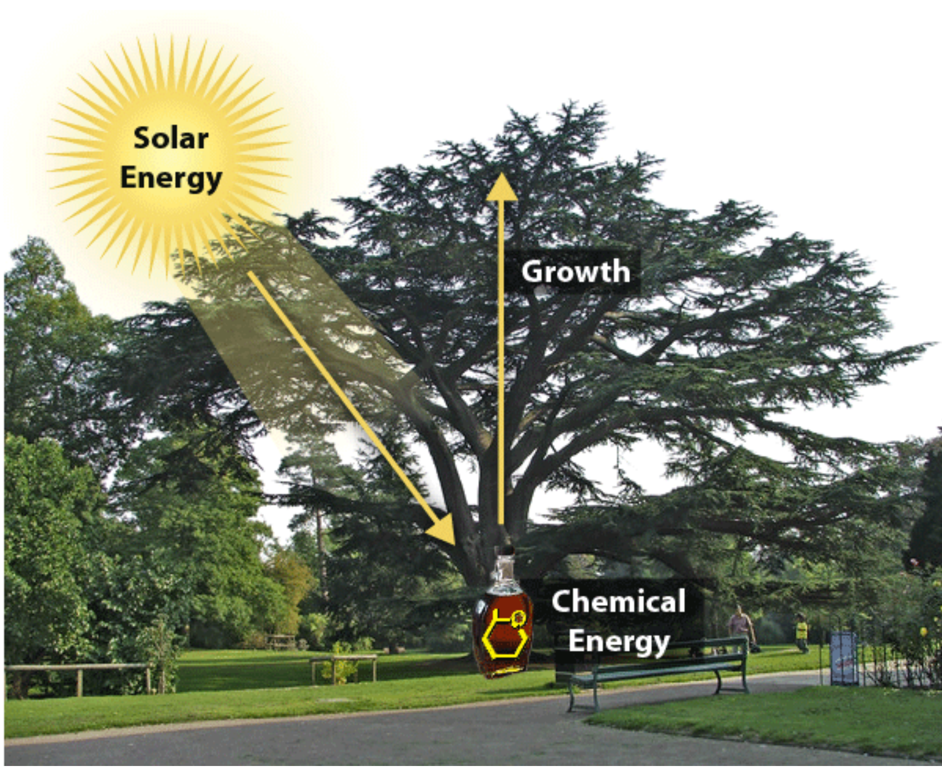
Energy cannot be created or destroyed. Instead, energy is transformed from one form to another. Imagine that you climb a mountain trail ending in a steep cliff. Your body's movement (kinetic energy) is fueled by chemical energy from your food. As you move uphill, your body's chemical potential energy decreases (you break down molecules and use up stored food energy). At the same time, your body's *gravitational*potential energy *increases*. This kind of potential energy can be released by letting an object drop from a height. A fall from the top of the cliff would do a great deal of "work," so watch your step!

Chemical to Gravitational Energy



Converting chemical energy to gravitational energy. © Copyright Iain Lees and licensed for reuse under the CC BY-SA 2.0 licence.

Where does chemical energy in food come from? The sun provides solar energy, the energy source for most living things. Plants and other photosynthetic organisms can use solar energy to build sugar molecules from simpler raw materials (carbon dioxide and water). A sugar molecule stores chemical energy in the bonds that join its atoms. The energy stored in sugar can be released and used to build other types of biological molecules (proteins, lipids, etc.), which also contain stored chemical energy in their complex structures.



Energy from the sun can be converted into chemical energy (in sugars) by photosynthetic organisms. This chemical energy can then be used to do other work like building the components needed for growth.

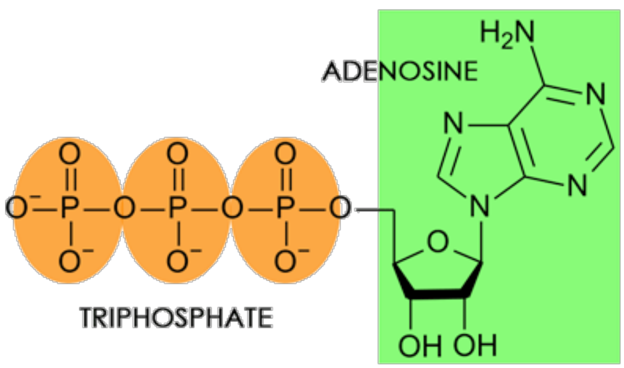
Heat: An Energy Waste

To us, it seems that the sun has burned forever and will always keep shining. However, the sun is fueled by nuclear energy generated by atoms colliding in its incredibly hot core. Eventually, the supply of fuel in the sun will be depleted and our sun's long life will end. This illustrates an inescapable fact about energy: it tends to lose quality over time. It dissipates, spreading out in space, and loses its intensity.

Heat is the energy possessed by any substance because of the random jiggling of its molecules and atoms. It is a low form of energy, disorderly, and spreads out rapidly through most materials. Every kind of energy conversion generates at least some heat energy as a byproduct. For example, the breakdown and use of chemical energy in food also releases heat. Heat can be helpful in keeping our bodies warm, but for the most part heat energy is a loss: an energy waste that cannot be recovered. No organism can capture heat and use it to do work or to make food. Instead, heat seeps out of organisms and eventually into space, leaving the biosphere forever.

ATP Structure

Adenosine triphosphate, or *ATP*, is an organic molecule that acts as the direct energy source for almost all cellular activities. ATP consists of a single adenosine molecule (composed of an adenine bound to a ribose sugar) linked to three phosphate ions.



ATP consists of a single adenosine molecule (green rectangle) linked to three phosphate ions (orange circles).

ATP is a relatively unstable molecule. Consequently it is never used for the long-term storage of energy in the cell. This job goes to other more stable compounds, like fats and sugars. ATP is specialized for direct and rapid transfers of energy. It is because of this instability that ATP is such a good energy currency for the cell (it's easy to "spend" this energy). ATP is like cash, while long-term energy storage molecules (such as fats and sugars) are more like a savings account.

Hydrolysis of ATP

Hydrolysis of ATP Releases Energy

ATP is an important molecule in biological systems because the chemical bond between the last two phosphates is unstable, and reactions that involve the removal of the terminal (last) phosphate release energy. This bond can be broken in a reaction involving water. This reaction is called a *hydrolysis* reaction ("hydro" means "water" and "lysis" means "separation";

together they mean "using water to separate"). The products of this reaction are inorganic phosphate (P) and *adenosine diphosphate (ADP),* which has only two phosphate groups. Taken together, ADP and P are more stable than ATP. The net result of ATP hydrolysis is the release of energy. This process is illustrated in the animation below.

WALKTHROUGH
Hydrolysis of ATP releases energy by breaking down ATP into ADP and an inorganic phosphate. Building ATP from ATP and an inorganic phosphate requires the input of energy in a condensation reaction.

ATP, the molecule with the higher energy content, can react to form ADP + P. This chemical reaction can also be reversed. ADP + P can combine to form ATP, a reaction referred to as a *condensation reaction*since two molecules are condensed into one. We know the first reaction (ATP → ADP + P) releases energy. Therefore, the second reaction (ADP + P → ATP) requires energy. The opposing reactions are like using and charging a rechargeable battery. When you use the energy stored in the rechargeable battery, it is like using up ATP (ATP hydrolysis). When you recharge the battery, you must put energy in (by plugging it into the electrical socket). This is like ATP formation, which is usually fueled by chemical energy extracted from sugar or fats.

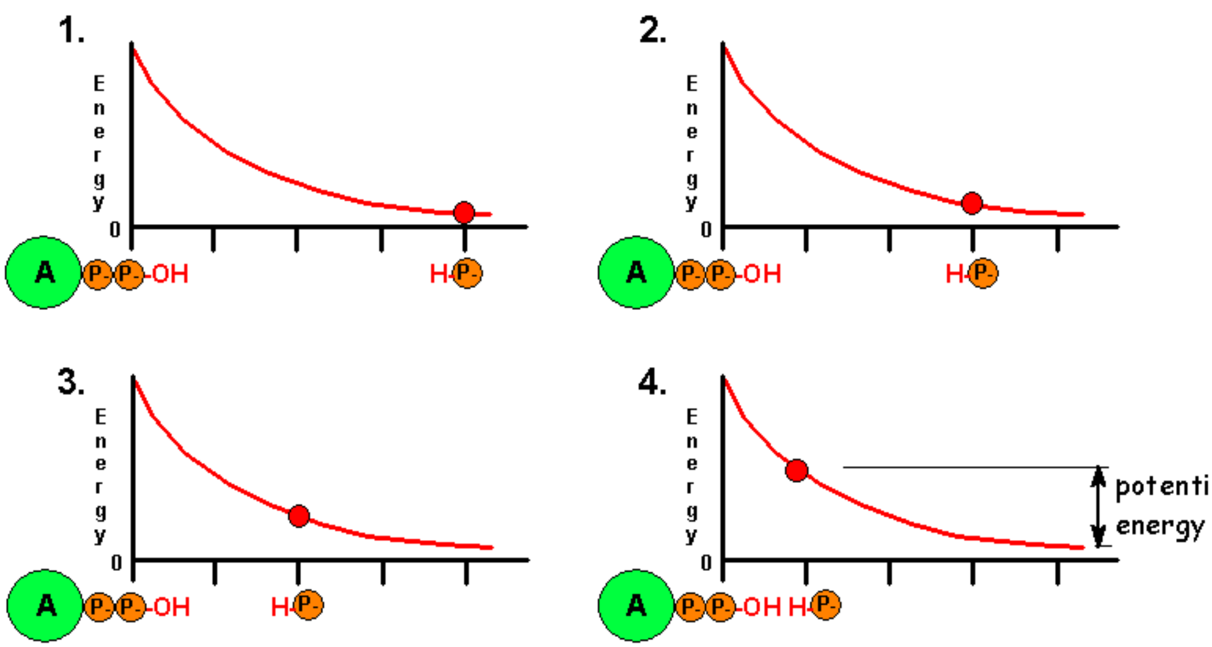
Virtually all the activities of the cell are powered by the energy released when ATP loses its terminal phosphate. For example, ATP hydrolysis provides the energy needed to form complex molecules from simpler ones (synthesis). ATP can also transfer energy by making proteins change shape when ATP is converted to ADP. When proteins change shape, their microscopic movements can add up to macroscopic motion, such as occurs when entire muscles contract. Similarly, ATP can transfer energy to specialized transport proteins embedded in the cell membrane and enable materials to be pumped in or out of the cell, against their concentration gradients (active transport).

Why ATP Hydrolysis Releases Energy

Change in Potential Energy with the Formation and Breakdown of ATP

The energy difference between ATP and ADP is largely due to the interaction between the negatively charged phosphate groups in each molecule. You may remember that unlike charges (+ and -) attract each other, while like charges (+ and +; or - and -) repel each other. Energy is therefore required to move two negative charges close to each other, which is what happens when ATP is made from ADP and phosphate. This is similar to the way in which energy is required to bring the two north poles of a bar magnet together.

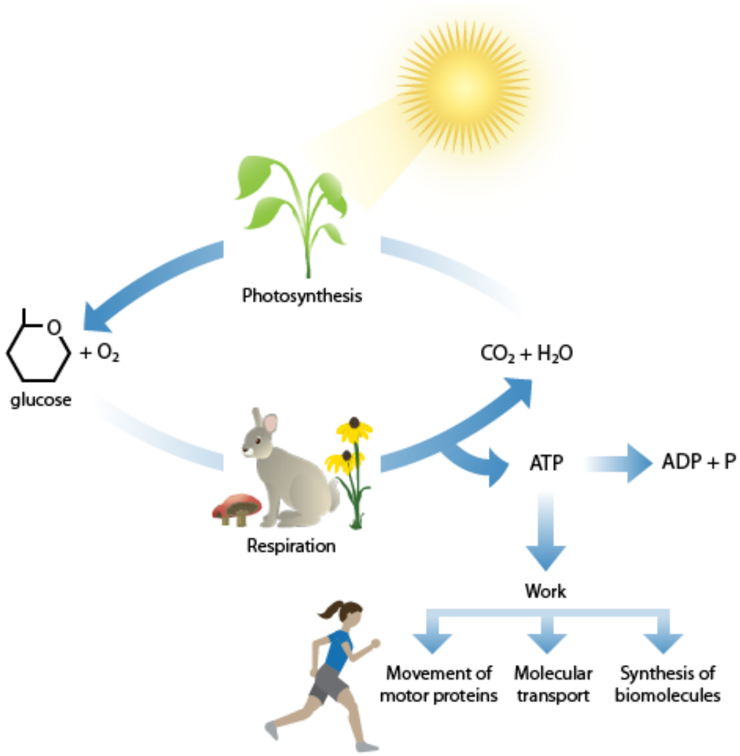
Examine the following figure, which illustrates the change in energy found within a chemical system as a phosphate ion is slowly brought closer to an ADP molecule. As the negatively charged phosphate gets closer to the negatively charged ADP molecule, more energy is required to overcome the particles' natural tendency to repel each other.



These diagrams illustrate the change in energy as a negatively charged phosphate approaches negatively charged ADP during ATP synthesis. As the phosphate moves closer to the ADP (from diagram 1 to diagram 4), the energy rises because like charges try to repel each other. When the phosphate is close (4), a large amount of potential energy has been stored in the ATP molecule. This energy is released when ATP is hydrolyzed and the newly formed phosphate moves away. This process is similar to rolling a ball up a hill. Energy is required to get the ball to the top of the hill and this energy exists as potential energy. However, when the ball is released, it quickly rolls down the hill. The energy that was used to push the ball up the hill is released as kinetic energy.

Flow of Energy in the Biosphere

Most life on Earth is fueled by solar energy through the process of photosynthesis. Photosynthetic organisms use sunlight to make organic molecules from simple raw materials (carbon dioxide and water). Cellular respiration and other processes break down organic molecules and use the energy released to build ATP molecules. ATP then transfers energy to drive many important processes in cells including movement, transport, and synthesis. In this way, the energy from the sun is transformed to chemical energy in molecules such as glucose and ATP. Eventually energy is released in forms like motion, heat, sound, or light.



Catabolism and Anabolism Explored

What is Metabolism?

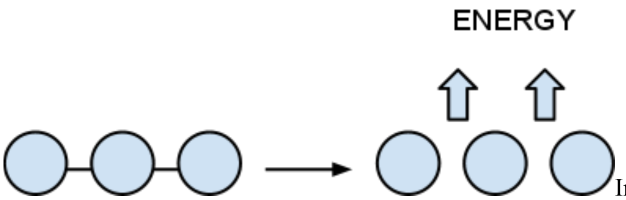
Metabolism is the sum of all chemical activity within a living organism. Reactions that release energy are called *exergonic* ("exer" refers to "out" and "gonic" refers to "energy," so these are "energy out" reactions). Reactions that require energy are called *endergonic* ("energy in"). Exergonic reactions can be used to power endergonic reactions. For example, building ATP from ADP and phosphate requires energy (it is an endergonic reaction). Exergonic reactions can provide the necessary energy to build *ATP*.

Catabolic reactions (also called "catabolism") break down larger, more complex molecules into smaller molecules and release energy in the process. The smaller end products of a catabolic reaction may be released as waste or they may be fed into other reactions. The energy that is released by catabolic reactions can be captured and used in many ways. Some of the energy is released as heat and increases the temperature of the cell. Sometimes the energy is stored in the chemical bonds of another molecule. And sometimes it can be used to do work, such as movement of cellular machinery to power the active transport of materials across cell membranes. Catabolic reactions are central to biological processes such as cellular respiration and the digestion of food molecules.

Cellular respiration is catabolic because it takes glucose (a complex molecule with 6 carbons) and reduces it to carbon dioxide (each with only one carbon) and water (oxygen joined to two hydrogens). Some of the energy released by this process is captured in ATP, which can be stored for later use.

Digestion of protein is also a catabolic reaction. It takes a very large protein molecule and breaks it down into several smaller polypeptides, then dismantles the polypeptides to yield individual amino acids.

Catabolic Reactions Release Energy and Reduce Complexity



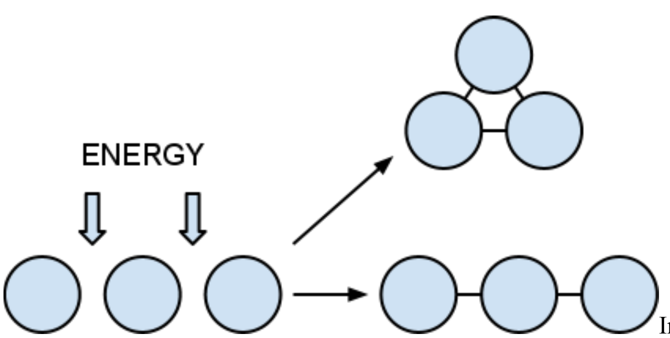
In the figure above, a larger molecule on the left is broken down into smaller and simpler components. As high-energy bonds are broken and replaced by lower-energy bonds, energy is released. Some of this energy may be captured to do cellular work.

Anabolic reactions use energy to build more complex molecules from relatively simple raw materials. "*Anabolic*" and "*catabolic*" sound similar but are opposites. To remember the difference, it may help to think about how "anabolic steroids" promote the buildup of muscle mass. All of the complex molecules of life — carbohydrates, lipids, proteins, nucleic acids — are generated by anabolic reactions. Anabolic reactions are central to processes like photosynthesis, protein synthesis, and DNA replication.

At this point, you may wonder *why* the cell has to break down complex molecules in order to build them up again. Different cells use and require different biomolecules for their specialized functions. For example,*carbohydrates* are good sources of energy. In plants, carbohydrates are usually stored as starch. In animals, they are stored as glycogen. Both are *polymers* of glucose, but they have different structures, and an animal cell cannot readily store or access starch. When an athlete "carbo-loads" the evening before a race, starches from foods like pasta are digested to simple sugars in a catabolic reaction. They are then rebuilt as glycogen (in an anabolic reaction) in the muscles and liver. That way, there is some extra energy stored and easily accessible for the muscle cells to use for the big race. Biomolecules are broken down to raw materials, then rebuilt *in a different form* to meet the needs of the organism. One molecule that is unique to your cells is DNA. No other organism (except an identical twin) has the same DNA as you, so your cells need to build it anew in order to pass it on to the next generation

Photosynthesis is an anabolic process you'll learn more about in this unit. *Protein synthesis* is an amazing feat of anabolism. Protein chains (polypeptides) are produced by linking together relatively simple amino acid monomers. In one polypeptide, thousands of amino acids may be strung together, and several different polypeptides may fold and bind to each other to form a large and complex protein molecule.

Anabolic Reactions Use Energy to Build Complex Molecules



In the figure above, several smaller components are joined by bonds to form larger, more complex molecules. Energy inputs are required to do this work.

ATP Moves Energy

ATP Carries Energy from Catabolic Reactions to Anabolic Reactions

Life requires energy to accomplish its anabolic reactions. This energy cannot be “made” from nothing, because energy cannot be created or destroyed. But energy can be transferred and transformed. Energy that is available to the cell must somehow be packaged in useful form and delivered where it is needed. This problem is solved through chemical transfers of energy from catabolic reactions to energy carriers and then from the energy carriers to the substrates that are joined in anabolic reactions.

Life’s universal energy carrier is adenosine triphosphate (ATP). ATP acts as a shuttle that transfers energy from catabolic reactions that release energy from complex molecules (such as cellular respiration) to the anabolic reactions that consume energy (such as protein synthesis). The energy released from catabolic reactions can be stored for later use through the formation of ATP by combining ADP plus a phosphate group. Then, when energy is required for anabolic reactions, ATP can be broken down into ADP and a phosphate group, releasing energy that was stored in the phosphate bond.

Energy: Summary

In this module, you learned about energy. Energy flows through living systems and cannot be recycled or reused. Eventually, energy is released as heat, and while this heat can be beneficial (it keeps us warm), it cannot be captured again and used to sustain the processes of life.

Ultimately, energy for life comes from the sun. It is captured by plants through the process of photosynthesis (an anabolic process) and is stored in the form of glucose (a sugar). Living organisms can then go through the process of cellular respiration (a catabolic process) to transform the energy stored in the glucose into ATP, which is used to do work in the cell.

Take some time to review this module before taking the quiz. The next module examines cellular respiration and photosynthesis more closely.

Key Terms

The following key terms were introduced in this module:

adenosine diphosphate (ADP)	adenosine triphosphate (ATP)	anabolic reaction	catabolic reaction
cellular respiration	chemical potential energy	energy	hydrolysis
kinetic energy	metabolic pathways		

Photosynthesis and Cellular Respiration

Objectives:

- Identify the types of organisms that are capable of photosynthesis.
- List compartments in eukaryotic cells where photosynthesis takes place.
- Identify the inputs and outputs of photosynthesis.
- Identify the role of chlorophyll and chloroplasts in photosynthesis.
- Describe how pigments of different colors interact with light and identify the function of diverse pigments in photosynthetic organisms.
- Identify the inputs and outputs for cellular respiration.
- Describe metabolic pathways as stepwise chemical transformations either requiring or releasing energy and recognize conserved themes in these pathways.
- Describe and list compartments in eukaryotic cells where respiration takes place.
- Recognize that during energy transformations, some energy is always lost as heat, including during cellular respiration.
- Recognize how photosynthesis and cellular respiration are interdependent; apply this knowledge to realistic examples.
- Compare and contrast photosynthesis and cellular respiration.
- Relate photosynthesis and cellular respiration in terms of carbon, oxygen, and energy.
- Compare and contrast photosynthesis, cellular respiration, and fermentation.

Photosynthesis

Plants, algae, and some bacteria can use light energy to turn carbon dioxide and water into simple sugars through the process of photosynthesis. These sugars can act as “building blocks” for the synthesis of other organic molecules, or they can store energy for later use. While the process of photosynthesis stores chemical energy for later use, most photosynthetic organisms access the stored energy the same way consumers do: they break down the sugars to build ATP using the process of cellular respiration, which occurs in subcellular organelles called mitochondria.

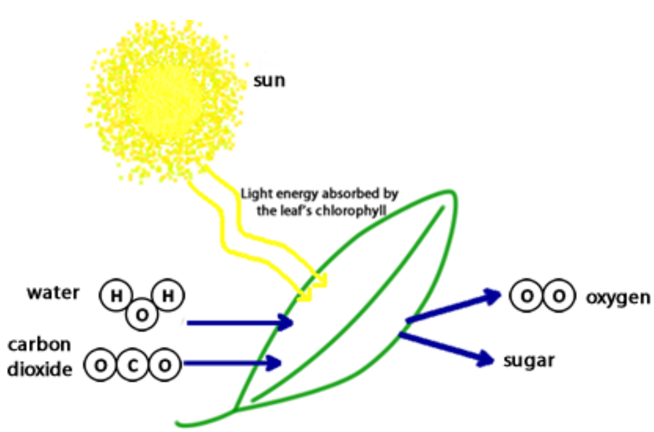
Photosynthetic producers have evolved an effective system for absorbing light and converting it into chemical energy. This biochemical solar energy system begins with a diverse array of (mostly green) pigments that are embedded in membranes. In plants and algae, these pigments are contained within specialized subcellular organelles called chloroplasts.

You may want to review the Cell Structures page.

Inputs and Outputs of Photosynthesis

The main purpose of photosynthesis is to convert energy from sunlight and store it as bond energy within sugars. Photosynthesis uses pigments (such as chlorophyll) in the chloroplasts to absorb light energy. This energy is used to produce sugars from carbon dioxide, while oxygen is given off as a byproduct. You will examine the function of pigments in more detail later.

Photosynthesis Transforms Light to Chemical Energy in Sugar



Light energy enables

photosynthesis. This process requires the participation of chlorophyll pigment; in plants it occurs mainly in leaves.

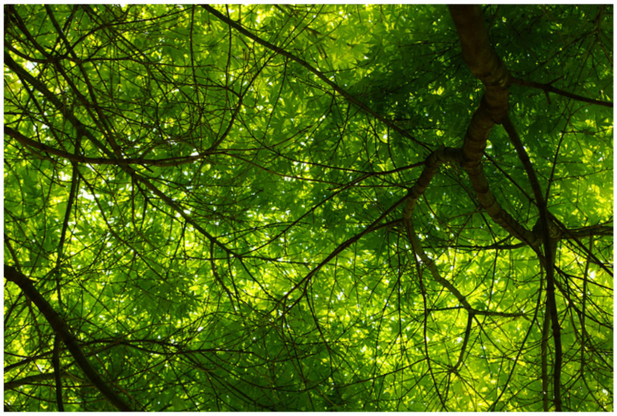
Some photosynthetic organisms (such as most algae and cyanobacteria) live in water. Their cells are equipped with pigments to absorb light, and they absorb water and other nutrients directly across the cell membrane. They are faced with a challenge involving the attenuation (loss) of light energy with increasing depth. As a result, many algae and cyanobacteria have adaptations that keep them floating near the water's surface.

Kelp Float to Reach Light

These kelp are anchored below and use air bladders for the top of the plant to reach the water's surface.

Land plants face a different set of challenges. Plant leaves are the main location of photosynthesis. They are often large, flat structures that are adapted for maximum light absorption. In many plants, leaves also are held high above the ground by tall stems. Growing tall is an adaptation that helps a plant get high-intensity sunlight, because short plants are more likely to be shaded by taller ones.

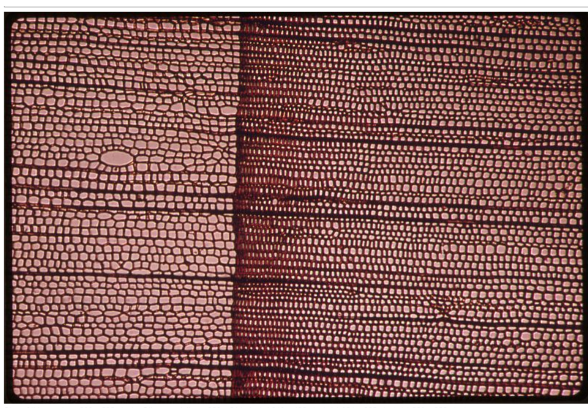
Plants Grow Tall to Compete for Light


Land plant leaves are often broad and flat, maximizing the surface area for light absorption. Many species also grow upward to gain access to high-intensity sunlight. Note also how the leaves are arranged: few gaps are left unfilled in this tree's canopy.

Land plants also face the risk of drying out. Plants have evolved traits that protect their above-ground portions from excess water loss. For example, plant leaves are sealed with a layer of waxy material called cuticle. Protected in this way, leaves cannot efficiently absorb water when it rains. Instead, land plants absorb water from the ground (through their roots).

Plants must then transport water upward to leaves and other tissues. This is quite a challenge for a tall plant. Plants have no moving parts that could power a pump, so their circulatory systems must work on different principles. Plants use specialized cells to move water. These cells are essentially long, thin tubes that transport water from the roots all the way up to hollow cavities in the leaves. Evaporation of water from leaves provides negative pressure that sucks water up the tubes. The thick cell wall that allows the tube cells to function without collapsing also provides the plant with structural stability. "Wood" is mainly the structural material that remains after these cells have died. Ultimately, an adaptation for moving water helps woody plants grow even taller than their less sturdy cousins, further enhancing their access to light.

Microscopic image of wood

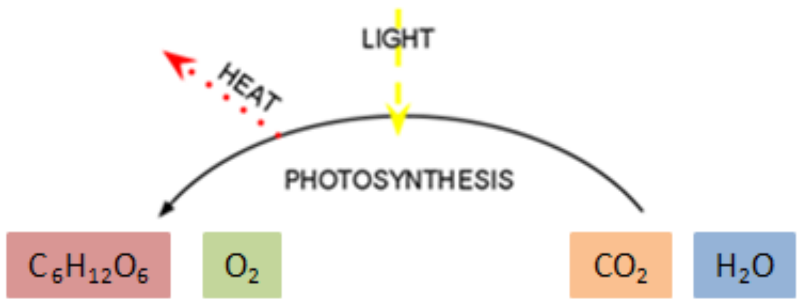

Under a microscope, you can see the individual transport cells that make up the wood.

The adaptations of plants have long been a subject of biological study. One of the first questions asked by early scientists was, "How do plants get their resources for growth?"

Where Do Plants Get Carbon?

Water and light are essential for building sugar ($C_6H_{12}O_6$), but neither of these contain carbon. To build sugar, photosynthesis needs a carbon source. Where do plants get this carbon? Do they get it from the soil, through their roots (like they get water)? Jean-Baptist van Helmont designed an experiment to test this in the 1600's. He planted a tree in a pot and watered it. He measured the weight of the soil and the tree both before and after the experiment. Applying the principle of conservation of matter, van Helmont knew that the tree's carbon couldn't just appear from nowhere. If the tree "ate" soil, then as it grew, the soil's mass should decline by a similar amount. Jean-Baptist van Helmont's experiment shows that the carbon needed for photosynthesis does not come from the soil. However, the experiment does not indicate where the carbon*does* come from. A number of other studies conducted by scientists over many decades were required to show the precise source of the carbon. Today, we know that CO_2 from the air is the source of carbon for photosynthesis.

Photosynthesis: A Summary



Photosynthesis is summarized in the diagram above. The sun provides energy that enables carbon dioxide and water to react to form glucose. Oxygen gas is a byproduct of this process.

How Photosynthetic Pigments Capture Light Energy

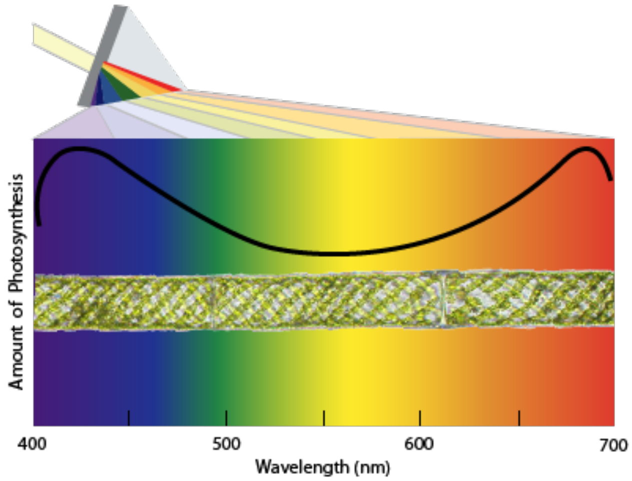
We know that plants require light. But "light" is a complex form of energy. Visible light is just a small part of a much broader spectrum including many forms of electromagnetic radiation. In many ways, light behaves as a wave. Different colors of light have different wavelengths. In a given period of time, short wavelengths deliver more energy to a surface than longer wavelengths. Thus blue light is higher in energy than red light.

Sunlight Includes All Colors of Visible Light

A rainbow vividly demonstrates that sunlight includes a range of light colors and wavelengths, from blue (shorter wavelengths) to red (longer wavelengths). Raindrops act as prisms, separating the wavelengths and making the colors apparent. © Copyright Rod Trevaskus and licensed for reuse under this Creative Commons Licence.

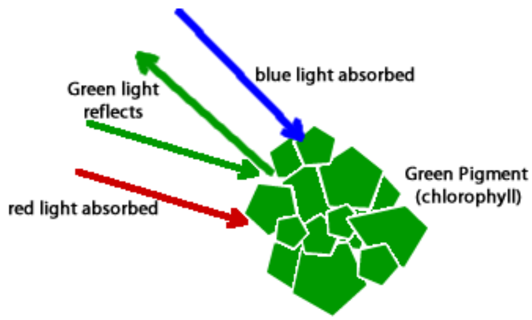
Are all wavelengths of light equally useful for photosynthesis? In 1883, a scientist named George Engelmann designed an experiment to answer this question. He shined a light through a prism to separate the different wavelengths so that they landed on different zones along the length of filaments of *Spirogyra*, a type of green algae. Examine the following image depicting Engelmann's results.

Engelmann's Action Spectrum Experiment



Pigments are colored substances that absorb light energy. Why does a pigment look red, green, purple, or blue? A given pigment absorbs only a limited set of light wavelengths. For example, a red pigment absorbs green and blue wavelengths. Red light, by contrast, is NOT absorbed: it is either reflected or transmitted through a solution containing the pigment.

Pigments Absorb Some Wavelengths and Reflect Others



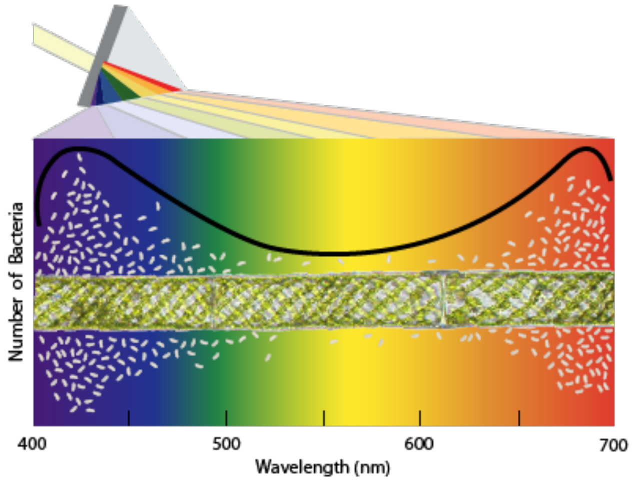
The green chlorophyll pigment appears green because it reflects and transmits light in the green wavelength range. Blue and red light, by contrast, are absorbed.

What happens to light energy that is absorbed by a pigment? In keeping with the law of conservation of energy, this energy does not disappear. Instead, it excites electrons in the pigment, boosting them to higher energy levels. In plants, the excited electrons from some pigments are transferred to other molecules, where they start the transformation of light energy into chemical potential energy.

If excited electrons are not removed from a pigment molecule, they will eventually “fall” back to their starting point. At this point, the pigment will release energy. In some pigments, a portion of the released energy is emitted as light. If you expose these fluorescent pigments to light and then place them in a dark place, they will glow. All pigments release at least some of the energy they absorbed from light as heat.

Photosynthesis Achieved by Algae

In the experiment mentioned above, George Engelmann used bacteria to measure the amount of photosynthesis achieved by algae. The bacteria he used in his study require oxygen to live. In each zone along the length of the filament, there were different wavelengths of light. So, some algal cells were photosynthesizing mainly with red light, others with green light, etc. The amount of photosynthesis supported by each wavelength was measured by how many bacteria were able to live in each zone.



O_2 is a product of photosynthesis. This product is essential for many living organisms, including humans and any other organisms that go through cellular respiration. When photosynthesis became widespread in the early Earth's oceans, it generated excess oxygen gas that changed the Earth's atmosphere. This increase in atmospheric oxygen concentration eventually changed the face of our planet as organisms that couldn't adapt died off and new organisms evolved.

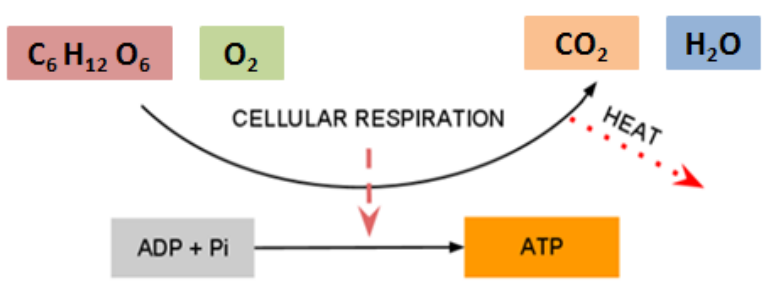
Cellular Respiration

As we have emphasized thus far, cells juggle energy through opposing reactions. Photosynthesis is an anabolic pathway fueled by solar energy that allows the synthesis of organic molecules from simple raw materials. Catabolic pathways reverse this process. They break molecules down into simpler components. The centrally important catabolic pathway that is complementary to photosynthesis is cellular respiration. Although there are may other catabolic reactions occurring in any cell, cellular respiration supplies the vast majority of ATP molecules required for cellular work in aerobic organisms.

If you compare the summary reactions of photosynthesis and cellular respiration, you will see that cellular respiration is photosynthesis "running in reverse":

sugar + $O_2 \rightarrow CO_2 + H_20$ + energy

Cellular Respiration Breaks Down Sugar and Captures Energy within ATP



Sugar and oxygen gas are converted to carbon dioxide and water in cellular respiration. In the process, heat is released and ADP is phosphorylated to produce ATP.

Cellular Respiration: A Central Catabolic Pathway

Cellular respiration is a key pathway in the metabolism of all aerobic organisms. On the macro scale, respiration refers to breathing: taking in oxygen and removing CO_2. But ultimately, the reason we need to breathe is to provide the oxygen needed to carry out cellular respiration in our cells and to remove the carbon dioxide produced as a byproduct.

Three important things happen during cellular respiration:

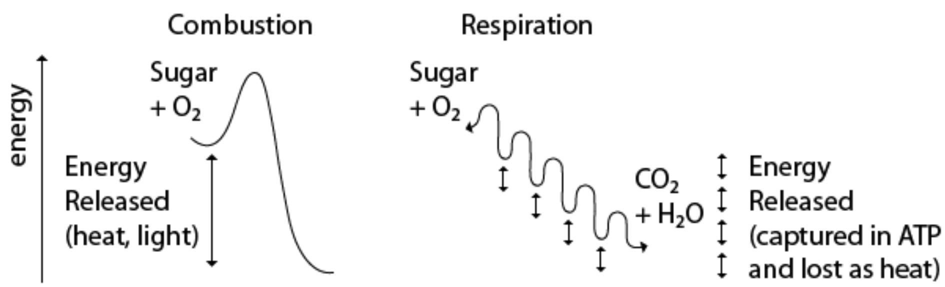
1. The carbon-containing molecules used as cellular fuel are broken down and converted to CO_2.
2. Electrons and hydrogen ions (H+) are produced as sugar is broken down and energy is harvested; oxygen (O_2) combines with these byproducts to produce water (H_2O).
3. The energy released when carbon-containing molecules are broken down is captured and used to generate ATP molecules; some energy is also lost as heat.

In eukaryotes, the breakdown of sugar begins in the cytoplasm (cytosol), while the consumption of oxygen and the generation of CO_2 and ATP synthesis happen inside specialized membrane-bound organelles called mitochondria.

Combustion vs. Respiration

Energy is released in small portions, so that some of the released energy can be captured in chemical bonds, ultimately as ATP. The process can be regulated at different steps, allowing cells more control over the process.

Combustion vs. Respiration



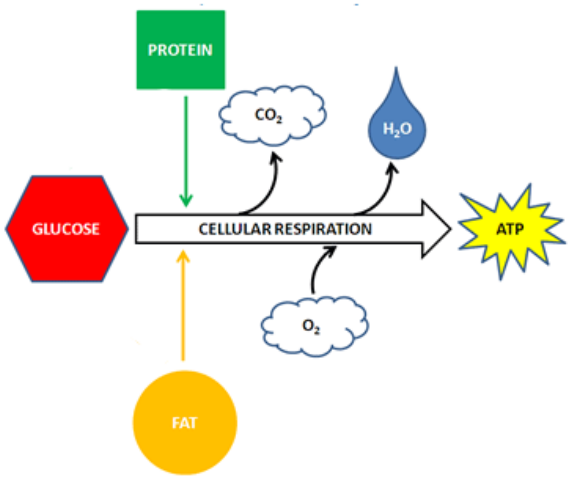
Both combustion and respiration release the same amount of energy. However, because combustion happens all at once, much of that energy is released as heat and light and cannot be captured by the cells. The stepwise process of respiration releases energy slowly so cells can capture the energy in ATP.

Use of Dietary Nutrients and Stored Fats in Cellular Respiration

Cellular respiration is a complex, multistep process. Dozens of different enzymes and intermediates are involved. Initial steps are accomplished in the cytoplasm, and additional steps occur in the mitochondria. At various points along the way, intermediates may be removed and used to synthesize fats and other molecules. Similarly, different types of food molecules may “feed in” to cell respiration at specific junctions in the process.

Even though glucose is the starting substance used in cellular respiration, organisms do not consume pure glucose as an energy source. Instead, many different kinds of fuel molecules must be partly broken down and then fed into various stages of the cellular respiration pathway. For example, complex carbohydrates are readily converted to glucose or similar sugars. Fats and proteins can also be used in cellular respiration, but they must be modified before they can feed into the process.

Many Fuels Feed into Cellular Respiration



In addition to carbohydrates, fats and proteins can also be used as fuels for cellular respiration. However, these fuels must first be partially broken down, and they feed in at intermediate steps within the pathway.

Photosynthesis / Cellular Respiration Cycle

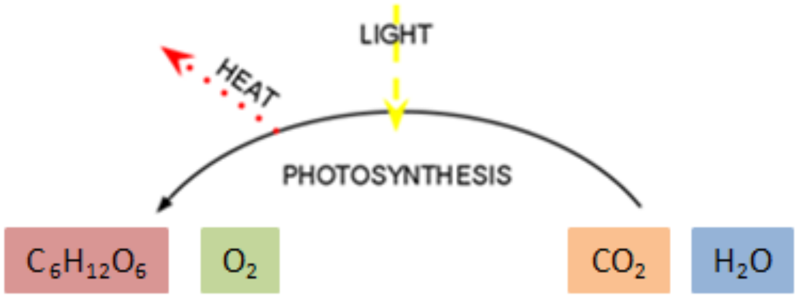
As you may recall, photosynthesis occurs in some bacteria; in eukaryotes it occurs in cells that contain chloroplasts. Such cells are found in algae and in the leaves and stems of plants. Photosynthetic organisms use light energy and simple building blocks (carbon dioxide and water) to make their own food. Cellular respiration is very widespread. It is completed in mitochondria, bacteria-like organelles that are found in protists, fungi, plants, and animals. Although the details of the two pathways are different, the overall reaction of cellular respiration is photosynthesis running in reverse. Cellular respiration extracts the stored energy from food molecules, uses it to “charge up” ATP, and releases carbon dioxide and water as wastes.

Photosynthesis and Cellular Respiration Recycle Carbon and Transfer Energy

In the last two sections, the topics of photosynthesis and cellular respiration have been introduced and discussed as independent processes. The focus of this module is on how the two processes are part of one larger cycle. There is a yin-yang relationship between the two processes — the product of one process is the starting material for the other.

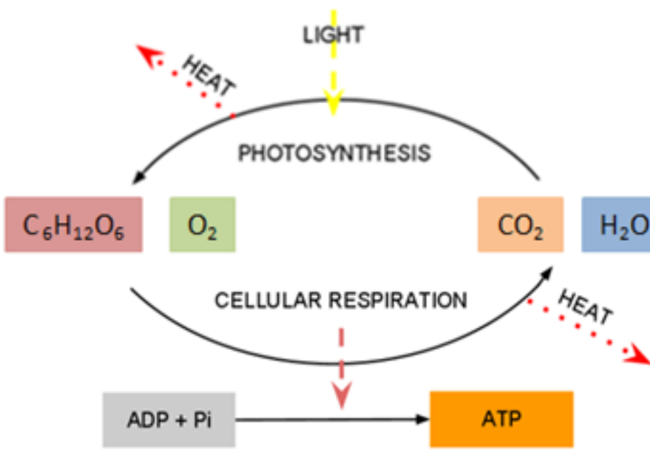
In the image below, you see a summary of photosynthesis. But photosynthesis does not occur in a vacuum. In fact, it is inevitably PAIRED WITH cellular respiration in most producers. They take most of the glucose they have produced and break it right down again in their own cells.

Photosynthesis Summary Reaction: CO_2 and H_2O to Glucose Using Light Energy



In the diagram above, photosynthesis is summarized. Carbon dioxide and water are joined to form glucose using light energy. Oxygen gas is also a byproduct of this process.

A full representation joins photosynthesis to cellular respiration in a cycle. The products of one reaction are the starting materials for the other.



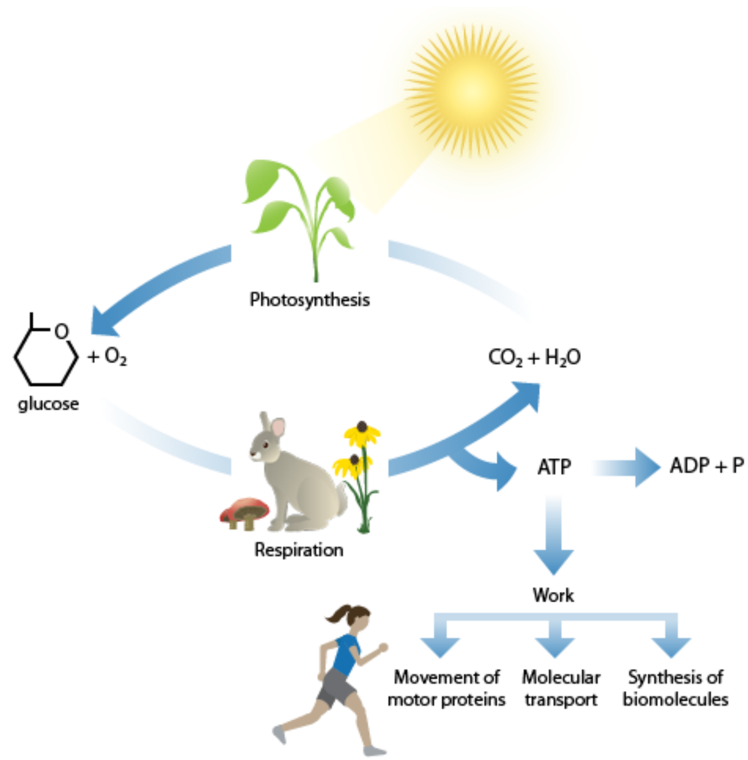
Cellular respiration and photosynthesis are interdependent. The glucose and oxygen produced by photosynthesis are used up in cellular respiration. Energy is transferred to “charge up” ATP, and heat, carbon dioxide, and water are released as waste products. The carbon dioxide and water are then available as raw materials for photosynthesis.

Cycling Between Photosynthesis and Cellular Respiration

This is how the cycling between photosynthesis and cellular respiration occurs: in photosynthesis, carbon dioxide and water, in the presence of light energy, are converted to make glucose and oxygen; while in cellular respiration, the products of photosynthesis (glucose and oxygen) are metabolized to make energy in the form of ATP and heat, releasing carbon dioxide and water. Because each process starts where the other ends, they form a cycle.

The photosynthesis / cellular respiration cycle isn’t restricted to the cells of an individual plant. To the contrary, it is a global cycle that makes all life on Earth interdependent. A growing photosynthetic producer carries out more photosynthesis than cellular respiration. Thus, it releases excess oxygen into the atmosphere and stores carbohydrates and other molecules in its body as growth. These materials are essential to virtually all other life forms on Earth. This interdependence is depicted in the diagram below.

Photosynthesis -Cellular Respiration Cycle

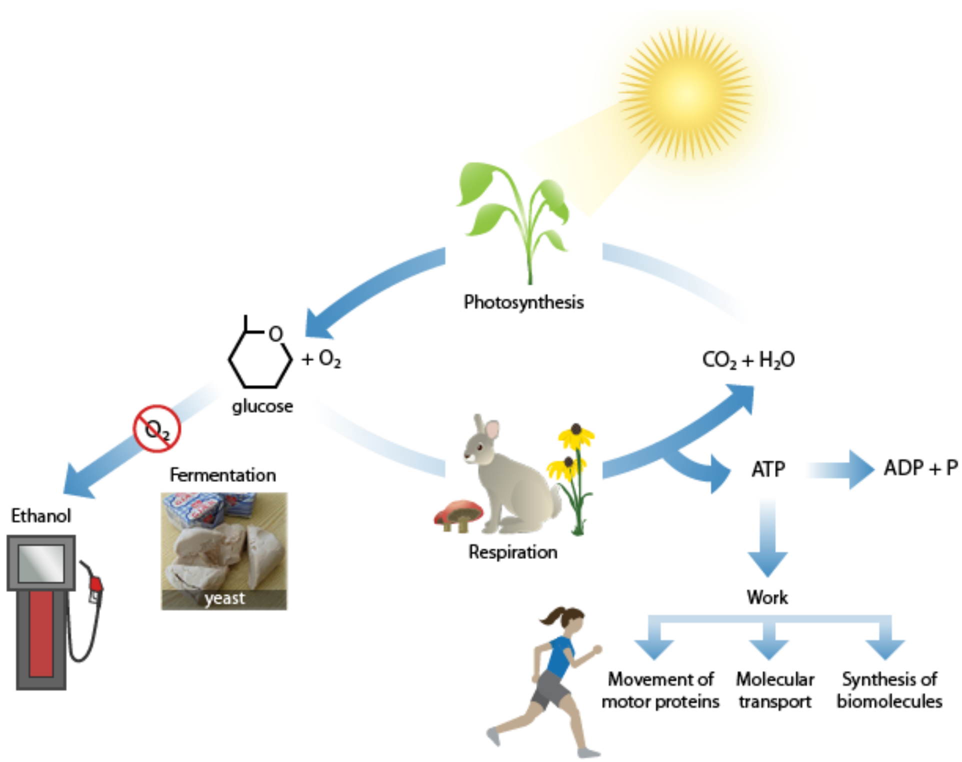


This image shows the cycling between the products of photosynthesis and cellular respiration. The two processes are intimately linked.

Relevance of the Photosynthesis / Cellular Respiration

The cycling that occurs between photosynthesis and cellular respiration is vital to the health of planet Earth. If there was no way for the carbon dioxide produced through cellular respiration to be utilized, respiring organisms (like humans, dogs, and even grass) would soon die of asphyxiation. Additionally, photosynthetic organisms are the base of almost every food chain on the planet, so without these organisms, mass starvation would ensue. Luckily, this planet is full of photosynthetic organisms. All of the breathable oxygen on Earth comes from photosynthesis. Just over half of the oxygen is produced by phytoplankton — drifting photosynthetic algae and bacteria — in the oceans. The rest comes from plants (trees, grass, etc.) on the land. Without this vital connection between photosynthesis and cellular respiration, life as we know it would cease to exist.

Cycling Between Photosynthesis and Cellular Respiration



An understanding of this balance is important in the modern world, with global warming in the headlines. Since the late 1700's, the amount of carbon dioxide in the Earth's atmosphere has been rising. This indicates that the natural recycling of carbon has been upset. The main source of excess carbon dioxide in our atmosphere is the burning of fossil fuels, which were created by photosynthesis millions of years ago. Meanwhile, deforestation removes photosynthetic organisms (trees) from the surface of the planet. Taken together, these human activities have changed Earth's atmosphere. The carbon dioxide concentration of Earth's air has increased by more than 35 percent since the 1700's. Such changes are very likely changing Earth's climate, and pollution and deforestation also have other detrimental effects on environmental health. We will return to explore these topics further in the Ecology unit. You will need to use your understanding of photosynthesis and respiration to fully grasp these issues.

Application Spotlight: Alternative Pathways

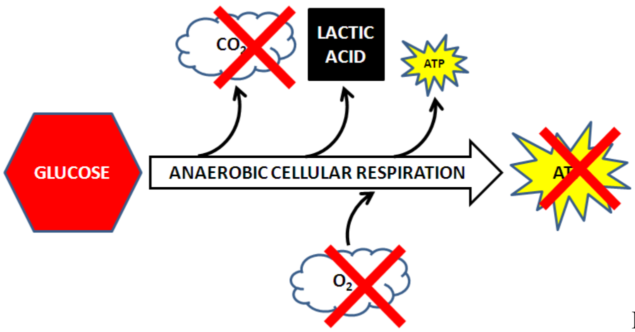
Metabolic pathways constitute a complex network of chemical reactions, with some pathways functioning like central "freeways" to which many other pathways connect. Pathways related to the harvesting of energy (chemical or solar) and biosynthesis of the major cellular components are conserved in many types of cells and organisms.

Many organisms use energy harvesting pathways other than photosynthesis and cellular respiration. Bacteria, in particular, have an astonishing array of metabolic options. The variety of metabolic options in the bacterial domain helps scientists classify evolutionary relationships between these organisms.

Many of these metabolic options do not require oxygen and are called anaerobic ("an-" means without and "aerobic" refers to oxygen). Fermentation breaks down organic molecules and stores energy as ATP. Although fermentation is the only ATP-producing pathway for some microbes, it is also commonly used by many organisms as a special-purpose pathway. For example, yeasts that decompose fruit can switch between aerobic cellular respiration (used when oxygen is abundant) to a form of fermentation that produces ethanol (used when oxygen is depleted). This allows yeast to continue to produce ATP even in rotten, oxygen-poor fruit.

Some human tissues also use fermentation under certain conditions. Sprinters and weightlifters have well-developed fast-twitch muscles. Fast-twitch fibers have fewer mitochondria and are not able to renew their supply of oxygen rapidly. Therefore, they have relatively poor endurance. However, fast-twitch fibers excel at producing strong contractions very quickly. They do this using the ATP created through a form of fermentation. This pathway does not break sugar all the way down to CO_2, but stops at an intermediate (lactic acid).

Lactic Acid Fermentation is a Partial Breakdown of Glucose



Fermentation reactions do not require oxygen, and they do not break all glucose down fully to carbon dioxide. Instead, they end with organic molecules that still contain considerable chemical potential energy. Such pathways produce only a tiny amount of ATP compared to aerobic cellular respiration.

Oxygen is not used in fermentation, and although some CO_2 may be produced, glucose is not fully broken down. Instead, fermentation ends with complex products (lactate, ethanol) that still contain quite a bit of chemical potential energy. The breakdown process is incomplete, and relatively little energy is available to drive the production of ATP. In addition, the byproducts of fermentation can be toxic. For example, a buildup of lactic acid may cause stiffness in an overworked muscle.

Fermentation is a very common metabolic pathway in microorganisms such as bacteria and yeast, resulting in alcoholic beverages, fermented milk products, and bread. In fermentation of alcoholic beverages, yeast is added to sugary juices or malt syrups. The container is sealed to exclude oxygen. Under these conditions, the yeast switches to fermentation and generates ethanol, the intoxicating "active ingredient" of alcoholic beverages. Eventually, however, ethanol concentrations reach a point where the yeasts themselves are inhibited and fermentation grinds to a halt. In this way, wine and beer are naturally limited in their alcohol content. High-alcohol liquors can be produced only by distillation, a chemical process that concentrates the alcohol.

Fermentation tank

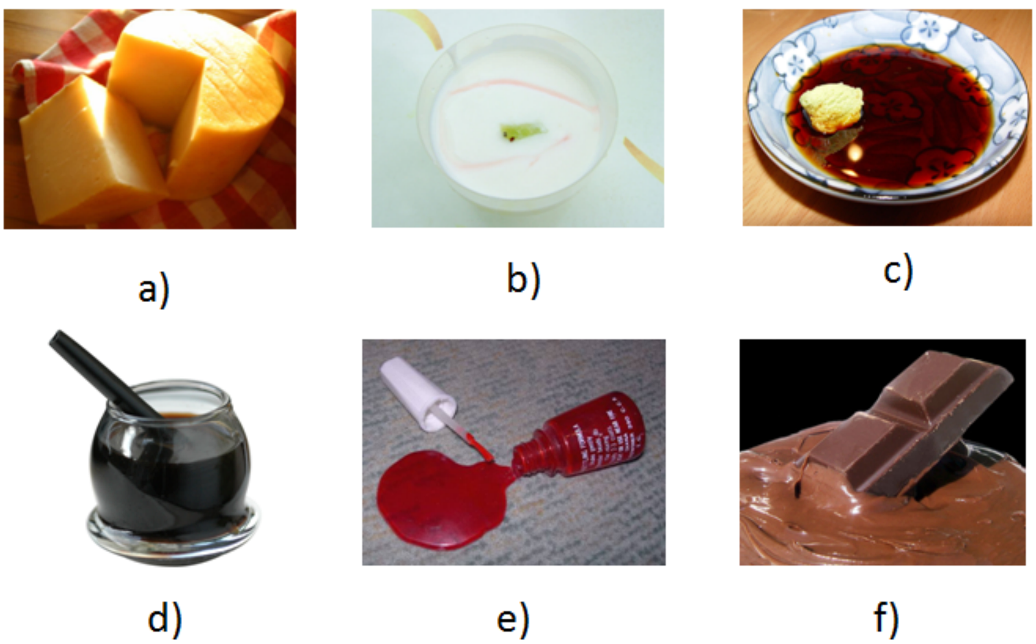
Cellular respiration and fermentation both break down organic molecules to build ATP. However, cellular respiration is aerobic, while fermentation is anaerobic. Cellular respiration produces more ATP.

Characteristic	***Cellular Respiration***	***Fermentation***
Energy source	organic molecules	organic molecules
ATP production	36-38 ATP produced	2 ATP produced
Oxygen	required (aerobic)*	not required (anaerobic)
End products	CO_2 and H_2O	variety of end products including: alcohols, acids, acetone

*Some bacteria can carry out forms of respiration that do not require oxygen.

Cellular respiration and fermentation both break down organic molecules to build ATP. However, cellular respiration is aerobic while fermentation is anaerobic; cellular respiration produces more ATP. The ATP yield in the table originates from one glucose molecule.

Products of fermentation



Fermentation can produce a variety of end products including: a) cheese, b) yogurt, c) soy sauce, d) vinegar, e) acetone (nail polish remover), and f) chocolate.

Photosynthesis and Cellular Respiration: Summary

Photosynthesis and cellular respiration are interdependent metabolic pathways. The products of cellular respiration (water and carbon dioxide) are the precursors that feed into photosynthesis. The products of photosynthesis (oxygen and glucose) are the precursors that feed into cellular respiration. This interdependence is an excellent illustration of how anabolic and catabolic reactions are also interdependent. Anabolic reactions use energy to build complex molecules, while catabolic reactions harvest the energy stored in the complex molecules by breaking them down into simple precursors. Catabolic reactions produce the energy required for anabolic reactions. In the next module, we'll look at how metabolic pathways are regulated.

Key Terms

Review this module and the following key terms introduced. When you are ready, check your understanding of photosynthesis and cellular respiration by taking the quiz linked below

anabolic reactions	alternative pathways	catabolic reactions	cellular respiration
chlorophyll	combustion	metabolic pathways	pathways
photosynthesis	photosynthetic organisms	pigments	

Pathways and Regulation

Objective

- Describe metabolic pathways as stepwise chemical transformations either requiring or releasing energy, and recognize conserved themes in these pathways.
- Describe the common features of metabolic pathways.
- Evaluate the effects of different factors (substrate and enzyme availability, presence of inhibitors) on a given metabolic pathway.
- Explain the role of regulation in metabolic pathways.
- Give examples showing how disordered regulation of metabolic pathways can cause disease.
- Apply knowledge of energy metabolism to the problem of obesity.

Common Characteristics of Metabolic Pathways

In the previous modules, you learned about metabolic pathways in cells — those "freeways" that shuttle energy and carbon in different directions. Metabolic pathways can be either anabolic or catabolic. Anabolic pathways build things up and catabolic pathways break them back down again, sometimes as a source of energy, other times to obtain building materials. Among the main pathways of the cell are photosynthesis and cellular respiration, although there are a variety of alternative pathways such as fermentation.

Metabolic Pathways

Metabolic pathways consist of an ordered set of chemical reactions that are catalyzed by enzymes. At the heart of metabolism are enzymes. These proteins embrace substrates, quickly generating products. One or more substrates bind to an enzyme's active site. As a result, the activation energy is reduced and the reaction proceeds much more quickly than it otherwise would. Without enzymes, metabolism would grind to a halt. Furthermore, the structural characteristics of enzymes allow the regulation of their function, thus allowing the regulation of the metabolic pathways they participate in. A huge diversity of enzymes is required to run the metabolic reactions necessary to maintain even a single cell.

Four Features of Metabolic Pathways

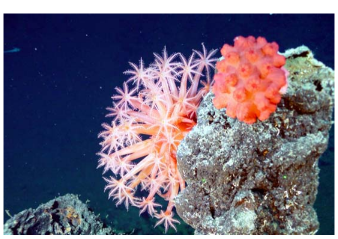
Regardless of their purpose, all metabolic pathways share four important features:

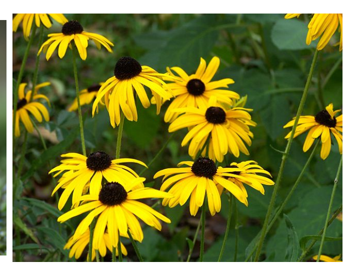
1. *Many pathways are universal among living organisms.* When you look at life, you may see a great deal of diversity. Those who study metabolism, by contrast, see a huge degree of overlap among the cells of all living things. Many of the fundamental enzymes that keep our cells working are found in only slightly different forms in creatures as varied as zebrafish, fruit flies, yeast, and nematode worms. This is partly why studies on model organisms can teach us so much about our own biology.

EXAMPLE

These organisms all use very similar metabolic pathways

Metabolic pathways (such as cellular respiration) are nearly universal. These organisms all use similar pathways.





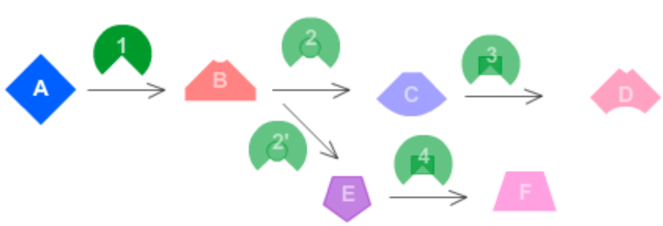
2. *Each pathway contains multiple intermediate products, and there are small molecular differences between the intermediates.* Pathways proceed in "baby steps." A chemical change that can be written and balanced as a single reaction may, in a real pathway, require dozens of reaction steps!

   A sample metabolic pathway

   This pathway shows the production of the end product "D" from the starting substrate "A." In this reaction, A is the substrate of enzyme 1, which produces B. Enzyme 2 then uses B as its substrate to produce C. Enzyme 3 then uses C as its substrate to produce D.
3. *Each step within the pathway, or the conversion from one intermediate to the next, is catalyzed by an enzyme.* Thousands of enzymes catalyze reactions in human cells. Each enzyme conducts a single chemical reaction. The coordination of many enzymes working together can produce a variety of outcomes.

   Another sample metabolic pathway

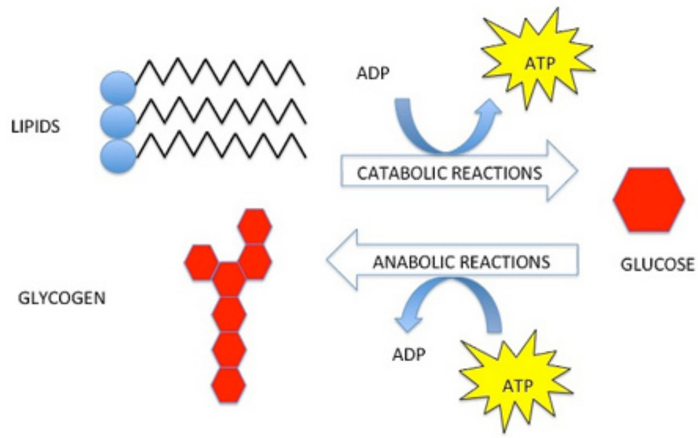
   

   Each enzyme within the pathway is specific to one reaction. The coordinated effort of many enzymes can produce a variety of final products.
4. *Each pathway is regulated to ensure the optimal use of resources and to maintain the health of the cell.* For example,

if there is plenty of ATP in a cell, the cellular respiration pathway (which produces ATP as its final product) will slow down. In a complex web of cause and effect, pathways influence themselves and each other. The net effect in a healthy cell is the maintenance of homeostasis. Stockpiles of raw materials, intermediates, and finished products are maintained at optimal levels, and the chemistry of the cell cytosol is also regulated, as are extracellular fluids.

Many metabolic pathways are reversible, which means that certain chemical reactions can go "either way," depending on the needs of the cell. For example, some of the reactions that are part of cellular respiration (which is a catabolic pathway) can become anabolic when there is a surplus of energy. A small number of steps utilize different enzymes in the forward versus the reverse direction. These enzymes are regulated in a coordinated fashion such that a pathway operates in only direction at time.

Catabolic and Anabolic Reactions



Animals use fats and complex carbohydrates such as glycogen for long-term energy storage. When energy is needed, catabolic pathways degrade lipids and glycogen to glucose or other intermediates of the cellular respiration pathway, resulting in ATP production. When there is excess ATP (for example after eating a meal rich in fats and sugars), parts of the cellular respiration pathway go "in reverse" to provide building blocks for the anabolic reactions building up lipids and glycogen.

Regulation of Pathways

At the heart of metabolism are enzymes. These proteins embrace substrates, quickly generating products. One or more substrates bind to an enzyme's active site. As a result, activation energy is reduced and the reaction proceeds much more quickly than it otherwise would. Without enzymes, metabolism would grind to a halt. Furthermore, the structural characteristics of *enzymes* allow the regulation of their function, thus allowing the regulation of the metabolic pathways they participate in. You may want to review the functions of enzyme proteins.

Metabolic pathways are regulated in order to maintain maximum efficiency or in response to environmental changes.

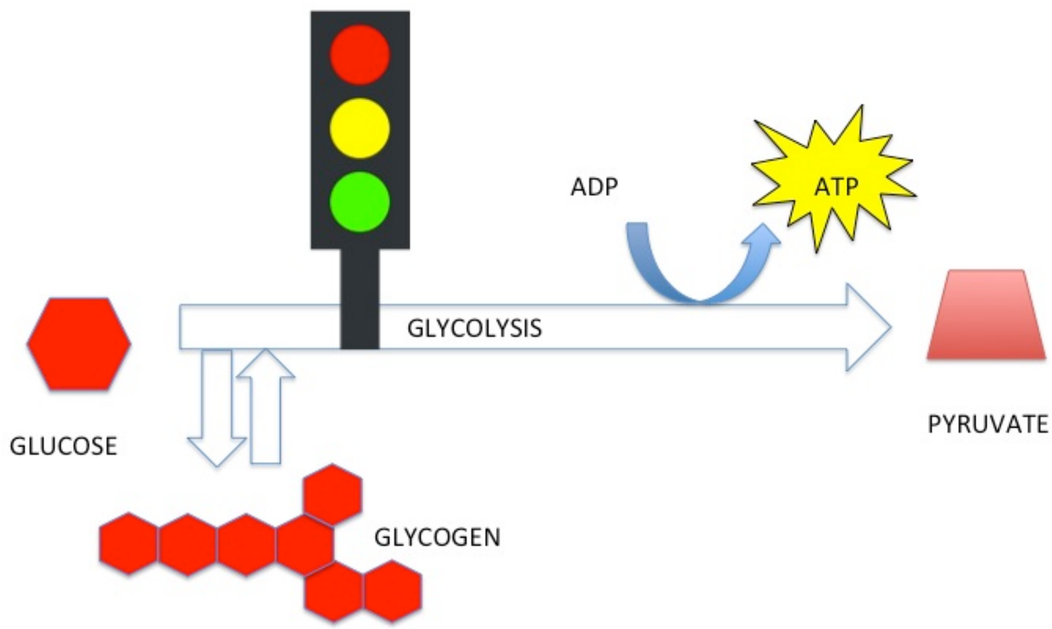
There are two major methods of pathway regulation. The first method involves changing the amount of the enzymes in the pathway. Since the reactions are catalyzed by the enzymes, if the enzyme is not present, the pathway is effectively shut off. Enzyme levels are usually altered by controlling the amount of mRNA produced from the gene that encodes the enzyme. You will explore how enzyme levels are regulated in the section on transcription.

Regulation of pathways by altering the amount of enzymes in the pathway is usually too slow to meet the second-by-second regulation needs of the organism. Consequently, many pathways are regulated by increasing or decreasing the activity of an enzyme due to the binding of a small regulatory compound. Typically, only a few steps in the pathway are regulated, and the regulated steps typically occur near the beginning of the pathway to prevent the accumulation of intermediates, which are seldom of use to the cell. Think of an assembly line: the speed of production will change depending on how much of the starting material is available, how quickly each of the workers completes the task, and how much of the final product is needed. Similarly, pathways are influenced by the availability of the starting materials, the activity of each enzyme in the pathway, and the concentration of product already present in the cell.

EXAMPLE

Glucose and Cellular Respiration

Let's look at an example of a metabolic pathway and explore one mechanism that regulates it. You may remember that cellular respiration is an essential catabolic pathway. Cellular respiration starts with a pathway called glycolysis, which degrades three-carbon glucose into a three-carbon molecule called pyruvate. Glucose can come from ingested carbohydrates, or from degradation of glycogen, a polysaccharide. When there is an excess of carbohydrates, they are stored as glycogen in an anabolic pathway.



Glycolysis is the first stage of cellular respiration, in which glucose is degraded to a three-carbon compound called pyruvate. In this process, ATP is formed. As with all pathways, glycolysis has several steps. The on-off switch of the pathway is found at the third enzyme (represented by a traffic light), which is inhibited by high levels of ATP. Synthesis and degradation of glycogen, a polymer of glucose commonly found in animal cells, occurs through an early intermediate of glycolysis.

Mechanisms for Pathway Regulation

Six general mechanisms can regulate the rate of each step in a pathway. The mechanisms differ in how rapidly they can respond to changes in the environment. Each of them is discussed below, with the more rapid forms of regulation at the top of the list.

1. *Substrate availability.* If the substrate concentration increases, the rate of a reaction will increase. Put simply, substrates must collide with enzymes to initiate binding. Such collisions will occur more often if the substrate is highly concentrated. Note that too much of the substrate can saturate the enzyme, so above a certain amount of substrate, the reaction speed will not increase anymore.
2. *Competitive inhibition.* An inhibitor "competes" with the substrate for the active site. If the inhibitor binds first, the substrate is blocked from entering and the enzyme is inhibited (cannot complete any reactions). Competitive inhibitors are often used as drugs to block an undesirable metabolic pathway. For example, sulfa antibiotics are competitive inhibitors of the bacterial pathway that produces folic acid, an essential molecule for nucleic acid synthesis. Products of a reaction are often competitive inhibitors, because they bind to the active site.
3. *Noncompetitive control.* This mechanism is similar to competitive control, except in this case substances bind to a site *away* from the active site. Binding can either enhance or inhibit the enzyme's function by changing the shape of

the active site. This is the example that you saw above with glycolysis.

4. *Feedback inhibition.* Both competitive and noncompetitive controls are often set up so that a product inhibits its own production by inhibiting enzymes at an early step in the synthesis process. This regulates the pathway: the product "turns off" its own production by inhibiting an enzyme on its own "assembly line." This prevents the overproduction of a substance and also prevents the waste of resources on unnecessary intermediate products. Feedback inhibition is observed when a product inhibits an earlier step in the pathway. Product inhibition occurs when the product inhibits the enzyme that was directly involved in making that product.
5. *Modification of the enzyme*. Chemical modification of enzymes (such as adding a phosphate group) can cause a change in the shape of the active site of the enzyme. The change may either increase or decrease enzyme activity. This is similar to noncompetitive control, except in this case the enzyme is chemically modified and control does not involve the binding of a large molecule to the enzyme.
6. *Changing enzyme concentrations.* Enzyme levels can be increased by 1) conversion of inactive forms of the enzyme to active forms, or 2) regulating the synthesis of the enzyme. An example of the former is blood clotting, where inactive precursors of clotting enzymes become activated, in a cascade, by blood vessel damage. This permits a very quick response to bleeding: all the necessary factors are present and require only an activating signal. Similarly, many digestive enzymes are activated only when they reach their destination (for example, gastric fluid of low pH). Elsewhere they are inactive — and thus do not digest the organ that secretes them. It takes longer to adjust enzyme levels by regulating the activity of genes that produce them. Such changes are most often seen in response to longer-term changes in the environment. For example, bacteria turn genes for digestive enzymes on and off depending on the nutrients that are available to them. Many animal genes are produced only during certain stages of development.

In summary, metabolic pathways are dynamic processes, continuously changing in response to environmental changes and cellular (or organismal) needs, while avoiding waste of resources. How much substrate or enzyme is available will determine the rate of reactions. Moreover, extreme "fine-tuning" of metabolism is possible through changes in enzyme activity due to the binding of inhibitors. This is a prime example of the relationship between structure and function.

Regulation and Human Health

To this point, you have learned much about how pathways work. They proceed as a series of steps catalyzed by enzymes. They are regulated by factors that modify enzymes or alter the expression of genes.

In living organisms, metabolic processes are tightly regulated under normal conditions. The cell, and the organism as a whole (e.g., the human body), tend to respond to external influences in ways that maintain a relatively stable internal environment. This ability or tendency is called homeostasis and depends on a complex set of stabilizing responses.

Cells live in dynamic environments. Therefore, it takes work to keep conditions stable in a cell. Precise regulation enables the cell (or body) to establish consistent internal conditions. Factors like pH, ion concentrations, and levels of various substrates and products are held within narrow bounds. This unique environment allows a diverse set of reactions to take place. Many of these chemical reactions are essential for life and all of them help maintain overall health.

Applications of Metabolic Regulation to Human Health

You had to work at staying upright because your body was in motion. In the cell or inside a body, countless dynamic processes are running at once. Many of them could easily disturb internal chemistry and throw things out of whack. So could changes in the external environment. As a result, many levels of regulation are constantly at work within your body, keeping internal processes balanced and compensating for external changes.

These concepts are not just academic, textbook issues. To the contrary! Many of today's most challenging health problems center on the regulation of metabolism. The loss of proper regulation can result in a number of diseases or disorders.

Substances that inhibit enzymes in a central pathway can have deadly effects for the cell or organism. For instance, the potent poisons cyanide and arsenic are inhibitors of cellular respiration. Lack of regulation, or dysregulation, of metabolic pathways can lead to serious diseases. Examples include phenylketonuria (PKU), Tay-Sachs disease, galactosemia, and maple syrup urine disease. Each of these is an inherited condition in which an altered gene produces an enzyme that does not function normally. As a result, metabolism is disrupted and health problems occur.

On the other hand, drugs often target metabolic pathways to correct diseases. For instance, angiotensin-converting enzyme (ACE) inhibitors are drugs that are commonly used to control high blood pressure. These drugs inhibit ACE; the result is reduced production of angiotensin, a molecule that increases blood pressure.

Application Spotlight: Energy Balance and Excess Weight

Many humans are able to maintain a stable adult body weight over a large number of years. Although it may seem perfectly normal, this is an amazing feat of metabolic regulation. As you eat, foods are broken down and metabolized. But the energy stored in the food's chemical bonds cannot be destroyed. Simply put, if more calories are consumed than are required for growth, activity, and maintenance, the excess energy is stored within the body. This energy is stored when enzymes catalyze the formation of new chemical bonds to create specific kinds of macromolecules (i.e., glycogen, fat, and protein), which tends to increase overall body mass. On the other hand, if not enough food calories are consumed, the body will begin to break down its own tissues as a source of energy, and will decline in mass as a result.

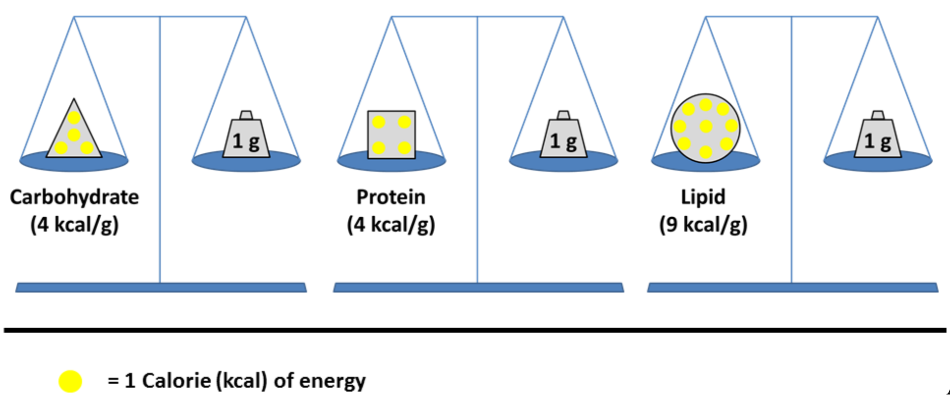
Note that when "calories" are being discussed in reference to food consumption, the word "calorie" actually refers to a kilocalorie. One kilocalorie is the amount of energy required to raise the temperature of one kilogram of water by one degree Celsius. It is the unit typically used when discussing human nutrition and energy balance. For your reference, a typical adult male requires about 2,500 calories per day; a female of average size might require 2,000 calories daily. The body's calorie requirement declines with age, and depends on many factors, including body size, sex, and physical activity.

As you have seen, the balance between caloric intake and output must be held within narrow limits to maintain a steady body weight. Yet some humans do this without conscious effort. How does this remarkable balancing act work?

First, consider what happens over the course of a typical day. After a meal, extra calories are initially stored in the liver and muscles as glycogen (a complex carbohydrate). Glycogen is broken down and used to supply glucose for intense exercise, and to provide glucose while we sleep. Breakfast provides fuel to rebuild some of the body's glycogen stores that were depleted overnight. Thus, over short time scales, glycogen storage is an efficient way to provide glucose when it's needed between meals.

Over longer time periods, body fat is used to store excess energy. When glycogen stores are full, the body switches over to storing the excess energy as fat. Remember that energy is stored within chemical bonds, and so it is the chemical bonds within glycogen and fat molecules that contain energy. Fat is an efficient way for the body to store extra calories, because it is able to pack more calories per unit mass when compared with carbohydrates or proteins (see Figure 8.2 below). You can think of body fat as a long-term, highly compacted energy reserve.

Fat Stores Maximum Energy per Unit of Mass



At 9 kilocalories per gram, fat stores more than twice as much energy per unit mass than proteins or carbohydrates.

Regulation and Human Health

How are caloric intake and energy output balanced? Your levels of hunger and overall metabolic rate change in response to your nutritional status. When your stomach is empty, a hormone called ghrelin is secreted. This acts on receptors in the brain to stimulate feelings of hunger. When the stomach is full, ghrelin secretion stops and so do your cravings for food.

If a person takes in less calories than required for maintenance and activity, glycogen reserves are broken down first. This leads to rapid weight loss early on, because each gram of glycogen associates with up to four grams of water. As glycogen is broken down, water is released in urine. Most of the initial weight loss is actually "water weight."

Later weight loss comes more slowly, because body fat stores a great deal of energy and is associated with much less water. Importantly, body fat is not just a storage bin. It also has a role as an endocrine (hormone-secreting) organ. For example, body fat secretes a hormone called leptin. This acts on target cells in the brain to produce feelings of "fullness." Loss of body fat leads to decreases in leptin and increasing feelings of hunger. Second, loss of weight also has effects on a person's energy output. As a person loses weight, total metabolism goes down simply because the body is getting smaller. More significantly, the per-pound*rate* of metabolism is turned down to conserve energy and resist what the body perceives as "starvation." A person in this state will feel sluggish and reluctant to exercise. Taken together, these and other mechanisms tend to automatically adjust our hunger and activity to maintain our weight.

When Regulation Goes Haywire: Obesity

Obesity is a condition in which body fat is excessive and interferes with normal function or impairs health. Obesity can make many physical activities difficult or impossible. It is associated with many increased health risks; type II diabetes (see below), hypertension, and heart disease are three serious conditions that are clearly more common among obese people than their normal-weight peers. Obese people also suffer socially and professionally because of weight-related bias and discrimination.

Why don't the normal regulatory mechanisms work to limit weight in people who become obese? This is a question that has fueled considerable research and debate. Findings suggest that there are many contributing factors. For example, many (but not all) obese individuals have very high circulating levels of leptin in keeping with their high body fat reserves. Yet the target cells in their brains do not respond to leptin in the normal way; they do not perceive satisfaction or fullness.

Obesity may result from a mismatch between our evolutionary adaptations and the realities of the modern world. We expend less calories each day on physical tasks than did previous generations of humans. More than 100 years ago, the average person may have expended 30 percent to 50 percent more calories each day than a typical modern American. In addition, today we have continuous access to an unprecedented array of calorie-rich foods. In times past, when food was scarce and could not be preserved easily, it was adaptive to feast on rich foods when they were available. Those who did so could build up fat and glycogen reserves, and thus were more likely to survive famines. Today, in a changed environment, the same behaviors predispose us to obesity.

When Regulation Goes Haywire: Obesity

Obesity is a condition in which body fat is excessive and interferes with normal function or impairs health. Obesity can make many physical activities difficult or impossible. It is associated with many increased health risks; type II diabetes (see below), hypertension, and heart disease are three serious conditions that are clearly more common among obese people than their normal-weight peers. Obese people also suffer socially and professionally because of weight-related bias and discrimination.

Why don't the normal regulatory mechanisms work to limit weight in people who become obese? This is a question that has fueled considerable research and debate. Findings suggest that there are many contributing factors. For example, many (but not all) obese individuals have very high circulating levels of leptin in keeping with their high body fat reserves. Yet the target cells in their brains do not respond to leptin in the normal way; they do not perceive satisfaction or fullness.

Obesity may result from a mismatch between our evolutionary adaptations and the realities of the modern world. We expend less calories each day on physical tasks than did previous generations of humans. More than 100 years ago, the average person may have expended 30 percent to 50 percent more calories each day than a typical modern American. In addition, today we have continuous access to an unprecedented array of calorie-rich foods. In times past, when food was scarce and could not be preserved easily, it was adaptive to feast on rich foods when they were available. Those who did so could build up fat and glycogen reserves, and thus were more likely to survive famines. Today, in a changed environment, the same behaviors predispose us to obesity.

Solutions to Obesity?

Our society's main effort to overcome obesity has come in the form of dieting. Diet fads constantly come and go — Atkins, South Beach, Acai Berry, the Hollywood diet, and pills, drinks, or even machines that purportedly melt away fat. In fact, the total sales of weight loss services and products were estimated at over $55 billion in 2009. Unfortunately, all of this effort and expense does not appear to do much good. Surveys, clinical trials, and literature reviews have repeatedly turned up a depressing pattern: about 80 percent of dieters regain lost weight within one to five years — and very often shoot past their prediet weight with each cycle.

If crash dieting is a bad idea, and we are “hardwired” to overeat, is there any hope for solving the obesity problem? Yes, there are many efforts in this direction.

- *Medical approaches:* For the extremely obese, surgical options that reduce the size of the stomach are often effective. These procedures may work partly by reducing the stomach’s output of ghrelin, thus reducing the hunger pangs associated with an empty stomach. Some drugs also show promise.
- *Behavior change:* Much research is now exploring how different practices — emotional support groups, healthy cooking classes, and more — can help obese people make small, sustainable changes to their lifestyles for weight control and better health.
- *Societal change:* Many are trying to reduce obesity by building parks and bike lanes, taxing snack foods and sugary sodas, changing school lunch menus, expanding physical education classes, posting calorie counts in restaurants, and much more. These efforts are meant to change the overall social and physical environment to encourage more physical activity and less intake of calorie-rich foods.
-

Pathways and Regulation: Summary

The more you learn about living organisms, the more complicated they seem. All organisms exist because of a series of complex chemical reactions that are tightly regulated to maintain homoeostasis.

Review the key terms from this module and when you are ready, take the module quiz.

Key Terms

The following key terms were discussed in this module:

alternative pathways	anabolic pathway	catabolic pathay	enzymes
inhibitor	metabolic pathways	substrates	

Unit Summary: Metabolism

In this unit you learned about one of the key features of life: *the ability to transform energy and matter*. Energy comes in different forms: light energy, potential energy in chemical bonds, heat, and mechanical energy of motion. Living organisms convert one form of energy into another in a stepwise matter using *metabolic pathways*. All metabolic pathways rely on enzymes (catalysts) to speed up chemical reactions and are carefully regulated.

Two types of pathways can be distinguished based on how they change the complexity of molecules: catabolic and anabolic pathways. *Catabolic pathways* break down large, complex molecules into simple ones and release energy. *Anabolic pathways* build complex molecules from simple building blocks.

The central anabolic pathway enabling most life on Earth is *photosynthesis*. Photosynthetic organisms (plants, algae, and cyanobacteria) use light energy to build sugar molecules from carbon dioxide and water. In this way, they effectively convert light energy from the sun into the chemical bond energy of sugar molecules. Sugar is a good medium-term energy storage molecule, but is not directly useful for doing work in cells.

To extract useful energy from sugar, cells rely on two major types of catabolic pathways: *cellular respiration* and *fermentation*. Cellular respiration involves the mitochondria and requires oxygen gas as an input. Fermentation does not require oxygen and occurs in the cytoplasm. In both of these pathways, some of the energy released by the breakdown of sugar molecules is captured in chemical bonds within ATP molecules.

ATP is a special molecule used by cells as their "energy currency." ATP supplies energy for other cellular processes: cell movement and division, membrane transport, and anabolic pathways enabling growth. Anabolic pathways use energy stored in ATP for building complex molecules from simpler ones.

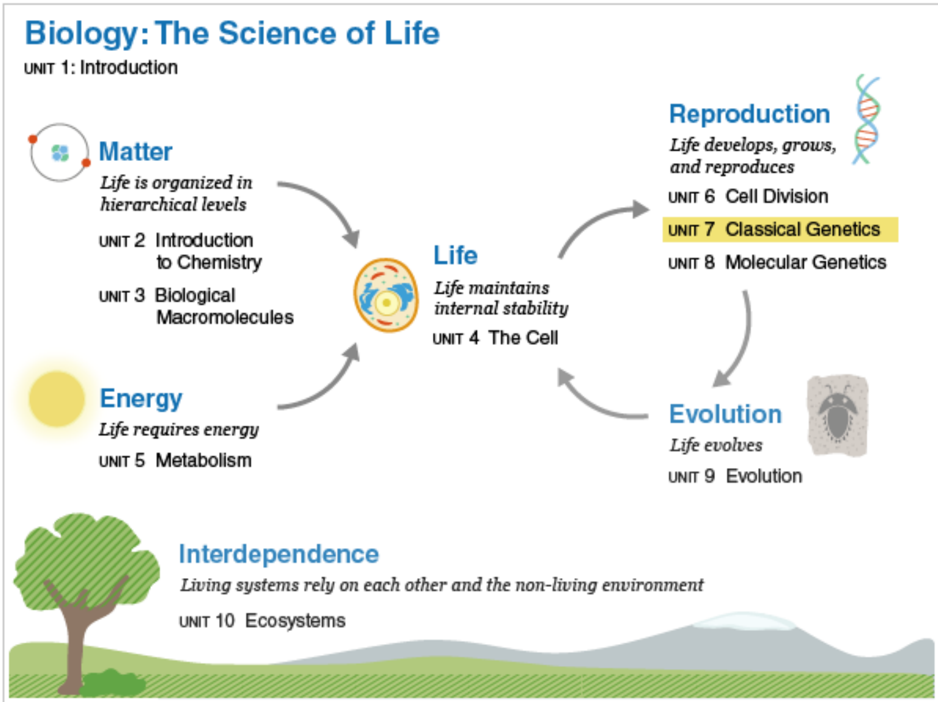
Photosynthesis and cellular respiration create a cycle of materials and enable the flow of energy to most life on Earth. Living organisms that do not do photosynthesis indirectly depend on the sun as the ultimate source of energy, because they derive their energy from food that is biological in origin. Although consumers may eat each other, the energy in organic matter can eventually be traced back to photosynthetic producers. In addition, the oxygen generated as a waste product by photosynthesis is a vital input to cellular respiration.

Metabolism is essential to all life and has many important applications to human health. Errors in regulation of metabolism affect energy balance of living organisms and may result in health problems, such as diabetes and obesity.

Before proceeding to take the Metabolism quiz, reflect upon the learning objectives. Do you think you could demonstrate your knowledge of each of these objectives? If so, you will be ready for the assessment.

Introduction to Classical Genetics

Why do children look like their parents? How do rose growers get so many different colors of roses — pink, red, white, yellow, purple, peach, striped, and many more? How can there be different-colored puppies within one litter?



Inheritance is the way that organisms pass traits to their offspring. Because offspring possess some (or all) of the genetic information from their parents, they also share many traits in common with their parents.

In the *Cell Division* unit, you learned that cells pass on a complete set of genetic information (contained in the DNA), which is transmitted from parent cells to daughter cells. This genetic information helps determine many of the characteristics of the offspring. In humans, for instance, *DNA* is responsible for a child's height and skin pigmentation. It also helps determine the overall health of the child by regulating many physiological characteristics, such as the condition of the heart and lungs, as well as brain and blood chemistry.

How much of our physiological makeup is determined by *genetics*, and how much is determined by other factors, such as personal choice and environment? This question is a source of ongoing debate in both scientific and philosophical communities. Environmental factors can influence our DNA, and our DNA can influence how we react to environmental factors. If we are ever able to answer this question, the answer will likely be complex.

In this unit, you will focus on the direct links between genetic information and visible traits. This will help you to learn how genetic information can be passed from one generation to the next and how these genes affect the later generation. We will introduce simple examples of traits that are clearly visible and have a direct correlation to genetics.

Heredity

Learning outcomes:

- Distinguish between phenotype and genotype.
- Illustrate the relationships between and among the following: protein, phenotype, genotype, DNA.
- Define the following: gene, chromosome, allele, haploid, diploid.
- Determine possible gametes from various germ cells that go through meiosis (focusing on one gene with two different alleles).
- Detail Mendel’s contributions to the field of genetics.
- Contrast dominant and recessive traits.
- Conduct a single-gene cross and interpret the results.
- Apply the law of segregation and predict the possible offspring in heredity problems.
- Describe the importance of independent assortment.
- Predict the outcomes of crosses with two traits and interpret the results.
- List the stages of meiosis and describe what happens at each stage.
- Describe the function of meiosis as it relates to sexual reproduction.
- Predict the number of genes/gene pairs of the progeny cells based on the number of genes of the parental cell.

Introduction to Heredity

The Cell unit discussed the components of the cell. One of these components is the DNA, which is arranged into one or more *chromosomes*. Each chromosome contains many genes. A *gene* is a region of a chromosome that has a specific function. For example, genes can contain information required to make a protein. How this happens will be discussed in the *Molecular Genetics Unit*.

DNA carries the information about how proteins are built, and proteins carry out many of the reactions necessary for living organisms. The Proteins module discussed the variety of roles proteins can play in a living organism. Some proteins produced by living organisms determine the traits we can observe. These visible traits are called the *phenotype* of an organism.

For example, protein enzymes in plants catalyze production of the pigments, resulting in flowers of different colors. The color of the flower is one of the observable traits, or the *phenotype* of the plant. The genetic information that produces these traits is called the *genotype* of an organism. Depending on the pigment production, the flowers can have red, blue, or white color. Flower color is determined by specific genes in the cells. The variations in the same gene are called *alleles*. In our example, different alleles of the pigment-producing gene can result in more or less pigment, and, consequently, in darker or light flower color.

In this unit, you will learn about the genotype and phenotype of diploid organisms. Diploid cells have two copies of each chromosome; haploid cells have only one copy of each chromosome. Because diploid cells have two copies of each chromosome, they also have two copies of every gene. One set of chromosomes (and, therefore, one copy of each gene) is from the mother (or egg) and one set is from the father (or sperm). Diploid cells can have two of the same alleles of a gene, or they can have two different alleles of a gene. Cells that have the same allele are called *homozygous* (“homo” meaning "same," and “zygous” referring to the reproductive cells produced from meiosis). These cells are called homozygous because all of their reproductive cells (*gametes*) will have identical alleles. Cells with different alleles are called*heterozygous* (“hetero” meaning "different") because they will produce reproductive cells that have different alleles of this gene.

Gamete Production

When you studied meiosis, you learned about how gametes were formed. But how are alleles dispersed into gametes through the process of meiosis? This activity will help you answer that question as you review the essential components of meiosis needed to understand inheritance. You may wish to review the Meiosismodule prior to continuing with this unit.

Mendel and his Peas: The Dawn of Genetics

Gregor Mendel was a nineteenth-century Augustinian monk in Bohemia, a country in Europe that is now part of the Czech Republic.

By U.S. National Library of Medicine (Gregor Mendel) Public Domain

In 1853, Mendel left the monastery for two years to study at the University of Vienna, where he learned about mathematics and botany. When he returned to the monastery, he began investigating how plants passed on their characteristics to their offspring. He was conducting this research only a few years before Charles Darwin published *On the Origin of Species*.

Mendel set out to understand inheritance by breeding pea plants. By collecting peas from pods produced after fertilizing two parent pea plants, Mendel could then grow those peas into new pea plants and see how these offspring resemble or differ from the parent plants. The heritable characteristics that Mendel studied included seed color and shape, pod color and shape, flower color and position, and stem length. Each of the traits that Mendel studied occurs only in two forms, or phenotypes. For instance, pea flower color is a trait that can exhibit either the purple phenotype or the white phenotype.

So if we know the phenotype, and we know that those two varieties would always result in same-color flowers, we can deduce that all individuals (plants) in that population (purple or white) have the same alleles for the gene that determines flower color.

Next, Mendel crossed the purple variety with the white variety. He manipulated his plants so he could control which plant pollinated which. In plants, pollen is the male gamete, landing on the flower to fuse with the ovule—the female gamete. The resulting zygote will give rise to the seed, or embryo.

When Mendel crossed purple and white flowers, the first generation of plants, which he designated “F1,” were all purple. Somehow, purple was “stronger,” or dominant over the white. So if the alleles of the purple flowers were symbolized by “B," then the allele corresponding to white flowers was “weaker” and is symbolized by “b.” If the genotype of the parent purple flower is BB, then the genotype of the parent white plant will be bb.

Let’s see what happened during that first cross. You will use a tool called a Punnett square, which graphically shows the possible combinations of the gametes of the parents. In a Punnett square, you place the possible gametes from each parent along the top and left side of the square. What you are representing here is the Law of Segregation: during meiosis I, the chromosome pair separates, resulting in haploid gametes. Each gamete will have only one allele.

Then you combine the possible gametes with each other to see all possible combinations, as shown in this example.

Punnett Square

WALKTHROUGH

As you can see, 100 percent of the offspring have the Bb genotype, but 100 percent also show the purple phenotype. You might expect the offspring to show a phenotype that somehow blends the parental phenotypes. Sometimes this happens, but in the case of these pea plants' flower color, the purple allele (B) is *dominant* over the white allele (b). Stated another way, the white allele (b) is *recessive* to the purple allele (B).

In many, but not all, cases it is possible to pinpoint a phenotype to one allele. Remember, alleles are variants of genes, and genes code for proteins. In this example, the purple color may be due to an enzyme that produces a purple pigment. If the allele codes for a mutated enzyme that does not perform as expected, the resulting flower would be white. A flower with BB or Bb genotype has the normal enzyme — purple pigment is produced — and even the heterozygous flower, which has only one allele for the normal enzyme, produces enough pigment for the flower to be purple. The bb flower, on the other hand, has no functioning enzyme, so the flower remains white.

There are some easily observable human traits that follow the Mendelian inheritance pattern, showing a dominant and a recessive allele. Examples include unattached earlobes (dominant) versus attached earlobes (recessive). The widow’s peak hairline, a cleft chin, rolling tongue, and hitchhiker’s thumb are others. Does the ability to roll your tongue make you more fit for survival? Not really! One common misconception is that dominant traits are more favorable from an evolutionary point of view. Another is that dominant traits are more common. We cannot stress enough that traits, and particularly human traits, are determined by complex interactions between genes and environment. In the early days of genetics, simple observable traits were used to describe inheritance patterns. Once the molecular basis of inheritance was established, scientists could tackle more complex interactions. You will learn more about this in the *Molecular Genetics*unit.

Monohybrid Crosses

Mendel's next experiment involved crossing the heterozygous purple-flowered offspring that resulted from his first cross. The crossing of two individuals heterozygous for a single gene is called a monohybrid cross. Let's see what happened.

Albinism is a recessive disorder related to the deficiency of an enzyme responsible for the synthesis of the pigment melanin. Only homozygous recessive individuals present the albino phenotype.

By Muntuwandi (Albino male)

After his first experiment with crossing involving one trait, Mendel conducted experiments looking at the inheritance of two traits. For example, he crossed true-breeding plants that had yellow, round seeds with true-breeding plants that had green, wrinkled seeds. The resulting F1 generation plants all produced yellow, round seeds.

The story became much more complicated when Mendel crossed the F1 generation plants with each other. This is called a *dihybrid cross*, as it is a cross between two individuals, both of whom are heterozygous for two traits.

In the F2 generation, Mendel observed the original phenotypes (yellow/round, green/wrinkled) and two additional phenotypes: green/round and yellow/wrinkled. The four alleles had combined with each other, independently of each other. This outcome demonstrates the *law of independent assortment*.

Mendel did not know of genes or alleles, he talked only of "units" specifying traits. Let's look in detail at what happens with the genotypes of a dihybrid cross.

As you remember from the Meiosis module, during meiosis I, after crossing-over, the chromosome pairs separate randomly. This means that Y and y will separate, as will R and r. But which goes to which gamete is random. So the Y allele in a chromosome can be associated with a chromosome containing the R allele or the r allele, and the R allele can be paired with a chromosome containing the Y allele or the y allele. Therefore, there are four possible gametes in a dihybrid cross.

There are exceptions to the law of independent assortment. We know now that peas have seven chromosomes, and Mendel happened to study traits coded by genes on different chromosomes, or on distant positions of the same chromosome, which assort independently due to frequent crossing-over. Genes that are very close together on a chromosome do not assort independently, and are said to be*linked*. The closer they are, the more probable that the gametes will receive parental combinations of alleles of those genes. All the genes in a chromosome are called a *linkage group*. Peas have seven linkage groups.

An example of linked traits in humans is human hair and skin color. You may have noticed that red hair and fair skin are often inherited together. This is because the genes for these traits are very close to each other on the same chromosome, and they rarely recombine.

Mendel published his results in 1866, but few read his work, and no one understood it entirely. When he became abbot of the monastery in 1871, he retired from science, and he died in 1884, unaware that his pioneering experiments would form the foundation for the study of modern genetics.

Heredity: Summary

Summary

For centuries, humans observed traits in themselves and in the animals and plants surrounding them. They realized that they were passed on from one generation to another, although not in a completely unequivocal way. Breeders of plants and animals figured out ways to enhance their traits by selecting individuals with the desired characteristics and crossing them with each other. But it was not until the experiments of Gregor Mendel in the nineteenth century that patterns of inheritance started to become clearer. Based on a simple model, the pea plant, with easily observable phenotypes governing flower colors, seed shape, and so on, he proposed that hereditary information was passed along in discrete units he called genes (at that time DNA was not known), and that genes could have two alternatives or alleles. According to Mendel's laws, alleles segregate during sexual reproduction, and combine independently from each other. We know now that genes are DNA sequences found in chromosomes, and the segregation is due to the process of meiosis you have already learned about.

Mendel also coined the terms dominant and recessive to describe the expression of only one form of the gene when both are present in the same organism (that is, when an organism is heterozygous for the gene).

Key Terms

allele	characteristics	dihybrid cross	dominant	F1 generation
F2 generation	gene	genotype	heterozygous	homozygous
law of independent assortment	law of segregation	monohybrid cross	P generation	phenotype
Punnett square	principle of dominance	recessive	trait	true-breeding

Non-Mendelian Inheritance

Objectives:

- Predict the outcomes of crosses involving incomplete dominance.
- Predict the outcomes of crosses involving codominance.
- Exemplify traits that are determined by two or more genes (polygenic inheritance).
- Predict the outcomes of inheritance problems involving epistatic genes and interpret the results.
- Illustrate, with examples, that both genes and environmental influences are responsible for the characteristics of different organisms.

Incomplete Dominance

Gregor Mendel's experiments that you studied earlier involve simple dominance, in which the offspring will show a trait from either one parent or the other, not a blend of those traits. In a case of simple dominance, crossing a red flower and a white one will produce a red flower, not a pink flower. If you think about traits that children inherit from their parents, you will realize that this does not always happen.

Continued genetic research has revealed that inheritance is usually more complicated than simple dominance. Some genes follow Mendelian patterns of inheritance, but many are governed instead by *non-Mendelian inheritance*. Mendel himself realized this when he looked at species and characteristics beyond the scope of his research. For example, although the cross of a true-bred purple-flowered pea plant with a true-bred white-flowered pea plant will result in purple flowers, the cross of true-bred red flower and true-bred white flower snapdragons will result in offspring with pink flowers. If the pink snapdragons are crossed with each other, pink, red, and white flowers will appear in a 2:1:1 ratio, respectively. How can this happen?

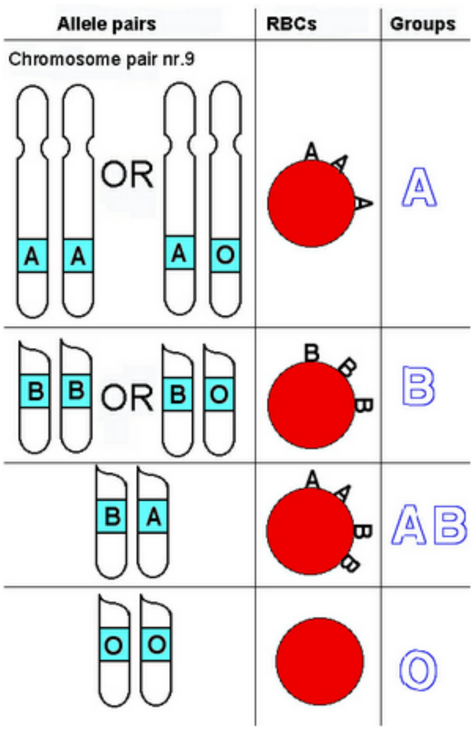
Snapdragons produce flowers with a variety of different colors. By Off2riorob (talk) (Snapdragons) CC-BY-3.0

In this inheritance pattern, called *incomplete dominance*, the heterozygous genotype exhibits an intermediate phenotype. In the snapdragon example, the intermediate phenotype is pink. What is the difference between the purple heterozygotes of the pea flowers and the pink heterozygotes of the snapdragon flowers? Think about what an allele is: a variation of a gene containing the recipe for a protein. In the flower color example, this protein could be an enzyme involved in the synthesis of a pigment. In the case of the pea plant, the presence of a single allele in the heterozygous plant was enough to provide all the pigment needed to give the dominant purple color. However, in the case of the snapdragon, the presence of only one allele does not provide enough pigment to give the flower a fully red hue—but there is enough pigment to tint it partially, thus providing the pink color of the heterozygous flower.

Codominance

So far, You've only learned about genes with two alleles — that is, two options for a gene coming from either parent — present in a chromosome pair. However, more than two alleles may be present in a population, resulting in what is referred to as a multiple-allele system. Human A, B, and O blood groups exist due to three possible alleles of the ABO gene, which codes for an enzyme that modifies carbohydrates present on red blood cells (Components of the Membrane). The A and B alleles code for two versions of the enzyme, while the O allele is mutated and does not code for a functional protein.

A and B are *codominant*, which means that if the individual has both A and B alleles, he will be of AB blood group, which expresses both enzymes. On the other hand, O is recessive, so only the homozygous recessive individuals will have an O phenotype (blood group O).

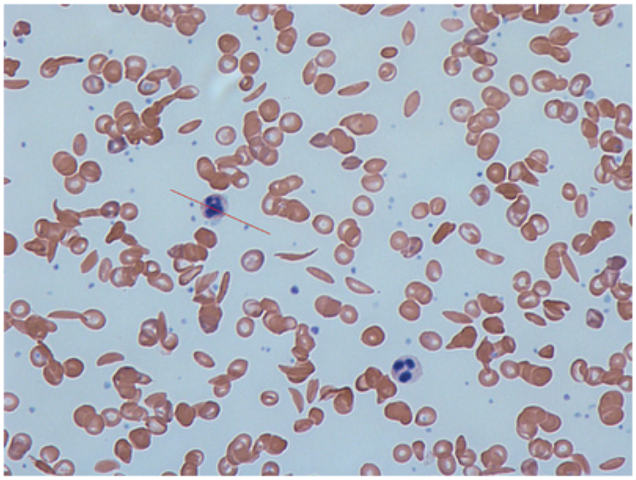


On the left is a diagram of the allele combinations resulting in the different ABO blood groups (middle and right columns). By Pr. Dr. Raynal (Wikipedia) (Allèles ABO) CC-BY-SA-3.0

When referring to human blood groups, you may have heard references to “A negative” or “O positive.” The term “positive/negative” here refers to the presence or absence of a membrane glycoprotein called Rh. The Rh glycoprotein was named after Rhesus monkeys because some of the original studies on the Rh factor were done on these animals. The expression of this protein presents a simple dominance pattern, with the presence of the Rh molecule (Rh positive) being dominant over the absence (Rh negative). So a person's blood is said to be A positive (A+) if both A and Rh molecules are present on that person’s red blood cells.

If the immune system of an Rh negative person is exposed to Rh positive red blood cells, it will produce antibodies against the Rh molecule. The next time the immune system meets Rh positive red blood cells, the antibodies will attack and destroy them. This scenario is rather unusual, except when a mother who is Rh negative is carrying an Rh positive baby. After the first pregnancy, her immune system develops anti-Rh antibodies, and in subsequent pregnancies these antibodies can cross the placenta and attack the red blood cells of the fetus. This results in hemolytic anemia, and could seriously affect the fetus. Luckily, Rh negative mothers today receive an anti-Rh antibody injection that prevents development of the anti-Rh response.

Another example of codominance is *sickle cell anemia* and *sickle cell trait*. In sickle cell anemia, hemoglobin — the protein that transports oxygen in the blood — is defective, giving the red blood cells a characteristic “sickled” appearance.



Normal (round) and sickled (elongated) red blood cells in a blood smear. By Dr Graham Beards (Sickle cells)

A change in one amino acid in the structure of hemoglobin makes it defective: the blood cells cannot transport oxygen effectively, and they accumulate in the blood vessels.

Patients homozygous for the defective allele have sickle cell anemia. Heterozygotes (having one “good” and one “bad” allele for hemoglobin) will present both types of hemoglobin. That condition is called sickle cell trait, where the individuals will present many red blood cells that become sickled under conditions of extreme physical exertion or low atmospheric oxygen. So while the phenotype can be considered intermediate, in fact it is actually a case of codominance. Interestingly, the sickle cell trait protects against malaria infection, and therefore remains prevalent in Sub-Saharan Africa, where malaria is endemic.

Polygenic Inheritance

Some traits, such as skin color and height, are determined by multiple genes. In humans, skin color is determined by at least three different genes, and probably more. This concept is called *polygenic inheritance*. Variation along a continuum often indicates that a trait has polygenic inheritance. Most visible traits are polygenic, and their genetics patterns are rather complicated.

In some instances the polygenic effect is rather straightforward. This situation is called epistasis. In epistasis:

- The products of two or more genes result in a certain phenotype.
- The expression of one gene masks or changes the expected phenotype of one or more other genes.

For instance, in Labrador retrievers, the allele for black fur color (B) is dominant with regard to the allele for brown (“chocolate”) fur color (b). However, there are also yellow Labs. The coats of yellow labs are created through epistasis. Another gene, E/e, is in play.

The reason for this distinction is an interaction between the two genes. The B gene is involved in the synthesis of the pigment melanin: B results in a black, and b in a brown color. The E gene is related to melanin deposition in the fur: E causes melanin to be deposited, and e suppresses melanin deposits. Being homozygous for e — that is, having the ee genotype (no melanin deposition) — results in fur with neither brown nor black pigment, which appears yellow, independent of the black or chocolate allele (B or b).

Pleiotropy

Many single genes can have numerous different effects, rather than just two. This capability is called*pleiotropy*. In the 1930s, for instance, researchers found a gene in chickens that leads most obviously to feathers that curl out, but that also (and less visibly) leads to increased metabolism, blood flow, body temperature, and digestive capacity, as well as fewer eggs laid. This pleiotropic gene is called the “frizzle” gene because of its effect on the appearance of the chickens.

Chicken expressing the frizzle gene. By Just chaos (Leghorn Frizzle Chicken) CC-BY-2.0

Another gene known to have pleiotropic effects in humans is fibrillin-1, which codes for a connective tissue protein. Marfan syndrome is caused by mutations in the fibrillin-1 gene. People with Marfan syndrome are usually tall and thin with long arms and legs, and they are at risk for heart disease and eye problems. The symptoms can be treated individually, and people with Marfan syndrome may have normal life spans.

Application Spotlight: Effect of the Environment

Characteristics that are influenced by environmental as well as genetic factors are called *multifactorial*. The idea of "nature versus nurture" — in other words, the relative influence of genetics versus environmental factors — has been and still is debated. Just looking at the genes of a given organism will not determine how that organism will develop and act. Even identical twins will show different characteristics, depending on the environment in which they live. Everyone is a product of their environment as well as their genetics.

Even when influenced by the environment, phenotypes have a normal range of expression. For instance, human height varies based on nutrition and genetics, but not many people are shorter than 4½ feet or taller than 7 feet. The range of phenotypic possibilities is called the *norm of reaction*. Hydrangeas, for example, may be blue, pink, or purple, but they are never naturally orange. Hydrangeas are blue in acidic soil with available aluminum, and they are pink in alkaline soil without available aluminum.

Some human characteristics have a narrow norm of reaction, such as blood type. Others have a wide norm of reaction, such as the number of blood cells in humans, which varies depending on factors that include physical fitness, presence or history of infections, and even the altitude at which a person lives.

The environment also affects human genes. Serotonin, a neurotransmitter that acts inside brain cells, lowers anxiety and depression during traumatic times. Mutations in the serotonin transporter gene may cause a reduced ability to cope with stress. That does not mean that the person is always depressed, but if the environment produces stress, the person may become depressed more easily than a person with unmutated serotonin transporter genes.

Taking a newborn blood sample for PKU testing. By Staff Sgt Eric T. Sheler, U.S. Air Force (Phenylketonuria testing) Public Domain

You already learned about PKU, a pleiotropic disorder caused by defects in a single gene coding for an enzyme that converts the amino acid phenylalanine to tyrosine. Newborns are tested for this defect very early in life, so that if the results are positive, they can be given a diet limiting phenylalanine ingestion. That way, the toxic buildup is prevented and the children can develop normally. PKU is an example in which environmental factors can modify gene expression.

Non-Mendelian Inheritance: Summary

Summary

The relationship between alleles is not always as simple as dominant/recessive. Sometimes the resulting phenotype is an intermediate of the dominant and the recessive phenotypes (as in incomplete dominance). Other times, two dominant alleles are expressed concurrently (as in codominance).

In the Mendelian pattern, it is possible to pinpoint a gene/allele coding for a specific protein to a particular trait. There are, however, more complex patterns to consider as well, such as epistasis, in which genes can influence each other's expression, and polygenic inheritance, in which more than one gene is responsible for a particular trait.

It is important to remember that genes alone do not determine everything — the environment plays an important role in shaping characteristics, too. There is lots to explore in the "nature versus nurture" relationship.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

codominant epistasis incomplete dominance
pleiotropy polygenic

Human Inheritance

Objectives:

- Analyze inheritance patterns of human traits and disorders.
- Compare the terms dominant, recessive, autosomal, and sex-linked.
- Describe how sex is determined in humans and other organisms.
- Determine genotypes and phenotypes of possible offspring in crosses involving sex-linked traits.
- Explain how errors in meiosis can result in aneuploidy.
- Analyze the information in a pedigree to determine the mechanism of inheritance (autosomal/sex-linked, recessive/dominant).
- Determine possible genotypes of individuals symbolized in a pedigree.
- Analyze inheritance patterns of human traits and disorders.

Introduction to Human Inheritance

There are around seven billion people on our planet, and everybody looks at least a little different from everyone else. Siblings are different from each other, and even identical twins—who are genetically identical—can show different traits over time. However, when we look at families over several generations, it becomes obvious that certain traits appear generation after generation. How can this extraordinary variability be explained?

In the previous module you learned about the inheritance patterns (Mendelian and non-Mendelian) that were studied using models such as peas, snapdragons, and dogs. Another organism that is often used is the fruit fly Drosophila. Common to these organisms is that they are relatively easy to breed and cross under controlled conditions. They also have a relatively short lifespan, which allows the tracking of traits for many generations. In the case of humans, genetic analysis is much more complicated. We live under a variety of conditions, so the environmental influences are much stronger. Humans choose their mates freely, families are usually smaller, and our lifespan is the same as that of the geneticists. Much information about transmission of human traits comes from the study of pedigrees, a chart of genetic connections similar to a family tree. In this module, you'll learn how to read pedigrees. You'll also look at the different patterns and factors that affect human inheritance.

Patterns of Inheritance

Many human traits are clear-cut and easy to test. These include the ability to bend back the thumb nearly 90 degrees (known as "hitchhiker's thumb"), to roll the tongue into a U-shape, and to taste a bitter chemical called phenylthiocarbamide. While these traits do not have considerable implications on human health and species survival, many others do. Some of them are related to disorders such as sickle cell anemia, hemophilia, Tay-Sachs disease, and Down syndrome, to name a few.


Left, a tongue-rolling girl. Tongue rolling is a dominant trait that follows Mendelian inheritance. By Gideon Tsang (Rolled tongue flikr)CC BY-SA 2.0 Right: Queen Victoria and the royal family. Hemophilia, a blood clotting disorder transmitted by sex-linked inheritance, affected 18 of Queen Victoria's 69 descendants. By M.W. Ridley (Queen Victoria and Royal Family) Public Domain

Some human traits (like the tongue-rolling ability) follow Mendelian patterns, which means they are controlled by a single gene. One of the alleles is *dominant*, and the other is *recessive*. Human genetic disorders following a Mendelian pattern are the least common. Most of those tend to be recessive, meaning that the defective allele causing the disorder is recessive.

That means only homozygous recessive individuals will show the disorder. The heterozygotes will be *carriers*, so while they carry the defective allele (and sometimes even express it, as in the sickle cell trait), they phenotypically do not present the full disorder. Other disorders may be dominant, wherein the defective allele causing the disorder is dominant. In this case, the presence of only one allele is enough to provoke the appearance of the disorder, and only homozygous recessive individuals show the healthy phenotype.

As you remember from the Meiosis module, of the 23 pairs of chromosomes found in a human somatic cell, 22 are autosomes, and the 23rd pair are sex chromosomes. Sex chromosomes are of two types: X and Y. Males have one X and one Y chromosome (XY), and females have two copies of the X chromosome (XX). If the gene responsible for the disorder is present on the autosomes, it is called an autosomal disorder. The term "autosomal" refers to chromosomes that are not sex determining. On the other hand, if the responsible gene is present on a sex chromosome, it is called a sex-linked disorder. Due to the fact that the male Y chromosome is very small and contains only genes related to sex determination, sex-linked disorders are due to defective alleles on the X chromosome. The following table shows the inheritance patterns of some human genetic disorders and abnormalities.

Pattern	Disorder	Main symptoms
Mendelian: autosomal dominant	Huntington's disease; Progeria	Degeneration of the nervous system; Premature aging
Mendelian: autosomal recessive	Cystic fibrosis; Sickle cell anemia	Abnormal glandular secretions provoking lung and digestive dysfunction; Anemia causing effects on the whole body
Sex-linked	Hemophilia; Red-green color blindness	Inadequate blood clotting; Inability to distinguish red from green
Changes in chromosome number	Down syndrome; Klinefelter syndrome; Turner syndrome	Mental impairment, heart defects; Sterility, mild mental impairment; Sterility, abnormal ovaries
Changes in chromosome structure	Chronic myelogenous; Leukemia	Overexpression of white blood cells; Organ dysfunction

Sex-Linked Traits

In humans, determination of sex is dependent on a special pair of chromosomes called the sex chromosomes. The other 22 pairs are called autosomes.

There are two types of sex chromosomes — X and Y. The X chromosome is large and carries many genes unrelated to sex. The Y chromosome, on the other hand, is much smaller and carries only the genes containing the instructions for "maleness," which are molecular signals that instruct the fetal gonads (sex organs) to develop as testes and not ovaries. In the absence of the Y chromosome, a fetus develops as female.

Females have two copies of the X chromosome (XX), while males carry one X and one Y (XY). When gametes are formed, females will have only gametes that contain the X chromosome; males will have some gametes with X and others with Y. For a male baby, a Y gamete from the father has to meet the mother's gamete. So the determination of a baby's sex depends on which gamete the father contributes.

About one out of every ten men is color-blind. People who are color-blind are unable to distinguish between certain colors, especially green and red. On the other hand, only about one out of every 200 women is color-blind. Why is there such a drastic difference between the sexes?

In 1910, an American geneticist named Thomas Hunt Morgan made an observation that began to shed some light on this question. One morning, when peering through a hand lens at a male fruit fly, he noticed that it didn't look right. Instead of having the normally brilliant red eyes of wild-type Drosophila melanogaster, this fly had white eyes. Morgan was particularly interested in how traits were inherited and distributed in developing organisms, and he wondered what caused this fly's eyes to deviate from the norm.


A fruitfly (Drosophila melanogaster) displaying the normal red-eyed phenotype. By André Karwath (Drosophila melanogaster - side)CC-BY-SA-2.5

He bred the white-eyed male with several true-bred, red-eyed females and obtained all red-eyed flies in the first generation. (Remember, true-bred organisms have a homozygous genotype.)

Morgan did crosses between the F1 hybrids, and he observed the following: 75 percent of the offspring were red-eyed, and 25 percent were white-eyed. So far, the results supported the Mendelian pattern of 3:1. But then he noticed something odd: all of the white-eyed flies were male.

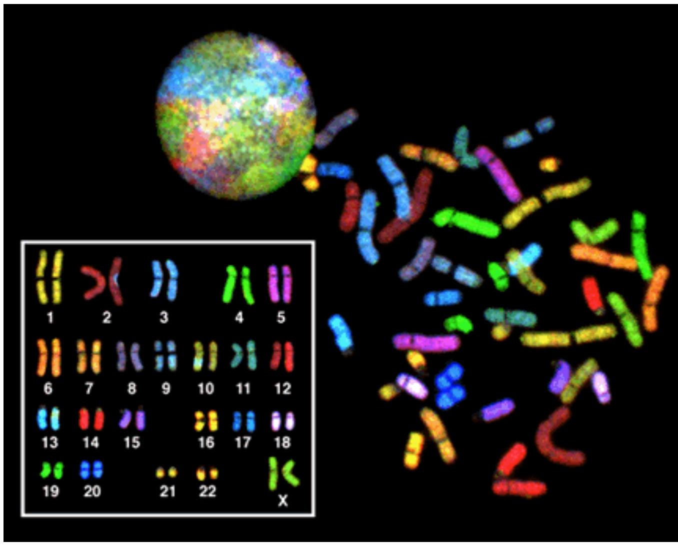
Morgan wondered why the white-eye trait was associated with the male sex. In Morgan's time, the idea that an additional pair of chromosomes was responsible for sex determination had just emerged. There were two plausible possibilities: either the trait was somehow linked to the sex chromosome, or the white-eyed trait was lethal for females, meaning that females with the phenotype would not develop past the egg stage. Morgan conducted a series of crosses using the F2 generation, and obtained some white-eyed females also, showing that the white-eyed characteristic was not lethal for females.

In a famous subsequent experiment, Morgan crossed white-eyed females with white-eyed males, obtaining only white-eyed offspring. This cross confirmed that the eye color trait was linked to the female sex chromosome. Because of this, the males are what is called *hemizygous* for this trait: they have only one allele present, which is in the X chromosome. The Y chromosome does not have the same genes as the X chromosome. Males have no heterozygous option: they either have the dominant allele (red-eyed) or the recessive allele (white-eyed).

The trait of white eyes in fruit flies is a *sex-linked trait*. It is located on a sex chromosome, so it occurs at different rates in males and females. Because it is located on the X chromosome, it is more specifically called an *X-linked gene*. In humans, the trait of color blindness results from a gene on the X chromosome. So do some more serious diseases, including Duchenne muscular dystrophy, which causes progressive muscle weakness. People with this disorder rarely live past the age of 25. A gene on the X chromosome codes for a muscle protein that is missing in people with Duchenne muscular dystrophy.

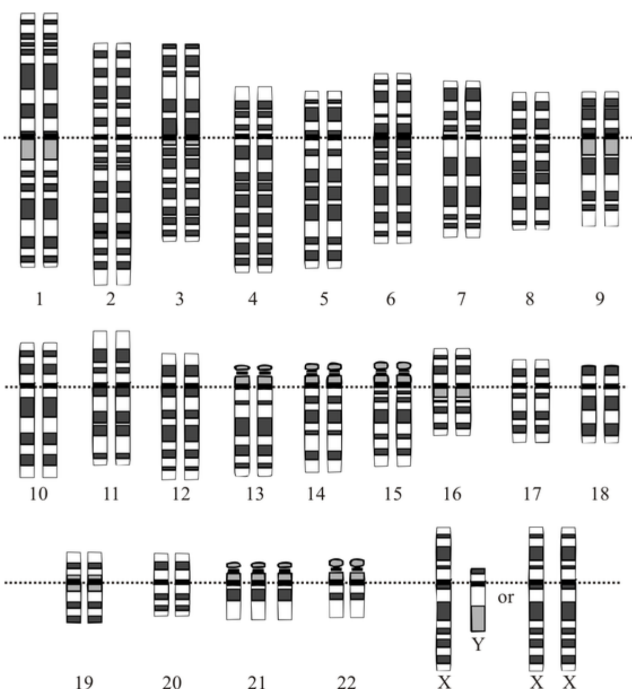
Chromosomal Inheritance

Human chromosomes are numbered from largest to smallest. Each of the 22 pairs of *autosomal*chromosomes have an identifying number, from 1 to 22; chromosome 1 is the biggest and chromosome 22 is the smallest. As you already know, the pair of sex chromosomes are named either X or Y. The chromosomes of a cell can be visualized using a process that takes a picture of the cell during mitosis, when chromosomes are easily visible. The picture that is produced is called a karyotype.



A karyotype visualizes the chromosomes of a cell. By National Human Genome Research Institute (Sky spectral karyotype) Public Domain

Karyotypes can be used to identify chromosomal abnormalities in cells or in developing fetuses. Amniocentesis is a medical procedure used to sample fetal cells from a pregnant mother. These cells, which are rapidly dividing, can be used to create a karyotype of the fetus. This karyotype can then help identify potential chromosomal abnormalities in the developing child. Abnormalities could include extra chromosomes, missing chromosomes, and even extra or missing pieces of chromosomes.



By National Human Genome Research Institute (Down Syndrome Karyotype) Public Domain

This karyotype has an extra chromosome 21. This condition is called “trisomy 21” because the cell has three ("tri") of these chromosomes instead of the usual two. This condition is more commonly called “Down syndrome.” There are relatively few examples of such large-scale chromosomal anomalies. Down syndrome results from an extra copy of one of the smallest chromosomes. Extra or missing copies of sex chromosomes can also result in viable embryos. Embryos with extra or missing chromosomes are often nonviable, and other chromosomal anomalies are not generally seen.

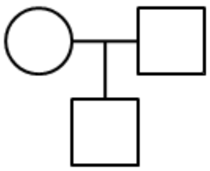
Aneuploidy is the condition of having too many or too few chromosomes, which results from errors in meiosis. If crossing-over does not occur correctly, the chromosomes can have extra pieces or missing pieces. If the chromosomes do not separate properly during anaphase, the resulting cells can have extra or missing chromosomes. This improper separation of chromosomes is called *nondisjunction*. Nondisjunction can occur in either meiosis I or meiosis II.

The following activity looks at aneuploidy that results from nondisjunction in Meiosis I.

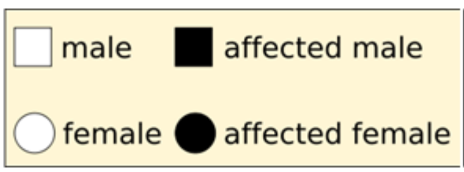
Pedigrees

Pedigrees are maps that can be used to trace genetic traits through generations of individuals. Pedigrees use the following symbols:

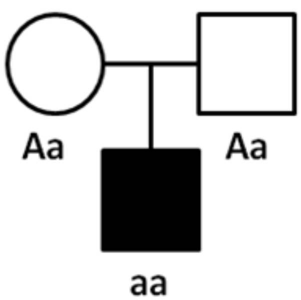
- Males are symbolized by squares.
- Females are symbolized by circles.
- Mated individuals are connected by a horizontal line, and children are connected to them by vertical branches extending down from the line.



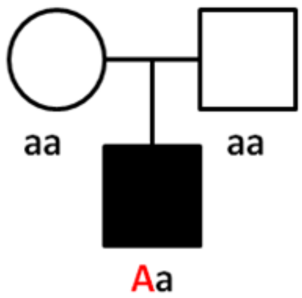
- Individuals expressing a genetic trait are shaded; individuals not expressing the trait are not shaded.



Pedigrees can be used to determine if the trait being studied is dominant, recessive, or X-linked. A trait is recessive if a child anywhere in the family has the trait and both parents do not. This must be the case because if the child has the trait and the parents do not, the only possible genotype option is:



It would not be possible for an affected individual to show a dominant trait that was not expressed in his or her parents, because this sets up an impossible situation where the child would have an allele that could not come from either parent:

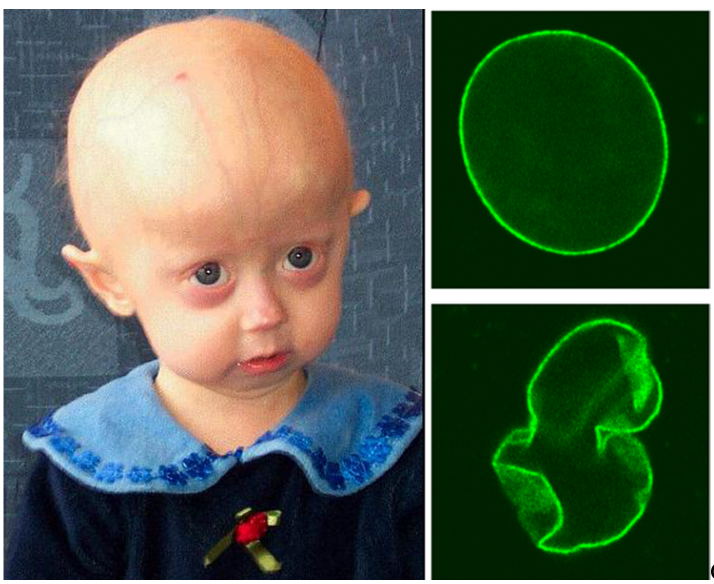


If there is no case where a child expresses the trait but neither parent does, then the pedigree is likely to be dominant. In a real-world situation, researchers would need to look at hundreds of individuals to be sure that this conclusion is statistically significant. But for the purposes of this activity, you will look at only a few individuals.

A trait that is significantly more common in males than females is likely to be X-linked. Again, in a real-world situation a much larger sample size would be needed to be sure of these conclusions. The X-linked traits used here are also recessive, so you will notice that they show both characteristics of being X-linked (mostly males) and characteristics of being recessive (child demonstrating a trait that neither parent has).

Application Spotlight: Progeria

Progeria (Hutchinson-Gilford Progeria Syndrome, HGPS)



Child with progeria. HGPS is a childhood disorder caused by mutations in one of the major architectural proteins of the cell nucleus. In HGPS patients, the cell nucleus has dramatically aberrant morphology (bottom, right) rather than the uniform shape typically found in healthy individuals (top, right). By P Scaffidi (Hutchinson-Gilford Progeria Syndrome) CC BY 2.5

HGPS is an extremely rare (one case per eight million live births) autosomal dominant disorder characterized by accelerated aging. The disorder is caused in the gene coding for lamin A, a protein involved in chromosome organization. The defective protein accumulates in the nuclear membrane of the cells, affecting many cellular processes. Symptoms start before age two, with thinning skin and weak muscles and bones. Aging is estimated to be eight to 10 times faster than normal. Patients die in their teens from stroke or heart attack. How do people “get” progeria? It is important to remember that because progeria patients die at a very young age, progeria is not inherited, but only appears as a random mutation. This explains its fortunately very low incidence.

Human Inheritance: Summary

Summary

This module explored the application of inheritance patterns to human characteristics and hereditary disorders. Many human conditions follow the Mendelian pattern, with a recessive allele being responsible for the diseased phenotype most of the time. In other cases, there may be a linkage of genes to a sex chromosome, most commonly the X chromosome. The traits for those genes are called sex-linked traits, and they were originally described by Morgan in his classical fruit fly experiments.

Some genetic disorders are caused by errors in the meiotic process leading to a lack of separation of chromosome pairs, called nondisjunction. These disorders can be visualized by using karyotypes.

Pedigrees or family trees are very useful to trace genetic traits in families. Following the trail of a particular disorder in a pedigree can clarify what its inheritance pattern is, and can provide useful information for genetic counseling.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

aneuploidy	autosomal	karyotype
pedigree	segregation	sex-linked

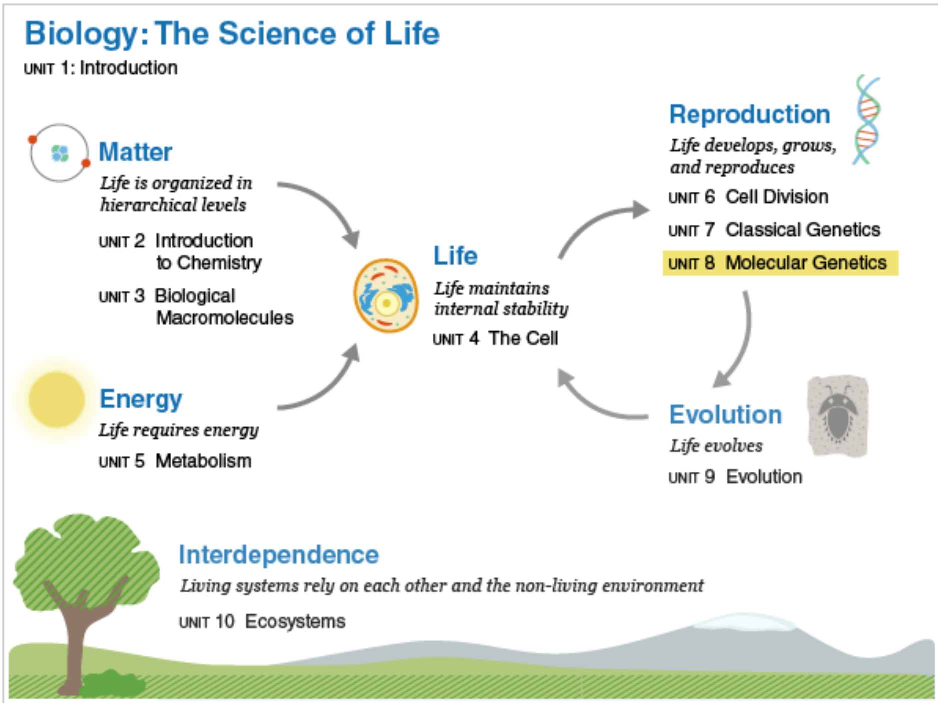
Unit Summary: Classical Genetics

One of the common characteristics of living organisms is that they carry their genetic information in the DNA molecule. However, long before the molecular basis of inheritance was known, humans observed traits and often manipulated them when breeding plants or animals with desirable characteristics.

In this unit you learned, through some of the groundbreaking experiments and observations of scientists such as Mendel and Morgan, the most common inheritance patterns. From simple dominance to polygenic inheritance, there are many ways the discrete units of inheritance Mendel called “genes” (without knowing precisely what they were), can combine and influence each other. However, not everything is determined by genes. Further studies have shown that the environment plays an important role in how those genes are or are not expressed. In the next unit, you will learn about how genetic information is inherited, expressed, and regulated at the molecular level.

Introduction to Molecular Genetics

- In the Classical Genetics unit, you learned about the mechanisms of inheritance, focusing mostly on the organism and population levels in the hierarchy of life. In the *Molecular Genetics* unit, you will learn about the molecular basis of traits that characterize the organisms. You will develop an understanding on the molecular level of how genetic information is organized and used by living organisms.



DNA carries all the information needed to build living organisms. Information in DNA is used to build proteins, which cause the physical traits, or phenotypes, of an organism. The central dogma describes how the information in the DNA is used to build a molecule of mRNA, which provides instructions to the ribosome for building the proteins that cause the physical traits.

If we compare traits of individuals within species, we find that they share certain traits, but they also show many differences among individuals. Fore example, rice (pictured below) shows variation in shape and color of seeds/grains. People also come in different shapes and sizes. What determines physical traits that characterize a person: hair color, eye color, height, weight? How about behavior: some people are risk-takers, others get easily anxious; some people love to be in large noisy crowds, others prefer quiet and solitude. What is more important in determining physical and behavioral traits — genetics or environment? This classic “nature vs. nurture” argument should not be phrased as “either/or,” because the answer is “both.” *The interactions between genes and environment determine the traits.*


Rice seed collection. Source: BY Kleomarlo (Rice diversity) CC-BY-2.0

A better question to ask is “To what extent is each trait determined by genetics and to what extent by environment?” The answer will vary by trait and is still being researched. It is not a trivial question to answer, and the numbers below are only rough estimates.

Estimated Genetic Contribution

Height	80% of variation due to genetics
Type I diabetes	70-90% of variation due to genetics
Type II diabetes	25% of variation due to genetics

In *Molecular Genetics*, first you will learn about the storage, transmission, and expression of genetic information (*central dogma of molecular biology*), whereby the information content in *DNA*sequences, called *genes*, is ultimately converted to a protein. Then you will look at the structure of genes and genomes and at the interactions between genes and the environment. Finally, you will examine how humans are able to manipulate genes through *biotechnology*.

DNA Function

Objectives:

- Relate the cellular location of DNA and RNA to their function.
- Describe how DNA functions as an information storage molecule.
- For DNA replication: identify molecular requirements, specify cellular location, and predict product.
- List the steps of PCR, and describe what happens in each step.
- Compare and contrast PCR and DNA replication.
- Transfer use of PCR amplification of tandem repeats to other applications, such as paternity.

Introduction to DNA Function and Replication

If you look at people around you, you will probably notice a fairly large variation in height. Some people are taller than you, while others are shorter than you. Consider this trait as an example that you want to understand on the molecular level. What kinds of molecules may be involved in determining a person's height? If you and your parents are relatively short (or tall), you may say that you inherited the short (or tall) stature from your parents. What molecule is involved in the transmission of information from one generation to the next? DNA. How does information contained in DNA affect your height? One possible explanation is that your DNA contains a gene encoding a protein called growth hormone. This protein is produced by the pituitary gland, travels to other tissues, and delivers a signal for the cells to grow and divide. Changes in the amount of protein produced or the sequence of amino acids in the protein can affect the function. If bone and muscle cells receive only a small number of signal molecules, the person will end up with a short stature. If they receive a large number of signal molecules, the person may end up being very tall. For a signaling protein (hormone) to deliver the signal, there must be a protein that can bind the hormone and receive the signal (receptor protein). The variation in height will result from any of the following:

- The amount of signaling protein produced.
- The amount of receptor produced in different tissues.
- How tightly the hormone and the receptor bind to each other; small variations in specific amino acids of either molecule can change the binding interaction.

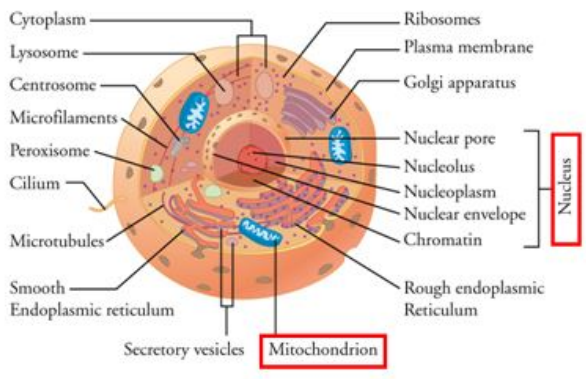
Note that a person who inherits "tall" genes may never grow very tall because of illness or inadequate nutrition. Conversely, a person who inherits a faulty growth hormone gene may grow relatively tall if he or she is treated with growth hormone. These are examples of how environment and genes interact to produce traits and phenotypes.

In this module, you will learn about how genetic information is stored in DNA and copied for the next generation. You will also look at a practical application of the process of DNA replication called the polymerase chain reaction (PCR). In the next module, you will learn how the genetic information stored in genes is expressed, resulting in the variety of traits and phenotypes of all organisms.

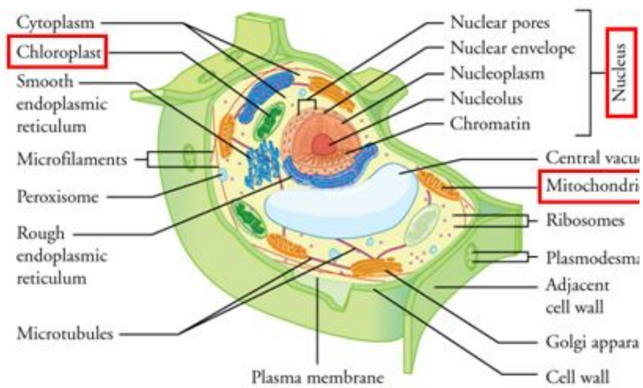
Nucleic Acid Functions and Location

Nucleic acids are macromolecules that carry out two main functions in the cell: storage of genetic information and synthesis of proteins. Two types of nucleic acids specialize in these functions: deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA is the genetic material that stores information for making proteins in all living organisms. Some viruses store their genetic information in RNA instead of DNA. This may seem as an exception to the universal use of DNA as genetic material; however, viruses are not cellular, and are not considered living organisms. DNA is found in the *nucleus* of eukaryotes and in two cellular organelles: *chloroplasts*, and *mitochondria*.

Location of DNA in Cells



Eukaryotic (Animal) Cell

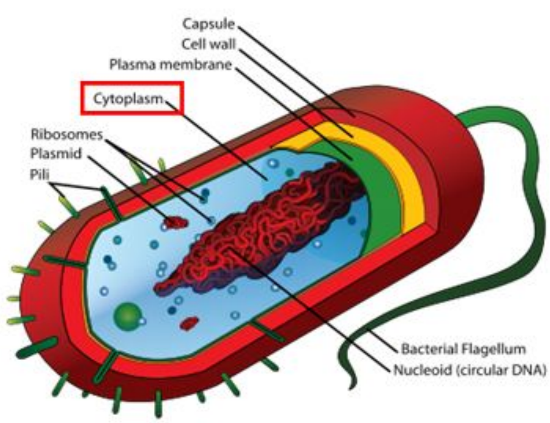


Eukaryotic (Plant) Cell

Location of DNA in Prokaryotic Cells

In prokaryotes, DNA is not enclosed in a separate compartment, but found in the cytoplasm.

Bacteria Cell



Regardless of where DNA is stored in the cell, it contains instructions for building proteins. For protein synthesis to occur, genetic information stored in DNA must first be copied into RNA. In eukaryotic cells, RNA is transported to the cytoplasm, where protein synthesis takes place. Thus, while both RNA and DNA can contain instructions for making proteins, DNA is used for storage of this information, while RNA is directly involved in making proteins.

To understand in more detail how nucleic acids function in transmission of genetic information and in protein synthesis, you must first consider the structures of these molecules and the relationship between structure and function.

Information Content of DNA

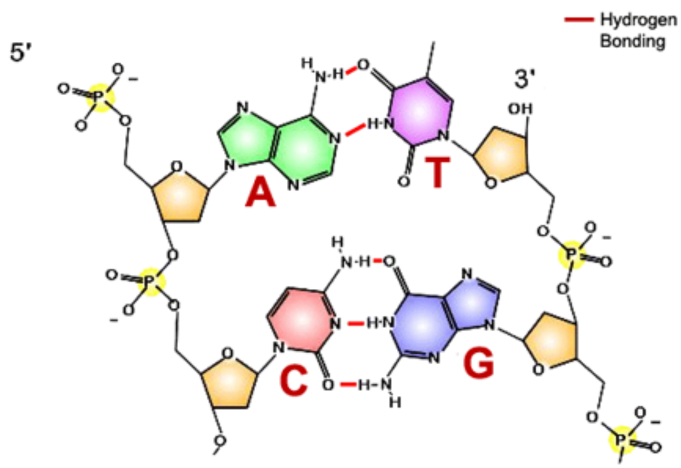
The genetic information of an organism is stored in DNA molecules. How can one kind of molecule contain all the instructions for making complicated living beings like ourselves? What component or feature ofDNA can contain this information? It has to come from the nitrogen bases, because, as you already know, the backbone of all DNA molecules is the same. But there are only four bases found in DNA : G, A, C, and T. The sequence of these four bases can provide all the instructions needed to build any living organism. It might be hard to imagine that 4 different “letters” can communicate so much information. But think about the English language, which can represent a huge amount of information using just 26 letters. Even more profound is the binary code used to write computer programs. This code contains only ones and zeros, and think of all the things your computer can do. The DNA alphabet can encode very complex instructions using just four letters, though the messages end up being really long. For example, the *E. coli* bacterium carries its genetic instructions in a

DNA molecule that contains more than five million nucleotides. The human genome (all the DNA of an organism) consists of around three billion nucleotides divided up between 23 DNA molecules, or chromosomes.

The information stored in the order of bases is organized into genes: each gene contains information for making a functional product. The genetic information is first copied to another nucleic acid polymer,RNA (ribonucleic acid), preserving the order of the nucleotide bases. Genes that contain instructions for making proteins are converted to messenger RNA (mRNA). Some specialized genes contain instructions for making functional RNA molecules that don't make proteins. These RNA molecules function by affecting cellular processes directly; for example some of these RNA molecules regulate the expression of mRNA. Other genes produce RNA molecules that are required for protein synthesis, transfer RNA (tRNA)and ribosomal RNA (rRNA).

In order for DNA to function effectively at storing information, two key processes are required. First, information stored in the DNA molecule must be copied, with minimal errors, every time a cell divides. This ensures that both daughter cells inherit the complete set of genetic information from the parent cell. Second, the information stored in the DNA molecule must be translated, or expressed. In order for the stored information to be useful, cells must be able to access the instructions for making specific proteins, so the correct proteins are made in the right place at the right time.

Both copying and reading the information stored in DNA relies on base pairing between two nucleic acid polymer strands. Recall that DNA structure is a double helix (see figure below).



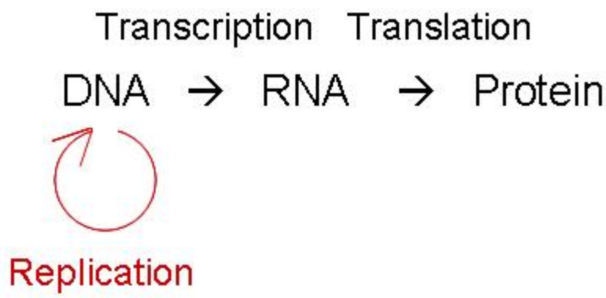
DNA Structure (B-helix)

Structure of DNA double helix. On the left: Sugar-phosphate backbone is shown in yellow, specific base pairings via hydrogen bonds (red lines) are colored in green and purple (A-T pair) and red and blue (C-G). On the right: Three-dimensional structure of DNA double helix. Click on the checkboxes to highight the A-T and C-G basepairs. Click on 'Spin On' to automatically rotate the DNA helix structure. Graphic by Madeleine Price Ball (DNA chemical structure) CC-BY-SA-2.0

The sugar deoxyribose with the phosphate group forms the scaffold or backbone of the molecule (highlighted in yellow in the figure above). Bases point inward. Complementary bases form hydrogen bonds with each other within the double helix. See how the bigger bases (purines) pair with the smaller ones (pyrimidines). This keeps the width of the double helix constant. More specifically, A pairs with T and C pairs with G. As we discuss the function of DNA in subsequent sections, keep in mind that there is a chemical reason for specific pairing of bases.

To illustrate the connection between information in DNA and an observable characteristic of an organism, let's consider a gene that provides the instructions for building the hormone insulin. Insulin is responsible for regulating blood sugar levels. The insulin gene contains instructions for assembling the protein insulin from individual amino acids. Changing the sequence of nucleotides in the DNA molecule can change the amino acids in the final protein, leading to protein malfunction. If insulin does not function correctly, it might be unable to bind to another protein (insulin receptor). On the organismal level of organization, this molecular event (change of DNA sequence) can lead to a disease state — in this case, diabetes.

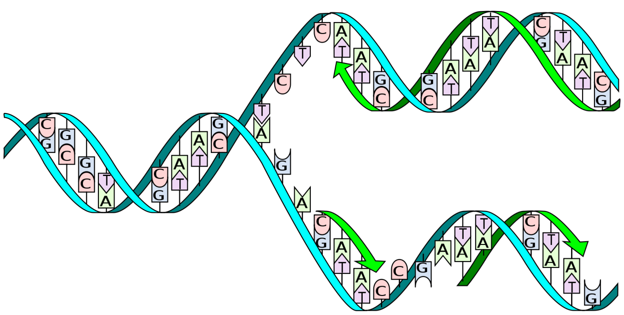
DNA Replication



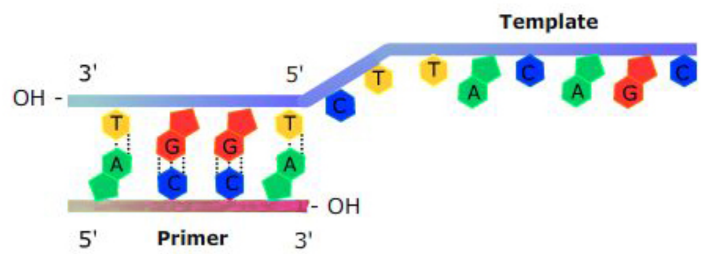
Before a cell can divide, it must first make a copy or *replica* of its DNA through a process called *DNA replication*. This process occurs during the S phase of the cell cycle, so by the time the cell enters the mitotic phase, there are two copies of the DNA molecule. This process of DNA replication takes place in the nucleus of the cell in eukaryotes, where the DNA molecule is found. It also occurs in the mitochondria in animal cells and chloroplasts in plant cells.

Think about this: it is critical that the copies of the DNA are exactly like the original, so the daughter cells are identical to the parent cells. There may be changes to DNA sequence by mutations (as you will see in another section), and meiosis introduces some genetic variability when gametes are produced. But for unicellular organisms or for somatic cells, DNA replication is a process that requires high fidelity.

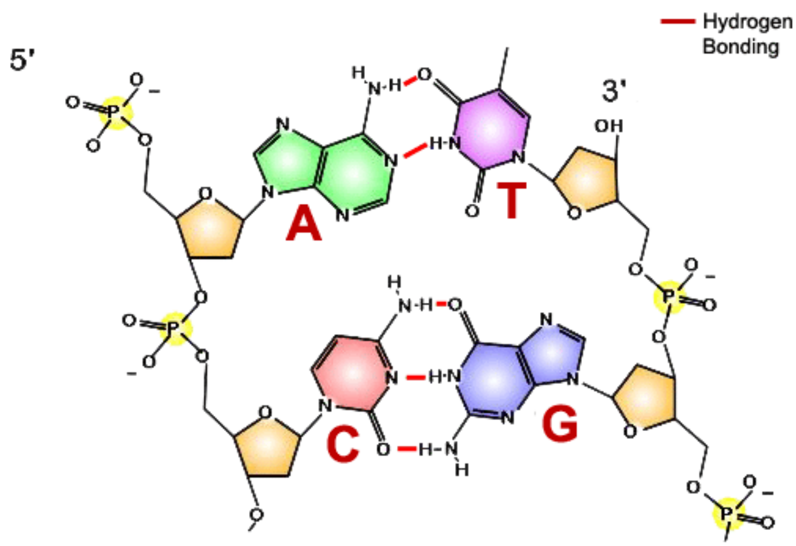
The process of DNA replication is catalyzed by a type of enzyme called *DNA polymerase* (*poly* meaning many, *mer* meaning pieces, and *ase* meaning enzyme; so an enzyme that attaches many pieces of DNA). Observe the figure below: the double helix of the original DNA molecule separates (blue) and new strands are made to match the separated strands. The result will be two DNA molecules, each containing an old and a new strand. Therefore, DNA replication is called semiconservative. The term *semiconservative* refers to the fact that half of the original molecule (one of the two strands in the double helix) is "conserved" in the new molecule. The original strand is referred to as the *template strand* because it provides the information, or template, for the newly synthesized strand.


By Madprime(wikipedia) (DNA replication split horizontal) CC BY-SA 2.0

DNA replication relies on the double-stranded nature of the molecule. One double stranded DNA molecule, when replicated, will become two double-stranded molecules, each containing one original strand and one newly synthesized strand. You remember that the two strands of DNA run antiparallel: one from the 5' to the 3', and the other from the 3' to the 5'. The synthesis of the new DNA strand can only happen in one direction: from the 5' to the 3' end. In other words, the new bases are always added to the 3' end of the newly synthesized DNA strand. So if the new nucleotide is always added to the 3' end of an existing nucleotide, where does the *first* nucleotide come from? In fact, DNA polymerase needs an "anchor" to start adding nucleotides: a short sequence of DNA or RNA that is complementary to the template strand will work to provide a free 3' end. This sequence is called a *primer*.

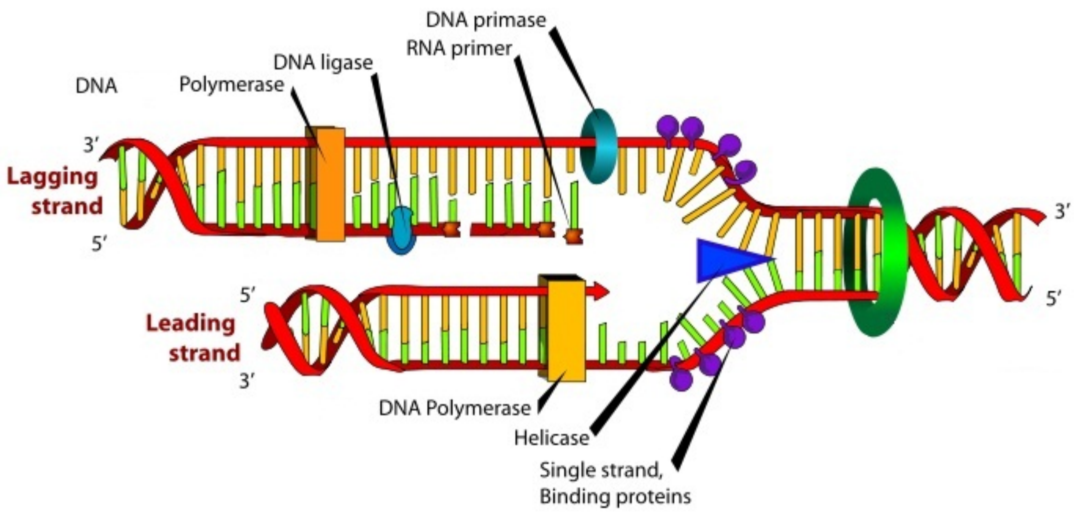


How does DNA polymerase know in what order to add nucleotides? Specific base pairing in DNA is the key to copying the DNA: if you know the sequence of one strand, you can use base pairing rules to build the other strand. Bases form pairs (base pairs) in a very specific way. The figure shows how A (adenine) pairs with T (thymine) and G (guanine) pairs with C (cytosine). It is important to remember that this binding is specific: T pairs with A, but not with C. The molecular recognition occurs because of the ability of bases to form specific hydrogen bonds: atoms align just right to make hydrogen bonds possible. Also note that a larger base (purine, A or G) always pairs with a smaller base (pyrimidine, C or T).



By Madeleine Price Ball (DNA chemical structure) CC-BY-SA-2.0

Now that you understand the basics of DNA replication, we can add a bit of complexity. The two strands of DNA have to be temporarily separated from each other; this job is done by a special enzyme, *helicase*, that helps unwind and separate the DNA helices. Another issue is that the DNA polymerase only works in one direction along the strand (5' to 3'), but the double-stranded DNA has two strands oriented in opposite directions. This problem is solved by synthesizing the two strands slightly differently: one new strand grows continuously, the other in bits and pieces. Short fragments of RNA are used as primers for the DNA polymerase.



By Mariana Ruiz (DNA replication) Public Domain

Polymerase Chain Reaction (PCR)

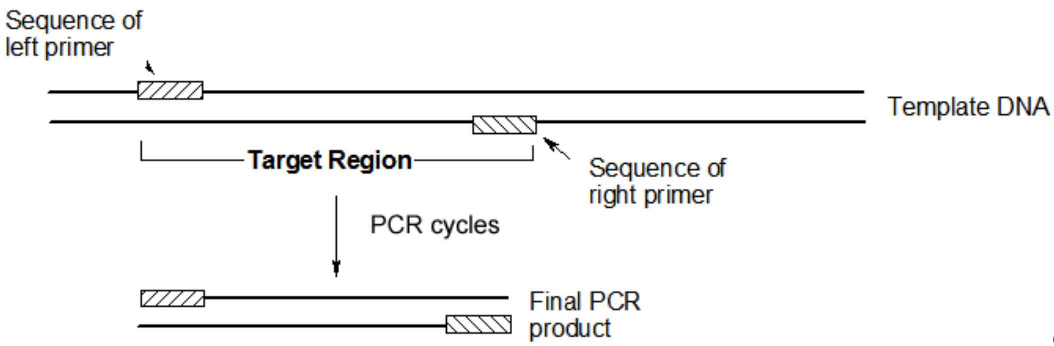
Polymerase Chain Reaction

You may remember from the movie Jurassic Park how the DNA of a dinosaur was recreated from a tiny amount of blood from a mosquito trapped in amber. While (so far) this is not possible in real life, the idea is based on one of the most useful tools for the manipulation of DNA: the *polymerase chain reaction*, or PCR. This technique was invented by Kary Mullis in 1983. PCR uses repeated cycles of DNA polymerase activity to amplify, or make many copies of, a small segment of DNA known as the target DNA. The target DNA resides within a larger DNA molecule that acts as a template. The amplified DNA, or PCR product, can also serve as a template, leading to a "chain reaction" that doubles the amount of PCR product after each cycle. Consequently, PCR can be used to amplify small amounts of DNA from forensic samples or historical artifacts. When scientists have a larger sample of DNA, they can determine the base sequence of the sample and use the data to compare the DNA sequences of different individuals. This process can help forensic scientists figure out the identity of a person who left blood at a crime scene. It can also help decide paternity disputes.


By Karlmumm(Wikipedia) (PCR masina kasutamine) CC BY-SA 3.0

How does PCR work?

PCR is essentially DNA replication, and just like DNA replication, PCR relies on the enzyme DNA polymerase. Because DNA polymerase requires a primer before it can start building a new strand of DNA, this is the first thing scientists must find (or design). These primers will provide a starting point for the DNA polymerase. In DNA replication, the primers are made of RNA nucleotides. In PCR, the primers are short DNA molecules consisting of a specific sequence that flanks the right and left ends of the target DNA sequence. The PCR product will contain the DNA sequences of the primers and the DNA between the primers.

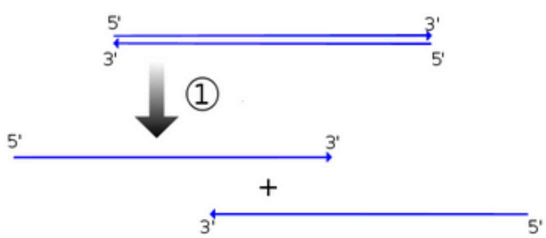


Overview of PCR.

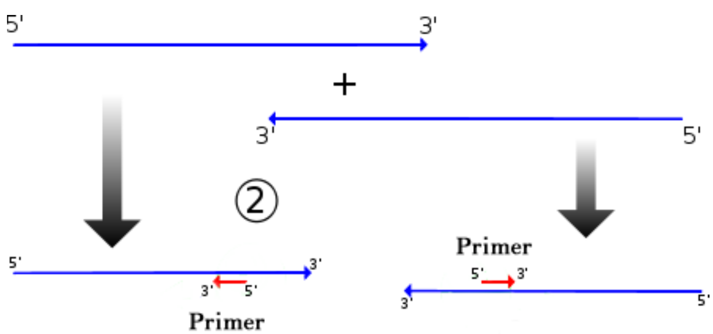
The target region is defined by the sequences of the two primers. The final PCR product contains the sequences of the two primers, plus any DNA sequences between the two.

Steps of PCR

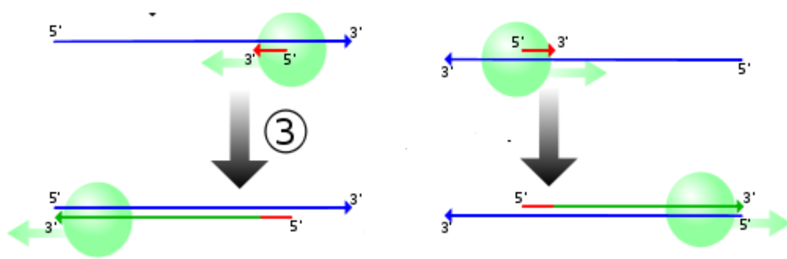
Step 1: The DNA template and primers must be converted to single-strand DNA. In DNA replication, DNA is separated by helicase. In the lab, we can accomplish the same thing by heating the DNA to 98oC (almost boiling temperature).



Step 2: In order for the DNA to be copied, the primers must bind. 98°C is too hot for the hydrogen bonds between complementary bases to form. Therefore, the reaction is cooled to ~55°C. This allows the hydrogen bonds between the primer and the target DNA sequence to form.



Step 3: In step 3, the temperature is raised to ~78°C, which activates DNA polymerase and stimulates copying of the DNA. The polymerase begins at the primer and copies the DNA to the end of the template.



After this process is complete, the temperature is again raised to 980C and a new cycle begins. At the end of each cycle, the sample contains double the amount of DNA template.

Watch the following video to review the steps of PCR.

Polymerase Chain Reaction

You might wonder how the DNA polymerase, as a protein, can resist such a high temperature. In fact, the DNA polymerases used for PCR are derived from organisms that can live at extremely high temperatures. The most common DNA polymerase used for PCR is called Taq, and it is found in the microbe *Thermus aquaticus*, which was first discovered in the Lower Geyser Basin at Yellowstone National Park.

Application Spotlight: Identify Suspects

Much of our DNA contains a number of short DNA segments that are repeated over and over again at different locations in our genome. The number of these tandem repeats at each location in the genome can differ from individual to individual, with 5 to 20 percent of individuals having the same number of tandem repeats at the same location.

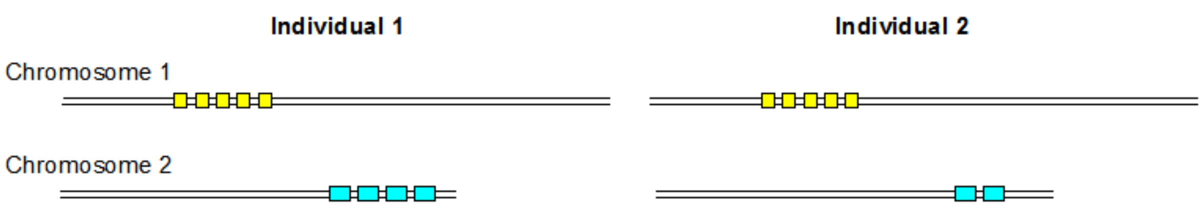
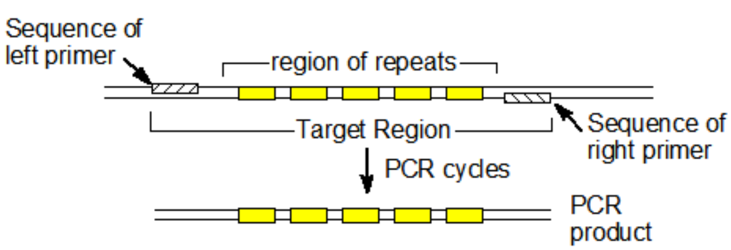


Illustration of the variation in tandem repeats in the human population. Two chromosomes are shown, and the tandem repeats in each chromosome are shown as yellow (chromosome 1) or blue boxes (chromosome 2). The two individuals have the same number of tandem repeats on chromosome 1, but a different number of repeats on chromosome 2.

Variations in the number of tandem repeats are detected by the polymerase chain reaction, using primers that bind to unique sequences on the edges of the repeat.



Amplification of repetitive DNA by PCR. The region of DNA containing the repeats is shown on the top; the PCR product is on the bottom.

If the two DNA samples show a different number of repeats, then the samples must have come from two different individuals. If two DNA samples show the same number of repeats at one location, then there is a chance that the two DNA samples came from the same individual. This is not a very reliable indication that the DNA samples came from the same individual, since a significant fraction of people can have the same number of tandem repeats at any one location in the chromosome. To increase the reliability of a positive match between the two samples, a total of 13 different locations of tandem repeats are amplified, and the number of repeats at each location are compared. If any of the 13 locations differ in the number of repeats, the two DNA samples came from different individuals. However, if all 13 agree, there is a greater than 99.99 percent probability that the two DNA samples came from the same individual. There is still a 0.01 percent chance that the DNA came from two different people who just happened to have the same number of tandem repeats at each of the 13 different locations.

Summary

DNA replication is essential for the continuity of genetic information throughout generations. A cell that is preparing to divide will replicate its DNA, using a variety of enzymes working in concert. Our understanding of DNA replication machinery has opened the door for a variety of advances, including the process of PCR. PCR is used to make many copies of a small segment of DNA, and it can be used to identify individual DNA samples.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

amino acids	chromosome	DNA polymerase	DNA replication
genome	nucleotides	ribosome	

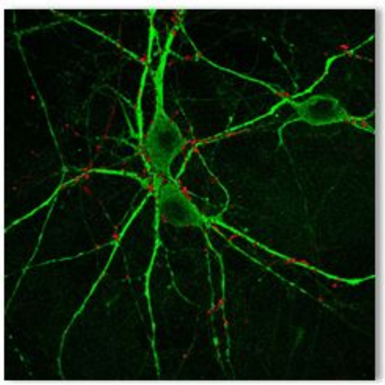
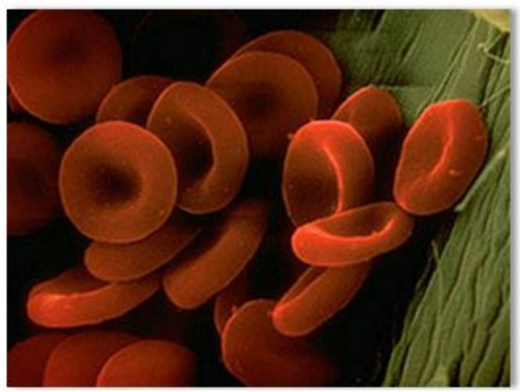
Gene Expression

Objectives:

- Define the central dogma of molecular biology, and identify its exceptions.
- Describe the link between DNA and visible traits.
- Explain transcription: identify molecular requirements, specify cellular location, and predict product.
- Compare and contrast DNA replication, PCR, and transcription.
- Explain translation: identify molecular requirements, specify cellular location, and predict product.
- Describe the distinct roles each of the three types of RNA play during translation.
- Predict how mistakes during DNA replication, transcription, and translation affect the cell.
- Classify mutations in the protein coding region of a gene based on their effect on amino acid sequence.
- Explain why a mutation in the BRCA gene leads to increased risk of cancer.

Introduction to Gene Expression

In the previous module, you learned how genetic information is stored in DNA and how it is passed in its totality to the next generation through the process of DNA replication. You also read about PCR, a practical application of the DNA synthesis process. In this module, we will focus on how this information is expressed. Information contained in DNA is organized into *genes,* and each gene contains instructions for making a functional product: an RNA molecule or a protein. This process of making the functional gene product is *gene expression.* Different cells can contain the same DNA, but they express different genes and produce different proteins according to their function. For example, red blood cells produce the protein hemoglobin, which is required for delivery of oxygen throughout the body. Nerve cells contain the same DNA, but the hemoglobin gene is not expressed. Instead, nerve cells make RNA copies of the genes that encode proteins required for signaling.

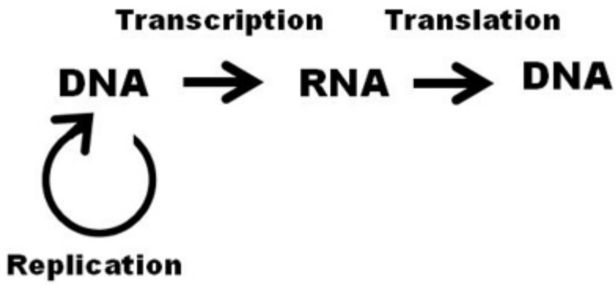


Both a nerve cell (left) and a red blood cell (right) develop from cells that have identical DNA, but the expression of different genes leads to structural and functional differences between the cells.

Even cells of the same type may express different genes and therefore produce different proteins, depending on their needs or environmental conditions. For example, pancreatic beta cells produce insulin when blood sugar levels are increased. Weightlifting increases muscle mass because it increases the production of proteins in the muscle cell. Sex hormones are not produced until the beginning of puberty.

Multiple proteins expressed at specific levels at specific times in the cell determine the phenotype. In this module, we will consider each of these processes in more detail, and we will conclude by looking at how changes in DNA sequence can affect the proteins encoded by DNA.

Central Dogma

The flow of information in a cell is described by the central dogma of molecular biology.



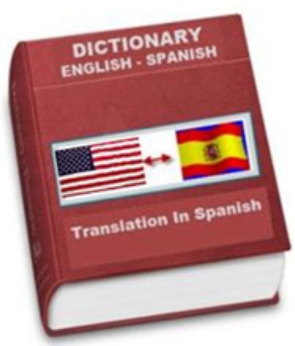
In eukaryotic cells, DNA stores the genetic information, which is passed from generation to generation through the process of DNA replication. During replication, the whole sequence of DNA is copied. In order for the information stored in DNA to be used by a living cell, the information must be expressed (*gene expression*). First, DNA is transcribed into one form of RNA called messenger RNA, or mRNA, through the process of transcription; then mRNA can be translated into an amino acid sequence forming a protein through the process of *translation*. The ribosome translates the RNA sequence into a protein sequence, using three nucleotide bases to encode each amino acid DNA also encodes two other RNA molecules, transfer RNA (tRNA) and ribosomal RNA (rRNA). Although these RNA molecules do not directly encode proteins, they are both required for protein synthesis.

Transcription and translation are often confused. Transcription is copying the information without changing the language. This word comes from the same root as *scribe*, a word that describes someone who made copies of books in medieval times. *DNA* and *RNA* are considered the same chemical "language" because their *monomers* are *nucleotides*.

Now, compare transcription to translation. Just as translators of books change information from one language to another, the cellular process of *translation* changes information from the language of nucleic acids (using nucleotides as the monomers) into the language of proteins (using amino acids as monomers).

Transcription

Translations



A scribe copying information by Meister des Maréchal de Boucicaut; artwork in the public domain. On right, a dictionary used totranslate from the language of English to Spanish.

Note that there are exceptions to the central dogma. It is thought that during the dawn of life, RNA was the first molecule to store genetic information, and certain viruses still have RNA as their nucleic acid component. In fact, certain viruses (among them the human immunodeficiency virus, or HIV) have an enzyme capable of making DNA using RNA as a template. However, you will recall that viruses are not cells, so it is safe to say that cells use DNA as their genetic material, and the flow of information goes as follows:

DNA => mRNA => protein

Gene expression, a process that is central to all living cells, can be summarized as a list of the following steps:

- the DNA double helix is separated
- an enzyme called RNA polymerase moves along one strand and transcribes the information from one strand of DNA into a strand of RNA
- the ribosome translates the RNA sequence into a protein sequence.

In eukaryotes, DNA and ribosomes reside in separate compartments, so an additional step is required: the transportation of RNA out of the nucleus and into the cytoplasm.

The animation below illustrates the process of gene expression in *eukaryotes*. Watch the animation, and then label still frames of the animation in the Learn By Doing activity.

Transcription: Making RNA

During gene expression, information stored in DNA is first copied (or transcribed) into RNA in a process called *transcription.* Only one of the two DNA strands is transcribed, and the order of bases in RNA is determined by the base pairing of the ribonucleotides with the DNA. In RNA, the base T is absent and U is present instead. As you know, A pairs with T, but because T is replaced by U in RNA, A pairs with U in RNA. If the transcribed DNA strand has the sequence

5'...AATTGCGC...3'

3'...TTAACGCG...5'

and the bottom stand is used as a template to produce the RNA copy, the sequence of the RNA will be

5' ...AAUUGCGC...3' - transcribed RNA strand

3'...TTAACGCG...5' -template DNA strond

Note that it the transcribed RNA has exactly the same sequence as the upper DNA strand, but with T replaced by U.

Translation: Making Proteins

The goal of translation is to make proteins. The sequence of amino acids in a protein is specified (or encoded) by the sequence of bases in the nucleic acid. You will recall that originally, the information is stored in DNA, but during transcription, an RNA copy of DNA is made. RNA molecules that contain instructions for making a protein are called *messenger RNA (mRNA)*. The sequence of bases in the mRNA determines which amino acid will be used in the protein. Every three bases encode for a single amino acid. These three bases are called *codons* or *triplets*.

The genetic code table below shows all possible combinations of three bases and the corresponding amino acids that the codons encode. For example, the mRNA codon UGG encodes for the amino acid tryptophan. Note that there are 64 codons and only 20 common amino acids. Three of the codons do not specify amino acids, but instead signal the end of translation; these are called *stop codons*. The remaining 61 codons encode for 20 amino acids. Of these, the codon for the amino acid methionine, AUG, has a dual role. It is used to signal the start of most protein-coding regions in the mRNA; thus, it is the *start codon*. The same codon is used if methionine occurs at an internal position in the protein sequence.

The genetic code is redundant; some amino acids are specified by multiple codons. This redundancy will become important when we try to predict how changes in nucleotide sequences affect the amino acid sequences of proteins. Remarkably, the genetic code table is almost universal, meaning that most organisms, from bacteria to humans, specify the same amino acids using the same codons. As a result, genes from one type of organism can be transferred to, and expressed in, the cells of another organism. You will learn more about these kinds of technologies later in this unit.

Examine the genetic code table and complete the Learn By Doing activity to make sure you understand how to use the table.

Genetic Code Table

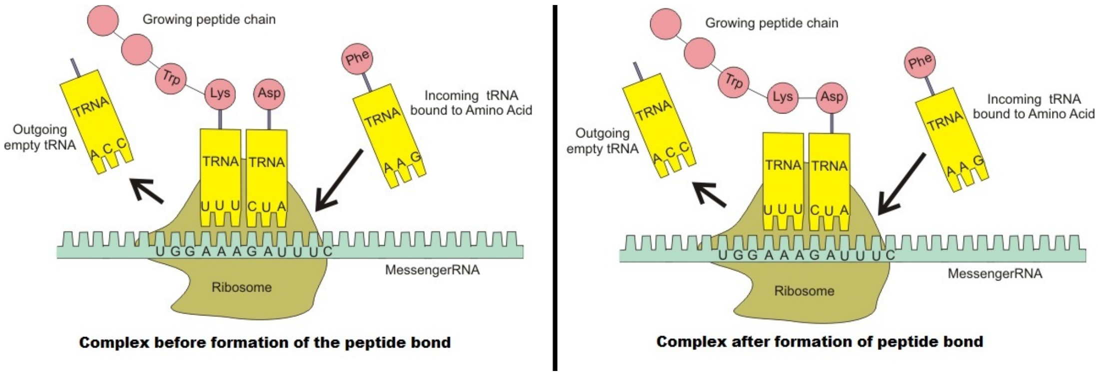
This table summarizes the amino acids that result from each codon on mRNA. The first letter in the codon is on the left. The second is on the top, and the third is on the right.

Codon Table

2nd base

1st base	U		C		A		G		3rd bsae
U	UUU	Phenylalanine	UCU	Serine	UAU	Tyrosine	UGU	Cysteine	U
	UUC	Phenylalanine	UCC	Serine	UAC	Tyrosine	UGC	Cysteine	C
	UUA	Leucine	UCA	Serine	UAA	Stop	UGA	Stop	A
	UUG	Leucine	UCG	Serine	UAG	Stop	UGG	Tryptophan	G
C	CUU	Leucine	CCU	Proline	CAU	Histidine	CGU	Arginine	U
	CUC	Leucine	CCC	Proline	CAC	Histidine	CGC	Arginine	C
	CUA	Leucine	CCA	Proline	CAA	Glutamine	CGA	Arginine	A
	CUG	Leucine	CCG	Proline	CAG	Glutamine	CGG	Arginine	G
A	AUU	Isoleucine	ACU	Threonine	AAU	Asparagine	AGU	Serine	U
	AUC	Isoleucine	ACC	Threonine	AAC	Asparagine	AGC	Serine	C
	AUA	Isoleucine	ACA	Threonine	AAA	Lysine	AGA	Arginine	A
	AUG	Methionine (Start)	ACG	Threonine	AAG	Lysine	AGG	Arginine	G
G	GUU	Valine	GCU	Alanine	GAU	Aspartic Acid	GGU	Glycine	U
	GUC	Valine	GCC	Alanine	GAC	Aspartic Acid	GGC	Glycine	C
	GUA	Valine	GCA	Alanine	GAA	Glutamic Acid	GGA	Glycine	A
	GUG	Valine	GCG	Alanine	GAG	Glutamic Acid	GGG	Glycine	G

The genetic code table allows us to convert the information contained in a nucleic acid into an amino acid sequence. How does the cell do this during translation? Translation from one language to another requires a dictionary, a book that connects words in two different languages. In the cell, we need a molecule that connects codons and amino acids. That molecule is transfer RNA (tRNA). Each tRNA contains three bases that can pair with a particular codon in mRNA (complementary base pairing). Each tRNA also carries a specific amino acid. The tRNA binds mRNA via base pairing and brings the correct amino acids to the growing polypeptide chain.



By Boumphreyfr(Wikipedia) (Peptide syn) CC BY-SA 3.0

The last type of RNA molecule that is critical for translation is ribosomal RNA (rRNA). rRNAs are components of the ribosome. The ribosome is a large macromolecular complex composed of rRNA and ribosomal proteins. The ribosome catalyzes the formation of peptide bonds between the amino acids. Some ribosomes are located in the cytosol and translate cytosolic proteins. Some ribosomes are attached to membranes; these ribosomes translate proteins destined to be inserted into the membrane or secreted outside the cell.

To summarize, three types of RNA carry out distinct roles in translation: mRNA encodes the protein, tRNA brings amino acids to mRNA, and rRNA is a component of the ribosome required for catalysis.

In the exercise below, you will simulate the process of transcription and translation and build a small protein. Complete the activity and then answer the questions below.

By University of Maryland University College CC-BY-NC

Mutation

None of the processes discussed so far are free of errors. Errors can be made during transcription if incorrect nucleotides are incorporated into the growing RNA strands. Errors can happen during translation if incorrect amino acids are inserted into a growing protein, or if translation is terminated too soon. Errors during gene expression have generally short-lived effects and can be overcome by additional RNA or protein synthesis.

Errors during DNA replication can have a much longer lasting effect. If incorrect nucleotides are incorporated into a newly synthesized DNA strand, the error may be passed on to future generations. Such heritable changes are referred to as mutations. Some mutations happen due to large scale rearrangements of DNA molecules that involve thousands or millions of nucleotides. We will limit our discussion here to small-scale changes that involve one or a few nucleotides in the coding sequence of a gene. These mutations include substitution of a single nucleotide base and insertion or deletion of one or more bases.

Let us consider how different types of mutations affect the proteins encoded by DNA. The sentence below represents a protein-coding gene. Each three letter word carries some meaning – equivalent to each amino acid being encoded by a three-letter codon in DNA.

THE CAT ATE THE HEN

- *Silent mutations.* A silent mutation changes the letter, but not the meaning. Recall that the genetic code is redundant: multiple combinations of three bases can encode the same amino acid.

THe CAT ATE THE HEN

- *Missense mutations*. A missense mutation changes a letter in DNA and also changes the encoded amino acid. It changes the meaning of the message as below:

THE BAT ATE THE HEN

- *Nonsense mutations*. A nonsense mutation changes an amino acid codon to a stop codon, terminating transcription:

THE stop

- *Frameshift mutations*. A frameshift mutation occurs when one or two bases are inserted into or deleted from a sequence. As a result, subsequent codons are read incorrectly in new groupings of three bases each:

Deletion of one nucleotide: introduces frame shift

TH|C ATA TET HEH EN (deletion of one base, the "E" in "THE")

Deletion of three nucleotides removes information, but no frame shift.

THH ECA TAT ETH EHE N (insertion of one base, an extra "H" in "THE")

There are many possible variations on the mutation types above. For example, three bases may be deleted in a group corresponding to one existing codon. In this rare instance, there would be no frame shift but a single amino acid would be missing from the encoded protein:

THE | ATE THE HEN

Next, we apply the classification above to an actual mutation observed in human DNA.

The activity below deals with a mutation in the gene that encodes the oxygen transport protein hemoglobin. The mutation causes hemoglobin to form long rods inside red blood cells. As a result, it is difficult for the cells to pass through blood vessels. This leads to a disease called sickle cell anemia in many of those who inherit the mutation.

Application Spotlight: Gene Mutations

BRCA Gene Mutations in Breast Cancer

In this module you learned about the role of DNA as the molecule that stores genetic information. Any damage to the DNA molecule can have serious consequences for the cell. There are many different cellular mechanisms to repair DNA damage or to stop a cell with errors in its DNA from dividing. The BRCA genes code for proteins involved in detecting and repairing double strand breaks in the DNA molecule.

If there is a defect in either of the genes BRCA1 or BRCA2, that will result in increased chances of DNA errors, which ultimately can increase the likelihood of cancer. BRCA genes are therefore considered *tumor suppressor* genes. Mutations in these genes produce a hereditary breast-ovarian cancer syndrome in affected families.

Women with harmful mutations in either BRCA1 or BRCA2 have an increased risk of breast cancer that is about five times the normal risk, and a risk of ovarian cancer that is about 10 to 30 times normal. While mutations in BRCA1 and BRCA2 account for only five to ten percent of all breast cancer cases in women, it is suggested that women with familial breast or ovarian cancer (when several female close relatives have or had cancer) be tested for BRCA mutations. Testing positive for BRCA mutations does not mean the person will definitely get breast cancer, because there are many other genetic and environmental factors involved. However, having this information may help those individuals to take preventive measures, such as more frequent mammograms.

Gene Expression: Summary

Summary

The central dogma of molecular biology describes the flow of information from DNA to protein. In this module you learned about transcription and translation. You also learned about mutations (changes in the DNA sequence) and how to predict their effects. At the end we discussed a real life example in which genes and environmental factors interact to produce an important health outcome (breast and ovarian cancer).

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

gene	codons	gene expression	mutation
RNA polymerase	nucleotides	transfer RNA (tRNA)	messenger RNA (mRNA)

Gene Regulation

Objectives:

- Distinguish among the terms *gene, allele, mutation, DNA, chromosome,* and *genome.*
- Identify the functions of the key parts of a protein-coding gene.
- Distinguish between prokaryotic and eukaryotic genomes.
- Describe how DNA is packaged in a eukaryotic cell and how the packaging changes during the cell cycle.
- Describe (identify) three types of interactions between environment and genes that can affect phenotype.
- Explain the role of each genetic element in the operon, and correctly order DNA control elements in an operon.
- Predict under which conditions the repressor protein will bind to its operator sequence.
- Describe the role of CRP protein in regulation of the lactose operator by glucose.

Introduction to Gene Regulation

You have probably seen Siamese cats--those graceful creatures with darker fur on their faces, tails, and paws. This is an example of a phenotype dependent on the interaction between genes and environment. Modern Siamese cats have a defective tyrosinase enzyme; tyrosinase is involved in the synthesis of melanin, the dark pigment of the skin. This defective enzyme is inactive at normal body temperatures, but it becomes active in cooler areas of the skin. This results in dark coloration in the coolest parts of the body, including the extremities and the face, which is cooled by the passage of air through the sinuses.

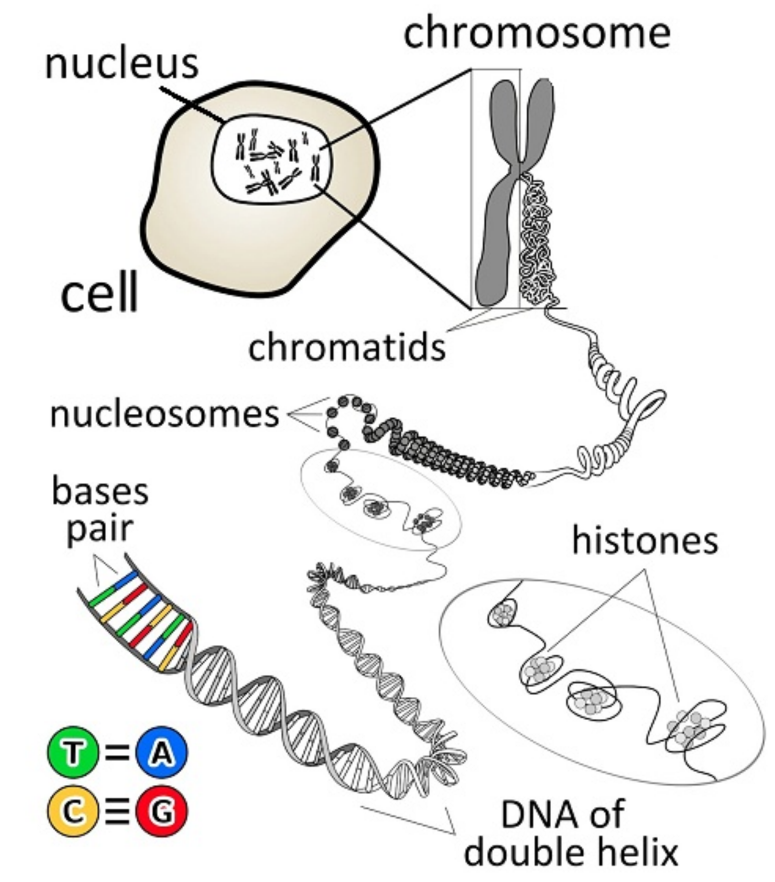
By Cindy McCravey (Neighbor's Siamese) CC BY 2.0

In this module, we will explore the connection between DNA and phenotype on the molecular level. We will start by clarifying the distinctions between genes, genomes, alleles, and other related terms. We will compare prokaryotic and eukaryotic genes and genomes, and we will look at how DNA is packaged into chromosomes with the help of specialized proteins. We will consider how gene expression can be regulated in the cell by interactions with other genes and environment.

What Is a Gene?

Throughout the genetics unit, we have been using the terms gene, allele, and DNA, along with several other related terms. Before we go on, we need to clarify the relationships among these terms. First, we need to distinguish between terms that relate to actual molecules and terms that relate to the information content of those molecules. The macromolecule that carries genetic information is *DNA*, which in the eukaryotic cell binds specialized proteins to create compact structures called *chromosomes*.

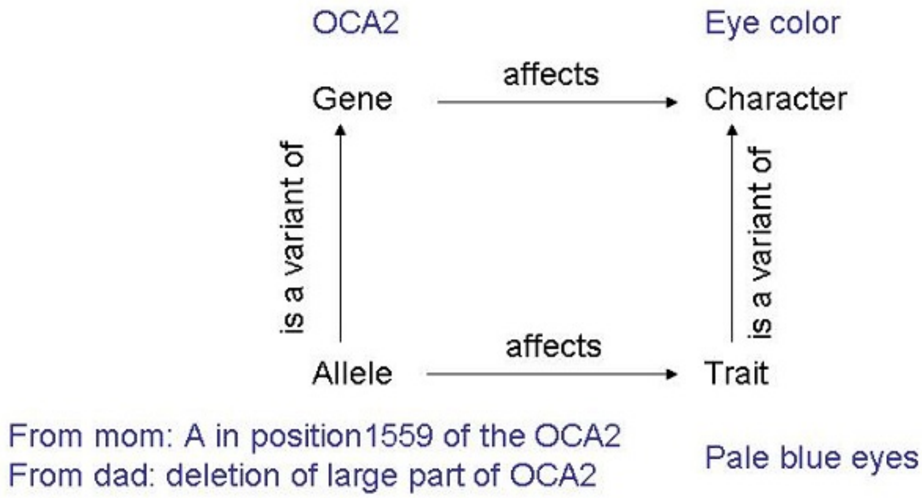
All the hereditary information contained within an organism is called a *genome*. The genome includes genes and noncoding DNA sequences. The human genome, for example, contains the DNA sequence (information) of 22 autosomal chromosomes, as well as the two sex chromosomes X and Y. The field of study that focuses on the properties of genomes is called *genomics*, which is related to but distinct from*genetics*, which focuses on individual genes or a group of genes.



By KES47 (Chromosome en) CC BY 3.0

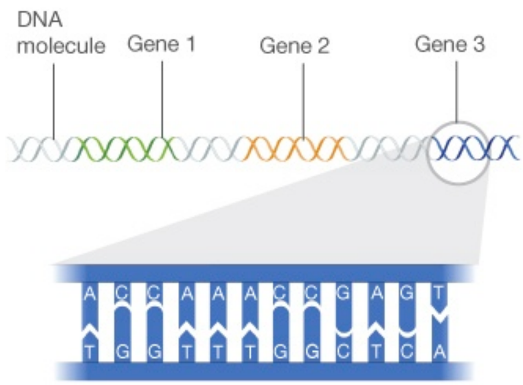
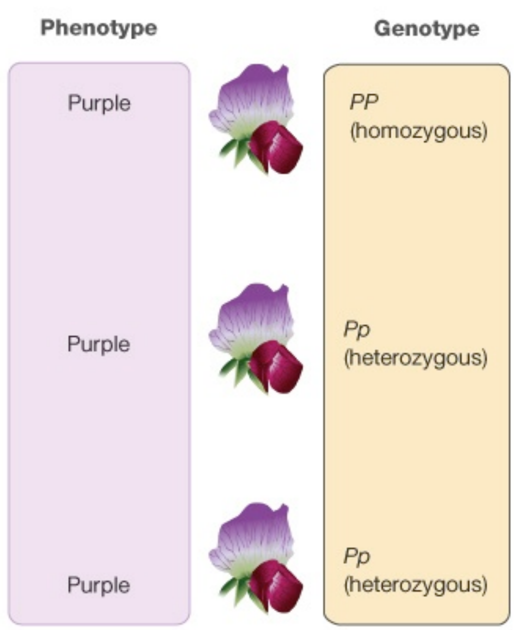
Genes carry the information required to produce a functional product (protein or RNA). The information is contained in the order of bases in the DNA. This information is “read” by the cell to produce, first RNA, and then a protein, during a process called *gene expression.* When a protein affects an observable characteristic of an organism (remember, observable characteristics represent an organism’s phenotype), the gene encoding that particular protein can be linked to that *characteristic* or *character* (e.g., hair color, eye color, or height). *Traits* are specific variations in characteristics (e.g., black hair or blue eyes). For example, the gene encoding growth hormone (a protein) affects the height of an individual; in this case, height is the characteristic, and tall or short stature are the traits. Some genes can be linked to the development of diseases. Nearly all observable characteristics depend upon multiple genes. Therefore, when we hear someone refer to the “obesity gene,” “Alzheimer’s gene,” “breast cancer gene,” and so on, it is important to realize that these labels imply (or should imply) one of the multiple genes that contribute to each of these conditions.

What is the connection between genes and traits? We must now consider *alleles*, which are observed variations in the sequence of bases for a particular gene. Two alleles of a gene may differ by a single base. On one end of the spectrum, an allele may refer to a total deletion of a gene. A diploid organism has two alleles of each gene, one from the organism’s mother and one from its father. The combination of the two alleles of a particular gene is the genetic determinant of the phenotypic traits of the organism. Note that in addition to genetic factors, environment also contributes to traits. We will consider environmental effects in a later section.



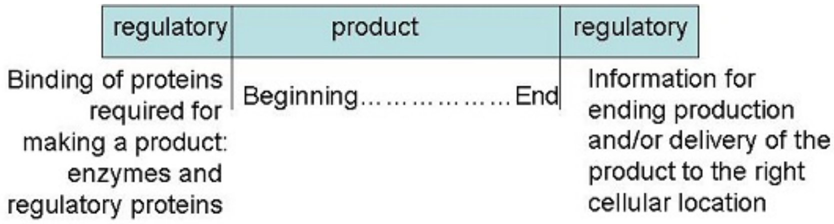
The arrows in the diagram show the relationships among the key terms *gene, allele, trait,* and *character* (or *characteristic*). The characteristic of eye color is used as an example to illustrate these relationships. Eye color depends upon production of the pigment melanin. Pigment production depends upon transport of tyrosine (the amino acid required to produce melanin) across the cell membrane. The transporter protein is encoded by the gene OCA2. A person with brown eyes produces functional transporter protein and plenty of pigment, leading to dark eye color. A mutation G to A in position 1559 of the coding DNA sequence of OCA2 leads to amino acid change in the transport protein; instead of alanine in position 481, threonine is present. This leads to reduced function of the transporter, which in turn results in decreased production of melanin. When the second allele is a deletion, an albino phenotype results (pale blue eyes, pale skin and hair color).

What is the difference between allele and *mutation*? Any change in the DNA of an organism is called a*mutation*. Mutations can be advantageous, harmful, or neutral (in which case they have no effect on the phenotype). Mutations include large deletions and rearrangements in the DNA, but they can also be changes in a single base. *Mutation* is a more general term than *allele* because mutation does not necessarily involve a specific gene, but can include deletion or rearrangement of multiple genes. Multiple alleles of a gene arise by mutation, and they will be passed on to the offspring and will persist in the population.

Term	Definition	Example
Character	Heritable characteristic that varies among individuals, such as the color of peas	
Trait	Variant of a character, such as yellow for peas	
Gene	Unit of heredity passed from parent to child, consisting of a specific nucleotide sequence (of DNA in plants or animals, or RNA in some viruses).	
Allele	Version of a gene that produces a specific trait. For example, the flower colors purple and white are caused by different alleles.	In Mendelian genetics, an allele is represented by a single letter. The dominant gene is represented by a capital letter (F), the recessive gene by a lowercase letter (f). In modern genetics, an allele could be represented by a sequence of the letters that represent the nucleotides in DNA (G, C, A, and T) or a sequence of letters representing the amino acids those nucleotides code for (such as lysine, serine, or alanine).
Homozygous	Having two copies of the same allele for a given gene.	
Heterozygous	Having two different alleles for a given gene.	
Genotype	Genetic makeup. The genotype results in the phenotype. An organism displaying a phenotype inherited as a single recessive gene must be homozygous for that gene.	

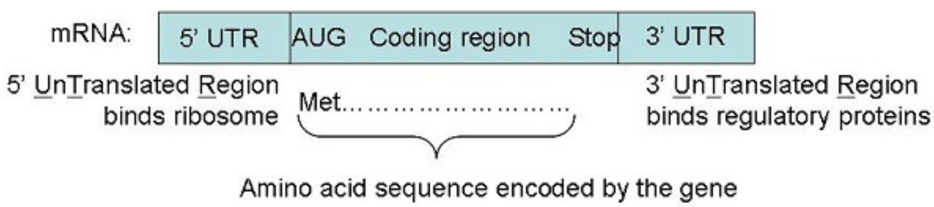
Gene Structure

In the previous module, we mentioned different kinds of genes. Some genes produce functional RNA (rRNA and tRNAs), but most genes code for proteins. Remember that a gene is information residing in the order of bases in a DNA molecule. The general organization of information of any gene can be represented as follows:



In this module, we will focus on the structure of the protein-coding genes. A protein-coding gene contains information for making the mRNA that is translated into a protein. First, let's consider what kind of information in the mRNA is required to produce a protein during translation, and then we will step back and look at the information in the gene that is required for transcription.

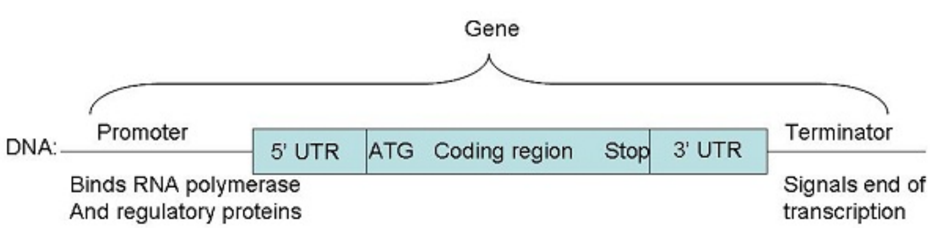
To encode a protein, mRNA needs a protein-coding region and regulatory regions. The coding region of the gene (and the coding region of mRNA) has to start with a start codon: ATG in DNA and AUG in mRNA code for the amino acid methionine, Met. The coding region of a gene always ends with a stop codon TAA, TAG, or TGA (in mRNA, these will have a U instead of a T). The sequence between start and stop codons should contain nucleotides in multiples of three, encoding the sequence of amino acids in the protein. The untranslated regulatory regions (denoted by UTR) include a site for the ribosome to bind before the start codon (5' UTR) and a region after the stop codon (3' UTR). Both 5' and 3' UTRs can bind specific proteins involved in regulation of translation (how fast new protein product is built, how fast mRNA is degraded).



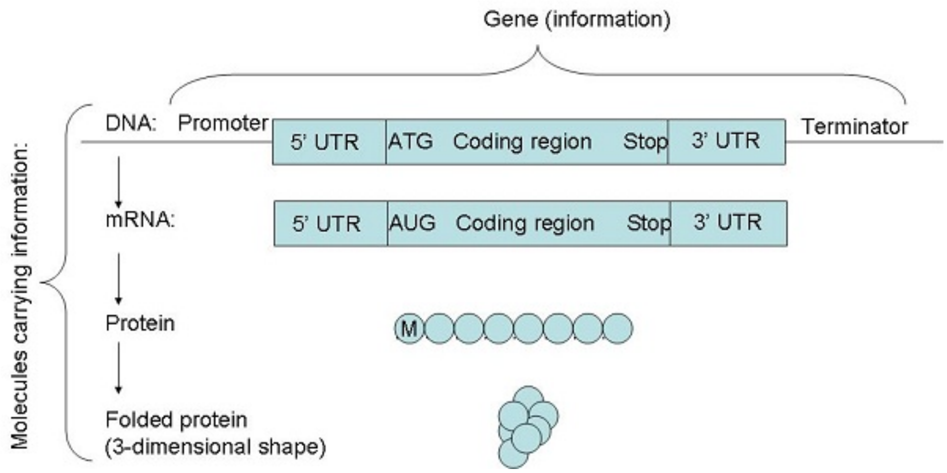
Note that mRNA in the figure above starts with 5' UTR, not with the start codon. The start codon signals the start of translation, not transcription. Next, we will consider DNA regions required for transcription.

Genes include regulatory regions at the beginning and the end of the transcribed DNA:

1. The *promoter* region of the gene "promotes" transcription by binding RNA polymerase.
2. The *terminator* region signals the end of transcription.
3. Regulatory regions before and after the transcribed region bind regulatory proteins. These proteins activate or inhibit transcription, depending on the signals from within the cell or from the environment.



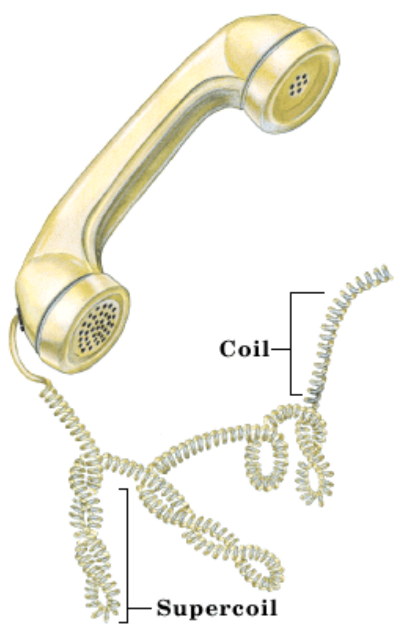
Putting the regulatory signals associated with RNA production together with those signals on the mRNA, we can represent the central dogma of molecular biology with the following diagram:



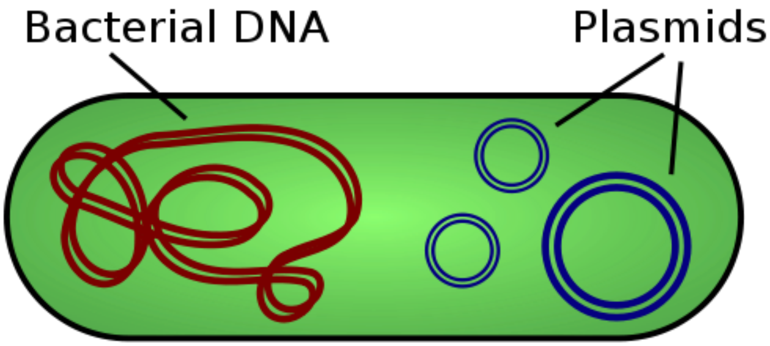
Genome Structure and Packaging

After considering individual genes, let's zoom out and consider a more global view: how genes are organized into genomes.

The prokaryotic genome resides on a circular piece of double-stranded DNA; there is no membrane to separate DNA from the rest of the cell. Most bacterial genomes are several million nucleotides long. The *E. coli* genome, for example, is approximately 5 million nucleotides long. Although this is a relatively small genome, the physical length of the DNA is longer than the length of the bacterial cell. In order to condense the DNA into a smaller size, the DNA is supercoiled. In supercoiled DNA, the double helix of the DNA contains additional turns beyond the normal one turn per 10 base pairs. These additional twists introduce strain into the DNA that is relieved by large-scale twists in the entire DNA molecule, or supercoils. A good model for supercoiling is an old-fashioned spiral phone cord. If you form the cord into a circle, and then rotate or twist one of the free ends relative to the other, you will introduce supercoils into the cord.



Many bacteria contain smaller, circular DNA molecules, called *plasmids*, in addition to the large DNA molecule that is their chromosome. Plasmids can replicate independently of the large DNA and can be transferred to other cells. Some naturally occurring plasmids carry genes encoding toxins and proteins that make bacteria resistant to antibiotics.

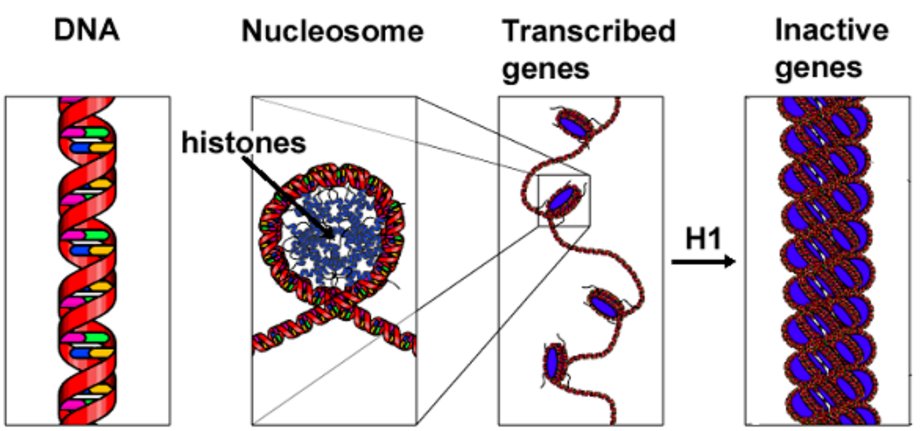


By Spaully(Wikipedia) (Plasmid) CC BY-SA 2.5

Plasmids provide a very useful tool for biotechnology. Scientists use them to insert "foreign" genes into bacteria so they can use the bacteria as "factories" to produce desired proteins. For example, to study a human disease caused by a malfunction in a specific protein, scientists need a large amount of the protein for experiments. Instead of purifying protein from human cells, scientists can combine coding DNA from the human genome with bacterial regulatory DNA regions on a plasmid, and introduce the plasmid carrying human gene into the bacteria. Growing a large amount of bacterial cells is much easier than obtaining large amounts of human cells. Combining DNA from different organisms is called *recombinant DNA technology*.

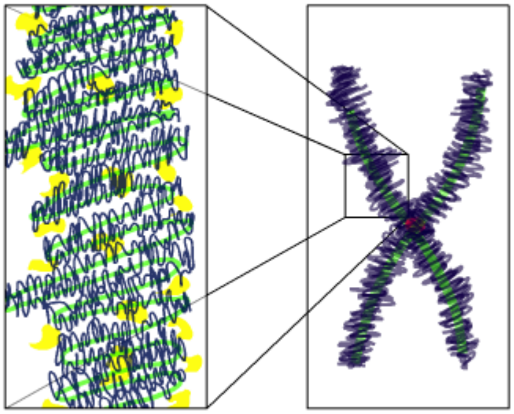
A eukaryotic genome resides on multiple linear DNA molecules in the nucleus. Each of these DNA molecules is called a *chromosome*. Eukaryotic cells also contain DNA in mitochondria and chloroplasts; mitochondrial and chloroplast genomes are circular like those of bacteria, and are typically considered separately from eukaryotic genomes.

In general, eukaryotic genomes are much larger than prokaryotic genomes, and they contain a lot more noncoding DNA. This presents a problem of packaging for eukaryotic -cells: how are they to fit very large DNA into a small compartment? Although eukaryotic DNA is supercoiled, this isn't enough to solve the packaging problem. Eukaryotic cells use special proteins (histones) to wind up DNA and fold it into*nucleosomes*, which are compact structures. DNA can be transcribed in this state. Further packaging of DNA into highly compact fibers makes genes inaccessible for transcription, leading to *gene silencing*. Gene silencing is an important way of regulating gene expression.



Packaging of DNA in Eukaryotes. Nucleosomes are formed by DNA looping around a collection of proteins called *histones*. Genes that are actively undergoing transcription can be found in nucleosomes. In the case of inactive (silenced) genes, the DNA is further compacted into thick fibers of the DNA-histone complex. By Richard Wheeler (Chromatin Structures) CC BY-SA 3.0

The shape of the chromosomes changes throughout the cell cycle. For example, when a cell needs to divide, DNA is further compacted by the addition of scaffolding proteins that help divide copies of the chromosomes equally. The most compact shape of the chromosomes can be observed during cell division.


The shape of the chromosomes changes throughout the cell cycle. For example, when a cell needs to divide, DNA is further compacted by the addition of scaffolding proteins that help divide copies of the chromosomes equally. The most compact shape of the chromosomes can be observed during cell division. By Richard Wheeler (Chromatin Structures) CC BY-SA 3.0

How DNA is Packaged

Genes and Environment

In the previous sections of this module, we discussed the structure and organization of genes and genomes. Throughout the molecular genetics module, we have been pointing out the connections between genotype and phenotype. Here, we will discuss the other important factor in determining the phenotype of an organism: environment. The effects of environment on phenotype can be fairly subtle or pretty dramatic. In certain groups of cold-blooded animals, such as Nile crocodiles, sex is determined by an environmental factor: average temperature during the middle third of the incubation period. Males will only hatch at temperatures between 89.1° and 94.1°F. Nests with higher or lower temperatures will produce predominantly females.

How does environment exert its influence on phenotype? Recall that at the molecular and cellular levels, phenotype depends on the molecules produced by the cell. Production of all molecules is catalyzed by protein enzymes that are encoded by the genome of the organism. Ultimately, if phenotype depends on protein function, then the environment must have a way of modifying the amount and the activity of proteins. Using the central dogma of molecular biology, we can deduce that environment may affect protein function at the level of protein, mRNA, or DNA.

Changes in protein function

Cells and organisms have to respond to changes in their environment. An organism that experiences a sudden increase in temperature will respond with increased expression of genes coding for heat-shock proteins; these proteins protect cells from damaged and unfolded proteins. A bacterial cell that depletes glucose in its environment will not die of starvation if an alternative energy source is available. In the presence of lactose, bacteria can "turn on" the lac operon containing genes required for metabolism of lactose. Regulation of this operon will be discussed in detail on the next page. The signaling occurs primarily through binding interactions between molecules and modifications of the proteins that often lead to changes in gene expression. These changes are short-lived and are not heritable.

Changes in DNA sequence

Long-term heritable changes can be produced by the environment at the level of DNA. Any environmental influence that can damage DNA has the potential to create mutations that can result in changing amino acid sequence of a protein or regulatory information. For example, high-energy radiation causes double-stranded breaks in DNA that can lead to deletions. UV light causes single nucleotide changes in DNA. Environmental toxins and viruses also cause mutations. Cumulative DNA damage in somatic cells throughout an organism’s lifetime contributes to the aging process. Only mutations in germ cells result in heritable changes passed on to the next generation of offspring.

Heritable changes in gene expression can occur via changes in DNA sequence or in DNA packaging. Mutations in regulatory regions of the gene can lead to increased or decreased protein production without affecting the amino acid sequence of the protein. One example of such mutation is found in the regulatory region of the human LCT gene on chromosome 2. The LCT gene codes for the enzyme lactase, required for breaking down lactose into glucose and galactose. In many adults, expression of the LCT gene is turned off or turned down, resulting in little or no lactase production. Lack of lactase in the intestines can lead to gastrointestinal distress (bloating, cramps, diarrhea, etc.) after consumption of moderate to large amounts of dairy products, giving rise to a condition called *lactose intolerance.* Other people are able to produce lactase well into adulthood. This ability has been linked to mutations in the regulatory region of the lactase gene that allow gene expression to continue after childhood.

Changes in DNA packing

Heritable changes in DNA packaging do not involve any changes in DNA sequence. This type of inheritance is *epigenetic* (from the Greek epi-, meaning over, above, or outside). You will recall from the previous page that compact packaging of DNA leads to gene silencing (transcriptionally inactive genes). Compact packaging of DNA requires modifications to DNA itself and to histones, which are DNA-binding proteins involved in packaging. DNA modification involves the addition of a methyl group ($-CH_3$) to specific bases on DNA (cytosine methylation), but does not change the sequence of DNA bases. The methylation pattern can be preserved during DNA replication, so the daughter cells will have the same methylation pattern as the parent cell. In germ cells, the pattern of DNA methylation can be passed through the gametes to the next generation of offspring.

One example of epigenetic silencing in somatic cells is common to all female mammals. One of the two X chromosomes in females is inactivated by epigenetic mechanisms (DNA methylation and histone modifications). The results of X-inactivation can be observed in calico or tortoiseshell cats. These cats are almost always female. The gene encoding the coat color resides on the X chromosome. A female cat (with two X chromosomes) could potentially carry one allele for a black coat and one allele for an orange coat. As a result, her phenotype will end up with patches of two different colors. This is because cells that inactivate the X chromosome with the black allele will express the orange allele, and after multiple cell divisions, a patch of orange fur will result. Cells that inactivate the X chromosome carrying the orange allele will give rise to black patches. The specific pattern of black and orange patches is not heritable because X-inactivation is random.


By Michael Bodega (6-year old tortoise shell cat) Public Domain

Epigenetic regulation and inheritance has been linked to cancer and obesity, aging and longevity, and other important processes. It is the key mechanism for interactions between genes and environment. Unlike the genome, which remains fairly unchanged throughout an organism's life cycle, the epigenome (consisting of the pattern of DNA methylation and histone modifications) is dynamic, responds to the environment, and can be heritable.

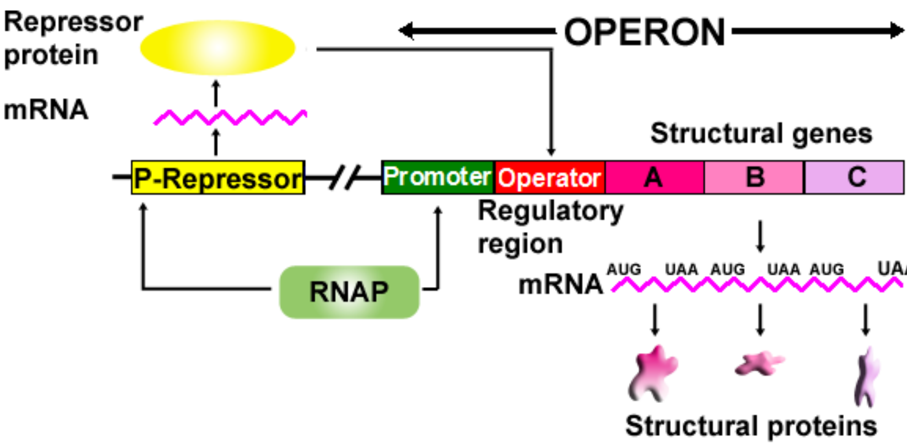
In summary, environment can influence phenotype by interacting with the genome in the following ways:

1. Environmental signals can change gene expression by affecting regulatory proteins.
2. Environmental signals can change DNA packaging, which affects gene expression.
3. Environmental mutagens can cause mutations in DNA.

Application Spotlight: Regulation in Bacteria

In this spotlight, we will explore in more detail changes in gene expression (transcription) due to changes in the environment. Eukaryotes have complex regulatory mechanisms; consequently, we will focus on gene regulation in prokaryotes. However, common principles of regulation are used by both prokaryotic and eukaryotic organisms, and an understanding of regulation in prokaryotes will help you understand eukaryotic regulation in future studies.

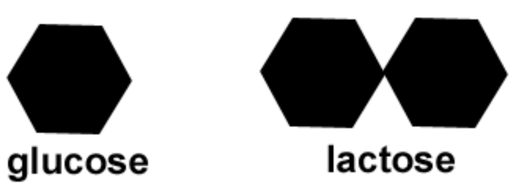
Many bacterial genes are expressed at the same time as part of an operon. The expression of the genes in the operon is controlled by a repressor protein. The repressor protein will bind to the regulatory region at a DNA sequence. This sequence is the *operator*. When the repressor is bound to the DNA, RNA polymerase cannot transcribe the structural genes because it is blocked by the repressor protein bound on the DNA; under these conditions, none of the enzymes required for the pathway is produced. Whether or not the repressor binds to the operator is controlled by the binding of a small molecule to the repressor. The small molecule is either the compound that enters the pathway (for catabolic, or degradative pathways) or the compound that is produced by the pathway (for anabolic, or synthetic pathways). The compound binds to the repressor protein and causes the repressor either to bind to the DNA (this is called positive control), turning off transcription, or to be released from the operator site on the DNA (this is called negative control), turning on transcription. You will explore both of these control mechanisms in the spotlight below.



The Bacterial Operon. The operon contains the promoter (green box), the operator sequence (red box), and two or more structural genes that code for structural proteins. If the operon is associated with metabolic pathways, the structural proteins would be the enzymes in the pathway. In addition to the genes in the operon, there is a separate gene that codes for the repressor protein, so its transcription is independent of the transcription of the operon. The repressor protein controls the expression of genes in the operon by binding to the operator DNA sequence, blocking the ability of RNA polymerase to transcribe the structural genes (A-C) for the operon. When the repressor is not bound to its operator, RNA polymerase can transcribe the operon and it will produce one long mRNA transcript, containing the coding information for the structural proteins.

Lac Operon

Bacteria can use a wide variety of carbon sources as fuel to extract energy for growth. Two common carbon sources are the sugars glucose and lactose (milk sugar). Glucose is a monosaccharide containing one six-membered ring, while lactose is a disaccharide made of glucose linked to galactose.



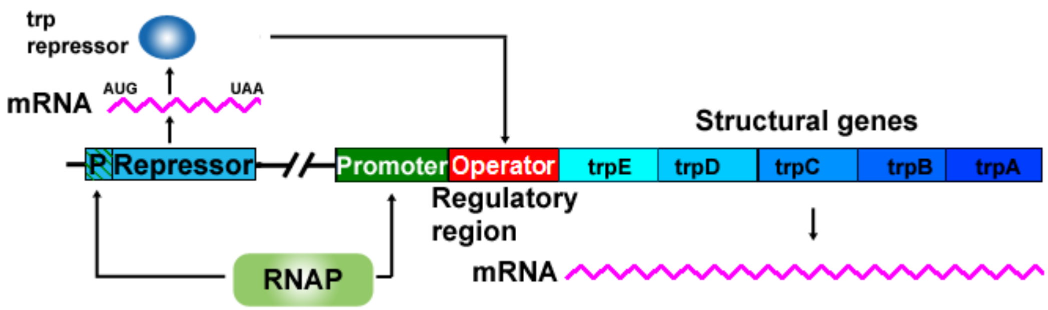
It is less efficient for bacteria to use lactose as an energy source because they must take additional steps to convert lactose into a form that can be used to extract energy. Each of these steps requires the synthesis of an enzyme, which is costly to the bacteria. Consequently, bacteria prefer to use glucose rather than lactose as a fuel source when both sugars are present. However, when lactose is present and glucose is not, the bacteria "turn on," or synthesize, the enzymes required for lactose metabolism, allowing the bacteria to use lactose for energy.

The genes for lactose metabolism are contained in an operon known as the *lac operon.* The lac operon is controlled by the lac repressor, which is produced from the lacI gene. The lacI gene has its own promoter; consequently, low levels of the lac repressor protein are present all of the time. Three structural genes in the operon, lacZ, lacY, and lacA, encode enzymes required for lactose metabolism.

Thus far, we have described what happens when either glucose is present or lactose is present. If both are present, glucose is used first by the bacteria, and only very small amounts of the enzymes for lactose metabolism are made. Complete the following Learn by Doing to understand how glucose turns off the lac operon, even if lactose is present.

Regulation of Biosynthetic Pathways

The enzymes for the synthesis of the amino acid tryptophan are contained in the Trp operon. The structure of this operon is shown below. The trp repressor binds the amino acid tryptophan, the end product of the biosynthesis of tryptophan (trp). As you can see, it has the same structure as the lac operon, but it contains more genes for the biosynthesis of trp.



Gene Regulation: Summary

Summary

Manipulation of DNA has opened an incredible array of possibilities for humanity. From the industrial production of biological molecules in bacteria, to gene therapy, biotechnology has brought dramatic changes to medicine, agriculture, forensics, and many other disciplines. In this module you revisited how a gene can be inserted and expressed in a bacterium. making possible the large scale production of an important hormone.

Key Terms

Review the following key terms introduced in this module. When you are ready, check your understanding of gene structure and regulation by taking the quiz linked below.

epigenetics nucleosomes operon promoter
repressor terminator

Biotechnology

Objectives:

- Explain the overall process of generating expression plasmids that can produce proteins in bacteria.
- Utilize a codon table to back-translate a given protein sequence.
- Design a synthetic gene with the correct codon optimization.
- Describe the role of each DNA segment in the expression plasmid in protein production.
- Predict fragments generated from a DNA sequence after digestion with restriction enzymes.
- Be able to predict which restriction sites are required on the end of the synthetic gene to allow insertion into the expression plasmid.

Introduction to Biotechnology

The ability to manipulate DNA has led to dramatic changes in medicine, agriculture, and many other aspects of society. For example, genes from other species are transferred into crop plants and livestock to provide them with desired traits. And many drugs are produced by bacteria, yeast, or other organisms that have been engineered to express human genes.

In this module, you will learn about how biotechnology is used to produce human growth hormone (huGH) for medical applications. HuGH is a protein made of 191 amino acids. It is necessary for the normal growth and metabolism of an individual. Worldwide, one in 4,000 to 10,000 individuals is born without the ability to make sufficient human growth hormone, causing a host of medical problems. These people can be helped with growth hormone injections, but growth hormone from other species (pigs, cattle) cannot be used. Only human growth hormone will produce the desired effects. Historically, the only source of human growth hormone was a small amount that could be extracted from recently deceased individuals (cadavers). this severely limited the supply that was available for medical use.

You will also learn about how biotechnology has solved this problem and decreased the cost of medical treatments that significantly improve the quality of life for many people.

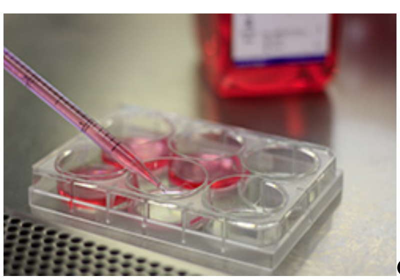
Producing HuGH: An Overview

The basic steps in producing human growth hormone (HuGH) in bacteria are:

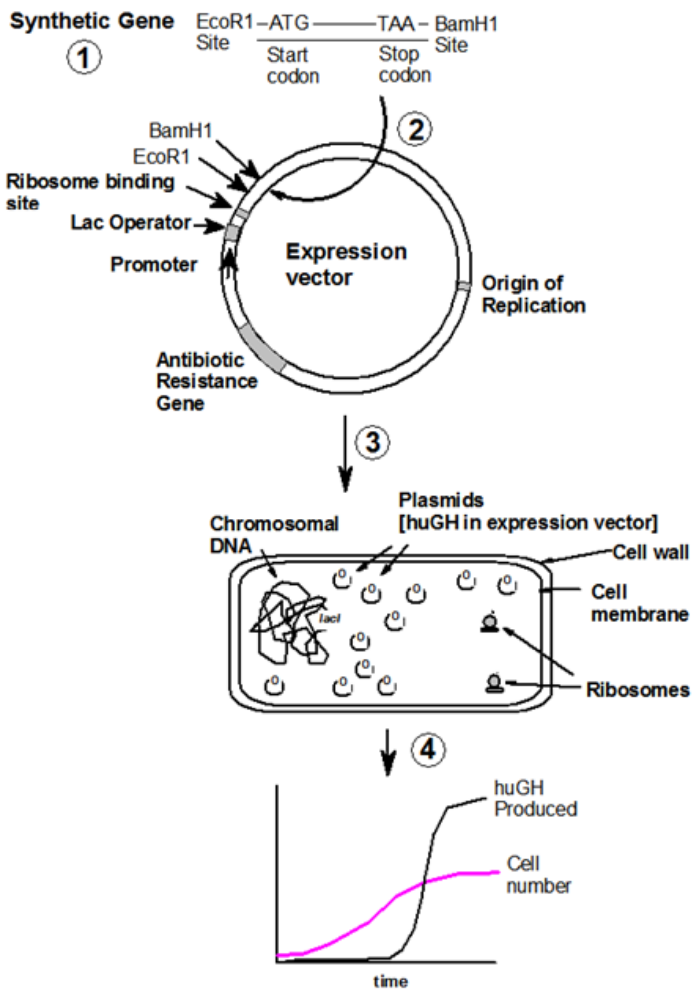
1. generation of a synthetic gene
2. inserting this gene into a bacterial expression plasmid,
3. introducing the plasmid into bacteria,
4. production and purification of the human growth hormone.

The synthetic gene provides the information that specifies the order of the amino acids in HuGH. The expression plasmid is a large closed circular piece of DNA. Various DNA sequences on the expression plasmid are required for maintenance of the plasmid in the cells. These sequences are present on all plasmids, regardless of the type of protein that is being made. The plasmid also contains DNA sequences (promoter for RNA polymerase, lac operator) that are required for the production of the mRNA that encodes HuGH. The bacterial cell provides the protein synthesizing machinery so that the mRNA can be translated to a protein. In order for the protein to be correctly made the mRNA must contain a ribosome binding site, a start codon, and a stop codon.

More recently, proteins used for medical treatment are produced in yeast or cultured mammalian cells that are grown in synthetic growth media. Protein production in yeast or mammalian cells avoids the possibility of having toxic bacterial impurities in the final product. The overall steps in producing the protein in yeast or mammalian cells are very similar to the steps described here, however the overall cost of producing the protein may be somewhat higher.



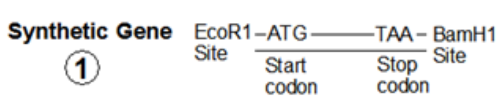
Growth of mammalian cells in tissue culture. The sterile plastic dish holds synthetic media (red liquid) that supports the growth of mammalian cells



Steps in the production of Human Growth Hormone in Bacteria.

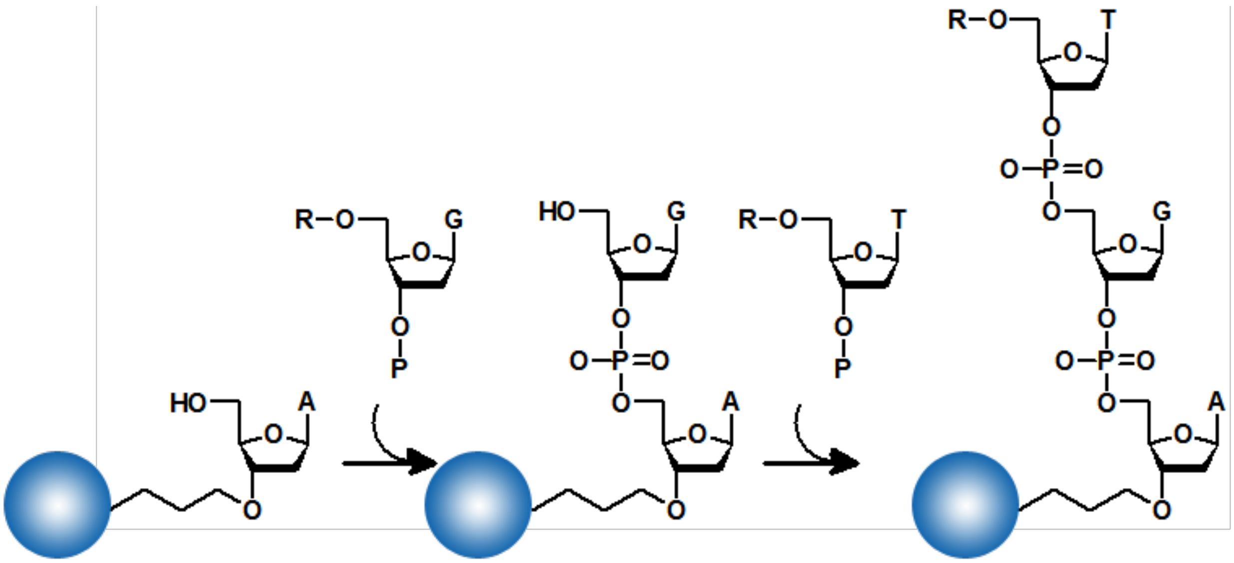
1. A synthetic gene is made that can be translated into the amino acid sequence of the human growth hormone.
2. This gene is inserted in the correct location in a closed circular piece of DNA (an expression plasmid) by use of restriction sites.
3. The expression plasmid is introduced into bacteria.
4. The bacteria are grown to a high cell density, and then lactose is added to induce the production of human growth hormone.

Generating a Synthetic Gene



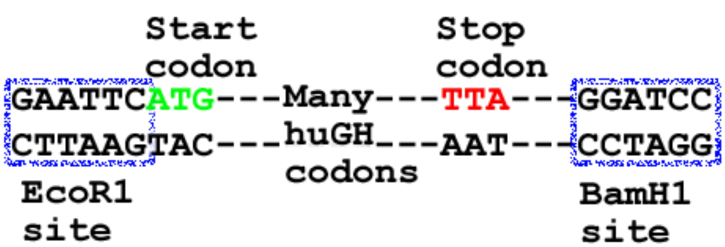
The first step in producing HuGH is to generate a synthetic gene whose nucleotide sequence codes for the amino acid sequence of the growth hormone. This sequence would contain the start codon, codons representing each amino acid in the growth hormone, and a stop codon. To do this, the known amino acid sequence for human growth hormone must be “back-translated” to a nucleic acid sequence. Since most amino acids can be coded for by more than one mRNA codon, this process is ambiguous. Because the genetic code is universal it would be possible to use the human codons to encode the sequence of amino acids. However, the host organism (which is bacteria in this example) often prefer certain codons over others, so the preferred codons must be used to optimize protein expression.

We will synthesize our HuGH gene using a chemical method called solid-phase synthesis. In this method, the first base of our DNA sequence is attached to a small glass bead. The next base is then added to the first, and so on, until the sequence is completed at which point the DNA is released from the glass bead. Any desired DNA sequence can be generated by this method. Current technology limits this approach to about 200 bases. If our gene is longer, we have to make it in segments and then join the individual segments together.



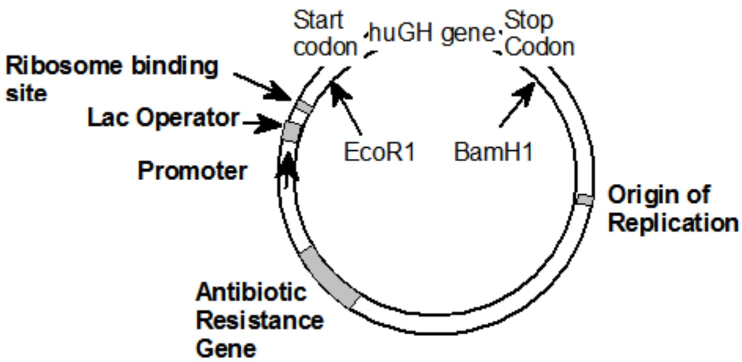
Chemical synthesis of DNA. The first base (A) is attached to a glass bead (blue sphere). The next base (G) is added, followed by the third base (T). This process is repeated until the entire DNA strand is completed. The linkage to the glass bead is then broken, and the completed DNA molecule is released. In contrast to the direction of synthesis by DNA polymerases (5'->3'), the chemical synthesis of DNA is in the reverse direction, beginning at the 3' end. The above diagram shows the synthesis of 5'-TGA-3'.

In addition to the codons, it is necessary to add additional sequences to the end of the gene to facilitate the insertion of our synthetic gene into the expression plasmid. These sequences are called restriction sites. Consequently the complete gene is:



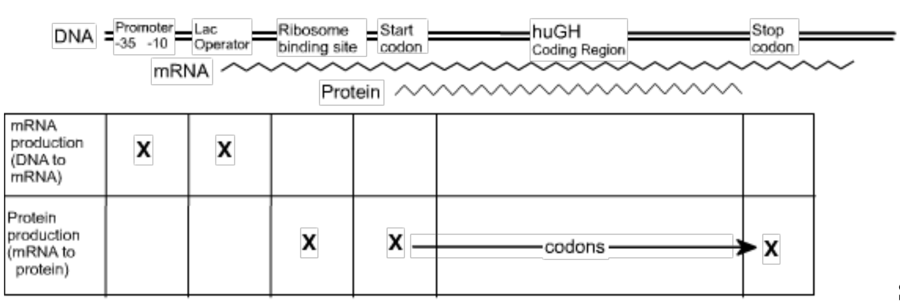
What Is an Expression Plasmid?

After you have generated your synthetic gene, you must insert the gene into an expression plasmid so it can be placed inside a living bacterial cell and translated into the HuGH protein. We will look at that step in detail on the next page. For now, let's assume that has been accomplished. Here we want to focus on the properties of the expression plasmid.



An expression plasmid is a closed circular molecule of DNA that has several unique properties associated with its DNA sequences. There are three general types of sequences that are found on expression vectors:

1. Sequences involved in maintaining the plasmid in the cell.
   - First, the expression plasmid contains a section of DNA that is an origin of replication. This ensures that when it is placed into a bacterial host cell, it will be successfully replicated. The origin of replication on the plasmid is similar to the origin of replication that is found on the bacterial chromosome.
   - The expression plasmid must also contain a section of DNA that encodes a protein that will confer antibiotic resistance on the bacterial cells that contain the plasmid. This provides a method to select the bacterial cells that contain the plasmid, because if they have the plasmid, they will be able to grow in the presence of an antibiotic while cells that do not have the plasmid will die.
2. Sequences that allow the insertion of the synthetic DNA into the plasmid.
   - These are short DNA sequences that are recognized by restriction endonucleases, in the case of this plasmid they are the EcoR1 and BamH1 sites. Restriction endonucleases cut the DNA at these sequences, allowing the insertion of the synthetic gene between the sites. The actual mechanism is discussed in the next section.
3. Sequences involved in transcribing the DNA to mRNA.
   - The expression plasmid must also contain a promoter that is recognized by RNA polymerase. This promoter is adjacent to the growth hormone gene and will enable the transcription of the growth hormone gene into mRNA.
   - The expression plasmid must contain a DNA sequence that allows a repressor protein to bind. The repressor protein can then act as an on-off switch for mRNA production. An on/off switch is important because the production of growth hormone can interfere with cell division and the production of the growth hormone should be off until a sufficient number of cells are obtained. The most common repressor protein that is used is the lac repressor. The lac repressor binds to a specific DNA sequence called the lac operator. You may want to review the properties of the lac operon. The addition of an inducer molecule, such as lactose, will cause the repressor to fall off of the DNA, allowing RNA polymerase to produce mRNA. It is important that the operator sequence is placed between the promoter and the DNA that encodes the mRNA so that mRNA cannot be made unless an inducer is added.
4. Sequences involved in translating the mRNA to Protein
   - The expression plasmid must have a DNA sequence that will encode a ribosome binding site on the mRNA. This sequence, which will be found at the beginning of the mRNA, will allow the mRNA to bind to the bacterial ribosome, initiating the process of protein synthesis. This segment must be part of the mRNA and it has to occur just before the start codon to position the mRNA correctly on the ribosome.



Summary of DNA sequences in the expression plasmid and their role in mRNA and protein production.

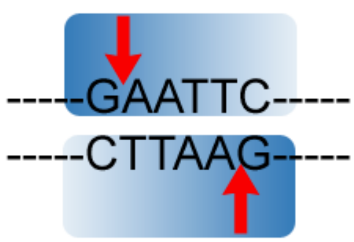
Restriction Enzymes: A useful Tool for Manipulating DNA

The step of inserting our synthetic DNA into the plasmid use two very important enzymes, restriction enzymes and DNA ligase. Restriction endonucleases are enzymes that recognize specific DNA sequences, such as GAATTC, and cut both strands of the DNA within these sequences. Typically four or six bases are recognized. Restriction enzymes are isolated from a number of bacterial species and the name of the enzyme reflects the original species. For example, the restriction enzyme EcoR1 was isolated from*Escherichia coli*. The normal biological function of restriction endonucleases is to protect the bacterial species from viruses by digesting the viral DNA as it enters the cell. Of course, the bacteria shouldn't digest their own DNA. Consequently, they have companion enzymes called DNA methylases, which add methyl groups to the bacterial DNA, protecting it from digestion.

There are hundreds of different restriction enzymes, each of which recognizes and cleaves a different DNA sequence or "restriction site". Examples of two such enzymes are shown below. A shorthand notation for the recognition site is given below each name. The "^" symbol indicates the site of cleavage. The DNA sequence that they recognize is shown on the left and the products of the digestion are shown on the right. The fragments that are produced after cleavage can contain single stranded overhangs (e.g. EcoR1) or have blunt ends, such as with PvuII.

Name (shorthand)	Recognition sequence	Clevage products	
EcoR1 (G^AATTC)	5'--GAATTC--3' 3'--CTTAAG--5'	5'--G 3'--CTTAA	AATTC--3' G--5'
PvuII (CAT^ATG)	5'--CATATG--3' 3'--GTATAC--5'	5'--CAT 3'--GTA	ATG--3' TAC--5'

The DNA sequences that are recognized by restriction endonucleases have a unique property in that the sequence on the top strand is identical to the sequence on the bottom strand, i.e. in the case of EcoR1 the sequence of the top strand is 5'-GAATTC. Taking the complement of that sequence to generate the bottom strand gives: 5' GAATTC. The other notable feature is that the cutting position is in the same location on both strands. Using EcoR1 as an example, the enzyme cuts between the G and the A. The symmetry in the recognition sequence and the cutting location is due to the fact that the active form of these enzymes contain two identical polypeptide chains. You can imagine that one chain recognizes and cleaves the top strand. The second chain, because it is identical to the first, recognizes the same sequence on the other strand and cleaves in the same location.

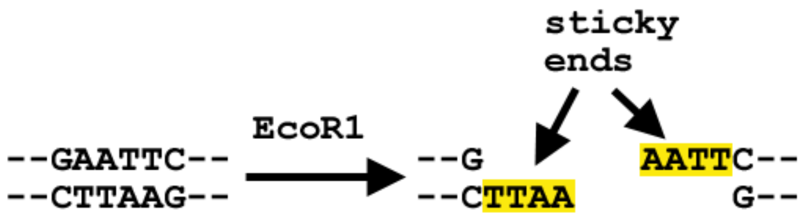


Cartoon diagram of EcoR1. The two blue rectangles represent the two identical subunits of the enzyme. The red arrow marks the cleavage location.

learn by doing

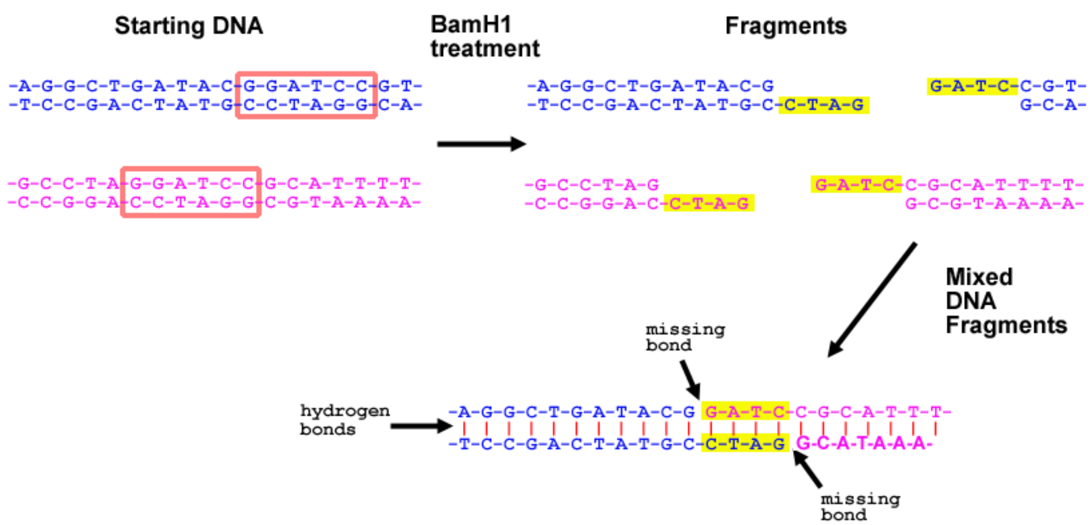
If the restriction enzyme does not cut at the center of its recognition sequence the cleavage products will contain short single-stranded segments of DNA. These are often called "sticky-ends" because they can stick to other DNA molecules that have complementary sticky ends. Enzymes that cut in the middle of their recognition sequences produce blunt end fragments.

Below, the formation of sticky ends after EcoR1 cleavage is illustrated.

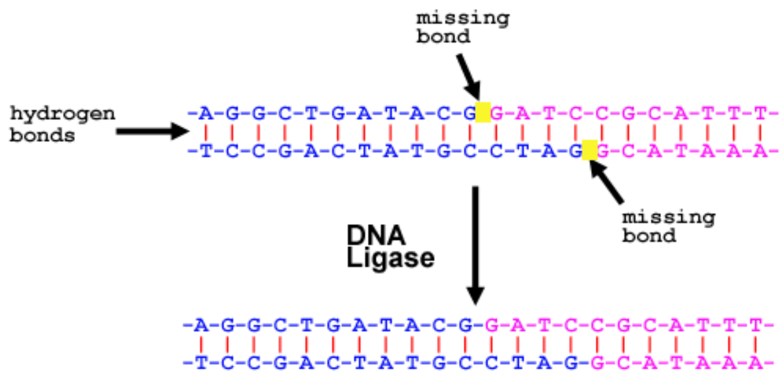


Because cleavage does not occur in the middle of the recognition sequence, the products have short single strand segments (highlighted). These sticky ends can "stick" to complementary single-stranded DNA sequences using normal DNA basepairing (A-T, G-C).

The presence of sticky ends on DNA fragments makes it easy to join DNA fragments. If two fragments are both cut with the same restriction enzyme, they will have complementary sticky ends. These will align and bind loosely to each other: hydrogen bonds will form between complementary bases.

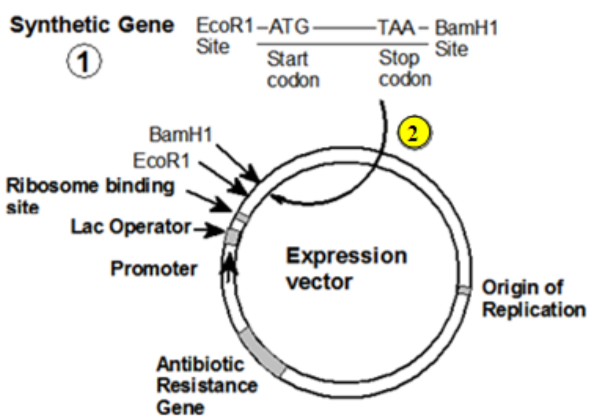


At this point, the two fragments are not firmly held together by covalent bonds; the sugar-phosphate backbone is still broken on both strands. DNA ligases can be used to rejoin DNA after it has been cut with the restriction enzyme. This reaction requires energy (usually ATP) and requires that the two pieces of DNA that are being joined are close to each other. Since the sticky ends hold the two ends close together it is easy for DNA ligase to join the fragments, reforming the phosphodiester bonds on both strands.



Although most of the time DNA fragments are joined using sticky ends, it is possible to join fragments that are blunt ended. This is more difficult however because there are no hydrogen bonds to hold the DNA fragments together.

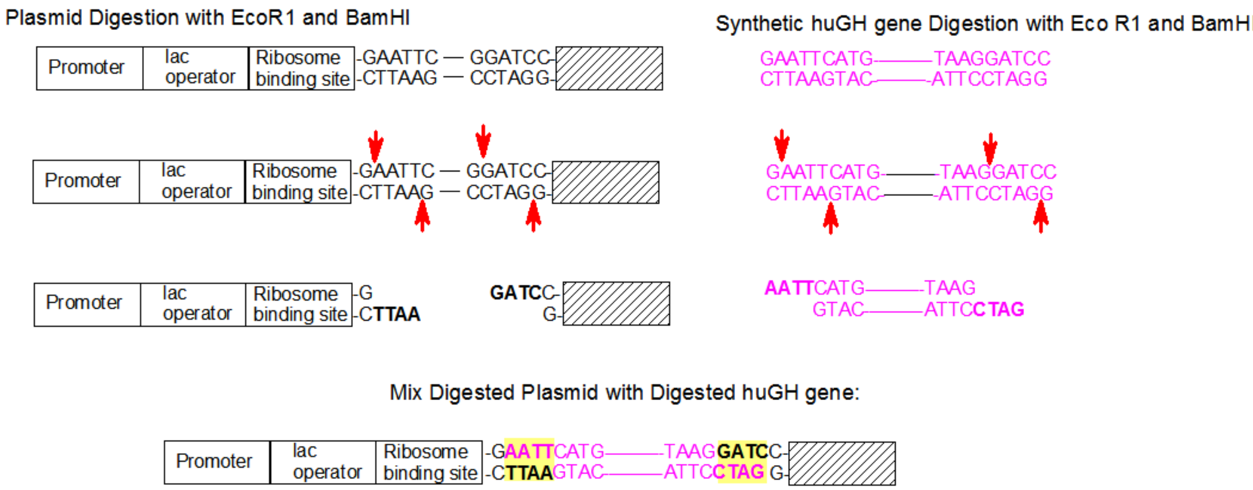
Place Gene Into Expression Plasmid



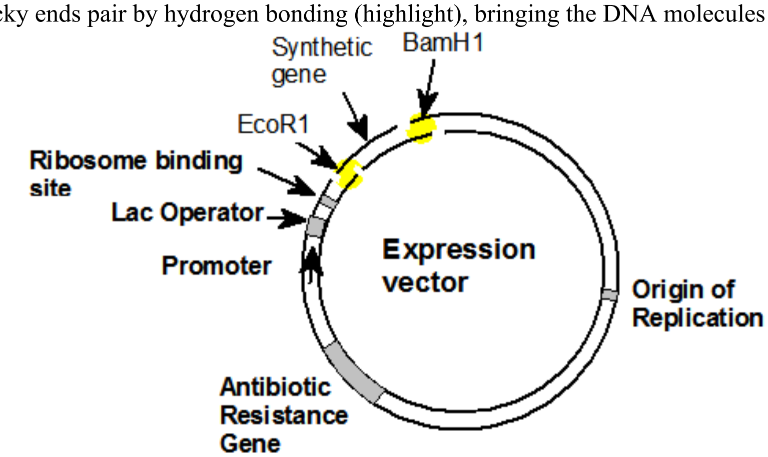
Insertion of the Human Growth Hormone Gene Into the Expression plasmid

Restriction endonucleases and DNA ligase are used to insert the synthetic gene into the correct location in the expression plasmid, just after the ribosome binding site.

The expression plasmid would have two different restriction sites after the ribosome binding site to facilitate the insertion of the synthetic gene. To utilize these sites it would be necessary to include these restriction sites at the end of our synthetic gene. The expression plasmid and the synthetic fragment would be cut with the restriction enzymes, mixed, and then treated with DNA ligase to re-seal the phosphodiester backbone:



Detailed process of joining the huGH gene to the expression plasmid. Both the plasmid and the huGH gene are cut with EcoR1 (G^AATTC) and BamHI (G^GATCC), generating sticky ends on both DNAs (bold text). After mixing the cut plasmid and huGH gene, the sticky ends pair by hydrogen bonding (highlight), bringing the DNA molecules close so that



they can be ligated by DNA ligase.
Combined expression plasmid - synthetic gene before ligation. The paired sticky ends are highlighted in yellow.

Introduce Expression Plasmid Into Host

Once the synthetic gene has been successfully spliced into the expression plasmid, the complete expression plasmid must be taken into the bacterial cell. This is a delicate process that must take place under special conditions. In these conditions, the expression plasmid is mixed with bacterial cells, allowing some of the cells to take up one circular DNA molecule. The origin of replication on the expression plasmid will cause the bacteria to replicate the plasmid along with its own chromosomal DNA. It is not possible to determine which cells have taken up the expression plasmid. Consequently, the cells are grown in the presence of an antibiotic and only those cells who have obtained the expression plasmid will live because of the gene for antibiotic resistance that is also present on the expression plasmid.

Production of HuGH

The cells containing the plasmid would be grown in culture media to a high density of cells to produce a high yield of huGH. Lactose would be added to the culture to cause the lac repressor to come off the DNA. This allows RNA polymerase to begin transcription of the growth hormone gene on the plasmid. The mRNA would be translated on the bacterial ribosomes, producing human growth hormone.

Biotechnology: Summary

Through biotechnology, we can now transfer genes among different types of cells. This and related tools are used to solve many problems in medicine and agriculture. In this module, you learned about an example that illustrates many of the basic procedures that are used in modern biotechnology.

You learned about the steps that can be used to produce a human protein (human growth hormone) in bacteria.

1. A synthetic gene is chemically synthesized using the known amino acid sequence of the target protein (HuGH) to determine the required DNA sequence. In cases where the genetic code is redundant (more than one codon specifies a single amino acid), those codons preferred by bacteria are selected when designing the synthetic DNA.
2. The synthetic DNA is inserted into an expression plasmid, using a combination of restriction endonucleases and DNA ligase. The expression plasmid contains DNA segments that are responsible for replication of the plasmid and a gene that confers antibiotic resistance to bacteria. The expression plasmid also contains the required signals for the initiation, regulation, and termination of mRNA from the inserted synthetic gene.
3. The expression plasmid is transferred into bacteria. Antibiotic is added to the culture medium so that only those bacteria containing the plasmid can grow.
4. The bacteria are cultured under conditions that favor rapid growth. The production of mRNA is initiated by the addition of lactose to the culture. Useful quantities of the final product - human growth hormone - can now be extracted from the medium.
5. The process above can be used to produce human insulin or virtually any other protein in bacteria, simply by changing the DNA sequence of the synthetic gene. A similar process is used to produce proteins in yeast or mammalian cells for biomedical applications.

The process above can be used to produce human insulin or virtually any other protein in bacteria, simply by changing the DNA sequence of the synthetic gene. A similar process is used to produce proteins in yeast or mammalian cells for biomedical applications.

Key Terms

Review the following key terms from this module. Click on the term to view a definition and additional information.

Antibiotic resistance	Codon optimization	Expression plasmid	DNA ligase
Lac operator	Lac repressor	Origin of replication	Restriction endonuclease
Ribosome binding site	Start codon	Sticky end	Stop codon

Unit Summary: Molecular Genetics

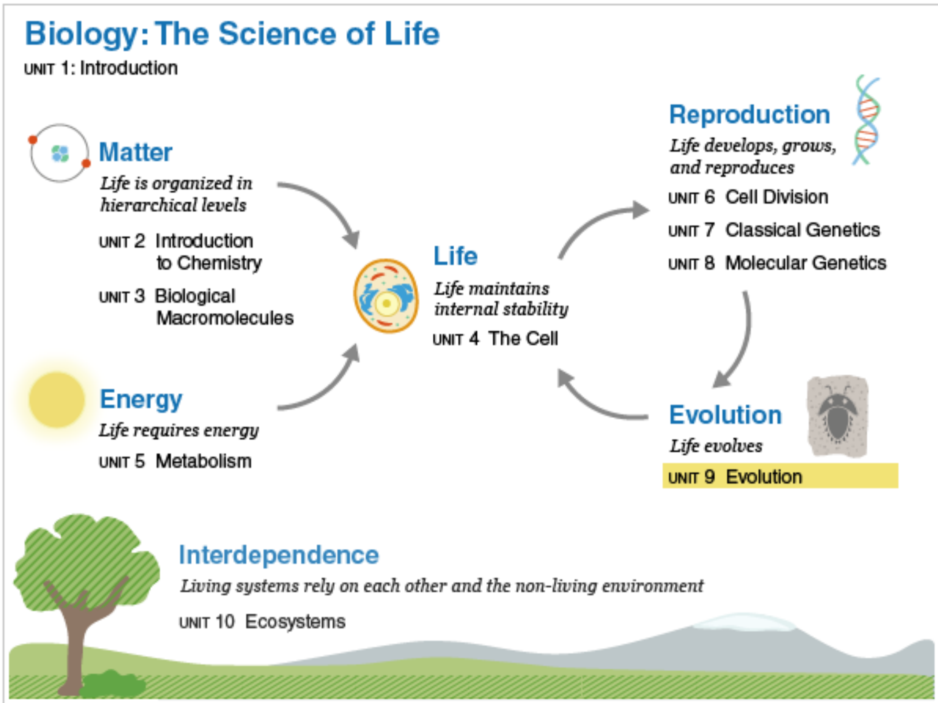
In this unit, you learned about genetic information from the molecular point of view. In the DNA Function module , you learned that genetic information is stored in the sequence of bases in the DNA molecules. The theme “structure determines function” clearly applies to DNA: the double-stranded structure of DNA provides a way for copying the information each time a cell has to divide because each of the two strands serves as a template for the new double-stranded DNA molecule (DNA replication). In the Gene Expression module, you learned how information stored in DNA is used by the cell to make proteins. Central dogma of molecular biology describes the flow of genetic information from DNA to RNA to protein. The two key processes involved in gene expression, transcription and translation, involve distinct enzymes and in eukaryotic cells are physically separated by the nuclear membranes. In this module you also considered how changes in DNA (mutations, genotype) can affect amino acid sequence of the proteins and their function (phenotype).

The connection between genotype and phenotype of the organism was further discussed in the Gene Regulation module. This module began with discussion of gene structure, including the parts of the gene required for regulation of gene expression: *coding DNA sequence, untranslated regions, promoter, operator, and terminator*. Comparison of eukaryotic and prokaryotic genes and genomes revealed important differences. Many prokaryotic genes with related functions reside next to each other on DNA (operons) and are expressed together in a single RNA. Eukaryotic genes are often fragmented: exons are interrupted by introns, which are removed from the final mRNA. The modular organization of eukaryotic genes gives more flexibility in gene expression, because one DNA sequence can give rise to different versions of RNA and protein in different cells. The module also addressed the interactions between genes and environment. In addition to DNA damage by mutagens, environment can affect gene expression directly via regulatory proteins, or indirectly by changing packaging of DNA.

The knowledge of molecular genetics can be applied to medicine. One application discussed in the*Biotechnology* module involves production of human proteins in bacterial, yeast or other cells grown in laboratory. Since genetic code is nearly universal, DNA from humans can be “read” by other cells and used to make proteins. However, differences in gene and genome structure between prokaryotic and eukaryotic cells require scientists to engineer new DNA molecules that combine both, coding information from a human gene and regulatory information from yeast or bacterial genomes. A large number of techniques have been developed for manipulating DNA: PCR is used to make copies of DNA fragments, specialized enzymes are used to cut and put together DNA fragments, and special procedures drive foreign DNA into the cells and induce expression of the foreign gene.

Unit Introduction: Evolution

Thus far you have learned a great deal about how cells function. In the genetics units you've learned how biological information is inherited and used. You are beginning to appreciate that each cell and organism is a complex and highly integrated unit.



Life changes and evolves over time. Evolution considers how life changes from one generation to the next and how these changes accumulate over very long periods.

Evolution builds on what you already know. It is a scientific theory that explores life on a different scale and provides another layer of explanation (Table 1). First, it goes beyond the brief lifetimes of individual organisms. Instead, evolution considers how life changes from one generation to the next and how these changes accumulate over very long time scales. Second, evolution is focused on collections of individuals: populations, species, and larger taxonomic groups (for example, birds or flowering plants). Evolution also adds another layer of explanation to biological thinking. So far we have focused mainly on "how" questions. How does a cell maintain homeostasis? How is information passed from parents to offspring, and how is that information used to construct living cells? Evolution helps us answer "why" questions: Why do cells of very different organisms have so much in common? Why are cave fish blind? Rather than taking the features of life as a starting point, evolution asks why those features exist today and how they originated in the past.

Characteristics of Evolutionary Theory

Attribute	*Characteristics*
Time scale	Generations to much longer time scales
Level of hierarchy	Populations to larger collections like taxonomic groups
Level of explanation	Explores "why" questions. Why do features of life exist as they do? What is their history?

As a scientific theory, evolution is more than a mere opinion or guess. In science, a "theory" is a broad explanation that is supported by a great deal of evidence and continues to inspire productive research. Scientists accept and use evolutionary theory because it is so strongly supported by evidence from many different sources. It fits our observations of the diversity and variability of physical traits in animals in different settings. The theory is now also supported by consistent and reproducible data gathered from fossils, a detailed understanding of the skeletal and organ structure of living organisms, and our twenty-first century abilities to examine and determine the structure and function of proteins and DNA in living things. Since the theory of evolution was first put forth in the 1850s and since some of the supporting evidence is based in ancient fossils, you might get the impression that evolution occurred in the past and is complete. That is not correct. In fact, evolution continues all around us today and evolutionary ideas are being applied to solve a huge range of problems of both academic and practical interest! Below are a few examples. You will learn about some of them in this unit. Evolutionary theory and models are used to:

- Combat drug resistance in disease-causing pathogens
- Fight against fast-evolving insect pests and weeds
- Figure out the origins of modern languages
- Design better products and software
- Develop targeted vaccines against seasonal influenza
- Discover the genes underlying human diseases

Evolution is that and much more. In the first module, we will introduce and define the biological theory of evolution. In the second module we will focus on relatively fast and subtle changes that occur within populations (microevolution). In the third module we will consider the much more dramatic changes that occur over long time scales and generate the diversity of life (macroevolution). As you learn, try to maintain an open mind and evaluate the evidence on its own merits. You will gain a better understanding of a scientific theory that is very influential in our society.

Roots of Evolution

People have been grappling with questions about the origins of life for nearly as long as we have been in existence. Every society has addressed these questions based on the information that was available at that time and place. Before the Scientific Revolution, people used many different sources of information to answer questions about the origins of life. Some of their ideas were based on direct observations, but many of them involved supernatural beings or spiritual forces. Stories were told to explain how the world and humans were made, but also to address questions of meaning: why the world exists and what human life is "for." Ideas were passed down as oral tradition (myth and folklore) or in the written documents of organized religions. Scientific study is much more narrowly focused on close examination of processes and objects in the natural world. In order for an explanation to be considered scientific, it must be based on verifiable observations. It must be possible to test it through observations or experiments. Ideas or explanations that do not meet these criteria are not necessarily "bad" or "wrong," but they are unscientific.

Scientific and non-scientific views are separate but potentially complementary ways of knowing. Scientific methods can be used to answer direct, factual questions about "what is" and "what probably was" through a clear procedure of observation and testing. Through an ongoing process scientists select ideas that best fit the available data. No religious tradition revealed the existence and function of DNA to humans: that was the fruit of scientific study and reasoning. However, answers derived from science are limited. They do not necessarily help with ultimate questions of meaning (why the Universe exists in the first place, what humans should be or do). Non-scientific ways of looking at the world (religion, philosophy) are more directly focused on these questions. Many scientists embrace religious ideas about the meaning and ultimate origins of life. However, they do not publish these ideas in scientific journals or used them to explain their detailed observations of the natural world.

In this course, we will focus on how the scientific community understands evolution and the origins of life. Like the community of science itself, we will restrict our scope to fairly narrow questions of how and when things probably happened, based on what we can observe today. Other explanations are better suited to philosophy or religion courses; they help us explore broader questions about why the Universe exists and what our place is within it.

Before defining the modern theory of evolution, we will consider its historic roots. You probably know that the scholar most widely recognized as the author of the theory of evolution was Charles Darwin. The first statement of modern evolutionary theory was his book On the Origin of Species, published in 1859. But Darwin didn't make up the theory from nothing, and he wasn't the first to ask questions about the ultimate origins of life. How did science deal with life's big "why" questions before evolutionary theory developed? What clues led scientists to propose and embrace evolution? To gain some insights into these questions, explore the Learn By Doing activity below.

What is Evolution?

In our society, the word "evolution" is used very broadly to mean any kind of change (usually for the better). Political views, hairstyles, and technologies all are said to "evolve." In science, the phrase "biological evolution" has a more precise meaning. *Biological evolution* is a change in inherited (genetic) features that occurs in populations and higher-level groups over time.

Evolution can be divided into two levels: microevolution and macroevolution. *Microevolution* is a process that occurs within a single population as inherited traits become more or less common from one generation to the next. It is a change in the genetic makeup of a population. Natural selection is the main process of microevolution; it shapes populations such that they become better-adapted to local conditions over time. For bacteria, viruses, insects, weeds, birds, small fish, and other species with short generation times, we can sometimes directly observe microevolution over periods of a few years or less.

Macroevolution involves bigger changes that occur more slowly and cannot be directly observed in most cases. It is the long-term evolution of biological lineages and includes the origin and extinction of species and larger taxonomic groups. According to current scientific thinking, all of life's diversity can be traced back to one or a few original cellular life forms. From this starting point, macroevolution has done a huge job in producing life's diversity. It has had a long time to work: scientists estimate that life on Earth is well over 3 billion years old. Over vast time spans, slow and subtle processes have produced the spectacular diversity of modern life.

Level of evolution	Level of hierarchy	What changes?	Time scale?
Macroevolution	Biological lineages: species and higher-level taxonomic groups	Biodiversity: features and numbers of species	Many generations; too slow to observe directly in most cases
Microevolution	Populations	Gene pool: genetic makeup of the population	One to many generations; may be observed directly in short-lived species
*Does not qualify*as biological evolution	Individual	Characteristics including features acquired through development, learning, injury, etc.	Single life span

To recap, below are the major components of the modern theory of biological evolution:

- Evolution is a change in the genetic makeup of populations or larger groups of organisms over generations of time.
- Natural selection is a key process of evolution and explains life's adaptive features.
- Life on Earth is ancient (at least 3.6 billion years old) and all life forms are related by ancestry from one or a few single-celled common ancestors.

Evolution is a change in a population, not in the characteristics of one individual over a single lifetime. As its body temperature, breeding status, and mood change, a lizard's colors may intensify or fade. But this has no effect on future generations of lizards. We must broaden our focus to see evolutionary changes: in a population of thousands or millions, what percentage of lizards inherit a light color pattern and what percentage inherit darker colors? How does this inherited trait change over many generations?

One striking feature of life is its adaptation: the exquisite "fit" between organisms and their natural environments. In their behavior, structure, and chemistry organisms are very well-suited to the conditions of life they experience. They may be astonishingly cryptic (camouflaged) in their natural backgrounds. They may tolerate extremes of cold, heat, salinity, or other factors unique to their habitat. Adaptive traits are any inherited characteristics - physical, chemical, or behavioral - that enable an organism's successful reproduction in a given environment.

"Bleached" form of lesser earless lizard (Holbrookia maculata) from White Sands National Monument, a region of white-sand dunes in New Mexico. The light color of lizards from this population results from a known mutation in a pigmentation gene and helps them avoid detection by visual predators.

Lesser earless lizard (Holbrookia maculata) from a typical habitat containing rocks and woody plants in the western United States. The broken outline and blotchy coloration of this lizard help it blend in with its local habitat and avoid detection by visual predators.

Why do adaptive traits exist? Natural selection is a process that produces and maintains adaptive traits within populations. It occurs under the following circumstances and through the following process:

1. *Heritable variation exists* in a population. In other words, the population includes different genetic types that can pass on their characteristics to their offspring. These types exist because of past mutations. In the example above, the “bleached” form of lizard has a known mutation in a pigmentation gene called Mc1r. Mutations in the same gene influence coloration in a wide range of animals including fish, falcons, mice, dogs, and humans.
2. *Selection* occurs: some of the genetic types reproduce more than others in a given environment. In the lizard example, imagine a time when most lizards in the White Sands area had a darker color form. A new “bleached” mutant appeared in the population. On the white background, “bleached” lizards probably survived much better than did those who inherited a darker color pattern. Experiments have confirmed that small animals that match their backgrounds are much less likely to be attacked by visual predators. A matching color pattern is an adaptive trait: it results in improved average reproductive success in the appropriate environment.
3. *Adaptation results:* over generations of time, those genetic types that reproduce more successfully become more common in a population. Adaptive traits become common as a result of past and ongoing natural selection. In the core of the White Sands area, the vast majority of lizards show the “bleached” color pattern.

We sometimes refer to organisms’ adaptive traits as “adaptations.” We also use the word “adaptation” as a verb, to describe the process of evolution that occurs over many generations of natural selection. In the White Sands National Monument, we see the outcome of past evolution - three different species of lizard all have “bleached” color forms that inhabit the white-sand dunes. But we can also see evidence of ongoing evolution. Within two of the three species, lizards of both color forms coexist around the edges of the White Sands and there is a gradual shift toward darker color patterns as one moves into the surrounding (brown-soiled) desert. In some areas there is noticeable variation; both color forms are present. No doubt there is ongoing selection as predators continue to hunt lizards, generation after generation. Although the lizards move around and breed with each other, natural selection maintains dark color types in dark habitats and “bleached” color forms in the White Sands.

To learn more: [Rosenblum, EB and others. 2009. Molecular and functional basis of phenotypic convergence in white lizards at White Sands. Proceedings of the National Academy of Sciences 107: 2113-2117]