Biology Essentials 1

BIOLOGY ESSENTIALS 1

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LAND ACKNOWLEDGEMENT

We acknowledge and honour the Anishanaabe, Huadenoshaunnee, and Lanape people of Southwestern Ontario as the traditional owners and custodians of the land and waterways on which Fanshawe College is located. Further, we acknowledge the cultural diversity of all Indigenous peoples, and pay respect to the Elders, past, present, and future.

We celebrate the continuous living cultures of the original inhabitants of Canada, and acknowledge the important contributions Indigenous people have, and continue to make, in Canadian society. The College respects and acknowledges our Indigenous students, staff, Elders, and Indigenous visitors who come from many nations.

–Fanshawe College Land Acknowledgement

As we begin our exploration of biology, it is important to recognize our relationship with the land on which we live and learn. The more we learn about the natural world throughout the course, the more we come to understand how deeply disconnected many of us have become from it. I acknowledge that to truly reconnect and learn to care for our land, we must follow the lead of Indigenous peoples who have maintained a profound and respectful relationship with nature.

"Canoeing" by Tom Harman, CC BY-NC-SA 4.0

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As someone who deeply values outdoor recreation, such as hiking, mountain biking, canoeing and camping, I am continuously reminded of the beauty and significance of this land. Engaging with nature through these activities enhances my appreciation for its wonders and the need for its protection. I commit to treating nature with care and respect and hope to foster a relationship with the land that honours its original caretakers.

As we learn about life throughout this course, let's also work to understand our place within it – as members of a shared living world.

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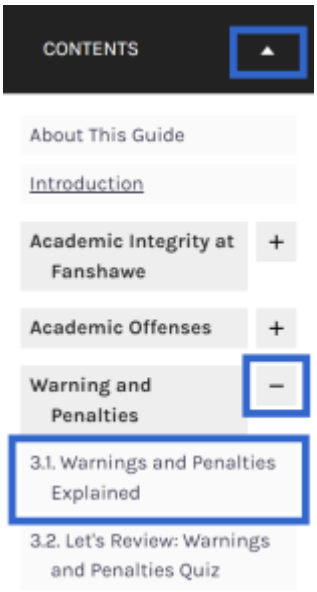

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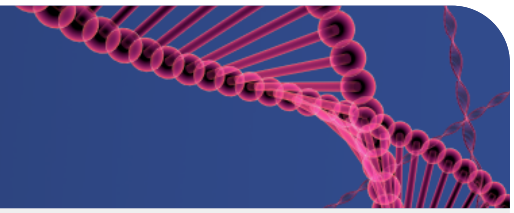
CHAPTER 1: INTRODUCTION TO BIOLOGY

Chapter Overview

Learning Objectives



By the end of this chapter, you will be able to:

- Define science.
- Compare inductive reasoning with deductive reasoning.
- Describe the goals of basic science and applied science.
- Outline the scientific process.
- Identify and describe the properties of life.
- Describe the levels of organization among living things.

1.1 THE NATURE OF SCIENCE

Scrolling through your social media feed or browsing the latest headlines, you'll quickly notice how many aspects of biology are discussed daily. You might see reports of E. coli outbreaks in spinach or Salmonella contamination in chicken. Or you might read about the latest efforts to find cures for diseases like COVID-19, Alzheimer's, and cancer. On a global scale, researchers are dedicated to protecting the planet, addressing environmental issues, and mitigating the effects of climate change. You might also see discussions about genetic engineering and CRISPR technology, revolutionizing medicine and agriculture by allowing scientists to edit genes precisely. All of these diverse efforts are related to biology.

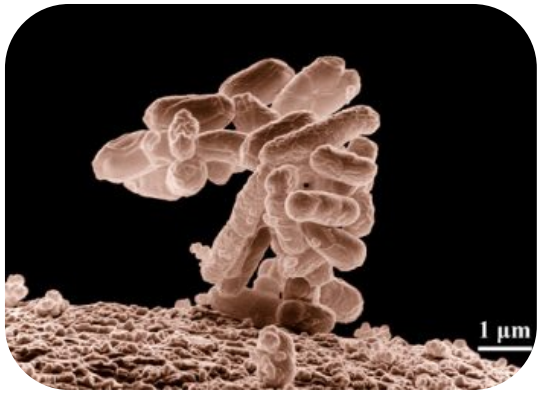


Figure 1.1.1 Biologists may choose to study *Escherichia coli* (*E. coli*), a bacterium that is a typical resident of our digestive tracts but which is also sometimes responsible for disease outbreaks. This micrograph visualizes the bacterium using a scanning electron microscope and digital colorization. Image by Eric Erbe, digital colorization by Christopher Pooley, both of USDA, ARS, EMU, Public Domain

Biology is the scientific study of life. That's a simple definition to remember, but what does it mean? To fully understand biology, we must break the definition into several components. First, if biology is the scientific study of life, then what is science?

The Nature of Science

Science (from the Latin scientia, meaning "knowledge") is a particular way of learning or knowing about the natural world.

The history of the past 500 years demonstrates that **science** is a compelling way of knowing about the world; it is mainly responsible for the technological revolutions that have occurred during this time. There are, however, areas of knowledge and human experience where science methodology cannot apply. These include answering purely moral questions, aesthetic questions, or what can be generally categorized as spiritual questions. Science cannot investigate these areas because they are outside the realm of material phenomena, the phenomena of matter and energy, and cannot be observed and measured.

The **scientific method** is research with defined steps, including experiments and careful observation. The steps of the scientific method will be examined in detail later, but one of the most critical aspects of this

method is the testing of hypotheses. A hypothesis is a suggested explanation for an event that can be tested. **Hypotheses**, or **tentative explanations**, are generally produced within the context of a **scientific theory**. A scientific theory is a generally accepted, thoroughly tested, and confirmed explanation for observations or phenomena. Scientific theory is the foundation of scientific knowledge. In addition, in many scientific disciplines (less so in biology), there are scientific laws, often expressed in mathematical formulas, describing how elements of nature will behave under certain conditions. However, laws do not represent an increase in certainty about the world compared with theories and supported hypotheses, as all aspects of science remain open to revision. Hypotheses are the day-to-day material that scientists work with, developed within the context of theories. Laws are concise descriptions of parts of the world that are amenable to formulaic or mathematical description.

Take a moment to test your knowledge of research terms by completing the drag-and-drop activity below.

Exercise 1.1.1

Text Description
Match each word with its definition.

1. _____ A method of research with defined steps that include experiments and careful observation
2. _____ A suggested explanation for an event
3. _____ A generally accepted, thoroughly tested, and confirmed explanation for a set of observations or phenomena
4. _____ Describe how elements of nature will behave under certain specific conditions

Possible answers:

- Scientific Method
- Hypothesis
- Scientific Law
- Scientific Theory

Answers:

1. ***Scientific Method:*** A method of research with defined steps that include experiments and careful observation
2. ***Hypothesis:*** A suggested explanation for an event
3. ***Scientific Theory:*** A generally accepted, thoroughly tested, and confirmed explanation for a set of observations or phenomena
4. ***Scientific Law:*** Describe how elements of nature will behave under certain specific conditions

Scientific Inquiry

One thing is common to all forms of science: the ultimate goal is "to know." Curiosity and inquiry are the driving forces behind the development of science. Scientists seek to understand the world and its operations. Two methods of logical thinking are used: inductive reasoning and deductive reasoning.

Inductive Reasoning

Inductive reasoning is a form of logical thinking that uses related observations to arrive at a general conclusion. This type of reasoning is common in descriptive science. **Descriptive (or discovery) science** aims to observe, explore, and discover. A life scientist, such as a biologist, records observations. These data can be qualitative (descriptive) or quantitative (consisting of numbers), and the raw data can be supplemented with drawings, pictures, photos, or videos. The scientist can infer conclusions (inductions) based on evidence from many observations. Inductive reasoning involves formulating generalizations inferred from careful observation and analyzing a large amount of data. Brain studies often work this way. Many brains are observed while people are doing a task. The part of the brain that lights up, indicating activity, is then demonstrated to be the part controlling the response to that task.

Jane Goodall's work with chimpanzees in Gombe Stream National Park is a classic example of descriptive science. Jane immersed herself in the chimpanzees' natural habitat for decades and meticulously recorded their behaviours and interactions. From these observations, she could infer general conclusions about chimpanzee behaviour, social structures, and their emotional lives. One of her most groundbreaking discoveries was observing chimpanzees making and using tools. She saw a chimpanzee strip leaves off a twig and use it to fish termites out of a mound. This observation challenged the prevailing belief that only humans used tools, leading to a significant shift in our understanding of animal behaviour and cognition.

Figure 1.1.2 Two young chimpanzees are playing together in the Gombe National Park in Tanzania. Here, the famous primatologist Jane Goodall spent many years researching the behaviour of chimpanzees in the wild. "Chimps in Gombe" by Cethuyghe, CC BY SA 4.0

Deductive Reasoning

In deductive reasoning, the thinking pattern moves in the opposite direction compared to inductive reasoning.

Deductive reasoning is a form of logical thinking that uses a general principle or law to forecast specific results. From those general principles, a scientist can extrapolate and predict the exact results that would be valid as long as the general principles are valid. For example, a prediction would be that if the climate is becoming warmer in a region, the distribution of plants and animals should change. Comparisons have been made between distributions in the past and the present, and the many changes that have been found are consistent with a warming climate. Finding the change in distribution proves the climate change conclusion is valid.

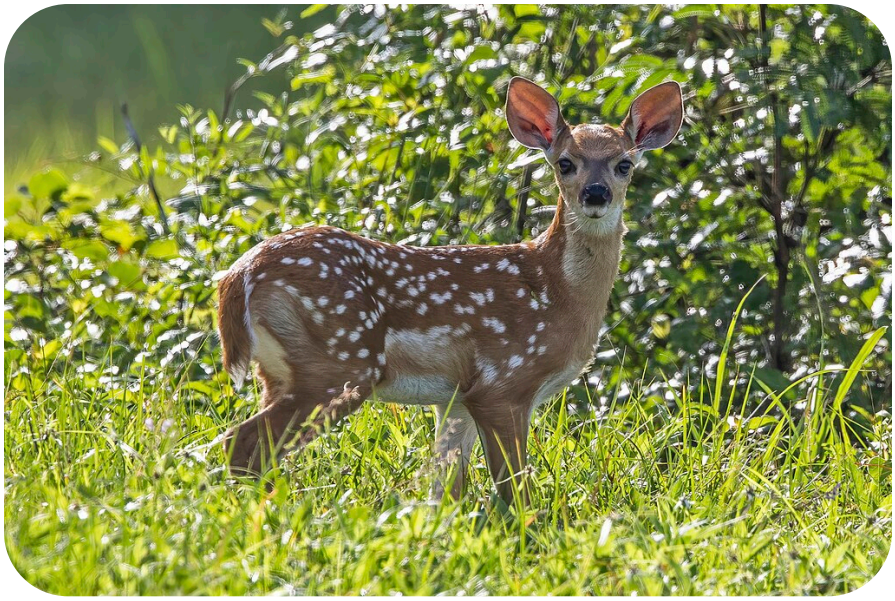


Figure 1.1.3 In Canada's boreal forests, the warming climate allows white-tailed deer to expand northwards and increase in abundance. Image by Charles J. Sharp, CC BY-SA 4.0

Deductive reasoning or deduction is the type of logic used in hypothesis-based science. **Hypothesis-based science** begins with a specific question or problem and a potential answer or solution that can be tested.

Inductive reasoning therefore works from the specific to the general, while deductive reasoning works from

the general to the specific. In reality, most scientific endeavours use a combination of descriptive science and hypothesis-based science. The boundary between these two main pathways of scientific study is often blurred. Observations lead to questions, questions lead to forming a hypothesis as a possible answer to those questions, and then the hypothesis is tested. Thus, descriptive science and hypothesis-based science are in continuous dialogue.

Basic and Applied Science

The scientific community has debated the value of different types of science for the last few decades. Is it valuable to pursue science to gain knowledge, or does scientific knowledge only have worth if we can apply it to solving a specific problem or bettering our lives? This question focuses on the differences between two types of science: basic science and applied science.

Basic Science

Basic science or "pure" science seeks to expand knowledge regardless of the short-term application of that knowledge. It is not focused on developing a product or a service of immediate public or commercial value. The immediate goal of basic science is knowledge for knowledge's sake, though this does not mean that, in the end, it may not result in an application.

The discovery of CRISPR sequences in bacteria was a result of basic scientific research. CRISPR–Cas9 is a technology derived from a natural defense mechanism found in bacteria. The CRISPR part refers to the DNA sequences, while Cas9 is a protein that acts like molecular scissors to cut DNA. Scientists were studying how bacteria defend themselves against viruses. They found that bacteria use CRISPR sequences to store fragments of viral DNA, which helps them recognize and destroy the virus if it attacks again. This system includes the Cas9 protein, which can cut the DNA of the invading virus.

Applied Science

In contrast, **applied science**, or "technology," aims to use science to solve real-world problems, making it possible, for example, to improve a crop yield, find a cure for a particular disease, or save animals threatened by a natural disaster. In applied science, the problem is usually defined for the researcher.

Once scientists understood how CRISPR-Cas9 worked in bacteria, they realized they could harness this system to edit genes in other organisms. They developed a method to guide the CRISPR-Cas9 system to make precise changes to the DNA of plants, animals, and even humans. Scientists are now doing applied research to determine practical applications of this tool, including:

- Medicine: Developing treatments for genetic disorders like cystic fibrosis and sickle cell anemia.
- Agriculture: Creating crops that are more resistant to pests and diseases.
- Research: Studying the function of specific genes to understand diseases better.

In summary, the initial discovery of CRISPR was a result of basic scientific research aimed at understanding bacterial immunity. This foundational knowledge was then applied to develop a powerful gene-editing tool with numerous practical applications.

Some may perceive applied science as "useful" and basic science as "useless." A question these people might pose to a scientist advocating knowledge acquisition would be, "What for?" However, a careful look at the history of science reveals that basic knowledge has resulted in many remarkable applications of great value. Many scientists think that a basic understanding of science is necessary before an application is developed; therefore, applied science relies on the results generated through basic science. Other scientists think it is time to move on from basic science and instead find solutions to actual problems. Both approaches are valid. Some issues demand immediate attention; however, few solutions would be found without the help of the knowledge generated through basic science. Without basic science, it is unlikely that applied science would exist.

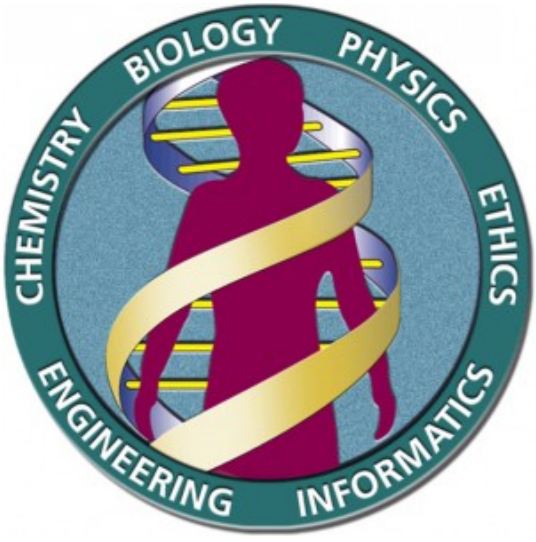


Figure 1.1.4 The Human Genome Project (1990-2003) generated the first sequence of the human genome. Image by .S. Department of Energy, Human Genome Project, Public Domain

The Human Genome Project is another example of the link

between basic and applied research. Initially, scientists analyzed and mapped human chromosomes to determine the DNA sequence and gene locations. The project eventually aimed to use this data for applied research, such as finding cures for genetic diseases.

While research efforts in both basic science and applied science are usually carefully planned, it is essential to note that some discoveries are made by serendipity, that is, utilizing a fortunate accident or a lucky surprise. Penicillin was discovered when biologist Alexander Fleming accidentally left a petri dish of Staphylococcus bacteria open. An unwanted mould grew, killing the bacteria. The mould turned out to be Penicillium, and a new antibiotic was discovered. Even in the highly organized world of science, luck can lead to unexpected breakthroughs when combined with an observant, curious mind.

1.2 THE SCIENTIFIC PROCESS

Figure 1.2.1 Sir Francis Bacon (1561–1626). Image by Paul van Somer I, Public Domain

Biologists study the living world by posing questions about it and seeking science-based responses. This approach is also common to other sciences and is often called the **scientific method**. The scientific process was used even in ancient times, but it was first documented by England's Sir Francis Bacon (1561–1626) (Figure 1.2.1). Biologists do not exclusively use the scientific method, but it can be applied to almost anything as a logical problem-solving method.

Question

The scientific process typically starts with an observation (often a problem to be solved) that leads to a question. Remember that science is very good at answering questions about the natural world but is by definition unable to answer questions about morals (what is right or wrong to do in a situation), aesthetics (what is beautiful or ugly), or spiritual matters (Do angels exist?). Scientific information can certainly influence the search for answers to these questions, but they are outside of the definition and scope of science alone.

Table 1.2.1 Comparison of Scientific and Non-Scientific Questions

Questions that can be answered using science	Questions that cannot be answered using science
What is the optimum temperature for the growth of E. coli bacteria?	How tall is Santa Claus?
Do birds prefer bird feeders of a specific colour?	Do angels exist?
What is the cause of this disease?	Which is better: classical music or rock and roll?
How effective is this drug in treating this disease?	What are the ethical implications of human cloning?

Let's think about a simple problem that starts with an observation and applies the scientific method to solve the problem. Imagine that one morning, when you wake up and flip a switch to turn on your bedside lamp, the light won't turn on. That observation also describes a problem: the lights won't turn on. Of course, you would next ask, "Why won't the light turn on?"

Hypothesis

Recall that a **hypothesis** is a suggested explanation that can be tested. A hypothesis is NOT the question you are trying to answer – it is what you think the answer to the question will be and **why**. To solve a problem, several hypotheses may be proposed. For example, one hypothesis might be, "The light won't turn on because the bulb is burned out." However, there could be other answers to the question, so that other hypotheses may be proposed. A second hypothesis might be, "The light won't turn on because the lamp is unplugged" or "The light won't turn on because the power is out." A hypothesis should be based on credible background information. A hypothesis is NOT just a guess (not even an educated one), although it can be based on your prior experience (such as in the example where the light won't turn on). In general, hypotheses in biology should be based on a credible, referenced source of information.

A scientific hypothesis must be **testable** and **falsifiable** to be considered valid. Testable means that there must be a way to design an experiment or collect data to evaluate the hypothesis. Falsifiable means that the hypothesis can be shown to be false through evidence. For example, the statement "Red is a better colour than blue" is neither testable nor falsifiable because it is based on personal preference, not measurable evidence. Similarly, the hypothesis "Ghosts visit famous landmarks" is not testable or falsifiable because it involves supernatural claims that cannot be evaluated using scientific methods. Scientists test hypotheses by conducting experiments designed to eliminate or disprove them. It's important to understand that a hypothesis can be supported by evidence, but it can never be proven. If an experiment fails to disprove a hypothesis, the hypothesis is considered supported – for now. However, future experiments or new evidence may lead to its rejection or refinement. This ongoing process is a key part of how science advances.

Experiments

Once you have identified a hypothesis, 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 should only test one variable, and all the other conditions are held constant. A **variable** is any part of the experiment that can vary or change during the experiment. By only adjusting one variable it allows researchers to isolate the effects of the variable being tested and determine its impact on the outcome.

- The **independent variable** is the variable that the researcher manipulates or changes in an experiment.
- The **dependent variable** is what the researcher measures in the experiment. It is the outcome that may change in response to the independent variable.
- A **constant** is a condition that is the same between all tested groups.
- A **confounding variable** is a condition that is not held constant that could affect the experimental results.

Hypotheses and predictions often tie in these variables:

"If [I change the independent variable in this way], then [I will observe that the dependent variable does this] because [of some reason]."

For example, the first hypothesis might be, "The light won't turn on because the bulb is burned out." The prediction would be, "If I change the light bulb, then the light will turn on because the bulb is burned out." In this experiment, the independent variable (the thing that you are testing) would be changing the light bulb, and the dependent variable is whether or not the light turns on. It would be essential to keep all the other aspects of the environment constant, for example, not messing with the lamp cord or trying to turn the lamp on using a different light switch. If the entire house had lost power during the experiment because a car hit the power pole, that would be a confounding variable.

Let's review variables by choosing the best response for the questions below.

Exercise 1.2.1

Text Description

1. You are testing the effect of pH on seed germination. What is the independent variable?

   a. Seed germination
   b. pH

2. A scientist is testing the effect of temperature on the speed at which apples turn brown. What is the dependent variable?

   a. Temperature
   b. Speed the apple turns brown
   c. pH

d. Type of fruit

3. You are testing whether there are more living organisms in water that comes from ponds or from rivers. What is the independent variable?

a. Type of organism
b. Temperature of water
c. Number of living organisms
d. Where the water came from

Answers:

1. pH

2. Speed the apple turns brown

3. Source of the water

Another important aspect of designing an experiment is to use experimental and control groups. The **experimental group** is the group in which the independent variable is changed, while the **control group** remains unchanged to serve as a baseline for comparison. The control group is not treated with the independent variable but is otherwise treated the same way as your experimental sample. Control groups help you to confirm that differences between your experimental groups are due to your independent variable rather than a different variable – they eliminate alternate explanations for your results (including experimental error and experimenter bias).

The following study shows the importance of using a control group.

Effectiveness of Different Fertilizer Brands

Question

Which fertilizer will produce the greatest number of tomatoes when applied to the plants?

Prediction and Hypothesis

If I apply different fertilizer brands to tomato plants, most tomatoes will be produced from plants watered with Brand A because Brand A advertises that it produces twice as many tomatoes as other leading brands.

Experiment

Purchase 10 tomato plants of the same type from the same nursery. Pick plants that are similar in size and age. Divide the plants into two groups of 5. Apply Brand A to the first group and Brand B to the second group according to the package instructions. After 10 weeks, count the number of tomatoes on each plant.

Independent Variable

Brand of fertilizer.

Dependent Variable

Number of tomatoes.

The number of tomatoes produced depends on the brand of fertilizer applied to the plants.

Constants

amount of water, type of soil, size of pot, amount of light, type of tomato plant, and length of time plants were grown.

Confounding variables

any of the above that are not held constant, plant health, diseases present in the soil or plant before it was purchased.

Results

Tomatoes fertilized with Brand A produced an average of 20 tomatoes per plant, while tomatoes fertilized with Brand B produced an average of 10 tomatoes per plant.

You'd want to use Brand A next time you grow tomatoes, right? But what if I told you that plants grown without fertilizer produced an average of 30 tomatoes per plant! Now, what will you use on your tomatoes?

graph

Results including a control group

Tomatoes which received no fertilizer produced more tomatoes than either brand of fertilizer.

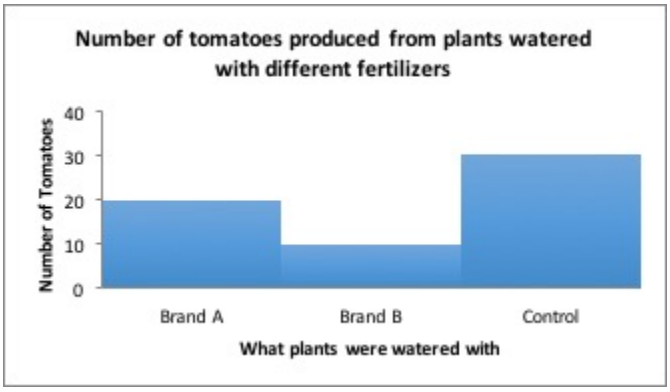


Figure 1.2.2. Number of tomatoes produced from plants watered with different fertilizers. Graphic by Tacoma Community College, CC BY 4.0

Conclusion

Although Brand A fertilizer produced more tomatoes than Brand B, neither fertilizer should be used because plants grown without fertilizer produced the most tomatoes!

At the beginning of the COVID-19 pandemic, there were many questions. *What is causing the illness? How is it spread? How can we stop it from spreading? Do masks work? Do vaccines work?* Scientists worldwide were completing experiments to try to answer these questions.

In this study, researchers used a machine to simulate coughs and visualize the effectiveness of different masks. They connected a mannequin's head to a fog machine to expel vapour droplets and used a green laser sheet to

visualize them. In this study, the control group would be the mannequin expelling droplets without any mask. The experimental groups would be the mannequins wearing different types of masks, such as single-layer bandanas, homemade two-layer cotton masks, and 3-ply surgical masks. This setup allows researchers to compare the effectiveness of each mask type against the baseline of no mask.

When vaccines were developed to prevent COVID-19, experiments, more specifically trials, needed to be done to determine their effectiveness at preventing disease. A drug trial is a formal process of testing a new treatment or product to evaluate its effectiveness.

In COVID-19 vaccine trials, participants were divided into two groups. One group received the actual vaccine, while the other group received a placebo. A placebo is a harmless substance that looks like the vaccine but has no active ingredients (e.g. saline solution, which is a harmless saltwater injection). The purpose of the placebo is to serve as a control to compare against the effects of the actual vaccine. By comparing the rates of COVID-19 in the control and experimental groups, researchers were able to determine the effectiveness of preventing disease.

Another important aspect of designing an experiment is to consider blinding techniques, such as single-blind (where only participants are unaware of group assignments) and double-blind (where both participants and researchers are unaware), to reduce bias.

Most vaccine trials follow a double-blind design where neither the participants nor the researchers know who is receiving the vaccine and who is receiving the placebo. This design helps eliminate bias and ensures that the expectations of either the participants or the researchers do not influence the results. For example, if participants knew they were receiving the placebo, they might behave differently or report symptoms differently than those receiving the vaccine. Similarly, if researchers knew who received the vaccine, they might unconsciously interpret the results in a biased way.

Results

Your experiment's results are the data you collect as the outcome. In the light experiment, your results are either that the light turns on or doesn't turn on. Based on your results, you can conclude. Your conclusion uses the results to answer your original question.

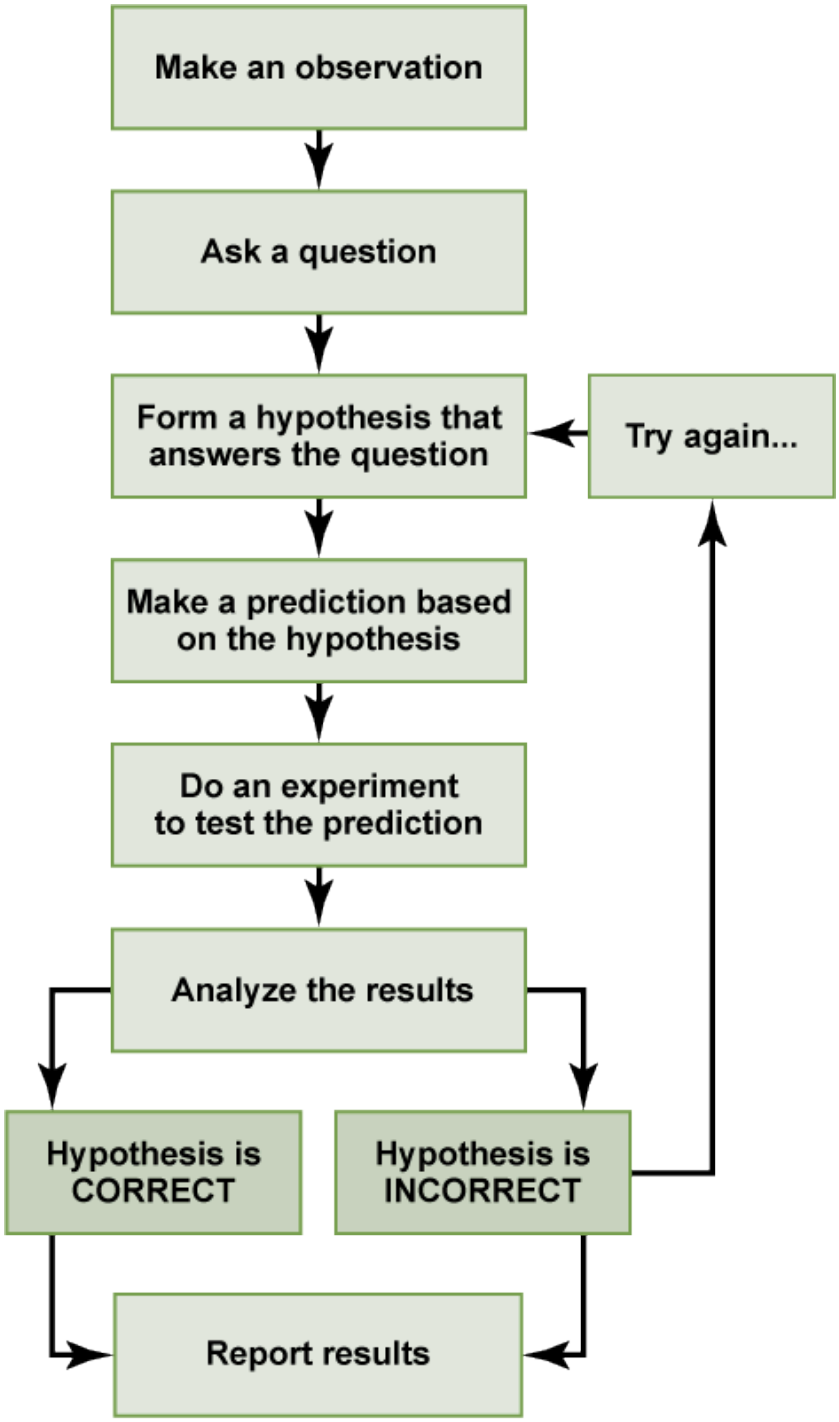


Figure 1.2.3 This flowchart describes the basic process of the scientific method. "The Scientific Method" by OpenStax, CC BY 4.0

Figure 1.2.3 Description

The Scientific Method process consists of a series of steps connected by arrows, showing how scientists

approach problem-solving and experimentation. 1. Make an Observation, 2. Ask a Question, 3. Form a Hypothesis That Answers the Question, 4. Make a Prediction Based on the Hypothesis, 5. Do an Experiment to Test the Prediction, 6. Analyze the Result, 7. Ask: Was the Hypothesis Correct? If correct, the flow continues downward to Report Results (Final step if Hypothesis is Correct). If incorrect, an arrow leads to the side with a box labelled "Hypothesis is INCORRECT" and directs back to Form a Hypothesis That Answers the Question to revise and try again.

In practice, the scientific method is not as rigid and structured as it might initially appear. Sometimes, an experiment leads to conclusions that favour a change in approach; often, an experiment brings entirely new scientific questions to the puzzle. Science usually does not operate linearly; scientists continually draw inferences and make generalizations, finding patterns as their research proceeds. Scientific reasoning is more complex than the scientific method alone suggests.

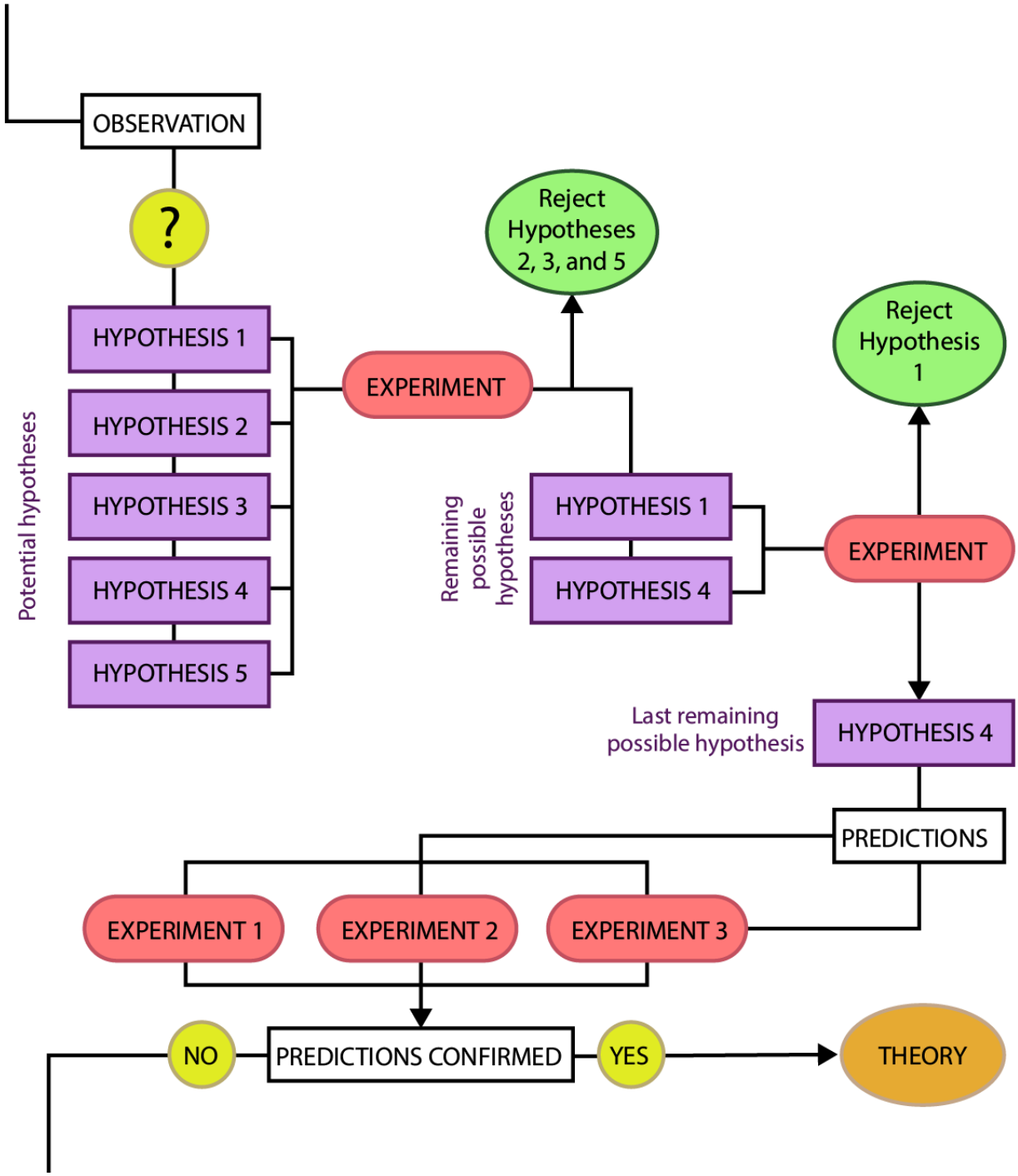


Figure 1.2.4 The actual process of using the scientific method. "The general process of scientific investigations" by Laura Guerin, CK-12 Foundation, CC BY-NC 3.0

Figure 1.2.4 Description

The image is a complex flowchart that illustrates that scientific reasoning is actually more intricate than the traditional linear model suggests. Multiple interconnected boxes represent the various steps of the scientific

process, with arrows pointing in various directions, indicating that the process is non-linear and often involves feedback loops, revisits, and adjustments. Arrows loop back from conclusions to earlier steps like hypothesis formation, experimentation, and even observation, showing that scientists often revisit and refine previous steps. Multiple pathways connect the steps, emphasizing that scientific investigation is rarely a straightforward process.

Let's put the scientific method into practice. Drag each item to its corresponding step in the process.

Exercise 1.2.2

Text Description
Applying the Scientific Method to Troubleshoot a Toaster
Steps: 1. Observation, 2. Question, 3. Hypothesis, 4. Prediction, 5. Experiment, 6. Results
Drag and Drop options:

- My toaster doesn't toast my bread.
- If something is wrong with the outlet, my coffeemaker also won't work when plugged into it.
- I plug my coffeemaker into the outlet.
- My coffeemaker works.
- Why doesn't my toaster work?
- There is something wrong with the electrical outlet.

Answers:

1. Observation: My toaster doesn't toast my bread.
2. Question: Why doesn't my toaster work?
3. Hypothesis: There is something wrong with the electrical outlet.
4. Prediction: If something is wrong with the outlet, my coffeemaker also won't work when plugged into it.
5. Experiment: I plug my coffeemaker into the outlet.
6. Results: My coffeemaker works.

Reporting Scientific Work

Whether scientific research is basic science or applied science, scientists must share their findings for other researchers to expand and build upon their discoveries. Communication and collaboration within and between science sub-disciplines are key to advancing knowledge in science. For this reason, an essential aspect of a scientist's work is disseminating results and communicating with peers. Scientists can share results by presenting them at a scientific meeting or conference, but this approach can reach only the few scientists that are present. Instead, most scientists present their results in peer-reviewed articles published in scientific journals. Peer-reviewed articles are scientific papers that are reviewed, usually anonymously, by a scientist's colleagues or peers. These colleagues are qualified individuals, often experts in the same research area, who judge whether or not the scientist's work is suitable for publication. The peer review process helps ensure that the research described in a scientific paper or is original, significant, logical, and thorough. Scientists publish their work so other scientists can reproduce their experiments under similar or different conditions to expand on the findings. The experimental results must be consistent with the findings of other scientists.

Many journals and the popular press do not use a peer-review system. Many online open-access journals, with articles available without cost, are now available, many of which use rigorous peer-review systems, but some do not. The results of any studies published in these forums without peer review are unreliable and should not form the basis for other scientific work.

1.3 CHARACTERISTICS OF LIFE

Biology is the science that studies life. What exactly is life? This may sound like a silly question with an obvious answer, but it is not easy to define life. For example, a branch of biology called virology studies viruses, which exhibit some of the characteristics of living entities but lack others. It turns out that although viruses can attack living organisms, cause diseases, and even reproduce, they do not meet the criteria that biologists use to define life. So then, what are the shared properties that make something "alive"?

Properties of Life

All groups of living organisms share multiple key characteristics or functions: order, sensitivity or response to stimuli, reproduction, adaptation, growth and development, regulation, homeostasis, and energy processing. When viewed together, these eight characteristics serve to define life.

Order

Organisms are highly organized structures that consist of one or more cells. Even very simple, single-celled organisms are remarkably complex. Inside each cell, atoms make up molecules. These in turn make up cell components or organelles. Multicellular organisms, which may consist of millions of individual cells, have an advantage over single-celled organisms in that their cells can be specialized to perform specific functions and even sacrificed in certain situations for the good of the organism as a whole. How these specialized cells come together to form organs such as the heart, lung, or skin in organisms like the toad shown in Figure 1.3.1 will be discussed later.

Figure 1.3.1 A toad represents a highly organized structure consisting of cells, tissues, organs, and organ systems. Image by Ivengo(RUS), Public Domain

Sensitivity or Response to Stimuli

Organisms respond to diverse stimuli. For example, plants can bend toward a source of light or respond to touch. Even tiny bacteria can move toward or away from chemicals (a process called chemotaxis) or light (phototaxis). Movement toward a stimulus is considered a positive response, while movement away from a stimulus is considered a negative response.

Watch this video to see how the sensitive plant responds to a touch stimulus.

Video: Mimosa pudica leaves folding when touched 3 by Brandizzi, [00:12] is licensed under a CC-BY 2.5 License.

Figure 1.3.2 The leaves of this sensitive plant (Mimosa pudica) will instantly droop and fold when touched. After a few minutes, the plant returns to its normal state. "Mimosa pudica" by Alex Lomas, CC BY 2.0

Reproduction

Single-celled organisms reproduce by first duplicating their DNA, which is the genetic material, and then dividing it equally as the cell prepares to divide to form two new cells. Many multicellular organisms (those made up of more than one cell) produce specialized reproductive cells that will form new individuals. When reproduction occurs, DNA-containing genes are passed along to an organism's offspring. These genes are the reason that the offspring will belong to the same species and will have characteristics similar to the parent, such as fur colour and blood type.

Figure 1.3.3 Opossum mother with offspring on her back. Image by Specialjake, CC BY-SA 3.0

Adaptation

All living organisms exhibit a "fit" to their environment. Biologists refer to this fit as adaptation and it is a consequence of evolution by natural selection, which operates in every lineage of reproducing organisms. Examples of adaptations are diverse and unique, from heat-resistant Archaea that live in boiling hot springs to the tongue length of a nectar-feeding moth that matches the size of the flower from which it feeds. All adaptations enhance the reproductive potential of the individual exhibiting them, including their ability to survive to reproduce. Adaptations are not constant. As an environment changes, natural selection causes the characteristics of the individuals in a population to track those changes.

Figure 1.3.4 Katydids have evolved to look like leaves. These adaptations have allowed them to escape predation by camouflaging into plants. Image, CC0

Growth and Development

Organisms grow and develop according to specific instructions coded for by their genes. These genes provide instructions that will direct cellular growth and development, ensuring that a species' young will grow up to exhibit many of the same characteristics as its parents.

Figure 1.3.5 Although no two look alike, these kittens have inherited genes from both parents and share many of the same characteristics. Image by Pieter & Renée Lanser, CC BY 4.0

Regulation and Homeostasis

Even the smallest organisms are complex and require multiple regulatory mechanisms to coordinate internal functions, such as the transport of nutrients, response to stimuli, and coping with environmental stresses. For example, organ systems such as the digestive or circulatory systems perform specific functions like carrying oxygen throughout the body, removing wastes, delivering nutrients to every cell, and cooling the body.

Figure 1.3.6 Polar bears and other mammals living in ice-covered regions maintain their body temperature by generating heat and reducing heat loss through thick fur and a dense layer of fat under their skin. "Polar Bear" by David, CC BY 4.0

To function properly, cells require appropriate conditions such as proper temperature, pH, and concentrations of diverse chemicals. These conditions may, however, change from one moment to the next. Organisms are able to maintain internal conditions within a narrow range almost constantly, despite environmental changes, through a process called homeostasis or "steady state"—the ability of an organism to maintain constant internal conditions. For example, many organisms regulate their body temperature in a process known as thermoregulation. Organisms that live in cold climates, such as the polar bear, have body structures that help them withstand low temperatures and conserve body heat. In hot climates, organisms have methods (such as perspiration in humans or panting in dogs) that help them to shed excess body heat.

Energy Processing

All organisms (such as the North American monarch butterfly shown in Figure 1.3.7) use a source of energy for their metabolic activities. Some organisms capture energy from the sun and convert it into chemical energy in food; others use chemical energy from molecules they take in.

Figure 1.3.7 North American monarch butterflies travel thousands of kilometres to overwinter in Central Mexico. Chemical energy derived from food is used to power flight for this long migration. Adult monarchs feed on a variety of nectar sources, but monarch caterpillars feed exclusively on milkweed. Monarchs are an endangered species in Canada. You can help by planting milkweed in your yard! Image by Thomas Bresson, CC BY 2.0

Levels of Organization of Living Things

Living things are highly organized and structured, following a hierarchy on a scale from small to large. The atom is the smallest and most fundamental unit of matter. It consists of a nucleus surrounded by electrons. Atoms form molecules. A **molecule** is a chemical structure consisting of at least two atoms held together by a chemical bond. Many molecules that are biologically important are macromolecules, large molecules that are typically formed by combining smaller units called monomers. An example of a macromolecule is

deoxyribonucleic acid (DNA), which contains the instructions for the functioning of the organism that contains it.

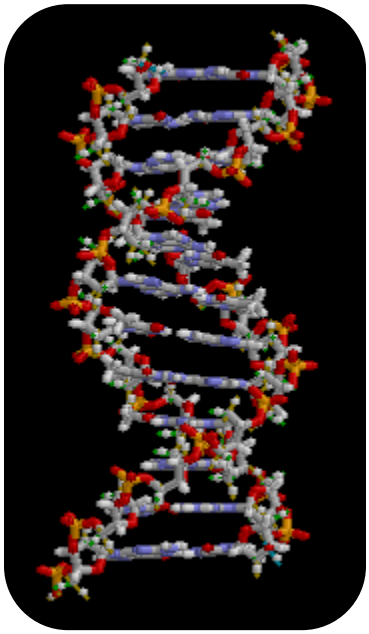


Figure 1.3.8 A molecule, like this large DNA molecule, is composed of atoms. Image by Brian0918, Public Domain

Some cells contain aggregates of macromolecules surrounded by membranes; these are called organelles. Organelles are small structures that exist within cells and perform specialized functions. All living things are made of cells; the cell itself is the smallest fundamental unit of structure and function in living organisms. (This requirement is why viruses are not considered living: they are not made of cells. To make new viruses, they must invade and hijack a living cell; only then can they obtain the materials they need to reproduce.) Some organisms consist of a single cell, and others are multicellular. Cells are classified as prokaryotic or eukaryotic. Prokaryotes are single-celled organisms that lack organelles surrounded by a membrane and do not have nuclei surrounded by nuclear membranes; in contrast, the cells of eukaryotes do have membrane-bound organelles and nuclei.

In most multicellular organisms, cells combine to make tissues, which are groups of similar cells carrying out the same function. Organs are collections of tissues grouped together based on a common function. Organs are present not only in animals but also in plants. An organ system is a higher level of organization that consists of functionally related organs. For example, vertebrate animals have many organ systems, such as the circulatory system, which transports blood throughout the body and to and from the lungs; it includes organs such as the heart and blood vessels. Organisms are individual living entities. For example, each tree in a

forest is an organism. Single-celled prokaryotes and single-celled eukaryotes are also considered organisms and are typically referred to as microorganisms.

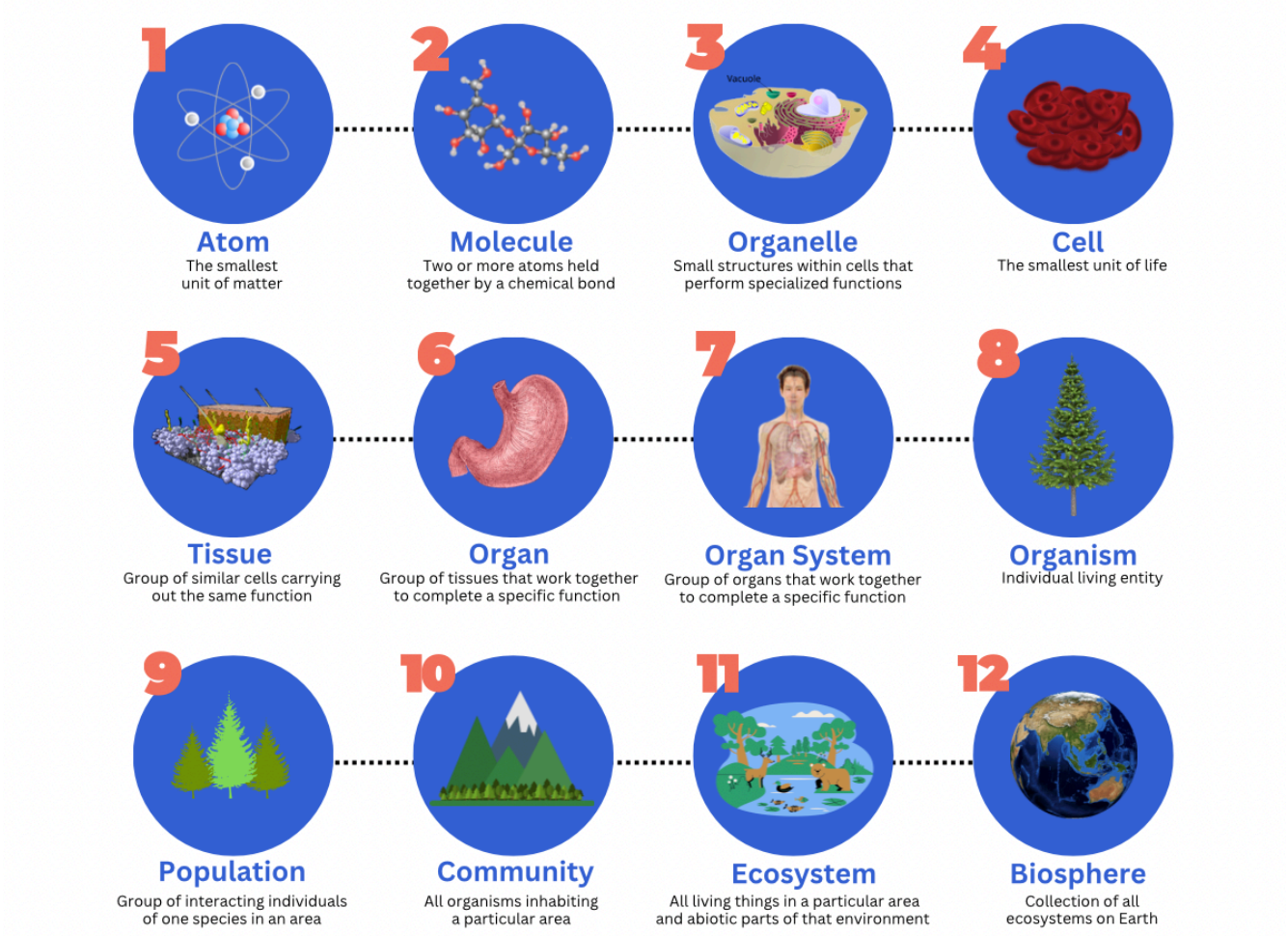


Figure 1.3.9 The 12 Levels Of Life

Figure 1.3.9 Description and Credits

The image is an educational infographic titled "12 Levels of Life," illustrating the hierarchical organization of biological structures, from the smallest unit of matter to the entire biosphere. Each level is represented by a numbered circle containing an image, a title, and a brief description. The circles are connected by dotted lines, showing the progression from simple to complex levels.

Levels of Life (1–12):
1. Atom image: A simple atomic model with a nucleus and orbiting electrons. Description: The smallest unit of matter.
2. Molecule: A chemical structure showing atoms connected by bonds. Description: Two or more atoms are held together by a chemical bond.

3. Organelle: A depiction of cell organelles, including the vacuole and mitochondria. Description: Small structures within cells that perform specialized functions.
4. Cell: Red blood cells. Description: The smallest unit of life.
5. Tissue: A cluster of similar cells forming tissue layers. Description: Group of similar cells carrying out the same function.
6. Organ: A human stomach. Description: Group of tissues that work together to complete a specific function
7. Organ System: A human body with internal organs highlighted. Description: A group of organs that work together to complete a specific function.
8. Organism: A tree representing an individual living entity. Description: Individual living entity.
9. Population: A group of identical trees. Description: Group of interacting individuals of one species in an area.
10. Community: A mountain landscape with diverse organisms. Description: All organisms inhabiting a particular area.
11. Ecosystem: A pond ecosystem with animals, plants, and water. Description: All living things in a particular area and abiotic parts of that environment.
12. Biosphere: Planet Earth. Description: Collection of all ecosystems on Earth.

Credit for images:

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- “Biosphere”, by Freddy Vale, CC BY-NC-SA 4.0

Exercise 1.3.1

Let's test your knowledge. Drag and drop each statement to its corresponding level.

Text Description
Levels: 1. Atom, 2. Molecule, 3. Organelle, 4. Cell, 5. Tissue, 6. Organ, 7. Organ System, 8. Organism, 9. Population, 10. Community, 11. Ecosystem, 12. Biosphere

Statements:

- Structures that perform functions within a cell.
- The digestive system includes multiple organs working together.
- A phospholipid is composed of many atoms.
- The stomach or intestine.
- All the plant and animal species in the park.
- Human blood cells.
- All the people in a park.
- Human skin tissue.
- A person in a park.
- Living organisms and the environment in which they live.
- A basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.
- Encompasses all the ecosystems of the Earth.

Answers:

- 1: Atom: A basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.
- 2. Molecule: A phospholipid composed of many atoms.
- 3. Organelle: Structures that perform functions within a cell.
- 4. Cell: Human blood cells.
- 5. Tissue: Human skin tissue.
- 6. Organ: The stomach or intestine.

- 7. Organ System: The digestive system, which includes multiple organs working together.
- 8. Organism: A person in a park.
- 9. Population: All the people in a park.
- 10. Community: All the plant and animal species in the park.
- 11. Ecosystem: Living organisms and the environment in which they live
- 12. Biosphere: Encompasses all the ecosystems of the Earth.

All the individuals of a species living within a specific area are collectively called a population. For example, a forest may include many white pine trees. These pine trees represent the population of white pine trees in this forest. Different populations may live in the same specific area. For example, the forest with pine trees includes populations of flowering plants and also insects and microbial populations. A community is a set of populations inhabiting a particular area. For instance, all of the forest's trees, flowers, insects, and other populations form the forest's community. The forest itself is an ecosystem. An ecosystem consists of all the living things in a particular area and the abiotic or non-living parts of that environment, such as nitrogen in the soil or rainwater. At the highest level of organization, the biosphere is the collection of all ecosystems, representing the life zones on Earth. It includes land, water, and portions of the atmosphere.

Exercise 1.3.2

Text Description

1. All of the following statements are true EXCEPT

a. Communities exist within populations which exist within ecosystems.
b. Communities exist within ecosystems which exist in the biosphere.
c. Tissues exist within organs which exist within organ systems.
d. Organelles exist within cells, which exist within tissues.

2. What is the smallest unit of biological structure that meets the functional requirements of "living"?

a. cell
b. organ

c. macromolecule
d. organelle

3. Which of the following sequences represents the hierarchy of biological organization from the most complex to the least complex level?

a. organ, organism, tissue, organelle, molecule
b. organelle, tissue, biosphere, ecosystem, population
c. organism, community, biosphere, molecule, tissue, organ
d. biosphere, ecosystem, community, population, organism

4. Drag the words into the correct boxes to explain how biology can be studied from a microscopic approach to a global approach.
Researchers can approach biology from the smallest to the largest, and everything in between. For instance, an ecologist may study a _____ of individuals, its _____, its _____, and its part in the _____.
Possible answers:

- biosphere
- population
- community
- ecosystem

5. Drag the words into the correct boxes to explain how biology can be studied from a cellular approach to an organismal approach.
When studying an individual organism, a biologist could examine the cell and its _____, the _____ that the smallest units make up, the _____ and their respective _____, and the sum total—the organism itself.
Possible answers:

- organs
- organ systems
- organelles
- tissues

Answers:

1. a. Communities exist within populations which exist within ecosystems.
2. a. cell
3. d. biosphere, ecosystem, community, population, organism
4. Researchers can approach biology from the smallest to the largest, and everything in between. For instance, an ecologist may study a ***population*** of individuals, its ***community***, its ***ecosystem***, and its part in the ***biosphere***.
5. When studying an individual organism, a biologist could examine the cell and its ***organelles***, the ***tissues*** that the smallest units make up, the ***organs*** and their respective ***organ systems***, and the sum total—the organism itself.

CHAPTER 1 SUMMARY

Key Takeaways

Biology is the science of life. All living organisms share several key properties: order, response to stimuli, reproduction, adaptation, growth and development, regulation, and energy processing. Living things are highly organized, following a hierarchy that includes atoms, molecules, organelles, cells, tissues, organs, and organ systems. Organisms, in turn, are grouped as populations, communities, ecosystems, and the biosphere.

- **Biology is relevant to daily life:** Scientists work to understand and solve global challenges such as climate change, disease prevention, and food security. Biology is critical when addressing issues like disease outbreaks, genetic engineering, environmental protection, and medical advancements that are regularly making headlines.
- **Scientific Inquiry and Logical Thinking:** Science aims to expand knowledge using curiosity-driven inquiry. Two key reasoning methods are inductive reasoning, which draws general conclusions from observations (e.g., Jane Goodall's chimpanzee studies), and deductive reasoning, which tests hypotheses based on general principles (e.g., predicting species distribution changes due to climate change).
- **Basic vs. Applied Science:** Basic science seeks to expand knowledge without immediate practical applications, while applied science uses scientific knowledge to solve real-world problems. Both are interconnected—discoveries from basic research (e.g., DNA structure) enable applied innovations (e.g., genetic testing and treatments).
- **The Scientific Method and Experimentation:** Science follows a structured process that includes forming hypotheses, conducting experiments, and analyzing results. A hypothesis must be testable and falsifiable, and experiments should control variables to ensure reliable conclusions. The peer-review process ensures the credibility of scientific findings.
- **Defining Life and Its Characteristics:** Biology is the science of life. Living organisms share essential traits: order, response to stimuli, reproduction, adaptation, growth and development, regulation, and energy processing. These characteristics distinguish living

things from non-living entities like viruses, which exhibit some but not all properties of life.

- **Biological Organization and Ecosystems:** Life is structured in a hierarchical organization. Atoms form molecules, which make up cells, tissues, organs, and organ systems. Organisms exist within populations, communities, and ecosystems, all of which contribute to the biosphere—Earth's interconnected life systems.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into six key takeaways.

Flashcards

Click on the flashcards to review key terms discussed in this chapter.
Text Description
Front of card:

1. Biology
2. Science
3. Scientific theory
4. Inductive reasoning
5. Deductive reasoning
6. Descriptive science
7. Hypothesis-based science
8. Basic science
9. Applied Science
10. Two methods of logical thinking used in science
11. Jane Goodall's work with chimpanzees is a classic example of _____.
12. Two types of science
13. Scientists studying how bacteria defend themselves is an example of _____ science.

14. Scientists using CRISPR-Cas9 to develop treatments for genetic disorders is an example of _____ science.
15. Scientific method
16. Who was the first to use the scientific method?
17. What are the typical steps involved in the scientific method?
18. Hypothesis
19. Variable
20. Define dependent and independent variables
21. What are the dependent and independent variables in the study testing the effectiveness of different types of masks (mentioned in 1.2)?
22. Confounding variable
23. Two groups involved in experiments
24. List the properties of life
25. Order
26. Response to stimuli
27. Reproduction
28. Adaption
29. Growth and development
30. Regulation
31. Energy processing
32. List the 12 levels of organization from smallest to largest
33. Atom
34. Molecule
35. Organelles
36. Cells
37. Tissues
38. Organs
39. Organ systems
40. Organisms
41. Populations
42. Communities
43. Ecosystem
44. Biosphere

Back of card:

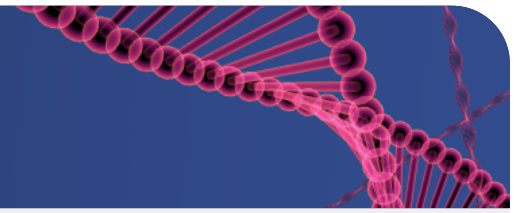
1. The study of living organisms and their interactions with one another and their environments
2. Systematic study of the natural world through observation and experimentation to gain knowledge and understanding
3. A thoroughly tested and confirmed explanation for observations or phenomena
4. A form of logical thinking that uses related observations to arrive at a general conclusion
5. A form of logical thinking that uses a general principle or law to forecast specific results
6. A form of scientific study that aims to observe, explore, and discover
7. A form of scientific study that begins with a specific explanation that is then tested
8. Seeks to expand knowledge and understanding without immediate practical applications
9. Uses scientific knowledge to solve practical, real-world problems
10. Inductive reasoning and deductive reasoning
11. Descriptive science
12. Basic science and applied science
13. Basic
14. Applied
15. A method of research with defined steps that include experiments and careful observation
16. Sir Francis Bacon
17. Observation, Question, Hypothesis, Prediction, Experiment, Results, Report
18. A suggested explanation for an event
19. Any part of an experiment that can vary or change during the experiment
20. Independent variable: variable that is changed in an experiment to test its effects on the dependent variable (i.e., what the researcher manipulates). Dependent variable: variable that is measured or observed in response to changes in the independent variable (i.e., what the researcher measures).
21. Independent variable: The type of mask used (e.g., no mask, single-layer bandana, homemade two-layer cotton mask, 3-ply surgical mask). Dependent variable: The distance and dispersion of droplets expelled from the mannequin's mouth during simulated coughs and sneezes.
22. Variable that is not held constant that could affect the experimental results
23. Control group: does not receive the treatment being tested (i.e., not treated with independent variable); the purpose is to serve as a baseline to compare the effects of the experimental treatment. Experimental group: receives the treatment being tested (i.e., independent variable is changed); the purpose is to determine the effect of the variable being tested by comparing its results to those of the control group.

24. Order, Response to stimuli, Reproduction, Adaptation, Growth and Development, Regulation, Energy Processing
25. Organisms are highly organized structures that consist of one or more cells. Order is one of the properties of life.
26. Organisms respond to diverse stimuli in their surroundings, such as moving toward light or away from chemicals. Response to stimuli is one of the properties of life.
27. Organisms can form new individuals and pass their DNA to their offspring. Reproduction is one of the properties of life.
28. All organisms exhibit a "fit" to their environment due to evolution by natural selection. These adaptations increase the chances of organisms surviving to reproduce. Adaptation is one of the properties of life.
29. Organisms have genes that provide instructions to direct cellular growth and development. Growth and development are one of the properties of life.
30. Organisms are able to maintain internal conditions despite environmental changes. Regulation is one of the properties of life.
31. All organisms use a source of energy for their metabolic activities. Energy processing is one of the properties of life.
32. Atoms, Molecules, Organelles, Cells, Tissues, Organs, Organ Systems, Organisms, Populations, Communities, Ecosystems, Biosphere
33. The smallest unit of matter
34. Two or more atoms held together by a chemical bond
35. Small structures within cells that perform specialized functions
36. The smallest unit of life. Displays all of the properties of life.
37. Group of similar cells carrying out the same function
38. Group of tissues that work together to complete a specific function
39. Group of organs that work together to complete a specific function
40. Individual living entity
41. Group of interacting individuals of one species in an area
42. All organisms inhabiting a particular area
43. All living things in a particular area and abiotic parts of that environment
44. Collection of all ecosystems on Earth

CHAPTER 2: CHEMISTRY OF LIFE

Chapter Overview

Learning Objectives



By the end of this chapter, you will be able to:

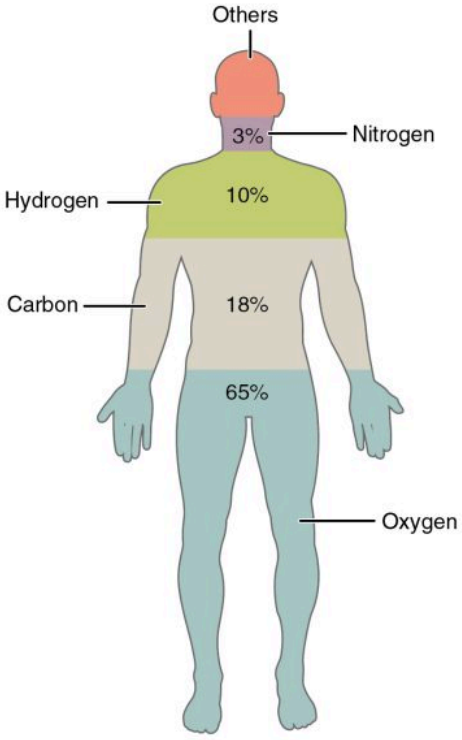
- Describe matter and elements.
- Describe the interrelationship between protons, neutrons, and electrons and how electrons can be donated or shared between atoms.
- Describe how the arrangement of electrons in an atom determines the formation and type of chemical bonds, including ionic, covalent, and hydrogen bonds.
- Describe the properties of water that are critical to maintaining life.

2.1 ATOMS AND ELEMENTS

At its most fundamental level, life is made up of **matter**. Matter occupies space and has mass. All matter comprises **elements**, substances that cannot be broken down or transformed chemically into other substances. Each element is made of atoms, each with a constant number of protons and unique properties. 118 elements have been defined; however, only 94 occur naturally, and fewer than 30 are found in living cells. Therefore, the remaining 26 elements are unstable, have not existed for long, are theoretical, and have yet to be detected.

Each element is designated by its chemical symbol (H, N, O, C, and Na) and possesses unique properties. These properties allow elements to combine and bond with each other in specific ways. Two or more elements that combine in a fixed ratio are called **compounds**. Compounds are more common than pure elements. An example of a compound is table salt or sodium chloride, which has equal parts of sodium (Na) and chlorine (Cl).

The four elements common to all living organisms are oxygen (O), carbon (C), hydrogen (H), and nitrogen (N).



Element	Symbol	Percentage in Body
Oxygen	O	65.0
Carbon	C	18.5
Hydrogen	H	9.5
Nitrogen	N	3.2
Calcium	Ca	1.5
Phosphorus	P	1.0
Potassium	K	0.4
Sulfur	S	0.3
Sodium	Na	0.2
Chlorine	Cl	0.2
Magnesium	Mg	0.1
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).		less than 1.0

Figure 2.1.1 The human body's main elements are shown from most to least abundant. Image by OpenStax, CC BY 4.0

Atoms

An **atom** is the smallest unit of matter that retains all of the chemical properties of an element. For example, one hydrogen atom has all of the properties of the element hydrogen, such as it exists as a gas at room temperature and bonds with oxygen to create a water molecule. Hydrogen atoms cannot be broken down into anything smaller while still retaining the properties of hydrogen. If a hydrogen atom were broken down into subatomic particles, it would no longer have the properties of hydrogen.

All atoms contain **protons**, **electrons**, and **neutrons** (Figure 2.1.2). The only exception is hydrogen (H), which is made of protons and one electron. A proton is a positively charged particle that resides in the **nucleus** (the core of the atom) of an atom and has a mass of 1 and a charge of +1. An electron is a negatively charged particle that travels in the space around the nucleus. In other words, it resides outside of the nucleus. It has a negligible mass and has a charge of –1.

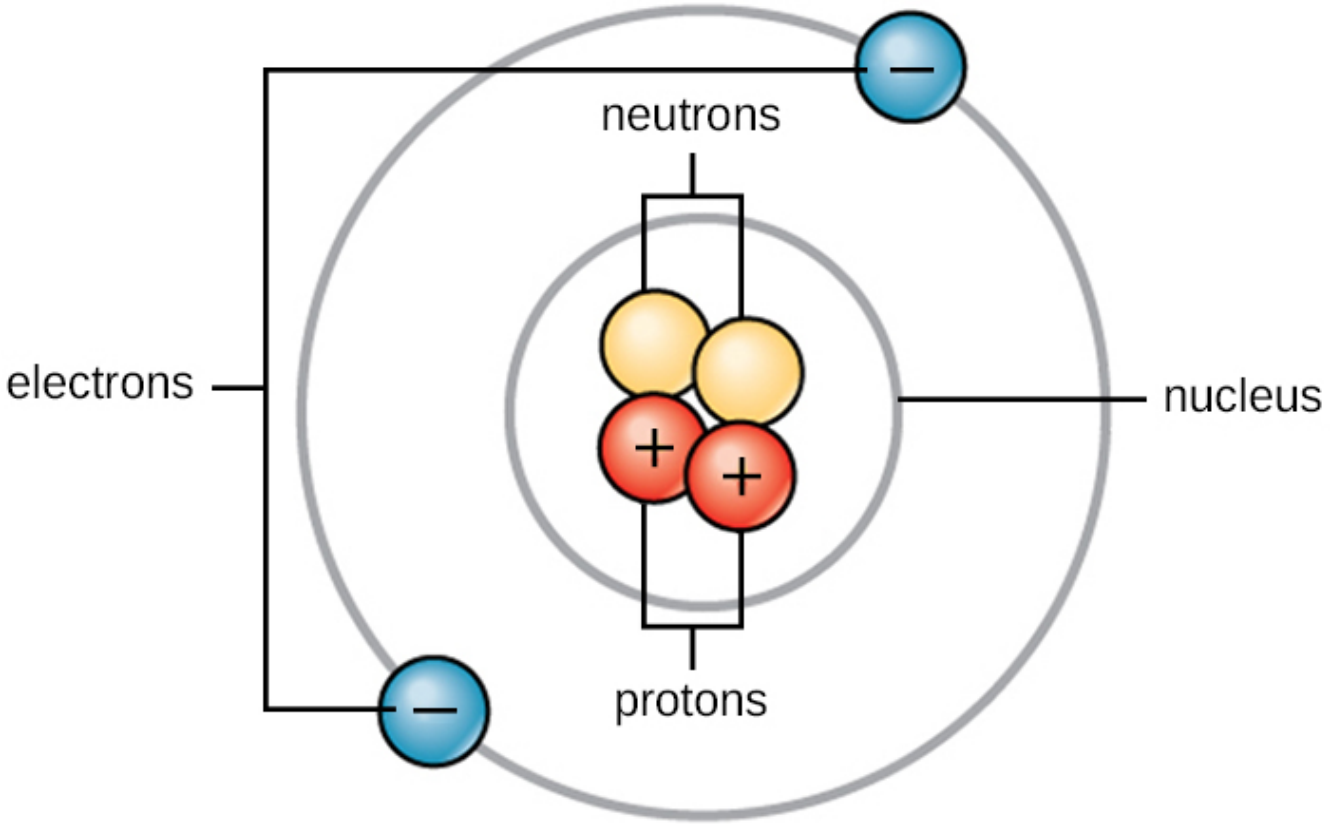


Figure 2.1.2 Atoms comprise protons and neutrons located within the nucleus and electrons surrounding the nucleus. Image by OpenStax, CC-BY 4.0

Neutrons, like protons, reside in the nucleus of an atom. They have a mass of 1 and no charge. The positive (protons) and negative (electrons) charges balance each other in a neutral atom with a net zero charge.

Because protons and neutrons each have a mass of 1, the mass of an atom is equal to the number of protons and neutrons of that atom. The number of electrons does not factor into the overall mass because their mass is so tiny.

Exercise 2.1.1

Text Description
Match each of the words below with the correct definition.

1. _____ Positively charged particle that resides in the nucleus.
2. _____ The smallest component of an element that retains all of the chemical properties of that element.
3. _____ Negatively charged particle found outside the nucleus.
4. _____ Particle in the nucleus without a charge.

Possible answers:

- electron
- atom
- neutron
- proton

Answers:

1. ***proton***: Positively charged particle that resides in the nucleus.
2. ***atom:*** The smallest component of an element that retains all of the chemical properties of that element.
3. ***electron:*** Negatively charged particle found outside the nucleus.
4. ***neutron:*** Particle in the nucleus without a charge.

At the most basic level, all organisms are made of a combination of elements. An element is a substance whose atoms all have the same number of protons. They contain atoms that combine to form molecules. In multicellular organisms, such as animals, molecules can interact to create cells that combine to form tissues, which make up organs. These combinations continue until entire multicellular organisms are formed.

Each element has its unique properties. Each contains a different number of protons and neutrons, giving it its atomic and mass numbers. An element's **atomic number** equals the number of protons that element contains. The **mass number**, or nuclear mass, is the number of protons and neutrons of that element.

Therefore, it is possible to determine the number of neutrons by subtracting the atomic number from the mass number.

These numbers provide information about the elements and how they react when combined. Different elements have different melting and boiling points and are in various states (liquid, solid, or gas) at room temperature. They also combine in different ways. Some form specific types of bonds, whereas others do not. How they combine is based on the number of electrons present. Because of these characteristics, the elements are arranged into the **periodic table of elements**, a chart of the elements that includes the atomic number and relative atomic mass of each component. The periodic table also provides key information about the properties of elements (Figure 2.1.3) —often indicated by colour-coding. The arrangement of the table also shows how the electrons in each element are organized and provides essential details about how atoms will react with each other to form molecules.

Isotopes are different forms of the same element with the same number of protons but a different number of neutrons. Some elements, such as carbon, potassium, and uranium, have naturally occurring isotopes. Carbon-12, the most common carbon isotope, contains six protons and six neutrons. Therefore, it has a mass number of 12 (six protons and six neutrons) and an atomic number of 6 (which makes it carbon). Carbon-14 contains six protons and eight neutrons. Therefore, it has a mass number of 14 (six protons and eight neutrons) and an atomic number of 6, meaning it is still the element carbon. These two alternate forms of carbon are isotopes. Some isotopes are unstable and will lose protons, other subatomic particles, or energy to form more stable elements. These are called **radioactive isotopes** or radioisotopes.

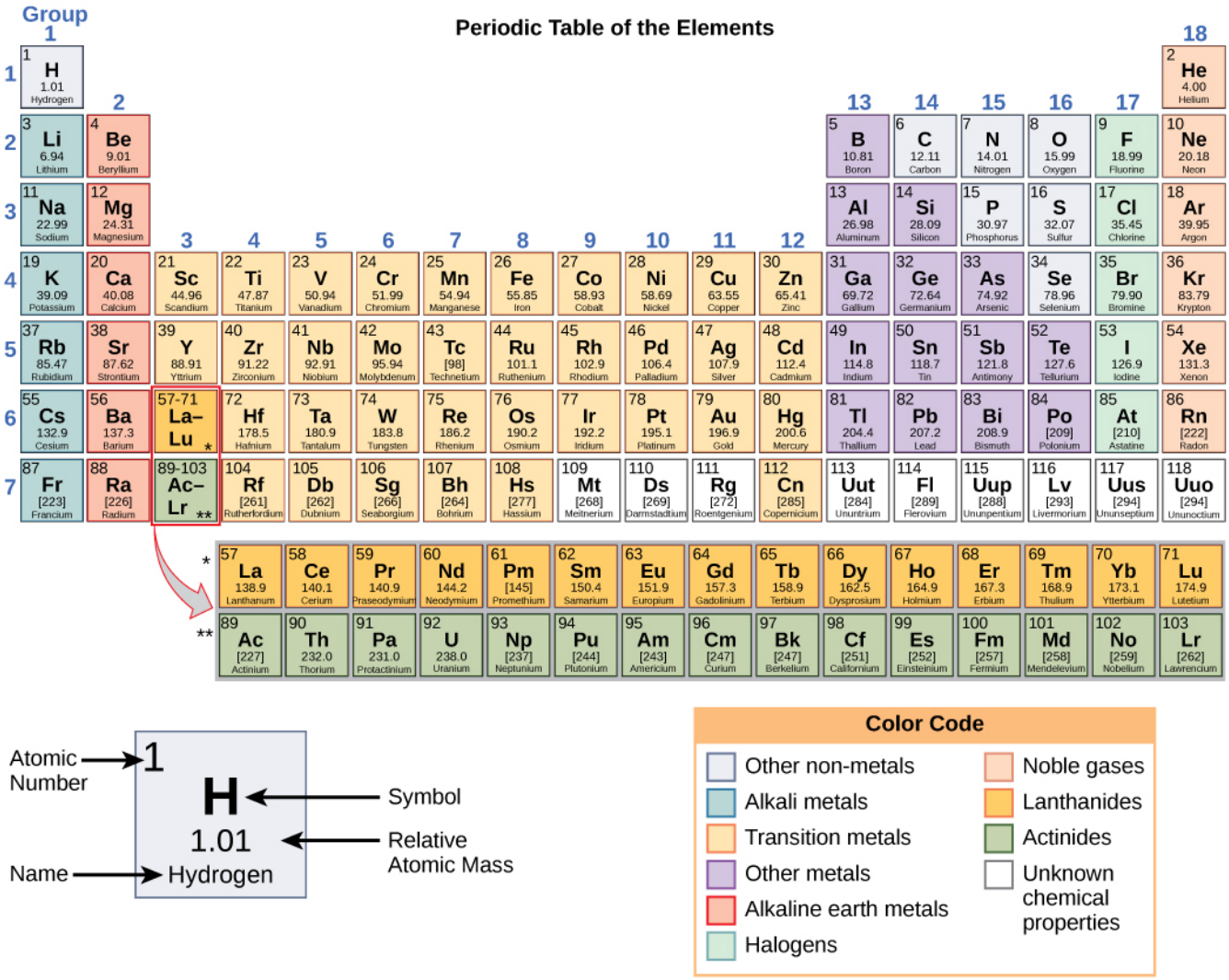


Figure 2.1.3 The periodic table, arranged in columns and rows based on the characteristics of the elements, provides key information about the elements and how they might interact to form molecules. Most periodic tables provide a key or legend to the information they contain. Image by OpenStax, CC BY 4.0

2.2 CHEMICAL BONDS

Electrons

How elements interact with one another depends on how their electrons are arranged and how many openings for electrons exist at the outermost region where electrons are present in an atom. Electrons exist at energy levels that form shells around the nucleus. The closest shell can hold up to two electrons. The closest shell to the nucleus is always filled first before any other shell can be filled. Hydrogen has one electron; therefore, only one spot is occupied within the lowest shell. Helium has two electrons; thus, it can fill the lowest shell with its two electrons. If you look at the periodic table (Figure 2.1.3), you will see that hydrogen and helium are the only two elements in the first row. This is because they only have electrons in their first shell. Hydrogen and helium are the only elements with the lowest shells and no other shells.

The second and third energy levels can hold up to eight electrons. For example, Nitrogen has an atomic number of 7. That means that it has 7 protons, so to remain neutral, it must also have 7 electrons. The first energy shell will hold 2 electrons. The second shell will hold the remaining 5 electrons.

Exercise 2.2.1

Build an atom yourself! Click on "Atom" in the activity below. Then, a nitrogen atom can be made by dragging the appropriate number of protons, neutrons, and electrons into the diagram. If you do it properly, you should end with a neutral atom with the proper mass number.

Answer

Your Nitrogen atom should have 7 protons, 7 neutrons, and 7 electrons.

The outermost shell is called the **valence** shell. An atom is most stable when all of the electron positions in the valence shell are filled. The **valence number** of an element is the number of electrons required to fill the valence shell. In the case of Nitrogen, it has 5 electrons in the outermost shell, so we would say that it has 5

valence electrons. Since the second shell can hold a maximum of 8 electrons, it means that there are 3 openings that can be filled, meaning a valence number of 3.

These vacancies in the valence shells get filled by sharing electrons, accepting electrons from another atom, or donating electrons to another atom. These interactions between atoms that hold them together are called **chemical bonds**.

Because the valence shells of the elements with low atomic numbers (up to calcium, with atomic number 20) can hold eight electrons, this is called the **octet rule**. An atom can donate, accept, or share electrons with other elements to fill its valence shell and satisfy the octet rule.

Types of Chemical Bonds

There are three main types of bonds: ionic, covalent, and hydrogen.

Ionic Bonds

An **ionic bond** is a type of chemical bond formed through the electrostatic attraction between oppositely charged ions. This occurs when one atom transfers one or more of its electrons to another atom, resulting in the formation of ions.

An **ion** is an atom that has lost or gained one or more electrons, resulting in a net electrical charge. Positive ions are formed by losing electrons and are called **cations**. Negative ions are formed by gaining electrons and are called **anions**.

For example, sodium only has one electron in its outermost shell. It takes less energy for sodium to donate that one electron than to accept seven more electrons to fill the outer shell. If sodium loses an electron, it has 11 protons and only 10 electrons, leaving it with an overall charge of +1. It is now called a sodium ion. The chlorine atom has seven electrons in its outer shell. Again, it is more energy-efficient for chlorine to gain one electron than to lose seven. Therefore, it tends to gain an electron to create an ion with 17 protons and 18 electrons, giving it a net negative (−1) charge. It is now called a chloride ion.

This movement of electrons from one element to another is referred to as **electron transfer**. Both ions now satisfy the octet rule and have complete outermost shells. Because the number of electrons is no longer equal to the number of protons, each is now an ion and has a +1 (sodium) or −1 (chloride) charge.

These ions stay together because positive and negative charges attract, creating an ionic bond between ions. When Na+ and Cl– ions combine to produce NaCl, an electron from a sodium atom stays with the other seven from the chlorine atom, and the sodium and chloride ions attract each other in a network of ions with a net zero charge.

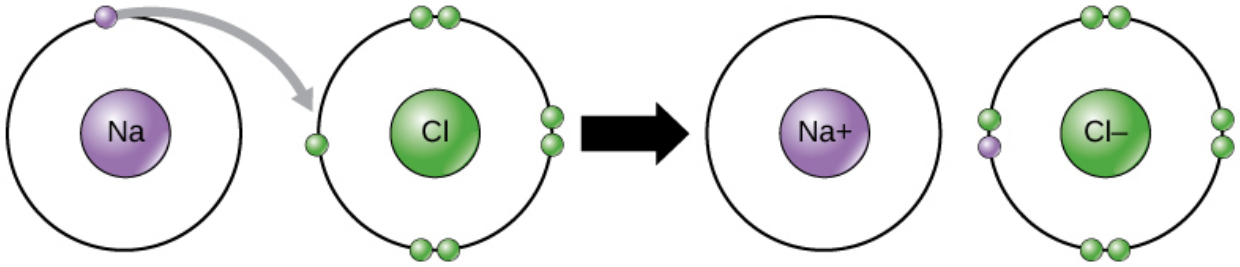
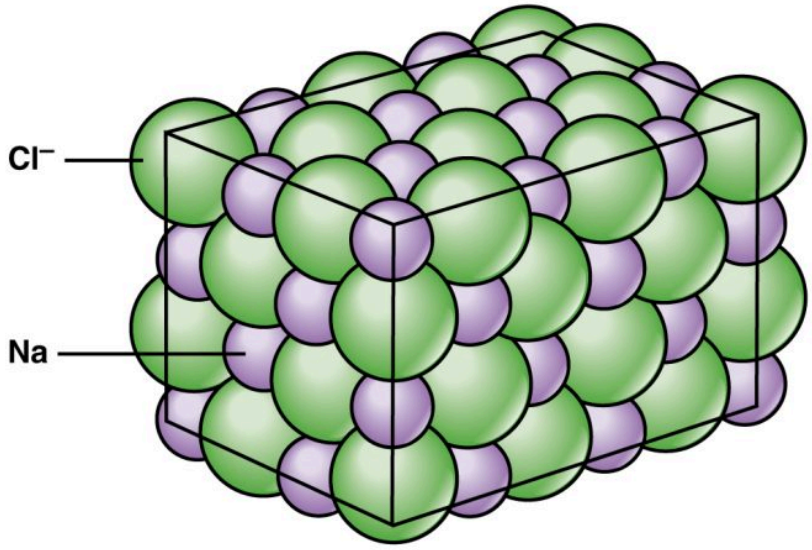


Figure 2.2.2 Elements tend to fill their outermost shells with electrons. To do this, they can either donate or accept electrons from other elements. Positively charged sodium and negatively charged chloride ions bond to make sodium chloride crystals or table salt. Image by OpenStax, CC-BY 4.0



(c)

Figure 2.2.3 The attraction of many sodium and chloride ions forms large groupings called crystals. Image by OpenStax, CC BY 4.0

Covalent Bonds

A **covalent bond** is another chemical bond between two or more atoms. These bonds form when a pair of electrons is shared between two elements. They are the strongest and most common chemical bonds in living organisms. Covalent bonds form between the elements that make up the biological molecules in our cells. Unlike ionic bonds, covalent bonds do not dissociate in water.

A group of two or more atoms held together by covalent bonds is called a **molecule**. For example, covalent bonds combine the hydrogen and oxygen atoms together to form water molecules. Two electrons from two hydrogen atoms are needed to fill the outer shell of an oxygen atom, hence the subscript "2" in H_2O. The electrons are shared between the atoms, dividing their time between them to "fill" the outer shell of each.

There are two types of covalent bonds: polar and nonpolar. **Nonpolar covalent bonds** form between two atoms of the same element or between different elements that share the electrons equally. For example, an oxygen atom can bond with another oxygen atom to fill its outer shell. This association is nonpolar because the electrons will be equally distributed between each oxygen atom. Two covalent bonds (double bond) form between the two oxygen atoms because oxygen requires two shared electrons to fill its outermost shell. Nitrogen atoms will form three covalent bonds (triple covalent) between two nitrogen atoms because each nitrogen atom needs three electrons to fill its outermost shell. Another example of a nonpolar covalent bond is found in the methane (CH_4) molecule. The carbon atom has four electrons in its outermost shell and needs four more to fill it. It gets these four from four hydrogen atoms, each atom providing one. These elements all share the electrons equally, creating four nonpolar covalent bonds.

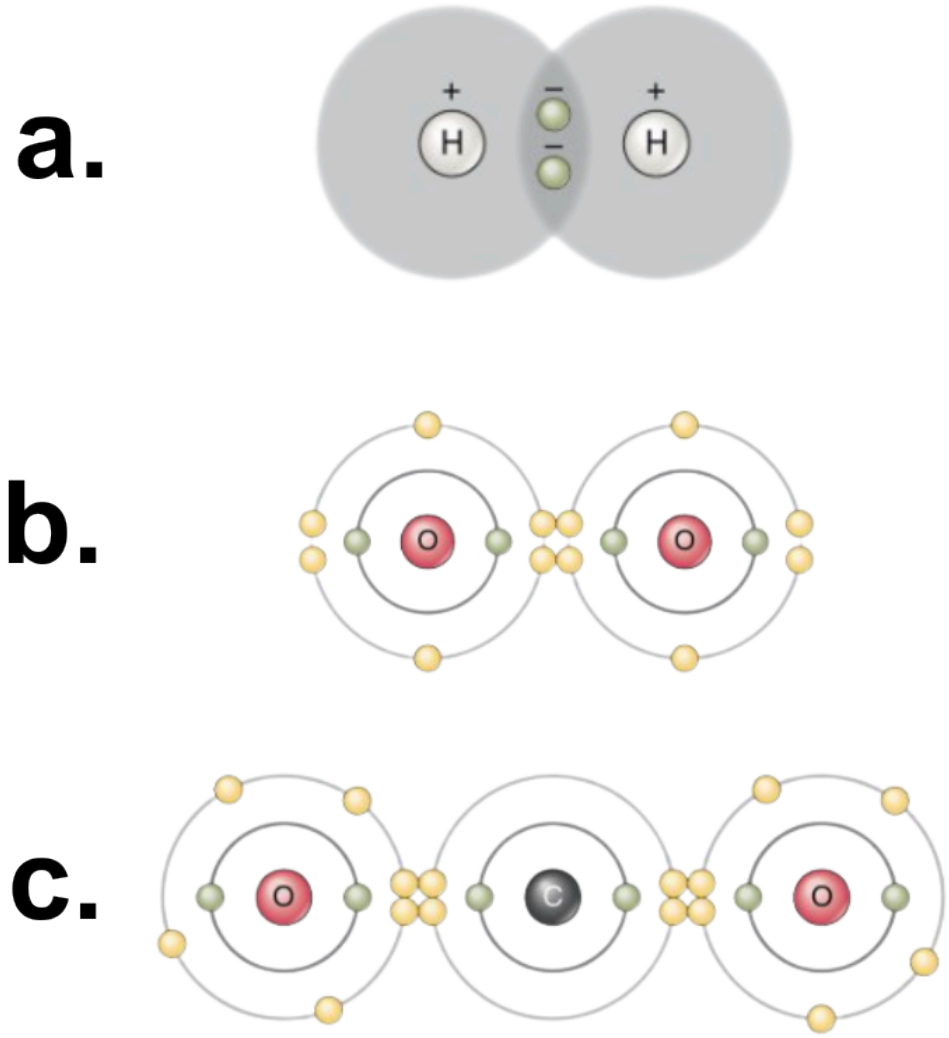
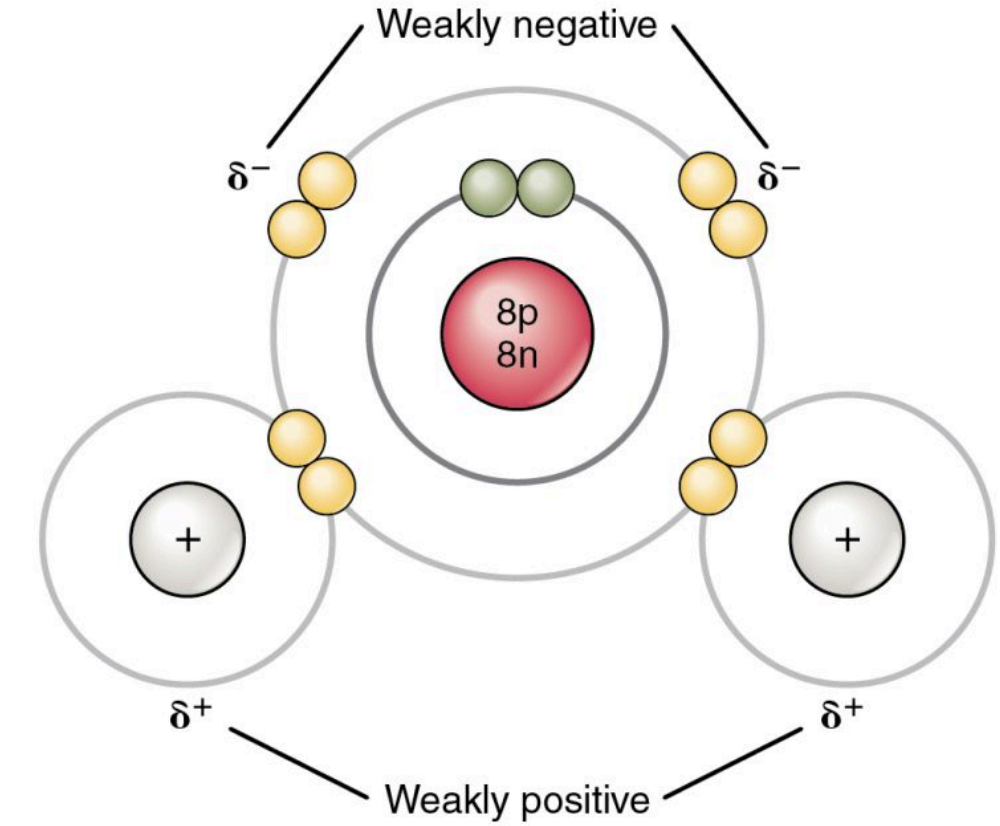
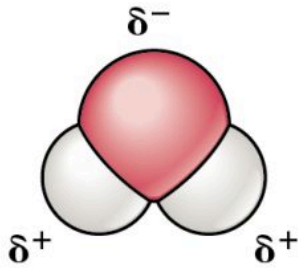


Figure 2.2.4 **a.** A single covalent bond: hydrogen gas (H—H). Two hydrogen atoms share their solitary electron in a single covalent bond **b.** A double covalent bond: oxygen gas (O=O). **c.** Two double covalent bonds: carbon dioxide (O=C=O). Image by OpenStax, CC-BY 4.0. Mods: Removed text; increased letters.

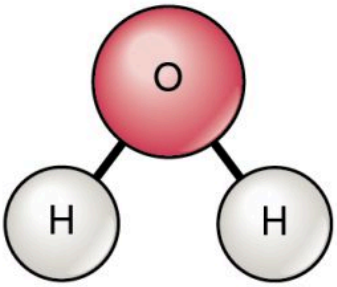
In a **polar covalent bond**, the electrons shared by the atoms spend more time closer to one nucleus than to the other nucleus. Because of the unequal distribution of electrons between the different nuclei, a slightly positive (δ+) or slightly negative (δ–) charge develops. The covalent bonds between water hydrogen and oxygen atoms are polar. The shared electrons spend more time near the oxygen nucleus, giving it a slight negative charge, than the hydrogen nuclei, giving these molecules a slight positive charge.



(a) Planetary model of a water molecule



(b) Three-dimensional model of a water molecule



(c) Structural formula for water molecule

Figure 2.2.5: Three representations of a water molecule. (a) Planetary model of a water molecule. The molecule exhibits partial charges (δ^+ and δ^-), indicating its polar nature. (b) Three-dimensional model of a water molecule. The oxygen atom is red, and the two hydrogen atoms are white. (c) Structural formula for a water molecule is a simplified structural diagram showing oxygen (O) bonded to two hydrogen (H) atoms. Image by OpenStax, CC-BY 4.0

Hydrogen Bonds

Hydrogen bonds are weak electrical attractions between neighbouring polar molecules. When polar covalent bonds containing a hydrogen atom form, the hydrogen atom in that bond has a slightly positive charge because the shared electron is pulled more strongly toward the other element and away from the hydrogen nucleus. Because the hydrogen atom is somewhat positive (δ+), it will attract neighbouring negative partial charges (δ–). When this happens, a weak interaction occurs between the δ+ charge of the hydrogen atom of one molecule and the δ– charge of the other molecule. This interaction is called a hydrogen bond. This type of bond is common; for example, the liquid nature of water is caused by the hydrogen bonds between water molecules. Hydrogen bonds give water the unique properties that sustain life. If not for hydrogen bonding, water would be a gas rather than a liquid at room temperature.

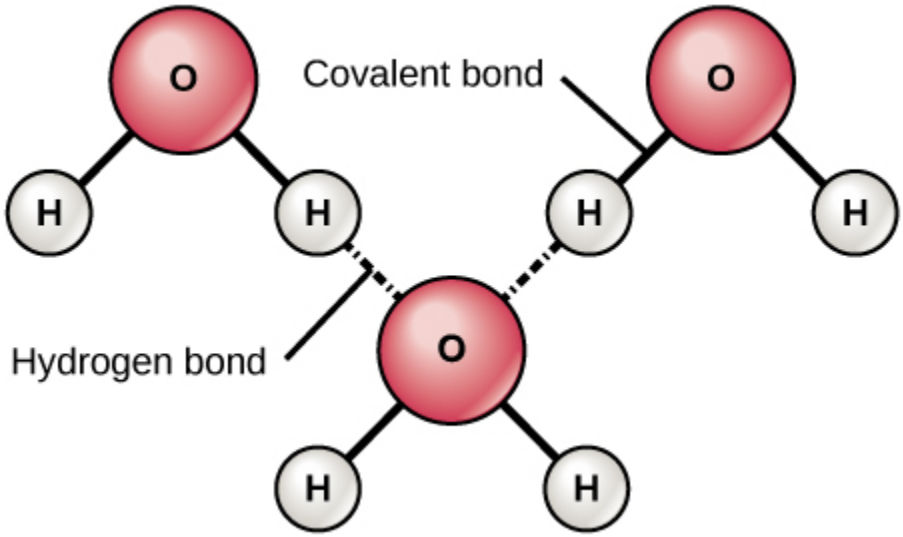


Figure 2.2.6 Hydrogen bonds form between slightly positive [latex](δ+)[/latex] and slightly negative [latex](δ–)[/latex] charges of polar covalent molecules, such as water. Image by OpenStax, CC BY 4.0

Hydrogen bonds can form between different molecules and do not always have to include a water molecule. Hydrogen atoms in polar bonds within any molecule can form bonds with other adjacent molecules. For example, hydrogen bonds hold two long strands of DNA together to give the DNA molecule its characteristic double-stranded structure. Hydrogen bonds are also responsible for some of the three-dimensional structure of proteins.

Exercise 2.2.2

Molecules and compounds are not the same thing!

Covalent bonds join the atoms in molecules. Compounds contain two different atoms joined by either covalent or ionic bonds. Molecular oxygen (O2) is a molecule containing two of the same atoms joined by nonpolar covalent bonds. However, O2 is not a compound because it contains only one type of atom. Water (H2O) is both a molecule and a compound because covalent bonds join the atoms in water and contain two different atoms: O and H.

Text Description

1. Identify the reactivity, valence number, valence electrons, and atomic number for Boron and Neon
Options: Inert, Reactive, 0, 5, 5, 3, 8, 10

2. One Na atom and one Cl atom. Identify the electron movement.

3. Which is nonpolar covalent and which is polar covalent: CH_4, H_20

4. NaCl is a molecule and a compound (True/False)

5. CH4 is a molecule and a compound. (True/False)

6. Identify where the Hydrogen bond and the Polar Covalent Bonds are in 2 water molecules.

7. Which statement about hydrogen bonds is correct?

   a. Hydrogen bonds allow water to change temperature rapidly
   b. Hydrogen bonds occur within (inside of) molecules, not between molecules
   c. Hydrogen bonds occur between hydrogens and the atoms they share electrons with
   d. Hydrogen bonds form between hydrogens

e. Hydrogen bonds occur between molecules, not within (inside of) molecules

8. The ion Cl^- has:

a. One more electron than protons
b. One more proton than neutrons
c. One more neutron than electrons
d. One more proton than electrons
e. One more neutron than protons

9. What type of chemical bond commonly forms WITHIN water molecules?

a. Polar covalent bonds
b. Hydrogen bonds
c. Covalent bonds
d. Molecular bonds
e. Polar ionic bonds

10. Among _____ of any particular element, the number of _____ can vary, and therefore, the mass number of the element will vary.

a. Isotopes; protons
b. Atoms; orbitals
c. Isotopes; neutrons
d. Ions; electrons
e. Electrons; protons

11. Which type of chemical bond involves the sharing of valence electron pairs between two atoms?

a. Atomic
b. Electronic
c. Hydrogen
d. Covalent
e. Ionic

Answer

1. Boron – reactive, valence number = 5, valence electrons = 3, atomic number = 5
Neon – inert, valence number = 0, valence electrons = 8, atomic number = 10
2. Na loses its valence electron to the Cl
3. CH_4 is nonpolar covalent; H_2O is polar covalent
4. False
5. True
6. Polar covalent bonds are between atoms in the molecule. Hydrogen bonds are between molecules.
7. e. Hydrogen bonds occur between molecules, not within (inside of) molecules
8. a. One more electron than protons
9. a. Polar covalent bonds
10. c. Isotopes; neutrons
11. d. Covalent

2.3 WATER

Do you ever wonder why scientists spend time looking for water on other planets? Water is essential to life; even minute traces of it on another planet can indicate that life could or did exist on that planet. Water is one of the more abundant molecules in living cells and the one most critical to life as we know it. Approximately 60 to 70 percent of your body is made up of water. Without it, life would not exist.

Structure of Water

The hydrogen and oxygen atoms within water molecules form polar covalent bonds. The shared electrons spend more time associated with the oxygen atom than the hydrogen atoms. There is no overall charge to a water molecule, but there is a slight positive charge ($\delta+$) on each hydrogen atom and a slight negative charge ($\delta-$) on the oxygen atom. In a solution of pure water, the partial negative charge on the oxygen is attracted to the partial positive charges on *other* water molecules, forming hydrogen bonds between water molecules. The hydrogen bonds between water molecules are responsible for all the properties of water.

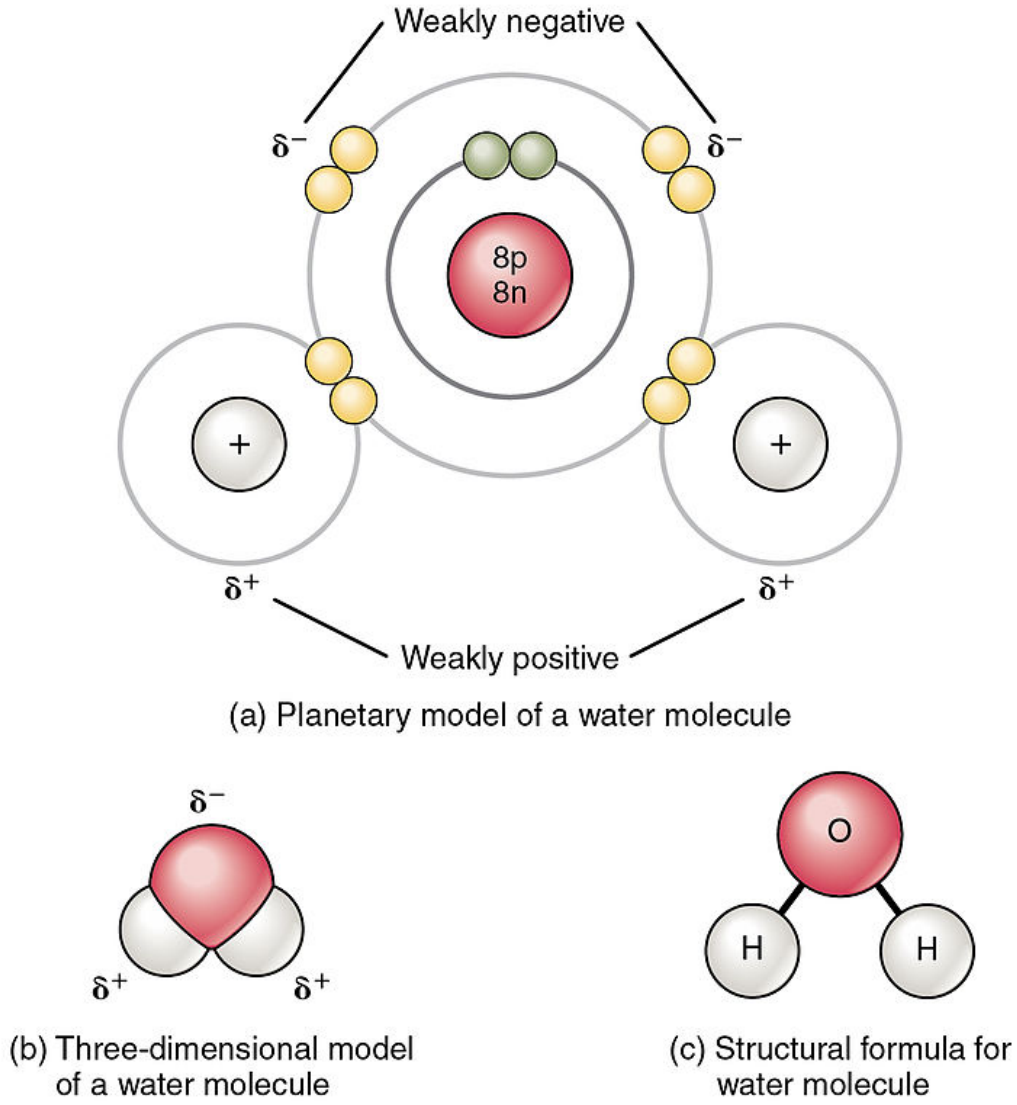


Figure 2.3.1 Polar Covalent Bonds in a Water Molecule. Image by OpenStax, CC BY 4.0

Properties of Water

The properties of water include:

Water is Cohesive

Figure 2.3.2 The weight of a needle on top of the water pulls the surface tension downward; at the same time, the surface tension of the water pulls it up, suspending the needle on the surface of the water and keeping it from sinking. Notice the indentation in the water around the needle. Image by Cory Zanker, CC BY 4.0

Cohesion is the tendency for molecules of the same kind to be attracted to one another. Cohesion allows water molecules to "stick together" via hydrogen bonding. Have you ever filled a glass of water to the top and slowly added a few more drops? Before it overflows, the water forms a dome-like shape above the rim of the glass because of cohesion.

Cohesion gives rise to **surface tension**, the capacity of a substance to withstand rupture when placed under tension or stress. When you drop a small scrap of paper onto a droplet of water, the paper floats on top of the water droplet, although the object is denser (heavier) than the water. This occurs because of the surface tension created by the water molecules. Cohesion and surface tension keep the water molecules intact and the item floating on top. If you place it gently without breaking the surface tension, it is possible to "float" a steel needle on top of a glass of water.

These cohesive forces are also related to the water's **adhesion** property 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 higher on the sides of the straw than in the middle. This is because the water molecules are attracted to the straw and adhere to it.

Cohesive and adhesive forces are essential for sustaining life. In the human body, cohesion of water molecules ensures that when water moves in and out of capillaries, one water molecule will be followed by many water molecules. This bulk movement of water ensures fluid balance within the body. The cohesion of water also allows water to flow from the roots up to the leaves to feed the plants.

Water Stabilizes Temperature

The hydrogen bonds in water allow it to absorb and release heat energy more slowly than many other substances. **Temperature** is a measure of the motion (kinetic energy) of molecules. As motion increases, energy and temperature increase. Water absorbs a great deal of energy before its temperature rises. Energy must be invested to *break the hydrogen bonds that hold water molecules together* before those water molecules can move freely. Once the hydrogen bonds have been broken, individual water molecules move faster (gain kinetic energy), resulting in a *change in temperature*.

The release of individual water molecules at the surface of the liquid (such as a body of water, the leaves of a plant, or the skin of an organism) is called **evaporation**. Evaporation of sweat, which is 90 percent water, allows for the cooling of an organism because breaking hydrogen bonds requires an input of energy and takes heat away from the body.

Conversely, water also takes a long time to cool. Once you have brewed your tea, you must wait for the tea to reach a drinkable temperature. As water cools, the molecules slow their movement and *energy is released as the hydrogen bonds between water molecules re-form*. That energy keeps the temperature of the water relatively constant, even though you have stopped heating the water.

The ability for water to stabilize temperature makes Earth habitable. Heat from the atmosphere is absorbed by water in oceans, ensuring that the temperature on Earth's surface does not exceed a livable temperature. Water can release heat to cool atmospheric air, again, keeping the temperature on Earth's surface relatively constant. Life on Earth is possible because of the ability of water molecules to form hydrogen bonds!

Water Expands Upon Freezing

For most substances, the solid state of matter is denser than the liquid state of the same substance. As atoms and molecules slow their movement at low temperature, they get closer together. Generally, this increases the **density** of a substance. Density is a measure of how much mass is contained in a given volume. It indicates how tightly matter is packed together.

Water is one exception to this rule. Ice is less dense (the molecules are farther apart) when frozen compared to liquid water. In liquid water, some molecules are bound together by hydrogen bonds, but some molecules move freely. As liquid water freezes and hydrogen bonds form between water molecules, it creates a rigid, lattice-like structure (e.g., ice) (Figure 2.3.3 a). The fixed geometry of the lattice prevents water molecules from packing close together and, therefore, from becoming denser as it freezes. Instead, water expands upon freezing.

This means that ice floats on the surface of a body of water (Figure 2.3.3 b). Ice will form on the water's surface in lakes, ponds, and oceans, creating an insulating barrier to protect the animal and plant life beneath from freezing in the water. If this did not happen, plants and animals living in water would freeze in a block of ice and could not move freely, making life in cold temperatures difficult or impossible.

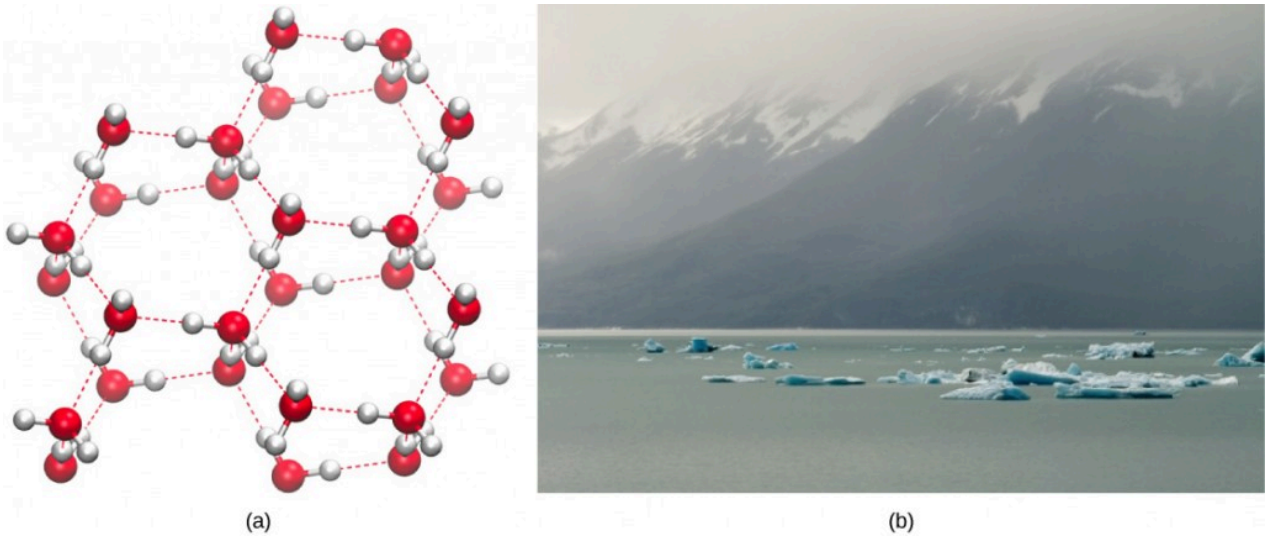


Figure 2.3.3 (a) The lattice structure of ice makes it less dense than the freely flowing molecules of liquid water. Ice's lower density enables it to (b) float on water. a: modification of work by Jane Whitney; b: modification of work by Carlos Ponte, CC BY 4.0

Water is a Versatile Solvent

Water is the solvent for most of life's chemical reactions. A **solution** is a uniform mixture of a liquid and substances dissolved in that liquid. A solution consists of a **solvent** (a substance capable of dissolving another substance) and a **solute** (a substance dissolved in the solvent).

Because water is polar, with slightly positive and negative charges, ionic compounds (such as salt) and polar molecules (such as sugar) can readily dissolve. The charged particles will form hydrogen bonds with a surrounding layer of water molecules. This is a sphere of hydration that keeps the particles separated or dispersed in the water. In the case of table salt (NaCl) mixed in water, the sodium and chloride ions separate, or dissociate, in the water, and spheres of hydration are formed around the ions. A positively charged sodium ion is surrounded by the partially negative charges of oxygen atoms in water molecules. A negatively charged chloride ion is surrounded by the partially positive charges of hydrogen atoms in water molecules. These spheres of hydration are also referred to as hydration shells. The water molecule's polarity makes it an effective solvent and is essential in its many roles in living systems.

When a substance readily forms hydrogen bonds with water, it can dissolve in water and is called **hydrophilic** ("water-loving"). Hydrogen bonds are not readily formed with nonpolar substances like oils and fats. These nonpolar compounds are **hydrophobic** ("water-fearing") and will not dissolve in water.

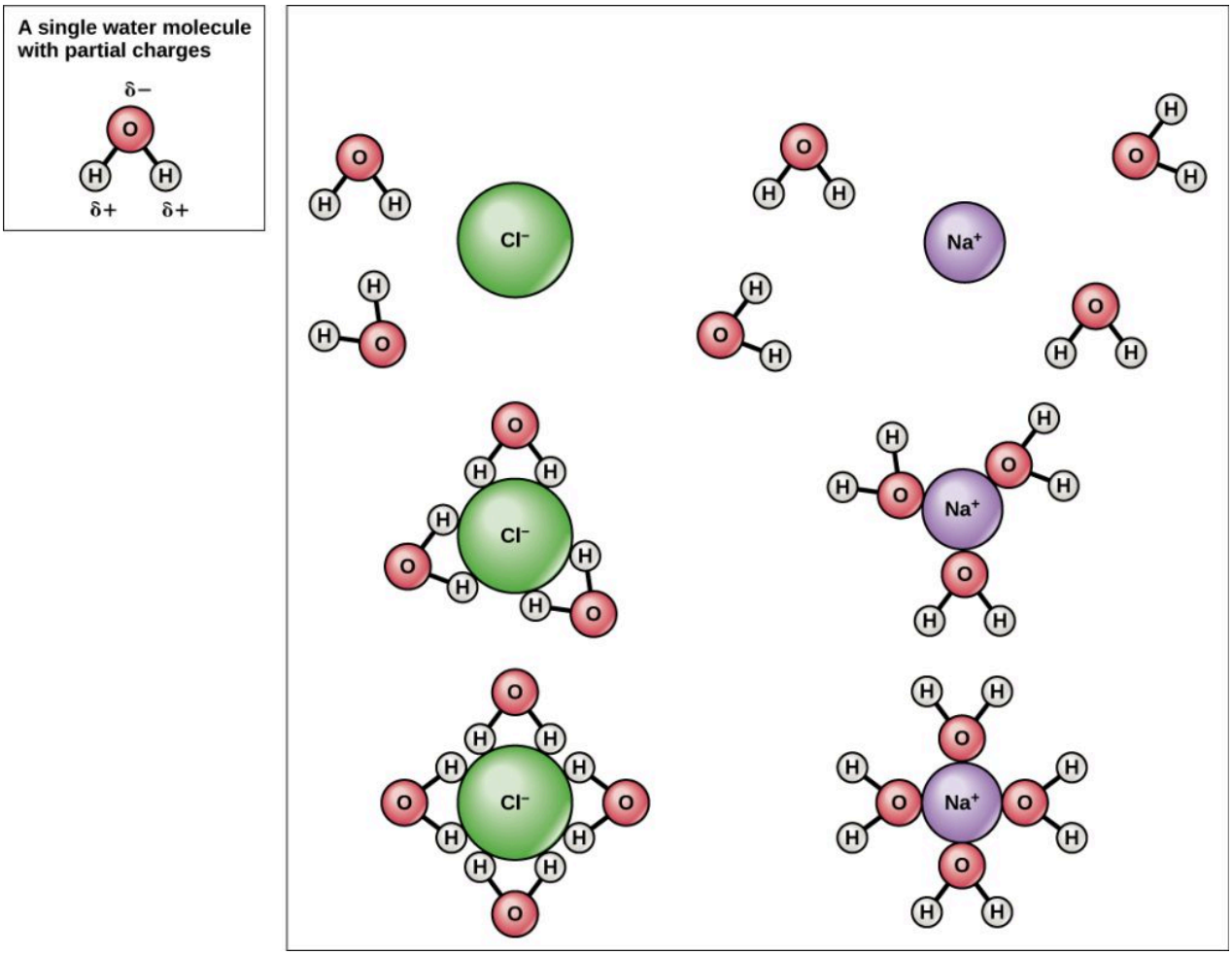


Figure 2.3.4 When table salt (NaCl) is mixed in water, spheres of hydration form around the ions. Image by OpenStax, CC BY 4.0

Water can dissolve a wide range of substances, which are crucial to facilitate chemical reactions and the transport of nutrients and waste within organisms. For example, blood, which is mostly water, is essential for transporting nutrients, oxygen, and waste products throughout the body.

Exercise 2.3.1

Text Description
Match each property of water with the correct description.

1. Water is _____ because the oxygen atom is partially negatively charged, and the hydrogen atoms are partially positively charged.
2. _____ substances dissolve easily in water, while _____ substances do not.
3. Water stabilizes _____ because it can absorb a lot of energy before it changes state (i.e., from liquid to gas).
4. Water is an excellent _____ because it can dissolve polar and ionic compounds.
5. _____ is caused by hydrogen bonds holding water molecules together. This also causes _____, which allows objects to float on the surface of the water, held up by all the hydrogen bonds.
6. _____ is the attraction between water molecules and other molecules.

Possible answers:

- hydrophobic
- Cohesion
- polar
- Hydrophilic
- Adhesion
- surface tension
- solvent
- temperature

Answers:

1. Water is ***polar*** because the oxygen atom is partially negatively charged, and the hydrogen atoms are partially positively charged.
2. ***Hydrophilic*** substances dissolve easily in water, while ***hydrophobic*** substances do not.
3. Water stabilizes ***temperature*** because it can absorb a lot of energy before it changes state (i.e., from liquid to gas).

4. Water is an excellent ***solvent*** because it can dissolve polar and ionic compounds.
5. ***Cohesion*** is caused by hydrogen bonds holding water molecules together. This also causes ***surface tension***, which allows objects to float on the surface of the water, held up by all the hydrogen bonds.
6. ***Adhesion*** is the attraction between water molecules and other molecules.

Buffers, pH, Acids, and Bases

The pH of a solution is a measure of its acidity or alkalinity. You have probably used **litmus paper**, treated with a natural water-soluble dye as a pH indicator, to test how much acid or base (alkalinity) exists in a solution. You might have even used some to ensure the water in an outdoor swimming pool is treated correctly. This pH test measures the number of hydrogen ions in a given solution in both cases. High concentrations of hydrogen ions yield a low pH, whereas low levels of hydrogen ions result in a high pH. The overall concentration of hydrogen ions is inversely related to its pH and can be measured on the **pH scale** (Figure 2.3.5). Therefore, the more hydrogen ions present, the lower the pH; conversely, the fewer hydrogen ions, the higher the pH.

The pH scale ranges from 0 to 14. A change of one unit on the pH scale represents a change in the concentration of hydrogen ions by a factor of 10, and a change in two units represents a change in the concentration of hydrogen ions by a factor of 100. Thus, small changes in pH represent significant changes in the concentrations of hydrogen ions. Pure water is neutral. It is neither acidic nor basic and has a pH of 7.0. Anything below 7.0 (ranging from 0.0 to 6.9) is acidic, and anything above 7.0 (7.1 to 14.0) is alkaline. The blood in your veins is slightly alkaline (pH = 7.4). The environment in your stomach is highly acidic (pH = 1 to 2). Orange juice is mildly acidic (pH = approximately 3.5), whereas baking soda is basic (pH = 9.0).

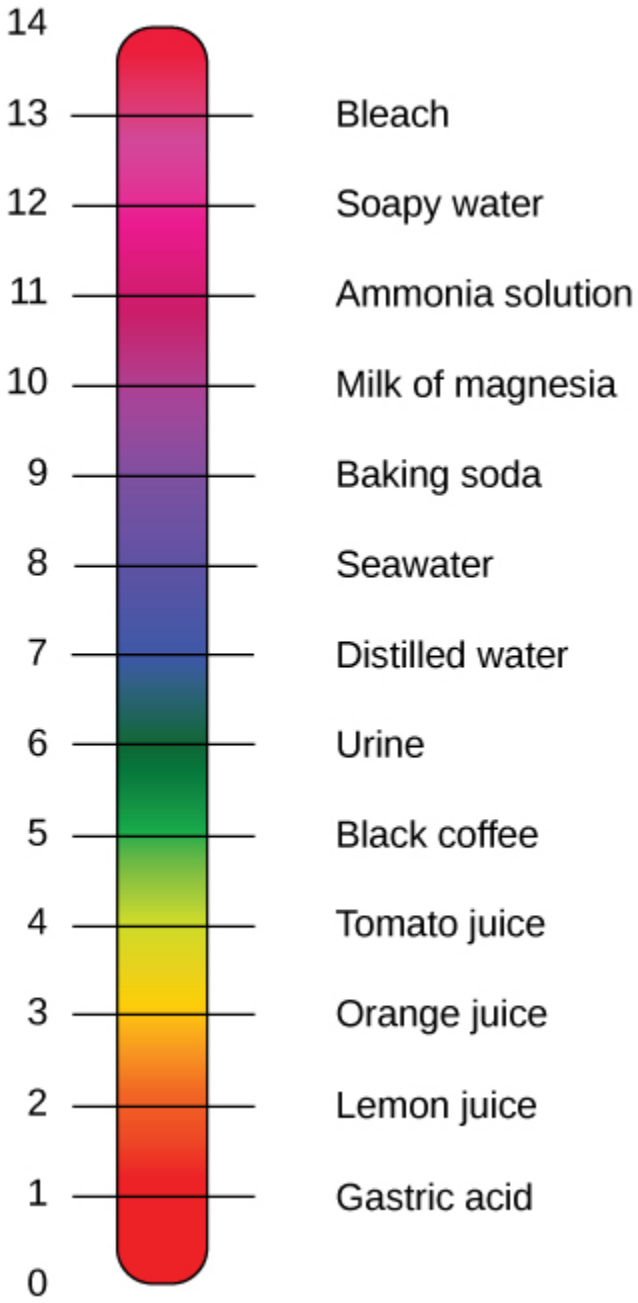


Figure 2.3.5 The pH scale measures the amount of hydrogen ions (H^+) in a substance. Modification of work by Edward Stevens, CC BY 4.0

Figure 2.3.5 Description

- Acidic examples below 7.0 include gastric acid (1), lemon juice (2), orange juice (3), tomato juice (4), black coffee (5), urine (6)
- Neutral example includes distilled water (7)
- Alkaline examples above 7.0 include seawater (8), baking soda (9), Milk of magnesia (10), ammonia

solution (11), soapy water (12), bleach (13)

Acids are substances that provide hydrogen ions (H+) and lower pH, whereas **bases** provide hydroxide ions (OH–) and raise pH. The stronger the acid, the more readily it donates H+. For example, hydrochloric acid and lemon juice are very acidic and readily give up H+ when added to water. Conversely, bases are those substances that readily donate OH–. The OH– ions combine with H+ to produce water, which raises a substance's pH. Sodium hydroxide and many household cleaners are very alkaline and give up OH– rapidly when placed in water, increasing the pH.

Most cells in our bodies operate within a very narrow window of the pH scale, typically ranging only from 7.2 to 7.6. If the body's pH is outside of this range, the respiratory system malfunctions, as do other organs. Cells no longer function properly, and proteins break down. Deviation outside of the pH range can induce coma or even cause death.

So, how is it that we can ingest or inhale acidic or basic substances and not die? Buffers are the key. **Buffers** readily absorb excess H+ or OH–, keeping the body's pH in the narrow range. Carbon dioxide is part of a prominent buffer system in the human body; it keeps the pH within the proper range. This buffer system involves carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-) anion. If too much H+ enters the body, bicarbonate will combine with the H+ to create carbonic acid and limit the decrease in pH. Likewise, if too much OH– is introduced into the system, carbonic acid will rapidly dissociate into bicarbonate and H+ ions. The H+ ions can combine with the OH– ions, limiting the increase in pH. While carbonic acid is an essential product in this reaction, its presence is fleeting because it is released from the body as carbon dioxide gas each time we breathe. Without this buffer system, the pH in our bodies would fluctuate too much, and we would fail to survive.

Exercise 2.3.2

Drag each item to its corresponding substance type.

Text Description
Substances that make up a pH solution: Acid, Base, and Neutral

Draggable items: pH equal to 7, pH greater than 7, pH less than 7, Water, Bleach, Orange juice, Alkaline, Readily donates H+, Readily donates OH-, High concentrations of hydrogen ions, Low concentrations of hydrogen ions

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Answers:

- Acid: pH less than 7; Orange juice, High concentrations of hydrogen ions, Readily donates H+
- Base: pH greater than 7; Alkaline, Bleach, Low concentrations of hydrogen ions, Readily donates OH-
- Neutral: pH equal to 7; Water

Text Description
Select all of the statements that are true about buffers.

a. Are a strong acid or a strong base.
b. Help maintain homeostasis.
c. Absorb excess H+ or OH-
d. Are uncommon in biological systems.

Correct answer(s): b. Help maintain homeostasis.; c. Absorb excess H+ or OH-

CHAPTER 2 SUMMARY

Key Takeaways

- **Basic Composition of Matter:** All living things are made of matter, which consists of elements that cannot be broken down chemically. Atoms, the smallest unit of an element, contain protons, neutrons, and electrons, with each element having a unique number of protons defining its atomic number.
- **Chemical Bonds and Stability**: Atoms form molecules through chemical bonds—ionic, covalent (polar and nonpolar), and hydrogen bonds—to achieve stability, often following the octet rule, where atoms aim for eight electrons in their outer shell.
- **Properties of Water:** Water's unique properties, such as cohesion, high heat capacity, ice expanding, and its role as a universal solvent, are due to hydrogen bonding. These properties are essential for sustaining life on Earth.
- **Isotopes and Ions:** Isotopes are variants of elements with the same number of protons but different numbers of neutrons, while ions are atoms with unequal numbers of protons and electrons, resulting in a net charge. Ions form through electron transfer, creating ionic bonds.
- **The Periodic Table's Role**: The periodic table organizes elements based on their atomic structure, revealing patterns in electron configuration, reactivity, and bonding tendencies. It helps predict how elements interact chemically.
- **pH, Acids, Bases, and Buffers:** The pH scale measures a solution's acidity or alkalinity, influenced by hydrogen ion concentration. Buffers maintain pH balance in biological systems, which is crucial for proper cellular function, by neutralizing excess acids or bases.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into six key takeaways.

Flashcards

Text Description

1. **Matter**: Anything that occupies space and has mass, composed of atoms
2. **Elements**: Pure substances are composed of one type of atom; they cannot be broken down into simpler substances by chemical reactions
3. **Compound:** Molecules that contain more than one element in a fixed ratio
4. **Atom:** The smallest unit of matter that retains all of the chemical properties of an element
5. **Protons**: Positively charged particles found in an atom's nucleus; determine an element's identity
6. **Electrons**: Negatively charged particles orbiting around an atom's nucleus; involved in chemical bonding and reactions
7. **Neutrons**: Particles with no charge found in the atom's nucleus; contribute to the atom's mass
8. **Nucleus**: Central region of an atom containing protons and neutrons; contains almost all of an atom's mass
9. **Atomic Number**: The number of protons in the nucleus of an atom, unique for each element
10. **Mass Number**: The total number of protons and neutrons in an atom's nucleus
11. **Periodic Table of Elements**: An organized chart listing all known elements, arranged by atomic number and chemical properties
12. **Isotopes**: Atoms of the same element with the same atomic number but different numbers of neutrons, resulting in different mass numbers
13. **Radioactive Isotopes**: Unstable isotopes that spontaneously emit radiation (particles and energy) to become more stable
14. **Valence electrons**: The electrons in an atom's outermost energy shell; determines chemical reactivity and bonding
15. **Valence number:** The number of electrons required to fill the valence shell
16. **Chemical Bonds**: Forces holding atoms together through interactions involving electrons (ionic, covalent, and hydrogen bonds)
17. **Octet Rule**: Atoms tend to gain, lose, or share electrons to obtain eight electrons in their outermost energy level (stable configuration)
18. **Ion**: An atom or molecule with a positive or negative charge due to the gain or loss of electrons

19. **Cations**: Positively charged ions formed by the loss of electrons
20. **Anions**: Negatively charged ions formed by the gain of electrons
21. **Electron Transfer**: The movement of electrons from one atom to another, forming ions
22. **Ionic Bond**: Attraction formed when electrons are transferred from one atom to another, creating oppositely charged ions that attract each other
23. **Covalent Bond**: Chemical bond formed when atoms share pairs of electrons
24. **Molecule:** A group of two or more atoms held together by covalent bonds
25. **Nonpolar Covalent Bonds**: Covalent bonds where electrons are shared equally between atoms, creating no charge difference
26. **Polar Covalent Bond**: Covalent bond where electrons are shared unequally, creating slightly charged poles in the molecule
27. **Hydrogen Bonds**: Weak attractions between partially positive hydrogen atoms and partially negative atoms (e.g., oxygen or nitrogen)
28. **Hydrophilic**: Substances that easily interact or dissolve in water ("water-loving")
29. **Hydrophobic**: Substances that repel or do not dissolve in water ("water-fearing")
30. **Temperature**: A measure of the average kinetic energy (motion) of molecules in a substance
31. **Evaporation**: The transformation of liquid into vapour, usually involving energy absorption and cooling effects
32. **Cohesion**: Attraction between molecules of the same substance (e.g., water molecules sticking together)
33. **Surface Tension**: Cohesion at a liquid's surface creating a "film" or resistance to external force
34. **Adhesion**: Attraction between different substances or molecules (e.g., water clinging to glass)
35. **Solution**: uniform mixture of liquid and substances dissolved in that liquid
36. **Solvent**: substance capable of dissolving another substance
37. **Solute**: substance dissolved in the solvent
38. **Litmus Paper**: Paper strips treated with dye that change colour in response to acidity or alkalinity
39. **pH Scale**: Numeric scale (0–14) measuring the acidity or alkalinity of a solution, where 7 is neutral, below 7 acidic, and above 7 basic
40. **Acids**: Substances releasing hydrogen ions (H^+) in water, lowering pH (below 7)
41. **Bases**: Substances releasing hydroxide ions (OH^-) or reducing hydrogen ions (H^+), raising pH (above 7)
42. **Buffers**: Substances or systems that resist changes in pH by accepting or releasing hydrogen

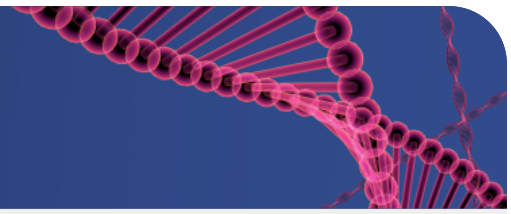
ions, maintaining a stable pH

43. **4 elements common to all living organisms:** Oxygen (O), Carbon (C), Hydrogen (H), and Nitrogen (N)
44. **3 subatomic particles:** protons (+), electrons (-), neutrons (o)
45. **Structure of water:** 2 hydrogen atoms and 1 oxygen atom, bonded via polar covalent bonds, resulting slight positive charge (δ+) on each hydrogen atom and a slight negative charge (δ-) on the oxygen atom
46. **Properties of water:** Water expands upon freezing, Water stabilizes temperature, Water is a versatile solvent, Water is cohesive
47. **Polar Molecule:** A molecule with a partial positive charge on one end and a partial negative charge on the other
48. **Why is water cohesive?** Hydrogen bonds between water molecules allow them to "stick" together
49. **What is the biological significance of water being cohesive?** It ensures bulk movement of water through living organisms (e.g. up a tree)
50. **How does water stabilize temperature?** To heat up, energy must be invested to break the hydrogen bonds that hold water molecules together before those water molecules can move freely. As water cools, the molecules slow their movement and energy is released as the hydrogen bonds between water molecules re-form.
51. **What is the biological significance of water stabilizing temperatures?** Water can absorb and release heat to ensure the temperature on Earth's surface does not exceed a livable temperature.
52. **Why does water expand upon freezing?** Hydrogen bonds form between water molecules as it freezes, which creates a rigid, lattice-like structure that prevents water molecules from packing close.
53. **What is the biological significance of ice being less dense than water?** Ice will float on the water's surface in lakes, ponds, and oceans, creating an insulating barrier to protect the animal and plant life beneath from freezing in the water.
54. **Why is water a versatile solvent?** Because water is polar, with slightly positive and negative charges, ionic compounds (such as salt) and polar molecules (such as sugar) can readily dissolve. The charged particles will form hydrogen bonds with a surrounding layer of water molecules.
55. **What is the biological significance of water as a solvent?** Water can dissolve substances to facilitate chemical reactions and transport of nutrients and waste within organisms (e.g. blood is mostly water)

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms.

CHAPTER 3: BIOLOGICAL MOLECULES

Chapter Overview



Learning Objectives

By the end of this Chapter, you will be able to:

- Identify and describe the four major classes of biological macromolecules—carbohydrates, lipids, proteins, and nucleic acids—and explain their roles in living organisms.
- Explain the significance of carbon in biological molecules, including its bonding properties that contribute to molecular diversity and complexity.
- Differentiate between dehydration synthesis and hydrolysis, describing how these processes contribute to the formation and breakdown of macromolecules in living systems.
- Analyze the structure and function of carbohydrates, lipids, and proteins, including the role of monomers, polymers, and specific examples such as glucose, triglycerides, and enzymes.
- Compare and contrast the structure, components, and functions of DNA and RNA, explaining their roles in genetic information storage and protein synthesis.

3.1 ORGANIC COMPOUNDS

Food provides an organism with nutrients—the matter it needs to survive. Many of these critical nutrients come from **biological macromolecules**, or large molecules necessary for life. These macromolecules are built from different combinations of smaller organic molecules. What specific types of biological macromolecules do living things require? How are these molecules formed? What functions do they serve? In this chapter, we will explore these questions.

Figure 3.1.1 Foods are sources of biological macromolecules. Photo by Anna Pelzer, Unsplash License

Figure 3.1.2 Macromolecules are built from building blocks that connect together like beads on a string. "Beads on a string" by Daniel, CC BY-NC-ND 2.0

Biological molecules are made up of subunits connected together by covalent bonds. Covalent bonds are strong and can hold these subunits together into long chains. If hydrogen bonds connected them, the subunits would easily separate from each other, and the biological molecule would come apart. If ionic bonds connected the subunits, the biological molecule would likely fall apart if it came into contact with water. Each type of biological molecule is made up of different subunits.

There are four major classes of biological macromolecules (carbohydrates, lipids, proteins, and nucleic acids), and each is an important component of the cell and performs a wide array of functions. Combined, these molecules make up the majority of a cell's mass. Biological macromolecules are **organic**, meaning that they contain carbon atoms. In addition, they may contain atoms of hydrogen, oxygen, nitrogen, phosphorus, sulphur, and additional minor elements.

Carbon

It is often said that life is "carbon-based." This means that carbon atoms, bonded to other carbon atoms or other elements, form the fundamental components of many, if not most, of the molecules found uniquely in living things. Other elements play important roles in biological molecules, but carbon certainly qualifies as the "foundation" element for molecules in living things. It is the versatile bonding properties of carbon atoms that play an important role.

Carbon contains four electrons in its outer shell. Therefore, it can form four covalent bonds with other atoms or molecules. The simplest organic carbon molecule is methane (CH_4), in which four hydrogen atoms bind to a carbon atom (Figure 3.1.3). However, carbon atoms can also bond to other carbon atoms to make long chains, often called **carbon skeletons** (Figure 3.1.4a). These skeletons form the backbone of organic molecules and can vary in length, branching, and the presence of double or triple bonds. Other elements, such as nitrogen, oxygen, and phosphorus, often branch off of the carbon skeleton (Figure 3.2.1b). These skeletons can also form rings (Figure 3.1.4c). This diversity of molecular forms accounts for the diversity of functions of biological macromolecules. It is based to a large degree on the ability of carbon to form multiple bonds with itself and other atoms.

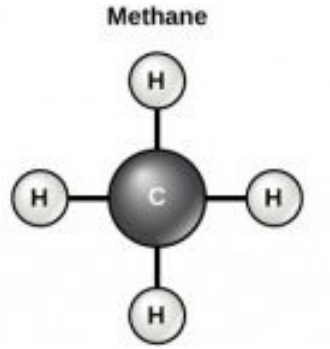


Figure 3.1.3 Methane (CH_4). Image by OpenStax, CC BY 4.0

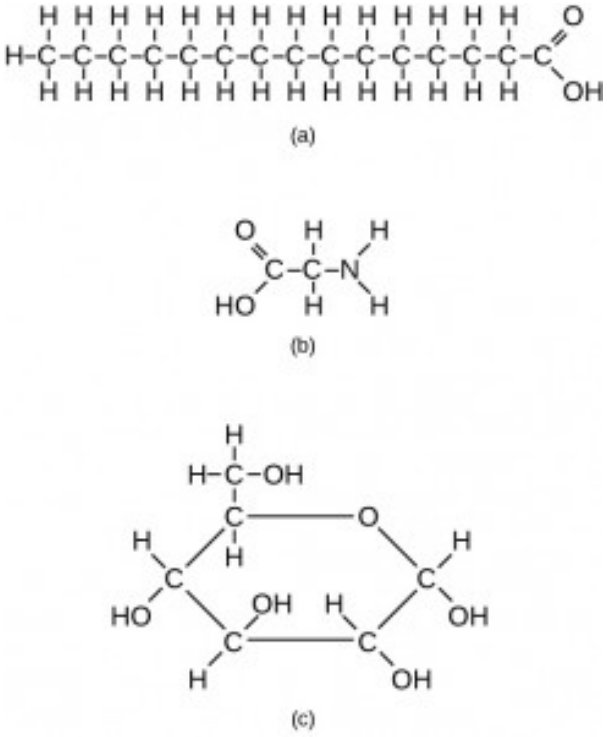


Figure 3.1.4 Carbon atoms can bond in various ways to other carbon atoms and the atoms of other elements. Image by OpenStax, CC BY 4.0

Dehydration Synthesis

Most macromolecules are made from single subunits, or building blocks, called **monomers**. The monomers combine with each other using covalent bonds to form larger molecules known as **polymers**. In doing so, monomers release water molecules as byproducts. This type of reaction is known as **dehydration synthesis**, which means "to put together while losing water."

In a dehydration synthesis reaction (Figure 3.1.5a), the hydrogen of one monomer combines with the hydroxyl (OH) group of another monomer, releasing a molecule of water. At the same time, the monomers share electrons and form covalent bonds. As additional monomers join, this chain of repeating monomers forms a polymer. Different types of monomers can combine in many configurations, giving rise to a diverse group of macromolecules. Even one kind of monomer can combine in various ways to form several different polymers. For example, glucose monomers are the constituents of starch, glycogen, and cellulose.

Hydrolysis

Polymers are broken down into monomers in a process known as **hydrolysis**, which means "to split water," a reaction in which a water molecule is used during the breakdown (Figure 3.1.5b). During these reactions, the polymer is broken into two components: one part gains a hydrogen atom (H+), and the other gains a hydroxyl molecule (OH–) from a split water molecule.

Dehydration and hydrolysis reactions are catalyzed, or "sped up," by specific enzymes. Dehydration reactions involve the formation of new bonds, requiring energy, while hydrolysis reactions break bonds and release energy. Most macromolecules have similar reactions, but each monomer and polymer reaction is specific for its group. For example, in our bodies, food is broken down into smaller molecules by enzymes in the digestive system. This allows for easy absorption of nutrients by cells in the intestine. A specific enzyme breaks down each macromolecule. For instance, carbohydrates are broken down by amylase, sucrase, lactase, or maltase. Proteins are broken down by pepsin, peptidase, and hydrochloric acid. Lipids are broken down by lipases. The breakdown of these macromolecules provides energy for cellular activities and the components that build new molecules.

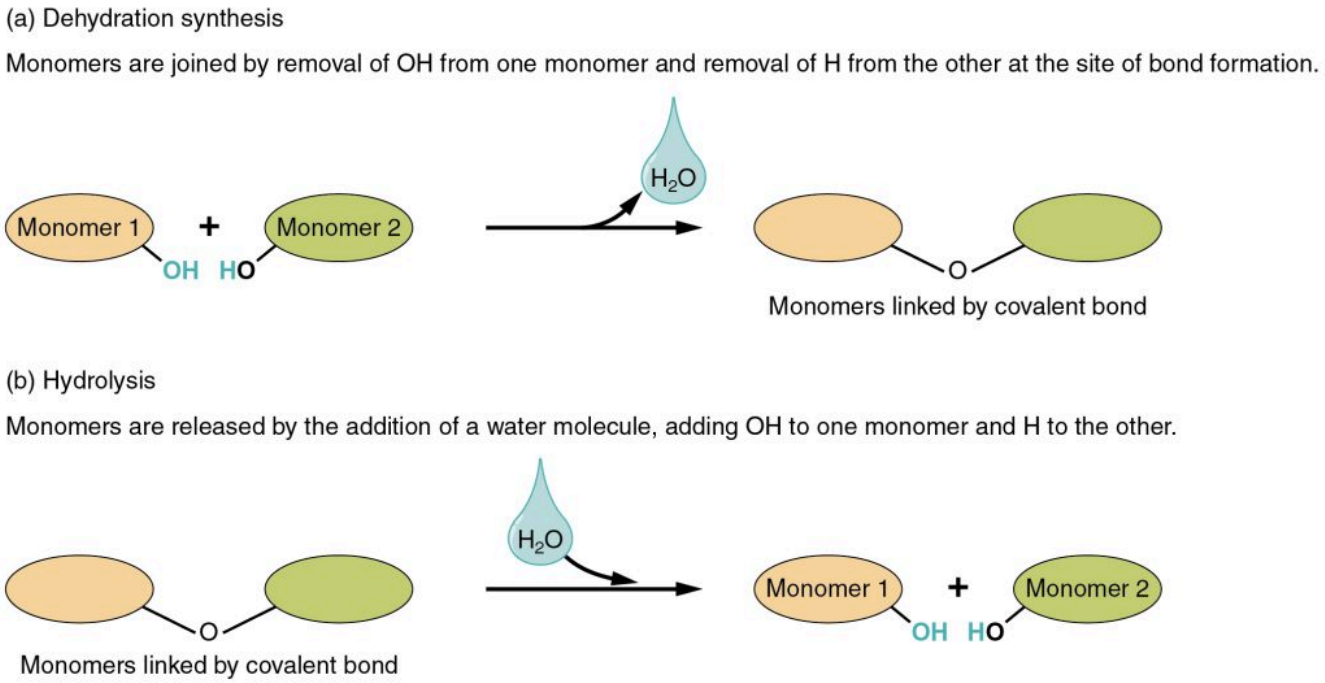


Figure 3.1.5 Dehydration Synthesis and Hydrolysis. Image by OpenStax, CC BY 4.0

Image Description

a. Dehydration Synthesis

Monomers are joined by the removal of OH from one monomer and the removal of H from the other at the site of bond formation. Water is removed, and monomers are linked by a covalent bond.

b. Hydrolysis

Monomers are released by the addition of a water molecule, adding OH to one monomer and H to the other, resulting in monomers linked by a covalent bond into two monomers.

Exercise 3.1.1

Text Description
Drag the words into the correct boxes

Carbohydrates, lipids, proteins, and nucleic acids are classes of _____. These molecules are _____, which means they contain carbon. Subunits of these molecules are called _____ and are connected together by strong _____ bonds.
Answer options:

- monomers
- organic
- biological macromolecules
- covalent

Answers:
Carbohydrates, lipids, proteins, and nucleic acids are classes of ***biological macromolecules***. These molecules are ***organic***, which means they contain carbon. Subunits of these molecules are called ***monomers*** and are connected together by strong ***covalent*** bonds.

3.2 CARBOHYDRATES

Carbohydrates are macromolecules with which most consumers are somewhat familiar. To lose weight, some individuals adhere to "low-carb" diets. Athletes, in contrast, often "carb-load" before important competitions to ensure that they have sufficient energy to compete at a high level. Carbohydrates are, in fact, an essential part of our diet; grains, fruits, and vegetables are all natural sources of carbohydrates. Carbohydrates provide energy to the body, particularly through glucose, a simple sugar. Carbohydrates also have other important functions in humans, animals, and plants.

Carbohydrates can be represented by the formula $(CH_2O)_n$, where n is the number of carbon atoms in the molecule. In other words, the carbon to hydrogen to oxygen ratio is 1:2:1 in carbohydrate molecules. Carbohydrates are classified into three subtypes: monosaccharides, disaccharides, and polysaccharides.

Monosaccharides

Monosaccharides (mono- = "one"; sacchar- = "sweet") are simple sugars, the most common of which is glucose. In monosaccharides, carbon atoms usually range from three to six. Most monosaccharide names end with the suffix -ose. Monosaccharides may exist as linear chains or ring-shaped molecules; in aqueous solutions, they are usually found in the ring form.

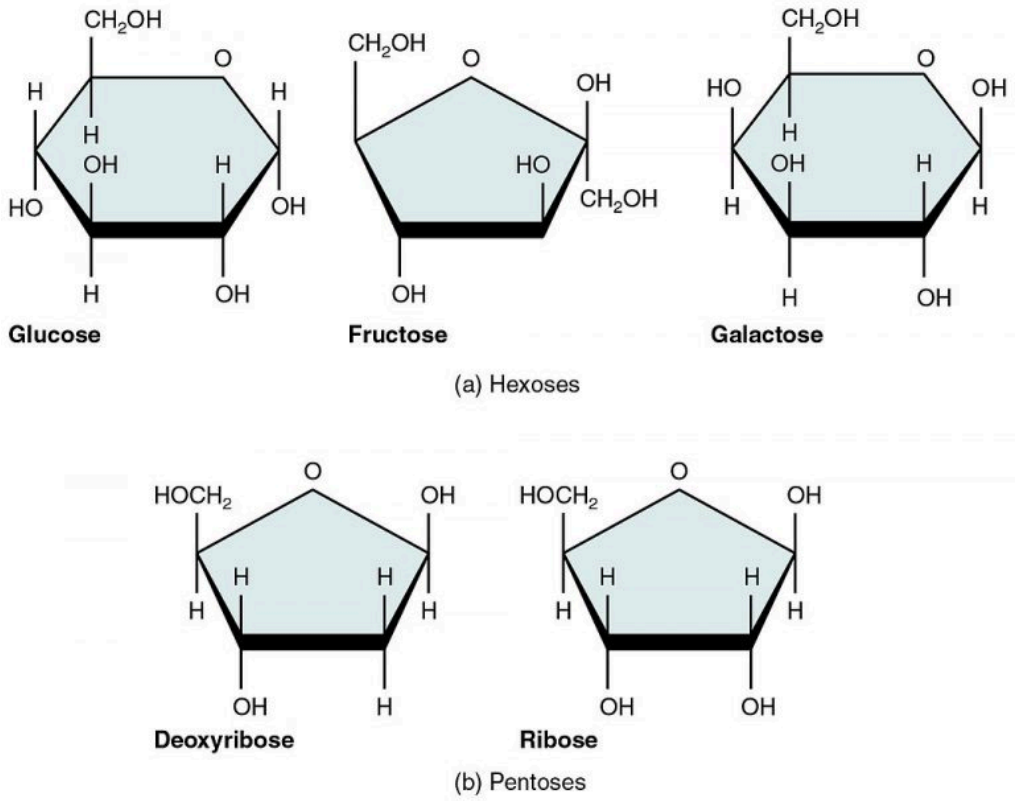


Figure 3.2.1 Five important monosaccharides. Image by OpenStax, CC BY 3.0

The chemical formula for glucose is $C_6H_{12}O_6$. In most living species, glucose is an important source of energy. During cellular respiration, energy is released from glucose, which is used to help make adenosine triphosphate (ATP). Plants synthesize glucose using carbon dioxide and water through photosynthesis, and the glucose, in turn, is used for the plant's energy requirements. The excess synthesized glucose is often stored as starch that is broken down by other organisms that feed on plants. Galactose (part of lactose or milk sugar) and fructose (found in fruit) are other common monosaccharides. Although glucose, galactose, and fructose all have the same chemical formula ($C_6H_{12}O_6$), they differ structurally and chemically (known as **isomers**) because of differing arrangements of atoms in the carbon chain.

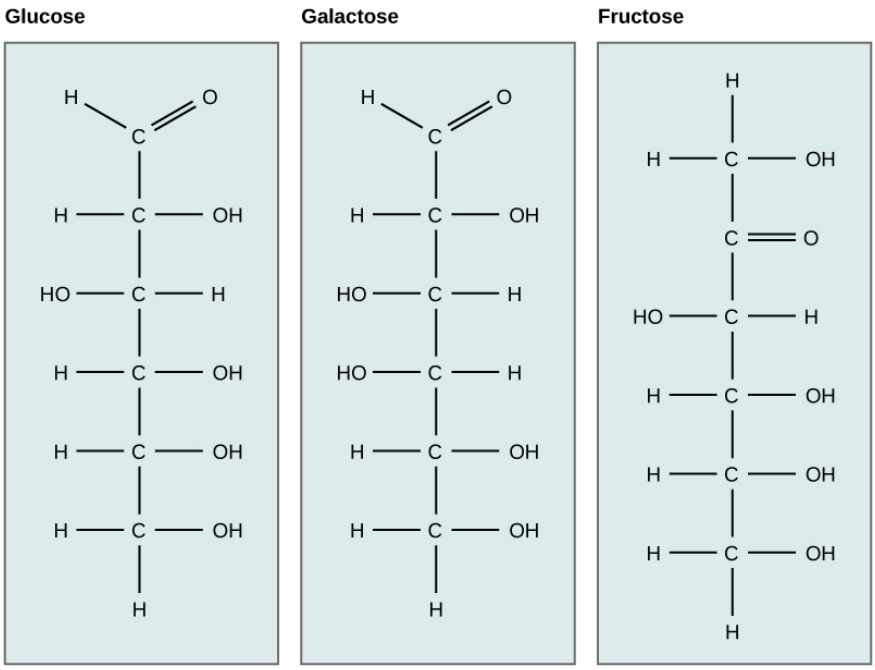


Figure 3.2.2 Glucose, galactose, and fructose are monosaccharides.
Image by OpenStax, CC BY 3.0

Disaccharides

Disaccharides (di- = "two") form when two monosaccharides undergo a dehydration reaction. During this process, the hydroxyl group (–OH) of one monosaccharide combines with a hydrogen atom of another monosaccharide, releasing a molecule of water (H_2O) and forming a covalent bond between atoms in the two sugar molecules.

Lactose is a disaccharide consisting of the monomers glucose and galactose. It is found naturally in milk. Maltose, or malt sugar, is a disaccharide formed from a dehydration reaction between two glucose molecules. The most common disaccharide is sucrose, or table sugar, which is composed of the monomers glucose and fructose.

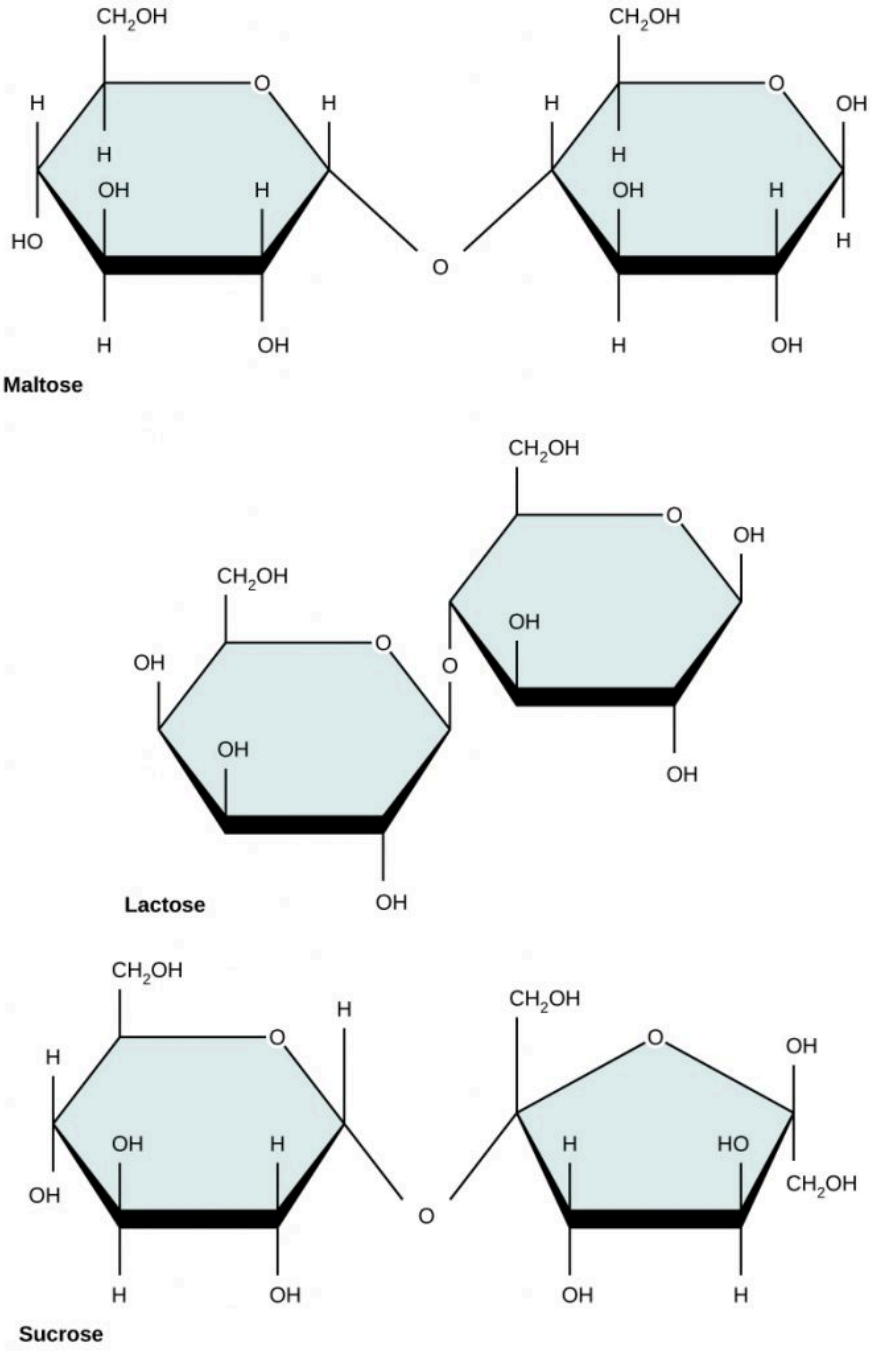


Figure 3.2.3 Common disaccharides include maltose (grain sugar), lactose (milk sugar), and sucrose (table sugar). Image by OpenStax, CC BY 4.0

Polysaccharides

Some carbohydrates consist of hundreds — or even thousands! — of monosaccharides bonded together in long chains. These carbohydrates are called **polysaccharides** ("many saccharides"). Polysaccharides are also referred to as complex carbohydrates. Complex carbohydrates that are found in living things include starch,

glycogen, cellulose, and chitin. Each type of complex carbohydrate has different functions in living organisms, but they generally either store energy or make up certain structures in living things.

Starch

Figure 3.2.4 Potatoes store glucose in the form of starch. Image by Jean Beaufort, CC0 1.0

Starch is a complex carbohydrate that is made by plants to store energy. For example, the potatoes pictured in Figure 3.2.4 are packed full of starches that consist mainly of repeating units of glucose and other simple sugars. The leaves of potato plants make sugars by photosynthesis, which are carried to underground tubers, where they are stored as starch. When we eat starchy foods such as potatoes, the starches are broken down by our digestive system into sugars, which provide our cells with energy. Starches are easily and quickly digested with the help of digestive enzymes such as amylase found in the saliva. If you chew a starchy saltine cracker for several minutes, you may start to taste the sugars released as the starch is digested.

Glycogen

Animals do not store energy as starch. Instead, animals store extra energy as the complex carbohydrate glycogen. Glycogen is a polysaccharide of glucose. In humans, glycogen is made and stored primarily in the cells of the liver and muscles. When energy is needed, the glycogen is broken down to glucose for cell use. Muscle glycogen is converted to glucose for use by muscle cells, and liver glycogen is converted to glucose for use throughout the rest of the body. Glycogen forms an energy reserve that can be quickly mobilized to meet a sudden need for glucose, but one that is less compact than the energy reserves of lipids, which are the primary form of energy storage in animals.

Glycogen plays a critical part in the homeostasis of glucose levels in the blood. When blood glucose levels rise too high, excess glucose can be stored in the liver by converting it to glycogen. When glucose levels in the blood fall too low, glycogen in the liver can be broken down into glucose and released into the blood.

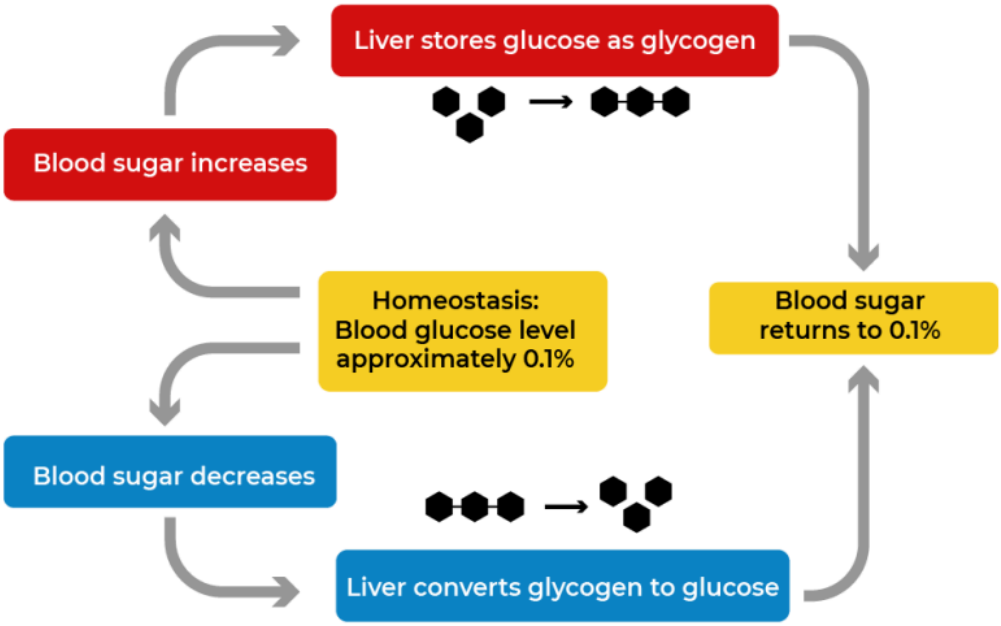


Figure 3.2.5 Glycogen in your liver can either collect glucose from your bloodstream to lower blood sugar or release glucose into the bloodstream to increase blood sugar. Image by Christine Miller [christinelmiller], CC0 1.0

Cellulose

Cellulose is a polysaccharide with a linear chain of several hundred to many thousands of linked glucose units. Cellulose is an important structural component of plants and many algae cell walls. Human uses of cellulose include the production of cardboard and paper, which consist primarily of cellulose from wood and cotton. The cotton fibres pictured are about 90 percent cellulose.

Figure 3.2.6 Cotton fibres represent the purest natural form of cellulose . Image by David Nance, Public Domain

Certain animals, including termites and ruminants such as cows, can digest cellulose with the help of microorganisms that live in their gut. Humans cannot digest cellulose, but it nonetheless plays an important role in our diet. It acts as a water-attracting bulking agent for feces in the digestive tract and is often referred to as "dietary fibre." In simpler terms, it helps you poop.

Figure 3.2.7 Chitin is an important structural component in fungal cell walls and the exoskeletons of insects. Image by Benjamin Balázs, Unsplash License

Chitin

Chitin is a long-chain polymer of a derivative of glucose. It is found in many living things. For example, it is a component of the cell walls of fungi, the exoskeletons of arthropods, such as crustaceans and insects, and the beaks and internal shells of animals, such as squids and octopuses. The structure of chitin is similar to that of cellulose.

The Right Molecule for the Job

Starch, glycogen, cellulose, and chitin are all made from the monomer glucose. So, how are they all so different? Their difference in structure and function is related to how they are linked together. Starch is linked in long chains with a small amount of branching; glycogen is linked in many branches, and chitin and cellulose form long single chains that pack together tightly. These variations of linking the same monomer, glucose, create a different way the molecule can be used. As shown in Figure 3.2.8, starch and glycogen have many exposed "ends" of their chains. These are areas where a glucose molecule can easily be removed for use as energy, whereas cellulose does not. For this reason, glycogen and starch are well-suited for energy storage in organisms, while cellulose is not. Conversely, cellulose packs many monomers together in a very strong mesh — this is why it is a great option for building strong cell walls.

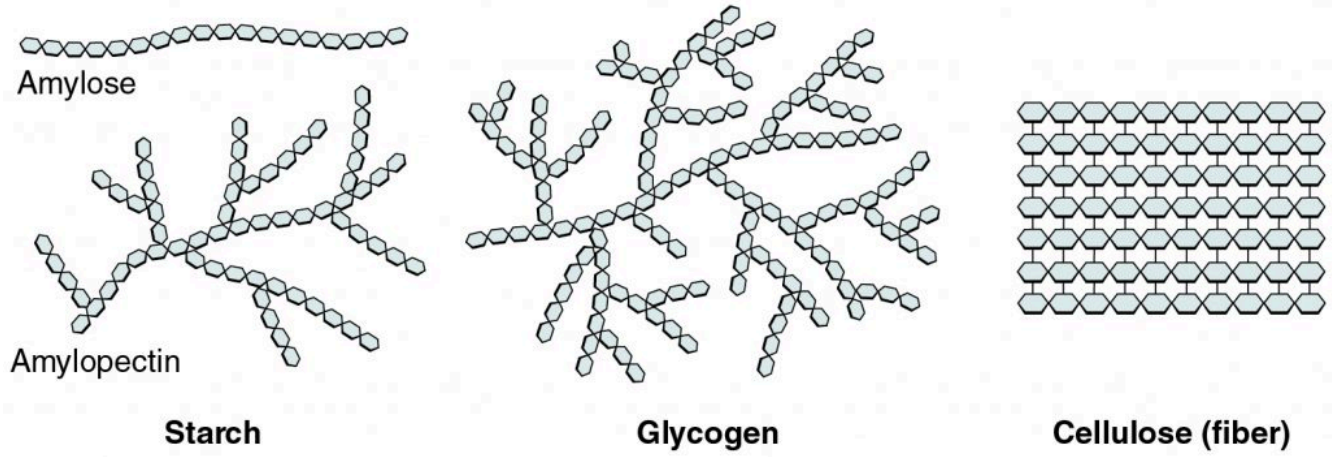


Figure 3.2.8 Starch, glycogen, and cellulose are all made of many linked glucose monomers. The shape and bonding of these monomers affect the function of the molecule. Image by OpenStax College, CC BY 3.0

Exercise 3.2.1

Text Description
Drag the words into the correct boxes

1. _____ is a major component in the cell walls of fungi and the exoskeletons of insects.
2. _____ is the storage form of glucose used by plants.
3. _____ is the storage form of glucose used by animals.
4. _____ is a major component in the cell walls of plants.

Possible answers:

- Starch
- Chitin
- Cellulose
- Glycogen

Answers:

1. ***Chitin*** is a major component in the cell walls of fungi and the exoskeletons of insects.
2. ***Starch*** is the storage form of glucose used by plants.
3. ***Glycogen*** is the storage form of glucose used by animals.
4. ***Cellulose*** is a major component in the cell walls of plants.

3.3 LIPIDS

Lipids include a diverse group of compounds that are united by a common feature. Lipids are hydrophobic ("water-fearing") or insoluble in water because they are nonpolar molecules. This is because they are hydrocarbons that include only nonpolar carbon-carbon or carbon-hydrogen bonds. Lipids perform many different functions in a cell. Cells store energy for long-term use in the form of lipids called 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 water-repelling nature. Lipids are also the building blocks of many hormones and are an important constituent of the plasma membrane. Lipids include fats, phospholipids, and steroids.

Figure 3.3.1 Hydrophobic lipids in the fur of aquatic mammals, such as this river otter, protect them from the elements. Image by Ken Bosma, CC BY 4.0

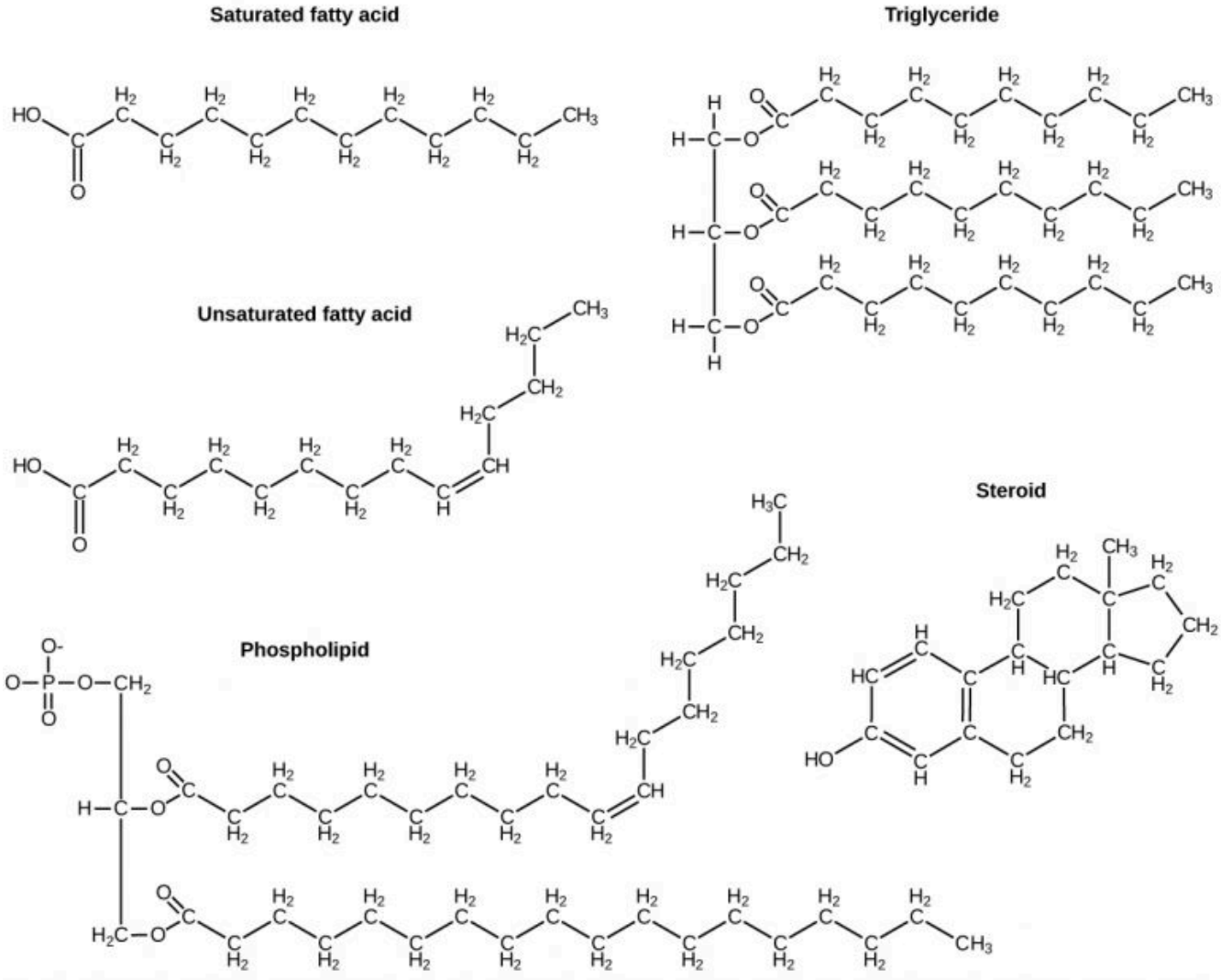


Figure 3.3.2 Lipids include fats, such as triglycerides, which comprise fatty acids and glycerol, phospholipids, and steroids. Image by OpenStax, CC BY 4.0

Fats

A fat molecule, such as a **triglyceride**, consists of two main components—glycerol and fatty acids. Glycerol is an organic compound with three carbon atoms, five hydrogen atoms, and three hydroxyl (–OH) groups. Fatty acids have a long chain of hydrocarbons to which an acidic carboxyl group is attached, hence the name "fatty acid." The number of carbons in the fatty acid may range from 4 to 36; the most common are those containing 12–18 carbons. In a fat molecule, a fatty acid is attached to each of the three oxygen atoms in the –OH groups of the glycerol molecule with a covalent bond.

During this covalent bond formation, three water molecules are released. The three fatty acids in the fat may be similar or dissimilar. These fats are also called triglycerides because they have three fatty acids.

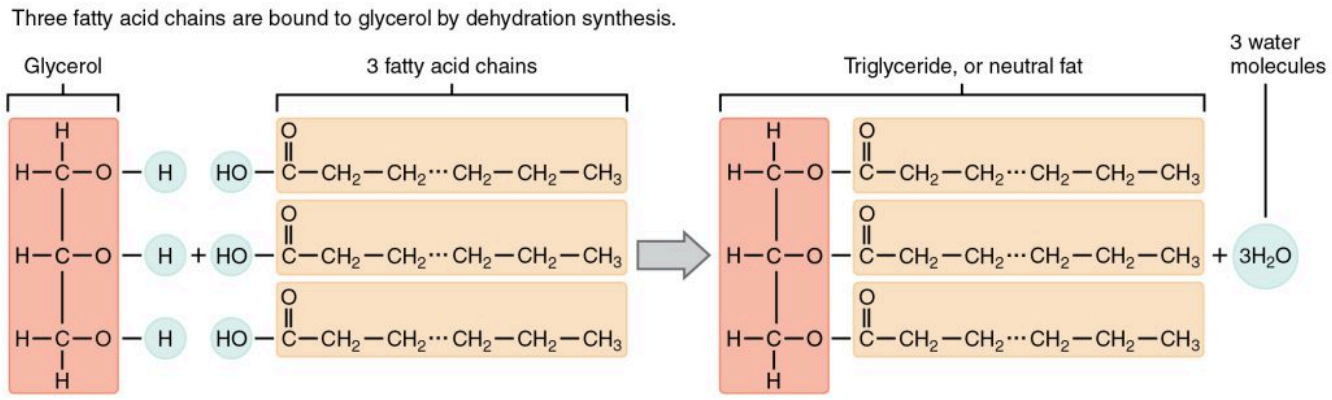


Figure 3.3.3 Triglycerides are composed of glycerol attached to three fatty acids via dehydration synthesis. Notice that glycerol gives up a hydrogen atom, and the carboxyl groups on the fatty acids each give up a hydroxyl group. Image by OpenStax, CC BY 4.0

Fatty acids may be saturated or unsaturated. In a fatty acid chain, the fatty acid is saturated if there are only single bonds between neighbouring carbons in the hydrocarbon chain. **Saturated fatty acids** are saturated with hydrogen; in other words, the number of hydrogen atoms attached to the carbon skeleton is maximized.

When the hydrocarbon chain contains a double bond, the fatty acid is an **unsaturated fatty acid**.

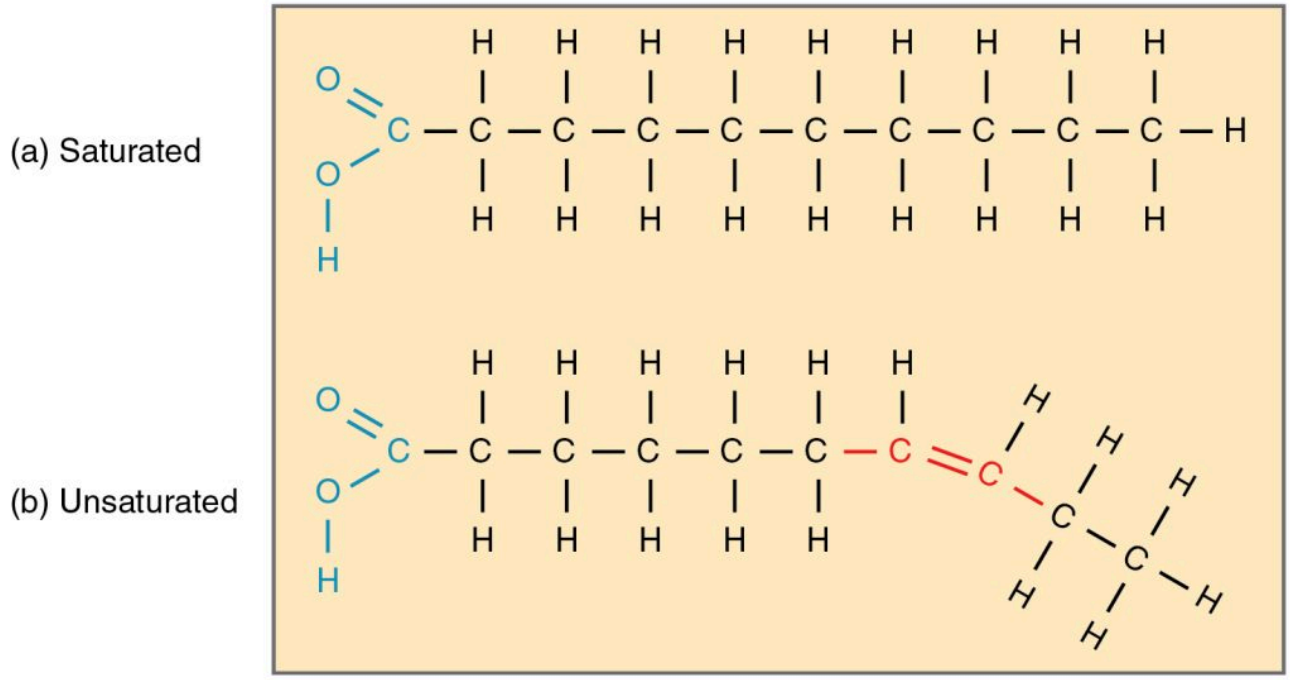


Figure 3.3.4 Fatty Acid Shapes: A fatty acid's saturation level affects its shape. (a) Saturated fatty acid chains are straight. (b) Unsaturated fatty acid chains are kinked. Image by OpenStax, CC BY 4.0

Most unsaturated fats are liquid at room temperature and are called **oils**. If there is one double bond in the

molecule, it is known as a monounsaturated fat (e.g., olive oil), and if there is more than one double bond, it is known as a polyunsaturated fat (e.g., canola oil).

Saturated fats tend to get packed tightly and are solid at room temperature. Examples of saturated fats are animal fats with stearic acid and palmitic acid contained in meat and fat with butyric acid contained in butter. Mammals store fats in specialized cells called adipocytes, where fat globules occupy most of the cell. In plants, fat or oil is stored in seeds and used as an energy source during embryonic development.

Oils are usually of plant origin and contain unsaturated fatty acids. The double bond causes a bend or a "kink" that prevents the fatty acids from packing tightly, keeping them liquid at room temperature. Olive oil, corn oil, canola oil, and cod liver oil are examples of unsaturated fats. Unsaturated fats help to improve blood cholesterol levels, whereas saturated fats contribute to plaque formation in the arteries, which increases the risk of a heart attack.

Like carbohydrates, fats have received a lot of bad publicity. It is true that eating an excess of fried foods and other "fatty" foods leads to weight gain. However, fats do have important functions. Fats serve as long-term energy storage. They also provide insulation for the body and protect vital organs. Therefore, "healthy" unsaturated fats in moderate amounts should be consumed on a regular basis.

Phospholipids

Phospholipids are a major component of the cell membranes of all living things. Each phospholipid molecule has a "tail" consisting of two long fatty acids and a "head" consisting of a phosphate group and glycerol molecule (see Figure 3.3.5). The phosphate group is a small, negatively charged molecule, causing it to be hydrophilic or attracted to water. The fatty acid tail of the phospholipid is hydrophobic or repelled by water. These properties allow phospholipids to form a two-layered cell membrane called a bilayer.

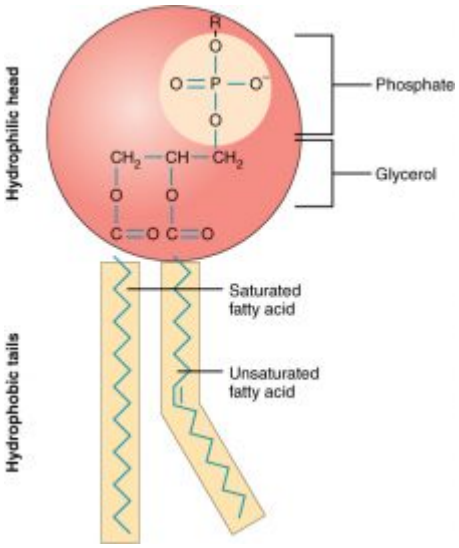


Figure 3.3.5 A phospholipid has a hydrophilic head and a hydrophobic tail. Image by OpenStax, CC BY 4.0

As shown in Figure 3.3.6, a phospholipid bilayer forms when many phospholipid molecules line up tail to tail, forming an inner and outer surface of hydrophilic heads. The hydrophilic heads point toward the cell's watery extracellular space and the watery inside space (lumen). The hydrophobic fatty acids are nestled in the inner space of the bilayer.

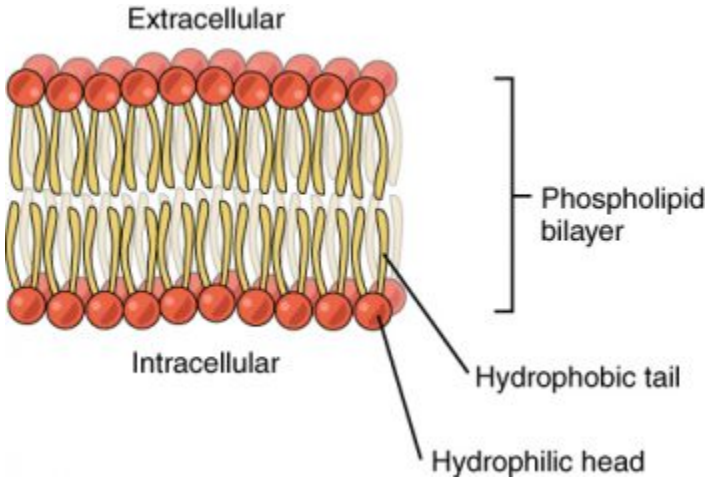


Figure 3.3.6 Cell membranes consist of a double layer of phospholipid molecules. Image by OpenStax, CC BY 4.0

Steroids

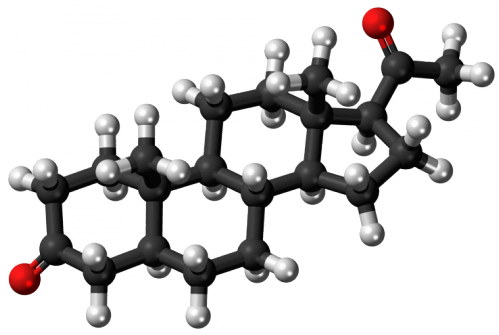
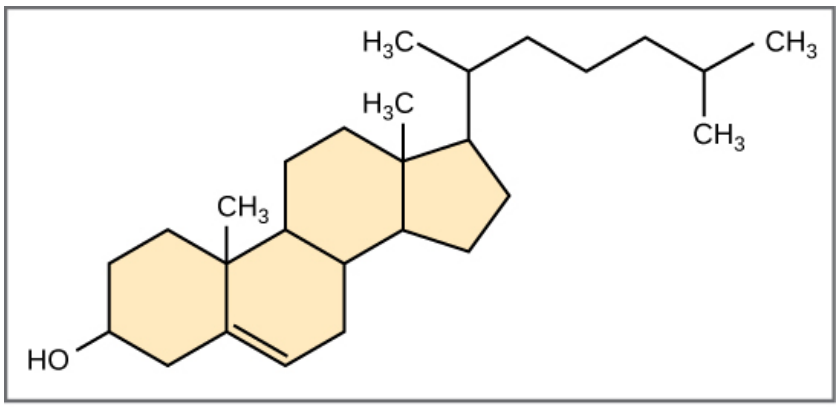
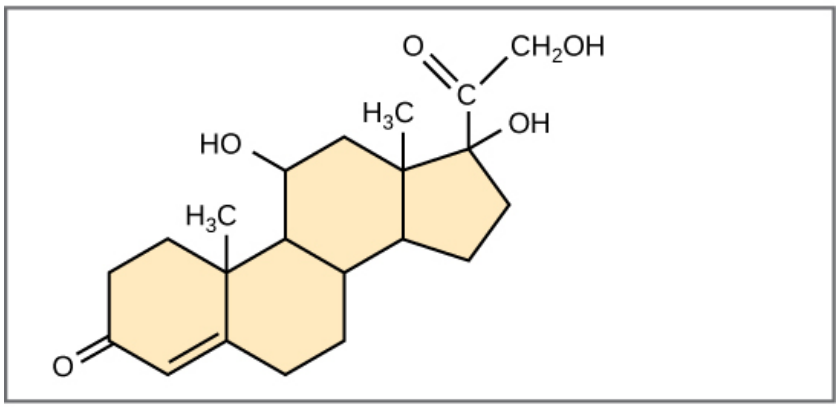


Figure 3.3.7 Progesterone is an example of a steroid. Image by Jynto, CC0 BY 1.0

Steroids are lipids with a ring structure. Each steroid has a core of four fused carbon rings (pictured in Figure 3.5.7). Steroids vary by the other components attached to this four-ring core. Hundreds of steroids are found in plants, animals, and fungi, but most steroids have one of just two principal biological functions. Some steroids (such as cholesterol) are important components of cell membranes, while many other steroids are hormones, which are messenger molecules. In humans, steroid hormones include cortisone — a fight-or-flight hormone — and the sex hormones estrogen, progesterone, and testosterone.



Cholesterol



Cortisol

Figure 3.3.8 Four fused hydrocarbon rings comprise steroids such as cholesterol and cortisol. Image by OpenStax, CC BY 4.0

Exercise 3.3.1

Text Description

1. Which of the following is a triglyceride?

a. Both fats and oils
b. None of the above
c. Oils
d. Fats

2. Oils are the storage form of lipids found in plants. (True/False?)

3. Which type of lipid functions as chemical messenger molecules?

a. Steroids
b. Fats
c. Oils
d. Phospholipids

4. Which two lipids are found in the cell membrane?

a. Fats and cholesterol
b. Cholesterol and phospholipids
c. Fats and phospholipids
d. Cholesterol and oils

Answers:

1. a. Both fats and oils
2. True
3. a. Steroids
4. b. Cholesterol and phospholipids

3.4 PROTEINS

Proteins are one of the most abundant organic molecules in living systems and have the most diverse range of functions of all macromolecules. Each cell in a living system may contain thousands of different proteins, each with a unique function. Their structures, like their functions, vary greatly. However, they are all polymers of amino acids arranged in a linear sequence and connected by covalent bonds.

Amino acids are the monomers that make up proteins (Figure 3.4.1). Each amino acid has the same fundamental structure, which consists of a central carbon atom bonded to an amino group (NH_2), a carboxyl group (COOH), and a hydrogen atom. Every amino acid also has another atom or group of atoms bonded to the central atom, known as the side chain or R group. There are 20 common amino acids commonly found in proteins, each with a different R group that determines its chemical nature (whether it is acidic, basic, polar, or nonpolar).

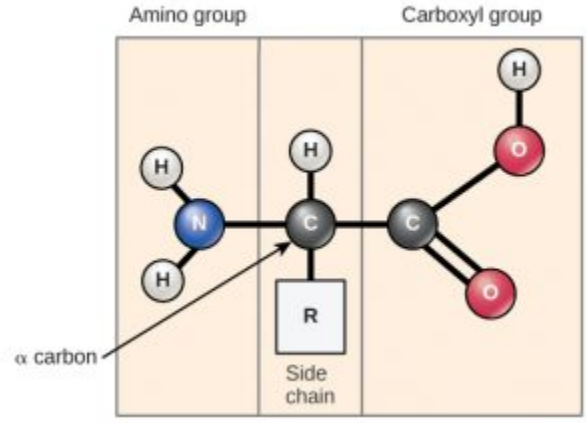


Figure 3.4.1 General structure of amino acids.
Image by OpenStax, CC-BY 4.0

The sequence and number of amino acids ultimately determine a protein's shape, size, and function. Each amino acid is attached to another amino acid by a covalent bond, a peptide bond formed by a dehydration reaction. The carboxyl group of one amino acid and the amino group of a second amino acid combine, releasing a water molecule. The resulting bond is the **peptide bond**.

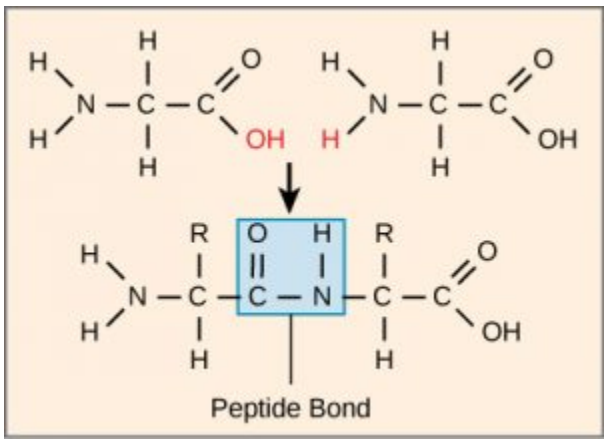


Figure 3.4.2 Peptide bond formation is a dehydration synthesis reaction. The carboxyl group of one amino acid is linked to the amino group of the incoming amino acid. In the process, a molecule of water is released. Image by OpenStax, CC-BY 4.0

The products formed by such a linkage are called **polypeptides**. While the terms polypeptide and protein are sometimes used interchangeably, a polypeptide is technically a polymer of amino acids. In contrast, the term protein is used for a polypeptide that has folded into a distinct shape and has a specific function.

Protein Function

The functions of proteins can be very diverse because the function depends on the protein's shape. The order of the amino acids determines the shape of a protein. Proteins are often hundreds of amino acids long and can have very complex shapes because there are so many possible orders for the 20 amino acids.

Type	Examples	Functions
Enzymes	Digestive enzymes (amylase, lipase)	Help catalyze chemical reactions
Transport	Hemoglobin	Carry substances throughout the body
Structural	Hair (keratin), ligaments (collagen)	Construct and provide support for different structures
Hormones	Insulin, adrenaline	Coordinate the activity of different body systems
Defence	Antibodies, immunoglobulins	Protect the body from foreign pathogens
Contractile	Actin, myosin	Allow muscle contraction
Storage	Legume storage proteins, egg white (albumin)	Provide nourishment in the early development of the embryo and the seedling

Protein Structure

The shape of a protein is critical to its function. To understand how the protein gets its final shape or conformation, we need to understand the four levels of protein structure: **primary, secondary, tertiary, and quaternary**.

Primary

Primary structure is the unique sequence and number of amino acids in a polypeptide chain. The unique sequence for every protein is ultimately determined by the gene that encodes the protein. Any change in the gene sequence may lead to a different amino acid being added to the polypeptide chain, causing a change in protein structure and function.

A hemoglobin molecule is made up of four chains, each with about 150 amino acids, totalling around 600 amino acids. Sickle cell anemia is a genetic disorder that results in a change in just one of those 600 amino acids. That one change causes the normally biconcave, or disc-shaped, red blood cells to assume a crescent or "sickle" shape, which clogs arteries. This can lead to a variety of serious health problems, such as breathlessness, dizziness, headaches, and abdominal pain, and dramatically decrease life expectancy in the affected individuals.

Secondary

Secondary structure refers to the localized folding patterns resulting from interactions between the non-R group portions of amino acids. The alpha (α)-helix and beta (β)-pleated sheet structures are the most common. Both structures are held in shape by hydrogen bonds.

Tertiary

Tertiary structure is the unique three-dimensional structure of a polypeptide. This structure is primarily caused by chemical interactions between various R groups. There may be ionic bonds or hydrogen bonds formed between R groups on different amino acids. Additionally, during protein folding, the hydrophobic R groups of nonpolar amino acids are positioned inside the protein, while the hydrophilic R groups are outside.

Quaternary

Quaternary structure involves the arrangement of multiple polypeptide chains which interact to create a functional protein. For example, as mentioned, hemoglobin is a combination of four polypeptide chains.

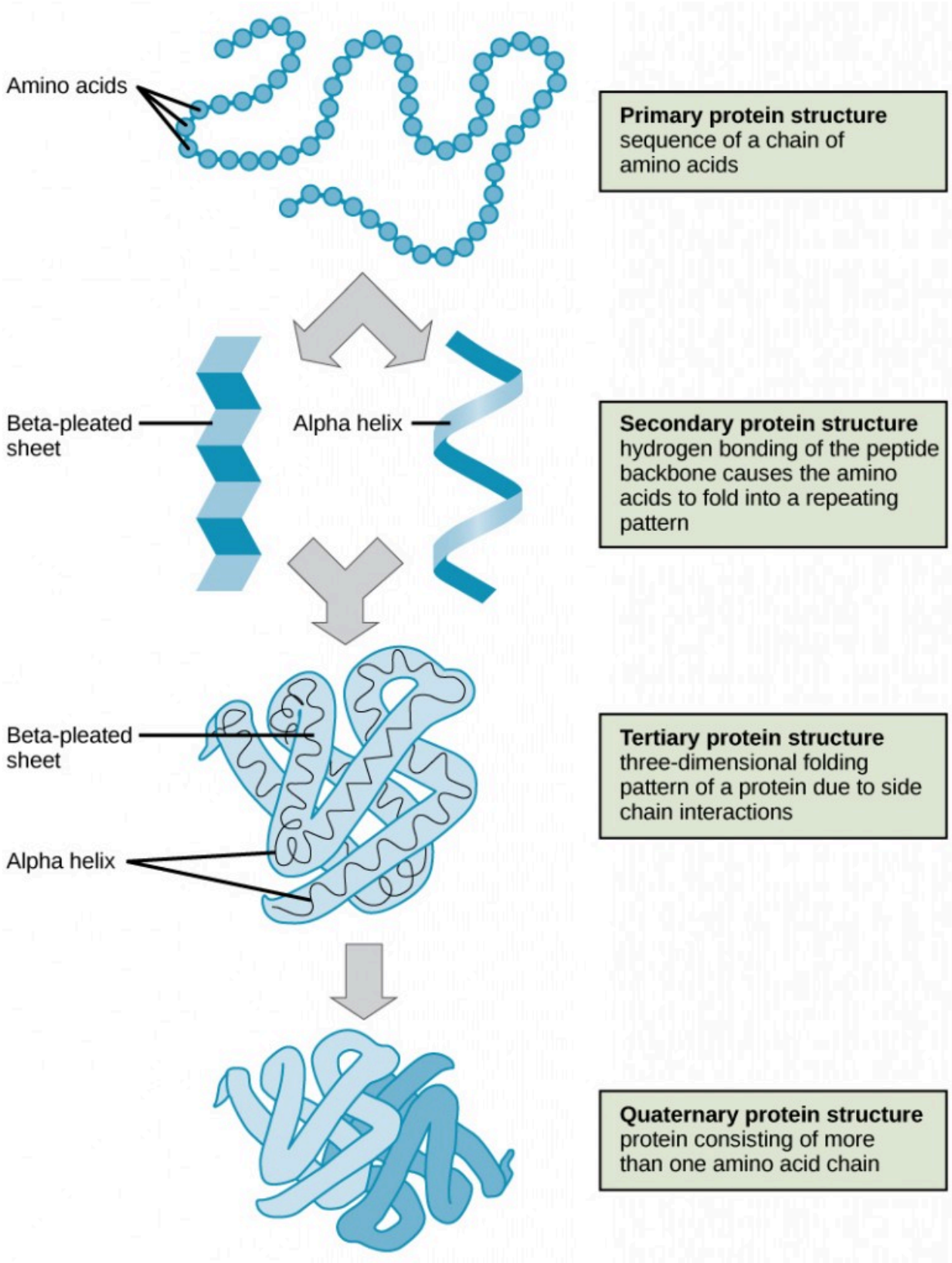


Figure 3.4.3 The four levels of protein structure. Image by OpenStax, CC BY 4.0 licence. A modification of work by the National Human Genome Research Institute, Public Domain.

Each protein has a unique sequence and shape held together by chemical interactions. When exposed to changes in temperature, pH, or chemicals, the protein may lose its shape, a process known as **denaturation**. Denaturation is often reversible because the primary structure remains intact, so the protein can regain its function once the denaturing agent is removed. Sometimes denaturation is irreversible, resulting in a loss of function. An example of protein denaturation is seen when an egg is fried or boiled; the albumin protein in the liquid egg white denatures in the heat, changing from clear to opaque white.

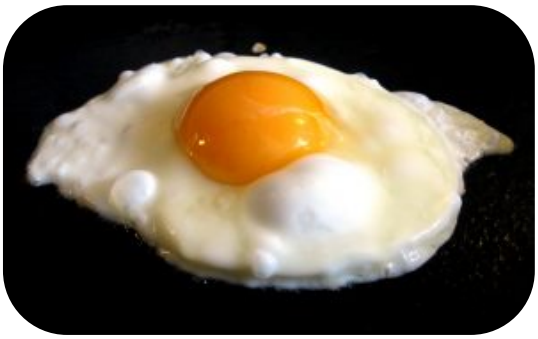


Figure 3.4.4 Albumin in the white denatures and then reconnects in an abnormal fashion. Image by Matthew Murdock, Public Domain

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3.5 NUCLEIC ACIDS

Nucleic acids are key macromolecules in the continuity of life. They carry the genetic blueprint of a cell and have instructions for the functioning of the cell.

Nucleic acids are made up of monomers known as **nucleotides**. The nucleotides combine with each other to form a polynucleotide, DNA, or RNA. Each nucleotide comprises a nitrogenous base, a pentose (five-carbon) sugar, and a phosphate group.

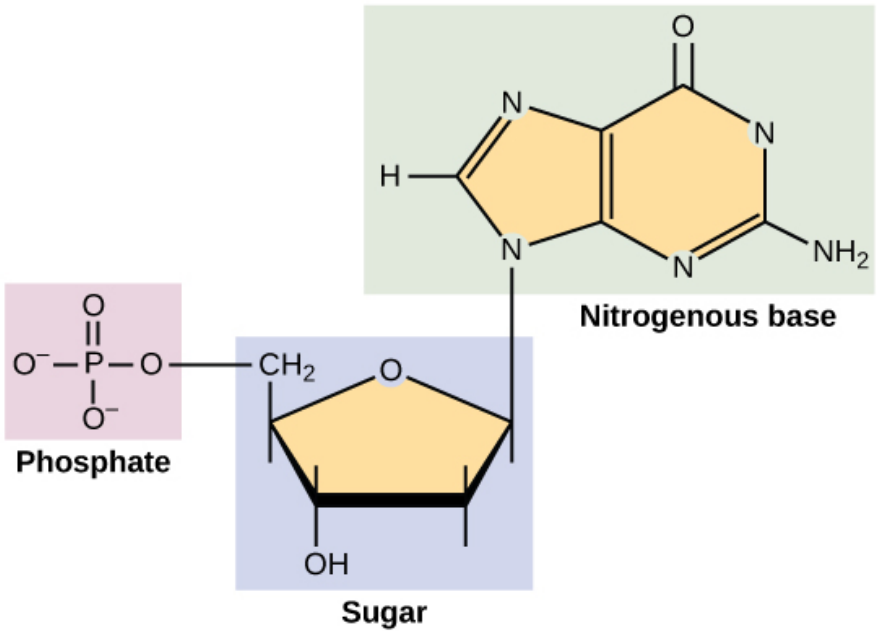

Figure 3.5.1 Components of a nucleotide. Image by OpenStax, CC BY 4.0

Types of Nucleic Acids

The two main types of nucleic acids are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). The specific sugars are slightly different for the DNA and RNA molecules, and the names of these molecules come from the sugars in their nucleotides; DNA contains the sugar *deoxyribose*, while RNA contains the sugar *ribose*.

DNA

DNA is the genetic material found in all living organisms, ranging from single-celled bacteria to multicellular

mammals.

Each nucleotide in DNA contains one of four possible nitrogenous bases: adenine (A), guanine (G), cytosine (C), and thymine (T). The order of the bases determines the information that the DNA carries. This is because the order of the bases in a DNA gene determines how amino acids will be assembled to form a protein.

DNA has a double-helical structure. It is composed of two strands, or polymers, of nucleotides. The strands are formed with covalent bonds between phosphate and sugar groups of adjacent nucleotides, and the nucleotides are bonded together using dehydration synthesis. The strands are bonded to each other at their bases with hydrogen bonds, and the strands coil about each other along their length, hence "double helix", which means a double spiral.

The alternating sugar and phosphate groups lie on the outside of each strand, forming the backbone of the DNA. The nitrogenous bases are stacked in the interior, like the steps of a staircase, and these bases pair; the pairs are bound to each other by hydrogen bonds. The bases pair so that the distance between the backbones of the two strands is the same all along the molecule. The rule is that nucleotide A pairs with nucleotide T and G with C; see section 9.1 for more details.

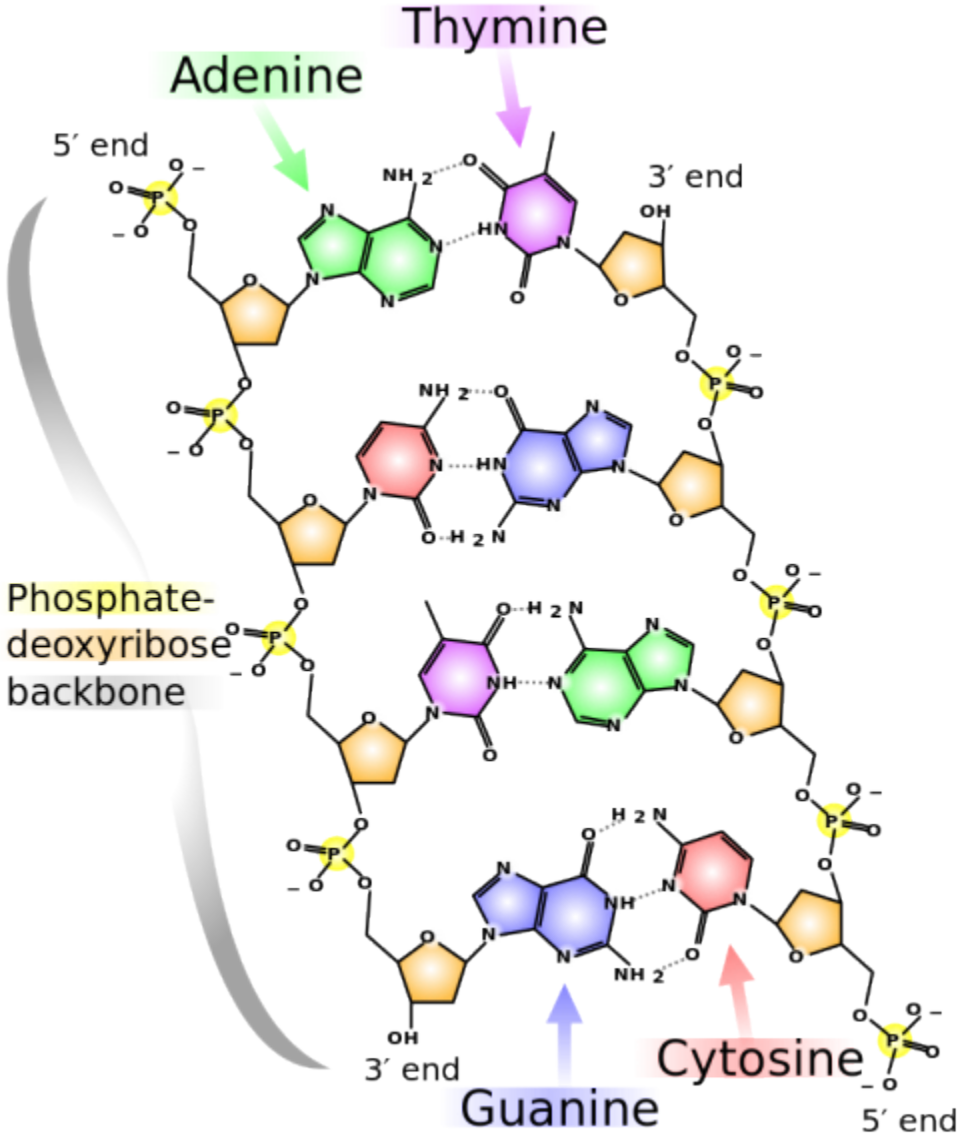

Figure 3.5.2 Chemical structure of DNA. Image by Madeleine Price Ball, CC BY-SA 3.0.

RNA

The other type of nucleic acid, RNA, is mostly involved in protein synthesis. The DNA molecules never leave the nucleus; instead, they use an RNA intermediary to communicate with the rest of the cell. This intermediary is the messenger RNA (mRNA). Other types of RNA—like rRNA, tRNA, and microRNA—are involved in protein synthesis and its regulation. RNA nucleotides also contain one of four possible bases: adenine, guanine, cytosine, and uracil (U) rather than thymine.

Feature	DNA	RNA
Function	Carries genetic information	Involved in protein synthesis
Location	Remains in the nucleus	Leaves the nucleus
Structure	DNA is a double-stranded "ladder": sugar-phosphate backbone with base rungs.	Usually single-stranded
Sugar	Deoxyribose	Ribose
Nitrogenous Bases	Adenine, Guanine, Cytosine, Thymine	Adenine, Guanine, Cytosine, Uracil

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CHAPTER 3 SUMMARY

Key Takeaways

- **Biological Macromolecules and Their Importance:** Living organisms require four major classes of biological macromolecules—carbohydrates, lipids, proteins, and nucleic acids—essential for structure, energy storage, genetic information, and cellular functions. These macromolecules are built from smaller subunits called monomers linked by covalent bonds.
- **Carbon's Role in Molecular Diversity:** Life is carbon-based due to carbon's ability to form four covalent bonds, allowing for complex structures such as chains, rings, and branches. This versatility enables the diversity of biological molecules found in living organisms.
- **Formation and Breakdown of Macromolecules:** Macromolecules are formed through dehydration synthesis, where monomers bond and release water. They are broken down via hydrolysis, which adds water to split polymers into monomers. Enzymes catalyze both processes, facilitating digestion and cellular metabolism.
- **Structure and Function of Carbohydrates, Lipids, and Proteins:**
    - Carbohydrates provide energy (e.g., glucose, starch, glycogen) and structural support (e.g., cellulose, chitin).
    - Lipids (fats, phospholipids, steroids) store energy, form cell membranes, and act as hormones.
    - Proteins are polymers of amino acids with diverse functions, including enzymatic activity, transport, structural support, and immune defence.
- **Nucleic Acids as Genetic Blueprints:** DNA and RNA are nucleic acids composed of nucleotides. DNA stores genetic information in a double-helix structure with base pairs (A-T, G-C), while RNA, typically single-stranded, plays a key role in protein synthesis, using uracil (U) instead of thymine (T).

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into five key takeaways.

Exercises

Text Description

1. Which of the following choices is an example of a monosaccharide?

   a. All options
   b. Galactose
   c. Glucose
   d. Fructose

2. What type of molecules are cellulose and starch examples of?

   a. Lipids
   b. Monosaccharides
   c. Disaccharides
   d. Polysaccharides

3. What parts are phospholipids important components of?

   a. The double bond in hydrocarbon chains
   b. The waxy covering on leaves
   c. The plasma membrane of cells
   d. The ring structure of steroids

4. What are the monomers that make up proteins called?

   a. Nucleotides
   b. Amino acids
   c. Chaperones

d. Disaccharides

5. Functions that lipids serve in plants and/or animals include _____ and _____, and phospholipids and steroids are important components of _____.

6. Drag the words into the correct boxes

A change in _____ sequence can lead to the substitution of a different _____ for the normal one in a _____ chain that causes a change in _____ structure and function. For example, in sickle cell anemia, the _____ chain has a single _____ substitution. Because of this change, the _____ red blood cells assume a _____, which can result in serious health problems.
Possible answers:

- amino acid
- gene
- disc-shaped
- protein
- amino acid
- crescent shape
- hemoglobin β
- polypeptide

7. Amino acids are connected together in a chain by what type of bond?

a. Ionic
b. Van der Waals
c. Hydrogen
d. Covalent

8. The complex 3-D structure of this molecule is made up of a primary, secondary, tertiary, and sometimes quaternary level.

a. Carbohydrate
b. Lipid
c. Nucleic acid
d. Protein

9. There is a coating on the feathers of waterfowl such as ducks that keeps them from getting wet. What molecule would this water-repelling coating be made of?

a. Lipid
b. Nucleic acid
c. Protein
d. Carbohydrate

10. You are studying a newly discovered species and want to analyze its genetic information. What type of molecule would you analyze?

a. Lipid
b. Protein
c. Carbohydrate
d. Nucleic Acid

11. A molecule ending in "-ose" (such as glucose, dextrose, lactose) is most likely to be what type of macromolecule?

a. Protein
b. Carbohydrate
c. Nucleic acid
d. Lipid

12. Select all of the types of macromolecules that are commonly used as sources of energy.

a. Carbohydrates
b. Nucleic acids
c. Lipids
d. Proteins

13. You are analyzing a macromolecule and determine that it is made up of amino acids. What type of molecule is it?

a. Nucleic Acid
b. Protein
c. Lipid
d. Carbohydrate

14. Drag the macromolecules into the correct category. Categories: Proteins, Carbohydrates, Nucleic Acids, & Lipids.

- Enzymes, structures, transport
- Glucose
- Amino Acids
- Nucleotides
- Sugar, phosphate, and nitrogenous base
- Quick source of energy
- Long-term energy storage
- Store genetic information
- Grains, fruits, and vegetables
- Monosaccharides
- Steroid hormones
- DNA and RNA
- Very complex 3-D structure
- $(C_1H_2O_1)_n$
- Fatty acids
- Hydrophobic

15. Match macromolecule structure vs function.

Categories: Carbohydrate Structure, Carbohydrate Function, Protein Structure, Protein Function, Lipid Structure, Lipid Function, Nucleic Acid Structure, Nucleic Acid Function

Options:

- Fatty acid chains contain between 4 and 24 carbons connected in a chain.
- $(C_1H_2O_1)_n$ molecules contain carbon-carbon and carbon-hydrogen bonds
- The order of the 20 different amino acids determines the shape.
- Polysaccharides form long fibrous chains.
- Waxes are hydrophobic.
- Specific order of nucleotides is important
- Carbon-carbon and carbon-hydrogen bonds contain high amounts of energy.
- Order of nucleotides provides instructions to the cell.
- Long fibrous chains can build structures such as cell walls.
- Hydrophobic molecules repel water.
- Molecules can have many different functions depending on their shape.
- Carbon-carbon and carbon-hydrogen bonds contain high amounts of energy.

Answers:

1. a. all options

2. d. polysaccharides

3. c. the plasma membrane of cells

4. b. amino acids

5. Functions that lipids serve in plants and/or animals include ***energy storage/insulation*** and ***insulation/energy storage***, and phospholipids and steroids are important components of ***cell membranes/cell membrane/membranes/membrane***.

6. A change in ***gene*** sequence can lead to the substitution of a different ***amino acid*** for the normal one in a ***polypeptide*** chain that causes a change in ***protein*** structure and function. For example, in sickle cell anemia, the ***hemoglobin β*** chain has a single ***amino acid*** substitution. Because of this change, the ***disc-shaped*** red blood cells assume a ***crescent shape***, which can result in serious health problems.

7. d. Covalent

8. d. Protein

9. a. Lipid

10. d. Nucleic Acid

11. b. Carbohydrate

12. a. Carbohydrates; c. Lipids

13. b. Protein

14. Carbohydrates: Quick source of energy; Glucose; $(C_1H_2O_1)_n$; Grains, fruits, and vegetables; Monosaccharides

Proteins: Amino Acids; Very complex 3-D structure; Enzymes, structures, transport

Nucleic Acids: Store genetic information; DNA and RNA; Nucleotides; Sugar, phosphate, and nitrogenous base

Lipids: Fatty acids; Hydrophobic; Steroid hormones; Long-term energy storage

15. Carbohydrate Structure:

- $(C_1H_2O_1)_n$ molecules contain carbon-carbon and carbon-hydrogen bonds
- Polysaccharides form long fibrous chains.

Carbohydrate Function:

- Carbon-carbon and carbon-hydrogen bonds contain high amounts of energy.
- Long fibrous chains can build structures such as cell walls.

Protein Structure:

- The order of the 20 different amino acids determines the shape.

Protein Function:

- Molecules can have many different functions depending on their shape.

Lipid Structure:

- Fatty acid chains contain between 4 and 24 carbons connected in a chain.
- Waxes are hydrophobic.

Lipid Function:

- Hydrophobic molecules repel water.
- Carbon-carbon and carbon-hydrogen bonds contain high amounts of energy.

Nucleic Acid Structure:

- Specific order of nucleotides is important

Nucleic Acid Function:

- Order of nucleotides provides instructions to the cell.

Flashcards

Text Description

1. **Biological macromolecules**: Large, complex molecules essential to life
2. **Organic**: Molecules containing carbon; fundamental to living organisms
3. **Carbon skeleton:** chain or ring of carbon atoms that forms the backbone of an organic molecule
4. **Monomers**: Building block of larger molecules; Monomers link together to form a polymer
5. **Polymer**: A large molecule composed of repeating building blocks called monomers
6. **Dehydration synthesis:** A chemical reaction where two molecules bond by removing a water molecule
7. **Hydrolysis:** A chemical reaction where a molecule is split into two smaller molecules by the addition of a water molecule
8. **Carbohydrates**: biological macromolecule that serves as a primary energy source for living organisms; sugars
9. **Monosaccharides**: simplest form of carbohydrates, consisting of single sugar molecules; e.g. glucose, fructose, galactose
10. **Isomer:** Molecules with the same chemical formula but different structural arrangements
11. **Disaccharides**: Carbohydrates composed of two monosaccharides bonded together; e.g. sucrose, lactose
12. **Polysaccharides**: Complex carbohydrates composed of long chains of monosaccharides linked together; e.g. starch, glycogen, cellulose, chitin
13. **Chitin**: Structural polysaccharide forming the exoskeleton of insects and fungal cell walls
14. **Starch**: Energy-storage polysaccharide in plants; composed of glucose units
15. **Glycogen**: Energy-storage polysaccharide in animals; stored mainly in liver and muscle cells
16. **Cellulose**: Structural polysaccharide provides rigidity to plant cell walls; it is not digestible by humans (“dietary fibre”)
17. **Lipids:** Diverse group of hydrophobic compounds that are insoluble in water; e.g. fats, phospholipids, steroids
18. **Fats:** A type of lipid that serves as a major energy source, provides insulation, and protects vital organs
19. **Triglyceride:** composed of one glycerol molecule bonded to three fatty acid chains
20. **Saturated Fatty Acids**: Fatty acids with no double bonds between carbon atoms; solid at

room temperature (e.g. animal fats)

21. **Unsaturated Fatty Acids**: Fatty acids containing one or more double bonds; liquid at room temperature (e.g. plant oils)
22. **Oil:** Unsaturated fats; liquid at room temperature; usually of plant origin
23. **Phospholipid:** Major component of cell membranes; contains a hydrophilic "head" and two hydrophobic "tails"
24. **Steroids:** Lipids with a ring structure; important components of cell membranes (e.g. cholesterol) or are hormones (e.g. testosterone and estrogen)
25. **Proteins**: Biological macromolecules composed of amino acids; most abundant organic molecules in living organisms; have a wide range of functions
26. **Amino Acids**: Building blocks (monomers) of proteins, each containing an amino group, a carboxyl group, and a unique side chain
27. **Peptide Bond**: A covalent bond formed between two amino acids during protein synthesis
28. **Polypeptides**: Long chains of amino acids linked together by peptide bonds; Fold into specific shapes to form proteins
29. **Primary Protein Structure**: Sequence of amino acids in a protein chain
30. **Secondary Protein Structure**: Local folding of polypeptide chains into alpha-helices and beta-pleated sheets stabilized by hydrogen bonds
31. **Tertiary Protein Structure**: The overall three-dimensional shape of a polypeptide is formed by interactions among amino acid side chains
32. **Quaternary Protein Structure**: Structure formed by two or more polypeptide chains (subunits) assembling into a functional protein
33. **Denaturation**: Loss of protein structure and function due to environmental conditions like heat, pH, or chemicals
34. **Nucleic Acids**: Biological macromolecules essential for storing and transmitting genetic information; e.g. DNA and RNA; composed of long chains of nucleotides
35. **Nucleotides**: building blocks of nucleic acids (DNA and RNA); Each nucleotide consists of a nitrogenous base, a sugar molecule and a phosphate group
36. **DNA:** Deoxyribonucleic Acid; Genetic material in living organisms
37. **RNA:** Ribonucleic Acid; Molecule involved in protein synthesis; single-stranded nucleic acid essential for translating DNA instructions into proteins
38. **4 main biological macromolecules:** Carbohydrates, Lipids, Proteins, Nucleic Acids
39. **Why is carbon a versatile atom?** Contains four electrons in its outer shell so can form four covalent bonds with other atoms or molecules. Carbon atoms often link together to form a variety of carbon skeletons

40. **Groups of carbohydrates:** monosaccharides, disaccharides, polysaccharides
41. **Monomer of carbohydrates:** monosaccharide
42. **Functions of starch:** Energy storage for plants
43. **Functions of glycogen:** Energy storage for animals
44. **Functions of cellulose:** Provides structural support in plant cell walls; helps maintain cell shape and rigidity
45. **Functions of chitin:** Provides structural support in fungal cell walls; forms exoskeletons in arthropods
46. **Groups of lipids:** Fats, phospholipids, steroids
47. **Common feature of all lipids:** hydrophobic ("water-fearing"); insoluble in water because they are nonpolar molecules
48. **Functions of fats:** long-term energy storage, insulation for body and protect vital organs
49. **Functions of phospholipids:** form cell membranes
50. **Saturated fats are saturated with:** hydrogen
51. **Monomer of proteins:** amino acid
52. **Components of amino acids:** Central carbon atom bonded to an amino group (NH2), a carboxyl group (COOH), a hydrogen atom, and a variable side group (R group)
53. **Types of proteins:** Enzymes, transport, structural, hormones, defence, contractile, storage
54. **Levels of protein structure:** Primary, secondary, tertiary, quaternary
55. **Monomer of nucleic acids:** nucleotide
56. **Components of nucleotide:** Nitrogenous base, a pentose (five-carbon) sugar, and a phosphate group
57. **Types of nucleic acids:** DNA and RNA
58. **Structure of DNA:** double-helix; sugar-phosphate backbone; sugar is deoxyribose; nitrogenous bases are adenine (A), guanine (G), cytosine (C), and thymine (T)
59. **Structure of RNA:** single stranded; sugar-phosphate backbone; sugar is ribose; nitrogenous bases are adenine (A), guanine (G), cytosine (C), and uracil (U)

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms

CHAPTER 4: CELL STRUCTURE AND FUNCTION

Chapter Overview

Learning Objectives

By the end of this Chapter, you will be able to:

- Explain the diversity and specialization of cells by identifying examples such as epithelial, bone, immune, and red blood cells.
- Differentiate between types of microscopes by comparing the structure, function, advantages, and limitations of light microscopes and electron microscopes.
- Summarize the historical development of cell theory by recognizing the contributions of Hooke, Leeuwenhoek, Schwann, Schleiden, and Virchow.
- Distinguish between prokaryotic and eukaryotic cells by describing their structural differences, including the presence or absence of a nucleus and organelles.
- Analyze the structural components common to all cells (plasma membrane, cytoplasm, DNA, ribosomes).
- Evaluate how size and surface area-to-volume ratio limit cell size.

4.1 CELLS

Your body has many kinds of cells, each specialized for a specific purpose. Just as a home is made from various building materials, the human body is constructed from many cell types. For example, epithelial cells protect the body's surface, covering the organs and body cavities. Bone cells help to support and protect the body. Cells of the immune system fight invading bacteria. Red blood cells carry oxygen throughout the body. Each of these cell types plays a vital role during the body's growth, development, and day-to-day maintenance. Despite their enormous variety, however, all cells share specific fundamental characteristics.

Figure 4.1.1 Diversity of human cells – a human T cell, developing nerve cells, a natural killer cell, red blood cells including T cells (orange) and platelets (green), and white blood cells.

Microscopy

Cells vary in size. With few exceptions, individual cells are too small to be seen with the naked eye, so scientists use microscopes to study them. A **microscope** is an instrument that magnifies an object. Most images of cells are taken with a microscope. Photographs taken with microscopes are called micrographs.

Light Microscopes

Light microscopes use visible light and a series of lenses to magnify specimens. They are relatively inexpensive, easy to use, and can provide detailed images of living organisms and cells. The downside is that they can only magnify up to around 1000 times, which may sound like a lot, but is still insufficient for observing small details or structures.

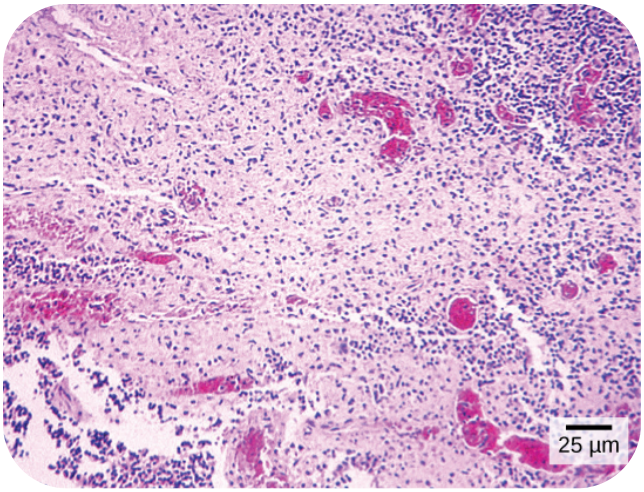


Figure 4.1.2 Salmonella bacteria viewed with a light microscope. Image by CDC, Armed Forces Institute of Pathology, Charles N. Farmer, Public Domain

Electron Microscopes

Electron microscopes use a beam of electrons instead of light to view specimens. They can magnify significantly smaller structures in much more detail than light microscopes. **Scanning electron microscopes** are used to see the details of cell surfaces. **Transmission electron microscopes** provide details of a cell's internal structures. The downside is that electron microscopes are significantly more expensive and bulkier than light microscopes, so they are less easily accessible. The preparation to view a specimen under an electron microscope will also kill it, so these microscopes cannot be used to view live organisms.

Figure 4.1.3 This scanning electron micrograph shows Salmonella bacteria (in red) invading human cells. Image modification of work by NIAID, NIH; scale-bar data from Matt Russell, CC BY-SA 4.0

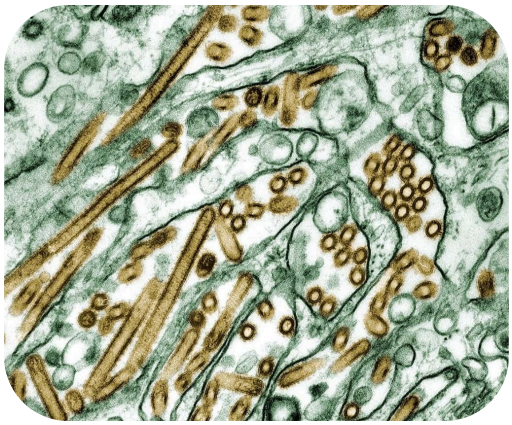


Figure 4.1.4 This transmission electron micrograph shows the inside of cells where you can see it is invaded with viruses (in brown). Image by Cynthia Goldsmith, USCDCP, CC0 1.0

Cell Theory

The first time the word cell was used to refer to these tiny units of life was in 1665 by a British scientist named Robert Hooke. Hooke was one of the earliest scientists to study living things under a microscope. The microscopes of his day were not very strong, but Hooke could still make an important discovery. When he looked at a thin slice of bark from a cork oak tree under his microscope, he was surprised to see that it was composed of many tiny units. Hooke called these units cells because they resembled cells in a monastery.

Soon after, Anton van Leeuwenhoek in Holland made other important discoveries using a microscope. Leeuwenhoek made his own microscope lenses, and he was so good at it that his microscope was more powerful than other microscopes of his day. In fact, Leeuwenhoek's microscope was almost as strong as modern light microscopes. Using his microscope, Leeuwenhoek was the first person to observe human cells and bacteria.

By the early 1800s, scientists had observed cells of many different organisms. These observations led two German scientists, Theodor Schwann and Matthias Jakob Schleiden, to propose cells as the basic building blocks of all living things. Around 1850, a German doctor named Rudolf Virchow was studying cells under a microscope when he saw them dividing and forming new cells. He realized that living cells produce new cells through division. Virchow proposed that living cells arise only from other living cells based on this realization. The ideas of all three scientists — Schwann, Schleiden, and Virchow — led to **cell theory**, which is one of the fundamental theories unifying all of biology.

Cell theory states that:

- All organisms are made of one or more cells.
- All the life functions of organisms occur within cells.
- All cells come from existing cells.

Categories of Cells

All cells share four common components:

1. A plasma membrane, an outer covering that separates the cell's interior from its surrounding environment.
2. Cytoplasm, consisting of a jelly-like region within the cell in which other cellular components are found.
3. DNA, the cell's genetic material.
4. Ribosomes, particles that synthesize proteins.

Based on whether or not they have a nucleus, there are two basic types of cells: prokaryotic cells and eukaryotic cells.

Prokaryotic Cells

Prokaryotic cells are cells without a nucleus. The DNA in prokaryotic cells is in the cytoplasm in a region called the nucleoid, rather than enclosed within a nuclear membrane. In addition, these cells are typically smaller than eukaryotic cells and contain fewer organelles. Prokaryotic cells are found in single-celled organisms, such as the bacterium represented by the model in Figure 4.3.3. Organisms with prokaryotic cells are called prokaryotes. They were the first type of organisms to evolve and are still the most common.

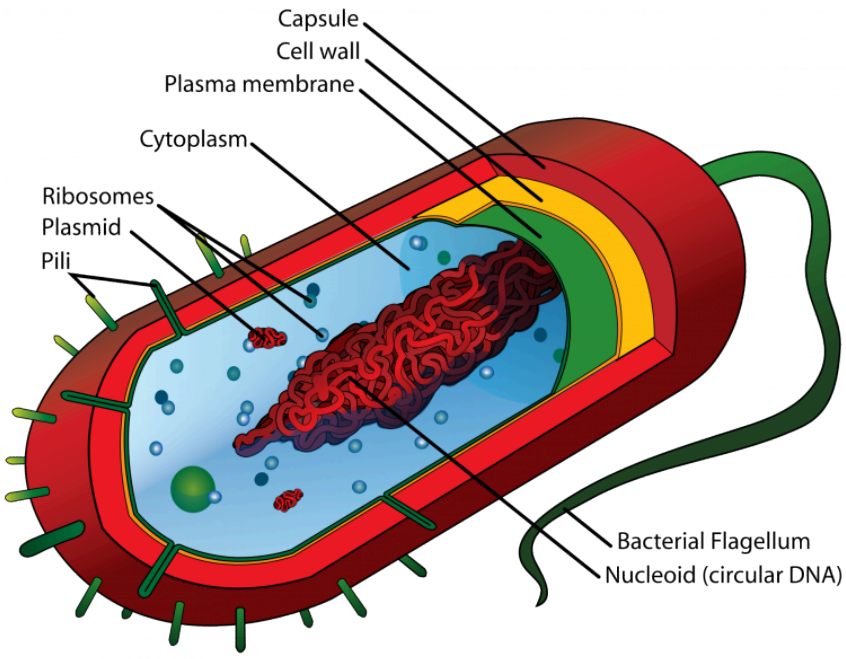
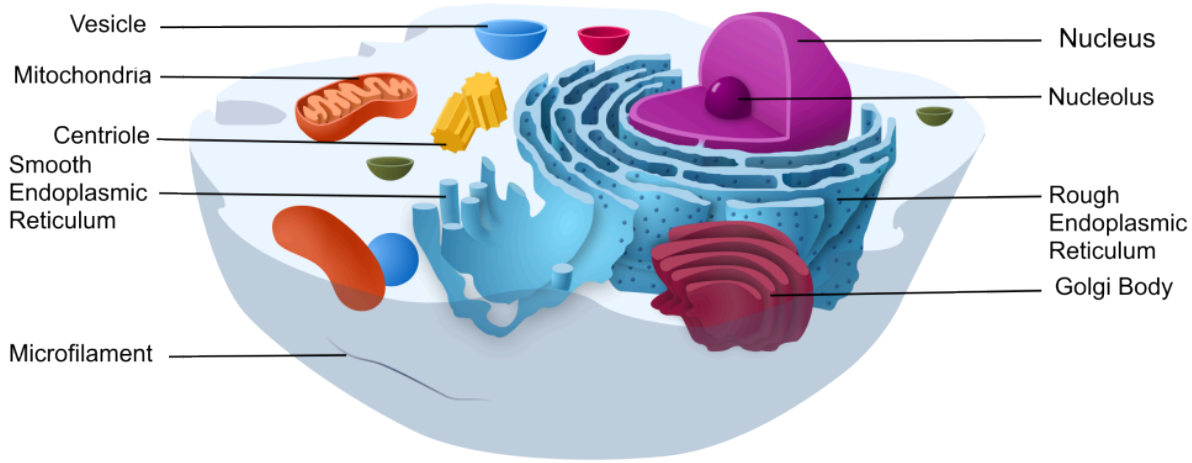


Figure 4.1.5 A prokaryotic cell. Image by Mariana Ruiz Villarreal, Public Domain

Eukaryotic Cells

Eukaryotic cells are cells that contain a nucleus. Eukaryotic cells are usually 10-100 times larger than prokaryotic cells. They are found in some single-celled and multicellular organisms. Organisms with eukaryotic cells are called eukaryotes, and they range from fungi to humans.

Besides a nucleus, eukaryotic cells also contain other organelles. An organelle is a structure within the cytoplasm that performs a specific job in the cell. Organelles called mitochondria, for example, provide energy to the cell, and organelles called vesicles store substances in the cell. Organelles allow eukaryotic cells to carry out more functions than prokaryotic cells can.



4.1.6 Eukaryotic cell. Image by Kelvin Song adapted by Christine Miller, CC0 1.0

Comparing Prokaryotic and Eukaryotic Cells

Table 4.1.1 Comparing Prokaryotic Cells and Eukaryotic Cells (Simon, E. J., Dickey, J. 2018, pg 57)

Prokaryotic Cells	Eukaryotic Cells
First evolved approximately 3.5 billion years ago	First evolved approximately 2.1 billion years ago
Found in bacteria and archaea	Found in protists, plants, fungi, and animals
Smaller, simpler	Larger, more complex
Most have cell walls; some have capsules, fimbriae, and/or flagella	Plant cells have cell walls; animal cells are surrounded by an extracellular matrix
Have a plasma membrane	Have a plasma membrane
No membrane-bound organelles	Membrane-bound organelles (for example, nucleus, ER)
Have a nucleoid region containing a single circular chromosome	Have a nucleus containing one or more linear chromosomes
Have ribosomes	Have ribosomes

Cell Size

Most organisms, even very large ones, have microscopic cells. Why don't cells get bigger instead of remaining tiny and multiplying? Why aren't you one giant cell rolling around school? What limits cell size?

Once you know how a cell functions, the answers to these questions are clear. To carry out life processes, a cell must be able to quickly pass substances in and out of the cell. For example, it must be able to pass nutrients and oxygen into the cell and waste products out of the cell. Anything that enters or leaves a cell must cross the plasma membrane. The size of a cell is limited by its need to pass substances across the plasma membrane. Small cells maintain a proper surface area-to-volume ratio. Large cells have too much volume compared to surface area so are not as efficient at transport processes.

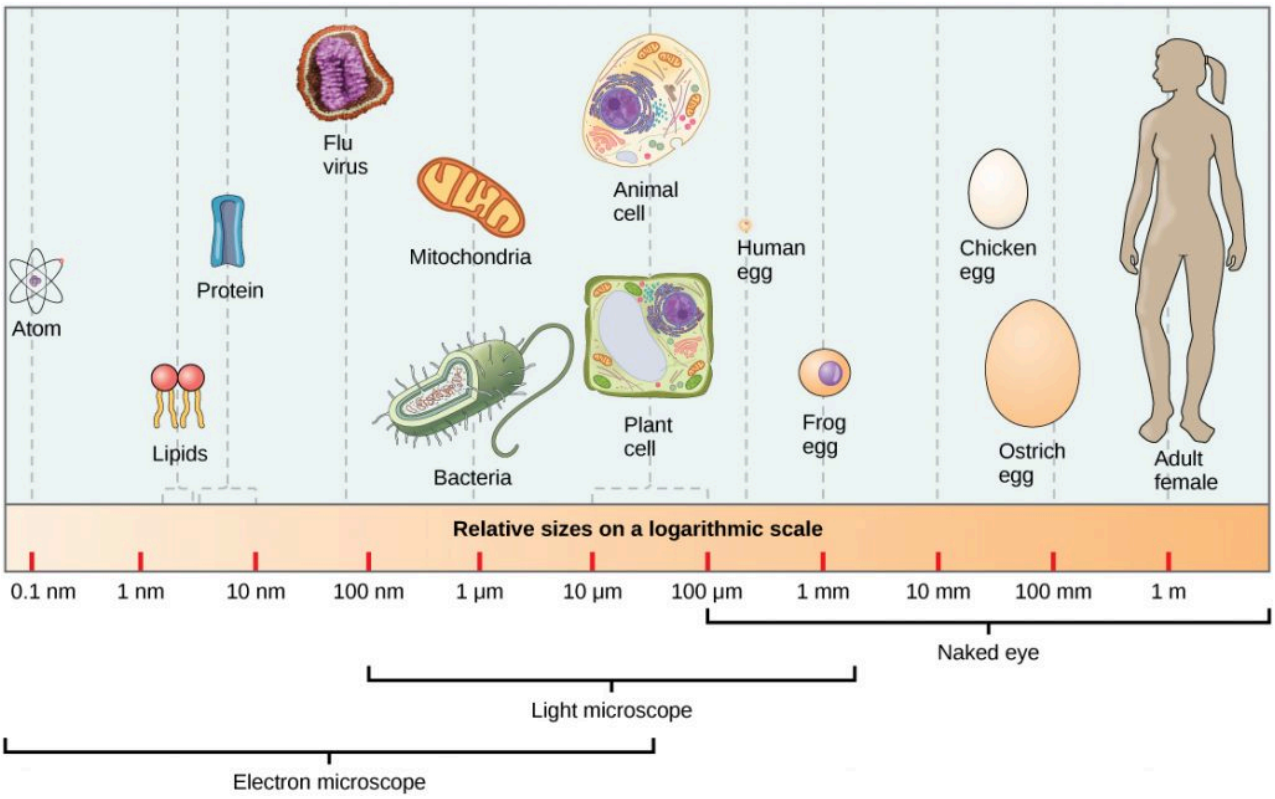


Figure 4.1.7 Relative sizes of different kinds of cells and cellular components. An adult human is shown for comparison. Image by Charles Molnar & Jane Gair, OpenStax, CC BY SA 4.0

Image Description

The following can be seen in an electron microscope and/or light microscope: Atom, Lipids, Protein, Flu virus, Mitochondria, Bacteria. Animal Cell. The following can be seen by the naked eye: Plant Cell, Human egg, Frog egg, Chicken egg, Ostrich egg, Adult human.

4.2 CELL STRUCTURE AND MOVEMENT

A common theme in biology is that structure and function are related. It is said that "form follows function," meaning that you can often deduce the function of a structure by looking at its form. You can see this at all levels in nature. For example, fish have streamlined bodies that allow them to move quickly through water. As we explore the different components of cells, you will see that this relationship between structure and function is also evident at the cellular level.

Let's start by looking at the components that provide cells with their basic structure.

Plasma Membrane

All cells have a plasma membrane. The **plasma membrane** is a structure that forms a barrier between the cytoplasm inside the cell and the environment outside the cell. Without the plasma membrane, there would be no cells. Although it is very thin and flexible, the plasma membrane protects and supports the cell by controlling everything that enters and leaves it. It allows only certain substances to pass through while keeping others in or out. You need to know its basic structure to understand how the plasma membrane controls what passes into or out of the cell.

The plasma membrane is composed mainly of phospholipids, consisting of fatty acids and alcohol. The phospholipids in the plasma membrane are arranged in two layers, called a **phospholipid bilayer**. The simplified diagram in Figure 4.2.1 shows that each individual phospholipid molecule has a phosphate group head (in red) and two fatty acid tails (in yellow). The head "loves" water (hydrophilic), and the tails "hate" water (hydrophobic). The water-hating tails are on the interior of the membrane. In contrast, the water-loving heads point outward toward the cytoplasm (**intracellular**) or the fluid surrounding the cell (**extracellular**).

Hydrophobic molecules can easily pass through the plasma membrane if they are small enough because they are water-hating, like the interior of the membrane. Hydrophilic molecules, conversely, cannot pass through the plasma membrane — at least not without help — because they are water-loving like the membrane's exterior.

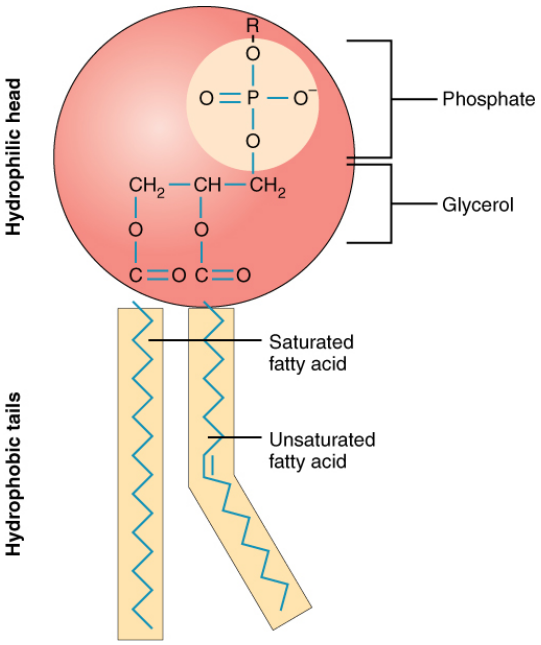


Figure 4.2.1 Phospholipid molecule. Image by OpenStax, CC BY 4.0

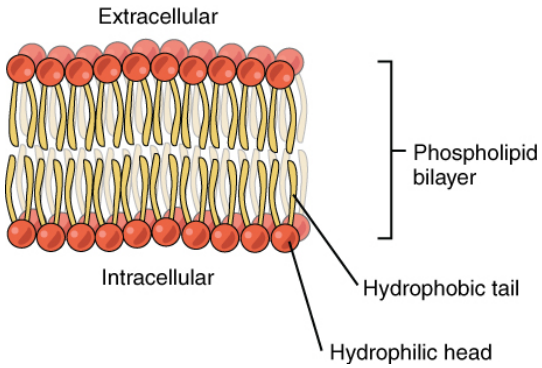


Figure 4.2.2 Phospholipid bilayer, Image by OpenStax, CC BY 4.0

The plasma membrane also contains other molecules, primarily other lipids and proteins. For example, molecules of the steroid lipid cholesterol (shown in yellow in Figure 4.2.3) help the plasma membrane keep its shape. Proteins in the plasma membrane (shown blue) include transport proteins that assist other substances in crossing the cell membrane, receptors that allow the cell to respond to chemical signals in its environment, and cell-identity markers that indicate what type of cell it is and whether it belongs in the body. The plasma membrane is often described as a **fluid mosaic**, meaning the components can flow and change position while maintaining the basic integrity of the membrane.

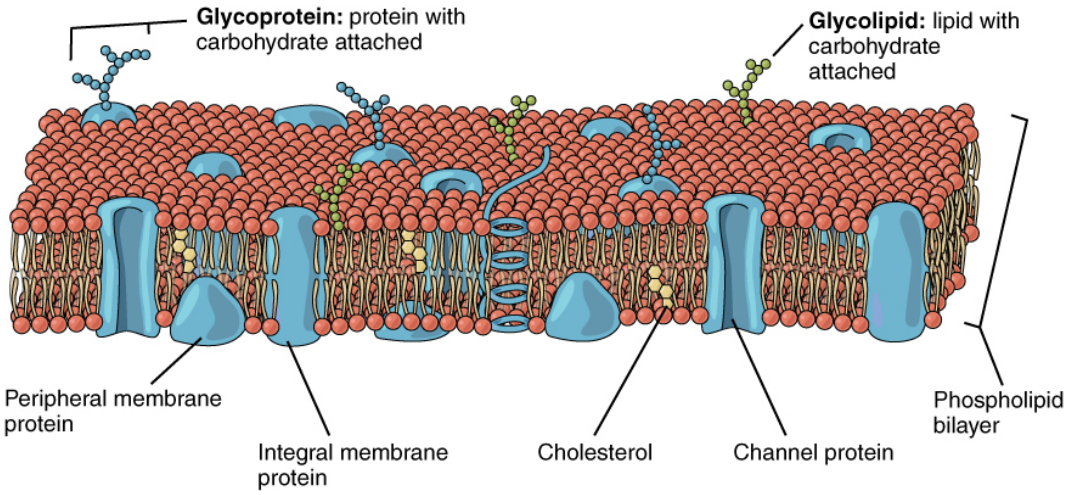


Figure 4.2.3 The plasma membrane contains many molecules embedded in the lipid bilayer. Image by OpenStax, CC BY 4.0

The Cytoplasm

The **cytoplasm** is a thick, usually colourless solution that fills each cell and is enclosed by the cell membrane. Cytoplasm presses against the cell membrane, filling out the cell and giving it its shape. In eukaryotic cells, the cytoplasm includes all of the material inside the cell and outside the nucleus. All of the organelles in eukaryotic cells (such as the endoplasmic reticulum and mitochondria) are located in the cytoplasm. The cytoplasm helps to keep them in place. It is also the site of most metabolic activities in the cell, allowing materials to pass easily throughout the cell.

The portion of the cytoplasm surrounding organelles is called cytosol. **Cytosol** is the liquid part of the cytoplasm. It comprises about 80 percent water and contains dissolved salts, fatty acids, sugars, amino acids, and proteins (such as enzymes). These dissolved substances are needed to keep the cell alive and carry out metabolic processes. Enzymes dissolved in the cytosol, for example, break down larger molecules into smaller products that cell organelles can use. Waste products are also dissolved in the cytosol before they are taken in by vacuoles or expelled from the cell.

The Cytoskeleton

Although cytoplasm may appear to have no form or structure, it is actually highly organized. A framework of protein scaffolds called the **cytoskeleton** provides the cytoplasm and the cell with structure. The cytoskeleton consists of thread-like microfilaments, intermediate filaments, and microtubules crisscrossing the cytoplasm. As its name suggests, the cytoskeleton is like a cellular "skeleton." It helps the cell maintain its shape and also helps to hold cell structures (like organelles) in place within the cytoplasm.

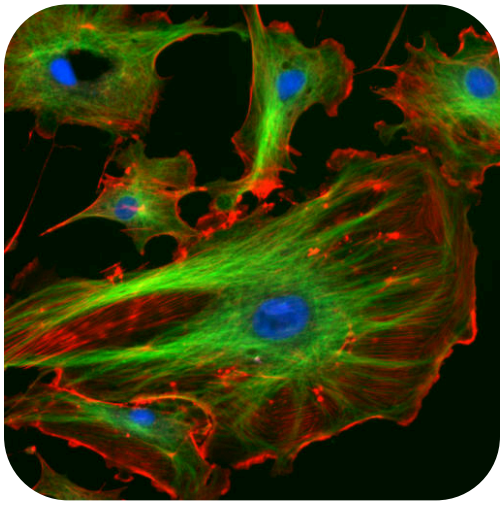


Figure 4.2.4 Filaments (green) and tubules (red) of the cytoskeleton. Image by National Institute of Health (NIH), Public Domain

Extracellular Matrix

The extracellular matrix is a network of proteins and polysaccharides outside most animal cells. The extracellular matrix holds the cells together to form a tissue and allows the cells within the tissue to communicate with each other.

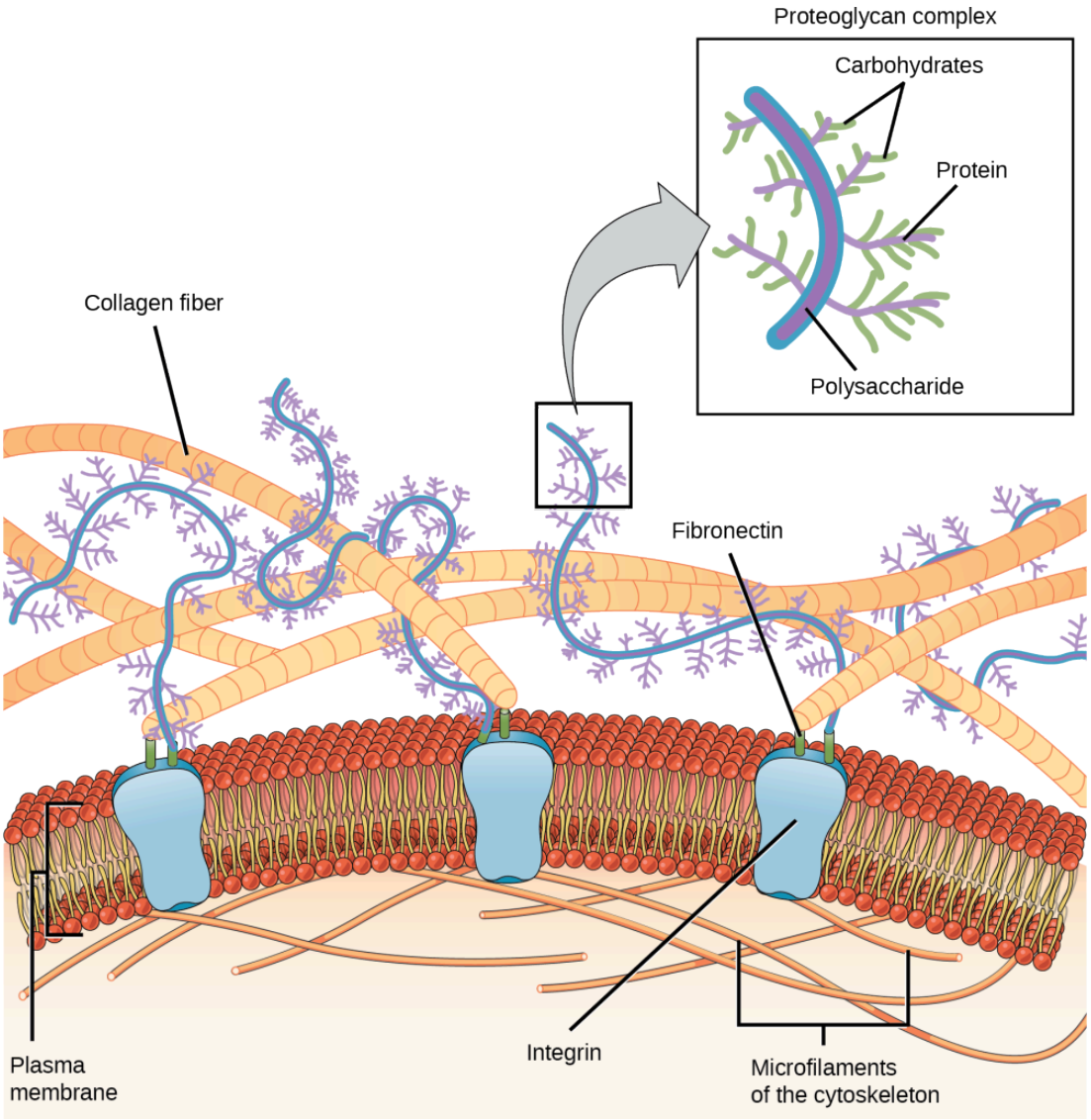


Figure 4.2.5 The extracellular matrix. Image by OpenStax, CC BY 4.0

Cell Movement

Some cells need to be able to move to explore their surroundings, carry out vital functions, and react to external signals. The cytoskeleton plays a crucial role in facilitating movement by providing structural support and enabling changes in cell shape. Some cells, including some prokaryotes and some animal cells, have additional structures to help with movement.

Flagella (singular flagellum) are long, whip-like structures that extend from the plasma membrane and help in movement. Sperm, Euglena, and many bacteria rely on flagella to help them swim through liquids. If present, a cell typically only has one or a few flagella.

Cilia (singular cilium) are short, hair-like structures that help in movement. When cilia are present, they are many in number and extend along the entire plasma membrane surface. They can be used to move entire cells (such as paramecium) or move substances along the outer surface of the cell (for example, the cilia of cells lining the fallopian tubes that move the ovum toward the uterus or cilia lining the cells of the respiratory tract that sweep foreign particles and mucus toward the throat).

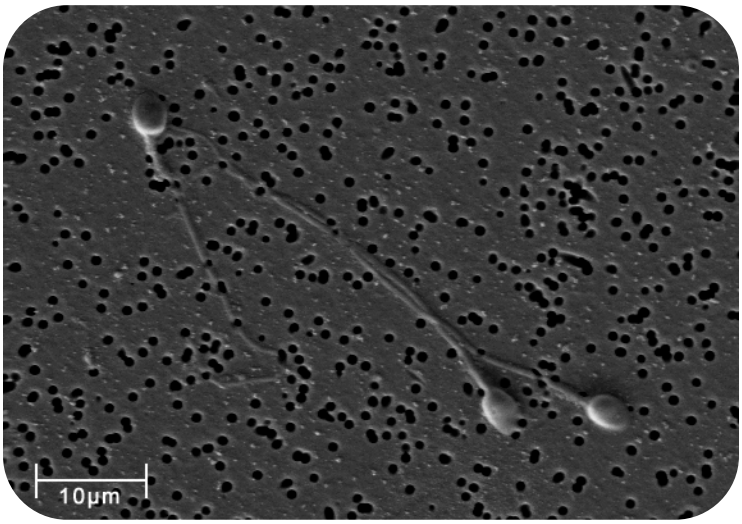


Figure 4.2.6 Human sperm with their long, whip-like flagella. Image, Public Domain

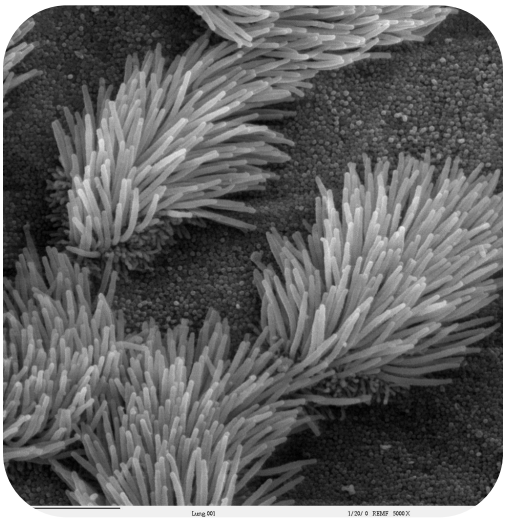


Figure 4.2.7 Brush-like cilia on lung epithelial cells. Image by Charles Daghlian, Public Domain

4.3 CELL ORGANELLES

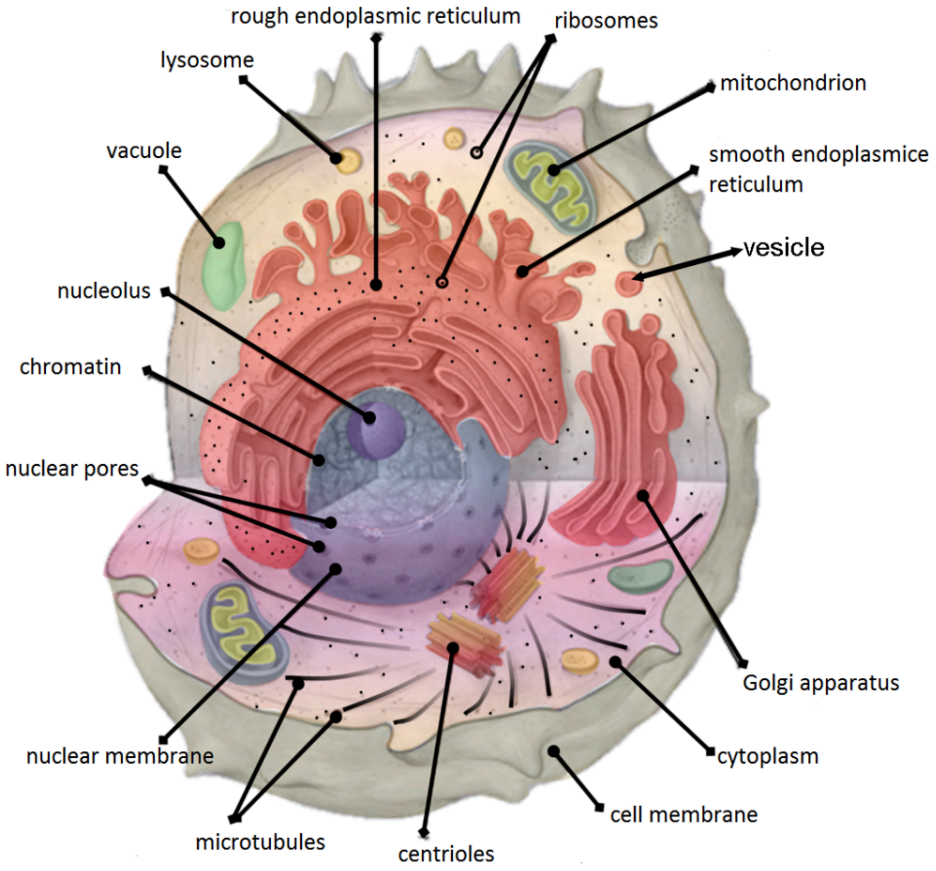


Figure 4.3.1 The cytoplasm is filled with many organelles, each doing its own specific job. Image by Koswac, CC BY 4.0

An **organelle** is a structure within the cytoplasm of a eukaryotic cell that is enclosed within a membrane and performs a specific job. Organelles are involved in many vital cell functions. Organelles in animal cells include the nucleus, mitochondria, endoplasmic reticulum, Golgi apparatus, vesicles, and vacuoles. Ribosomes are not enclosed within a membrane but are still commonly referred to as organelles in eukaryotic cells.

The Nucleus

The **nucleus** is the largest eukaryotic cell organelle and the cell's control centre. It contains most of the cell's DNA (which makes up chromosomes) and is encoded with the genetic instructions for making proteins. The function of the nucleus is to regulate gene expression, including controlling which proteins the cell makes. Most eukaryotic cells contain just a single nucleus, but some types of cells (such as red blood cells) contain no nucleus and a few other types of cells (such as muscle cells) contain multiple nuclei.

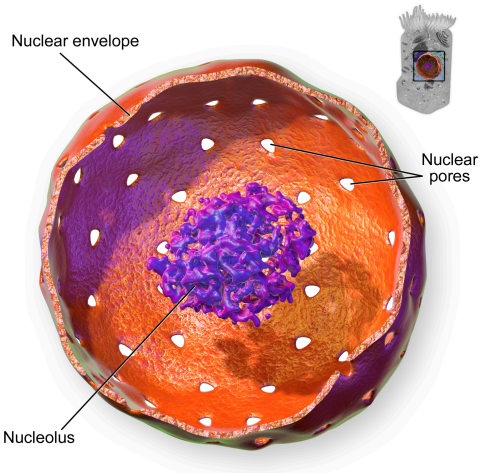


Figure 4.3.2 Closeup of a cell nucleus. Image by Blausen.com staff (2014), CC BY 3.0

As shown in the model pictured in Figure 4.3.2, the membrane enclosing the nucleus is called the **nuclear envelope**. This double membrane encloses the entire organelle and isolates its contents from the cellular cytoplasm. Tiny holes called **nuclear pores** allow large molecules to pass through the nuclear envelope with the help of special proteins. Large proteins and RNA molecules must be able to pass through the nuclear envelope so that proteins can be synthesized in the cytoplasm and the genetic material can be maintained inside the nucleus. The **nucleolus** is the dense region within the nucleus where ribosomal subunits are synthesized. After being produced in the nucleolus, ribosomes are exported to the cytoplasm, where they are assembled and used for synthesizing proteins.

Mitochondria

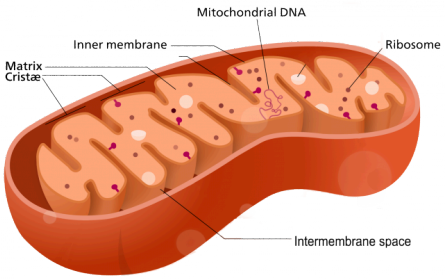


Figure 4.3.3 Mitochondria contain their own DNA and ribosomes. Image by Kelvinsong; modified by Sowlos, CC BY-SA 3.0

The **mitochondrion** (plural, mitochondria) is an organelle that makes energy available to the cell. This is why mitochondria are sometimes called the "power plants of the cell." They use energy from organic compounds (such as glucose) to make molecules of **ATP (adenosine triphosphate)**, an energy-carrying molecule that is used almost universally inside cells for energy.

Mitochondria (as in Figure 4.3.3) have a complex structure, including an inner and outer membrane. In addition, mitochondria have their own DNA, ribosomes, and a version of cytoplasm called the matrix. Does this sound similar to the requirements for being considered a cell? That's because they are!

Scientists think mitochondria were once free-living organisms because they contain DNA. They theorize that ancient prokaryotes infected (or were engulfed by) larger prokaryotic cells, and the two organisms developed a symbiotic relationship that benefited both of them. The larger cells provided the smaller prokaryotes with a place to live. In return, the larger cells got extra energy from the smaller prokaryotes. Eventually, the smaller prokaryotes became permanent guests of the larger cells, as organelles inside them. This theory is called **endosymbiotic theory** and is widely accepted by biologists today.

Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** is an organelle that helps make and transport proteins and lipids. There are two types of endoplasmic reticulum: rough endoplasmic reticulum (rER) and smooth endoplasmic reticulum (sER). Both types are shown in Figure 4.3.4.

- **rER** looks rough because it is studded with ribosomes. It provides a framework for the ribosomes, which make proteins. Bits of its membrane pinch off to form tiny sacs called vesicles, which carry proteins away from the ER.
- **sER** looks smooth because it does not have ribosomes. sER makes lipids, stores substances, and plays other roles.

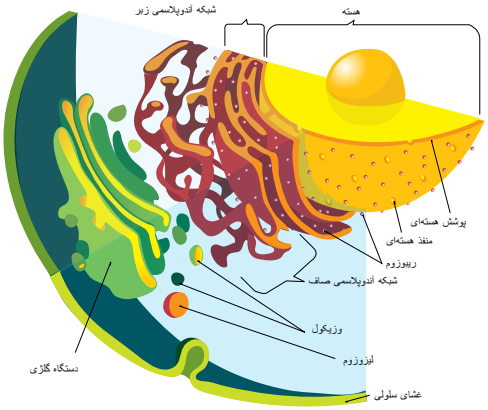


Figure 4.3.4 The nucleus, rER, sER, and Golgi apparatus. From the drawing, you can see how all these organelles work together to make and transport proteins. Image by Mariana Ruiz, Public Domain

Golgi Apparatus

The **Golgi apparatus** is a large organelle that processes, modifies, and packages proteins for use inside the cell or for export outside the cell. It functions like a post office: It receives items (proteins from the ER), modifies them (such as adding carbohydrate groups), packages them (into vesicles), and labels them for delivery to their correct destinations (to different parts of the cell or to the cell membrane for transport out of the cell). The Golgi apparatus is also involved in transporting lipids around the cell.

Vesicles and Vacuoles

Both **vesicles** and **vacuoles** are sac-like organelles made of phospholipid bilayers that store and transport materials in the cell. Vacuoles are larger and are primarily used for storage. Vesicles are much smaller than vacuoles and have a variety of functions. The vesicles that pinch off from the ER and Golgi apparatus membranes store and transport protein and lipid molecules. You can see an example of this type of transport vesicle in Figure 4.3.4. Some vesicles are used as chambers for biochemical reactions.

There are some vesicles which are specialized to carry out specific functions. **Lysosomes**, which use enzymes to break down foreign matter and dead cells, have a double membrane to ensure their contents don't leak into the rest of the cell.

Centrioles

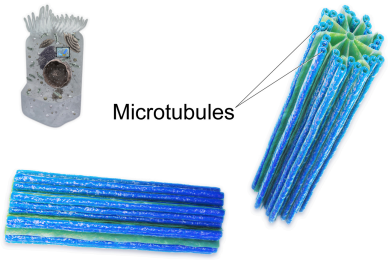


Figure 4.3.5 Centrioles. Image by Blausen.com staff (2014), CC BY 3.0

Centrioles are organelles involved in cell division. The function of centrioles is to help organize the chromosomes before cell division occurs so that each daughter cell has the correct number of chromosomes after the cell divides. Centrioles are found only in animal cells and are located near the nucleus. The centriole is cylindrical in shape and consists of many microtubules, as shown in the model pictured in Figure 4.3.5.

Ribosomes

Ribosomes are small structures where proteins are synthesized. Although they are not enclosed within a membrane, they are often considered organelles due to their essential role in the cell. Each ribosome is made up of two subunits (Figure 4.3.6), both composed of ribosomal RNA (rRNA) and proteins.

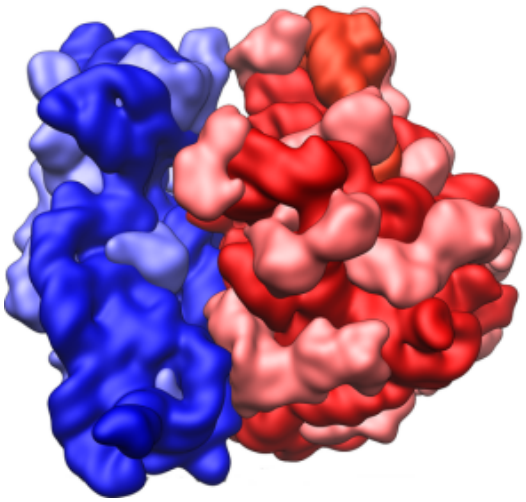


Figure 4.3.6 "Ribosome Shape" by Vossman, CC BY-SA 3.0. Mods: Used half of the image.

The genetic instructions from DNA in the nucleus are copied onto messenger RNA (mRNA), which travels to the ribosome. There, the ribosome reads the mRNA sequence and assembles amino acids in the correct order to build a protein. Ribosomes can be found floating freely in the cytoplasm or attached to the rough endoplasmic reticulum (rER).

Plant Cells

Plant cells have some additional organelles that animals do not, including a cell wall, chloroplasts, and a large central vacuole.

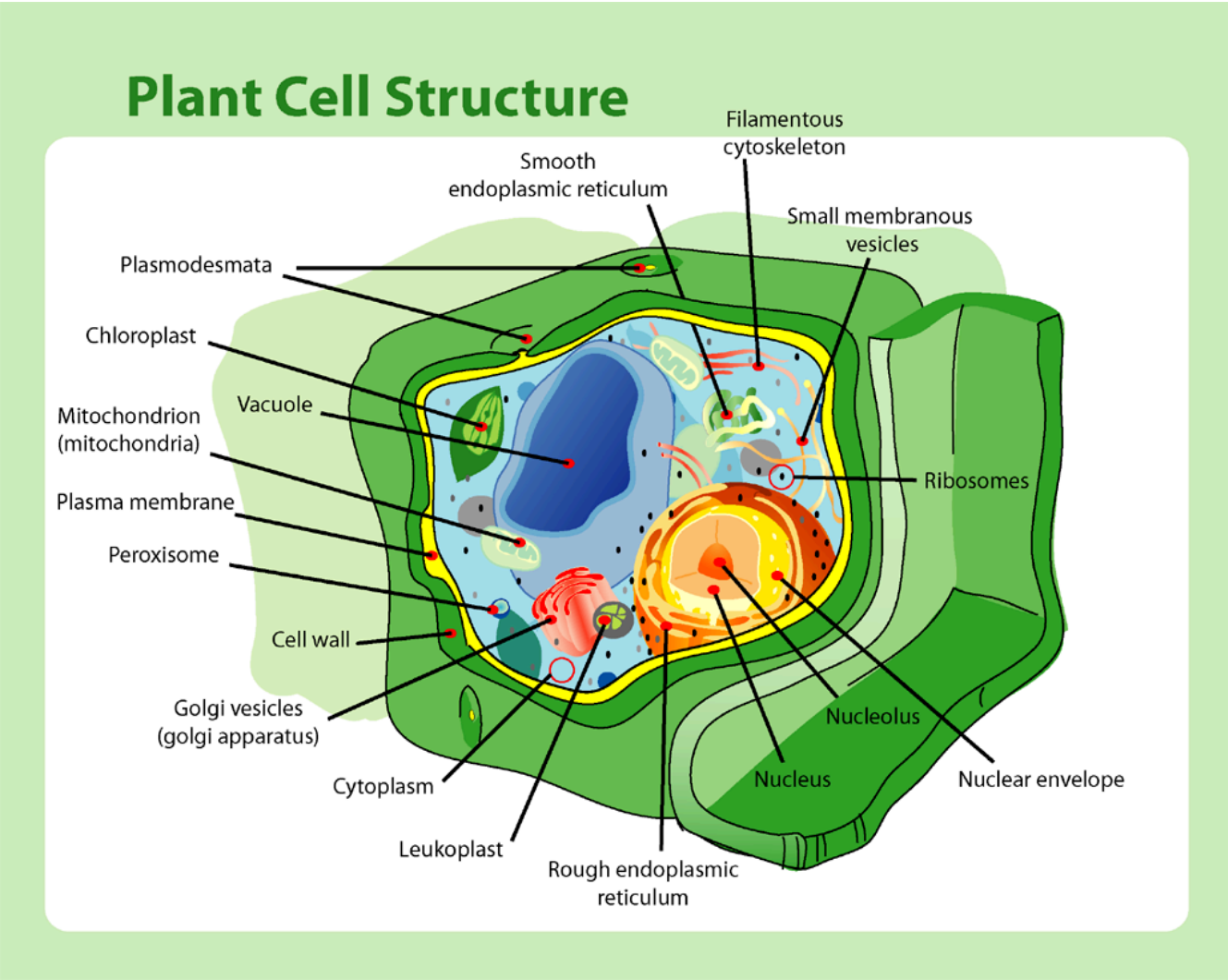


Figure 4.3.7 Features of a typical plant cell. Image by Mariana Ruiz, Public Domain

Cell Wall

The **cell wall** is a rigid covering that protects the cell, provides structural support, and gives shape to the cell. Fungal and protist cells also have cell walls.

The major organic molecule in a plant cell wall is cellulose, a polysaccharide made up of long, straight chains of glucose units. When nutritional information refers to dietary fibre, it refers to the cellulose content of food.

Chloroplasts

Chloroplasts function in photosynthesis and can be found in eukaryotic cells such as plants and algae. In photosynthesis, carbon dioxide, water, and light energy are used to make glucose and oxygen. This is the major difference between plants and animals: Plants are able to make their own food, like glucose, whereas animals must rely on other organisms for their organic compounds or food source.

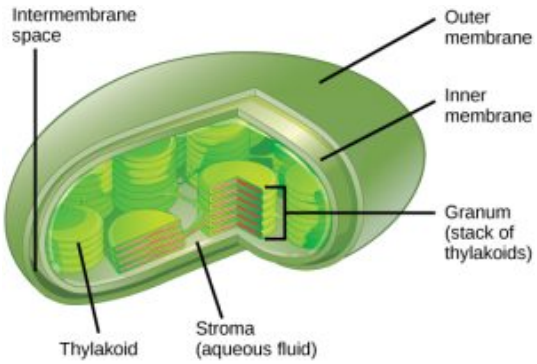


Figure 4.3.8 This simplified diagram of a chloroplast shows the outer membrane, inner membrane, thylakoids, grana, and stroma. Image by Charles Molnar and Jane Gair, OpenStax, CC BY-SA 4.0

Like mitochondria, chloroplasts also have their own DNA and ribosomes, suggesting they evolved through the endosymbiotic theory. Chloroplasts have outer and inner membranes. The inner membrane encloses a fluid called the stroma. Within the stroma is a set of interconnected and stacked membrane sacs called thylakoids (Figure 4.3.8). The chloroplasts contain a green pigment called chlorophyll, which captures the energy of sunlight for photosynthesis.

Large Central Vacuole

Plant cells each have a **large central vacuole** that occupies most of the cell. The central vacuole plays a key role in regulating the cell's water concentration in changing environmental conditions. The liquid inside the central vacuole provides turgor pressure, which is the outward pressure caused by the fluid inside the cell. This fluid may also have a bitter taste or even contain toxins to discourage insects and animals from eating the plant. The large central vacuole can also store pigments, which give flowers their vibrant colours, and help to attract pollinators. It also stores proteins in developing seed cells.

Exercise 4.3.1

Text Description

1. Drag the words into the correct boxes

1. The _____ contains the genetic instructions for the production of proteins.
2. The _____ organizes chromosomes before cell division.
3. The _____ is covered in attached ribosomes.
4. The _____ packages and modifies proteins.
5. The _____ assembles ribosomes.
6. The _____ use energy from glucose to make molecules of ATP.
7. The _____ synthesizes lipids.

Possible answers:

- mitochondria
- centrioles
- nucleolus
- smooth ER
- Golgi apparatus
- rough ER
- nucleus

2. All eukaryotic cells have a nucleus. (True/False)
3. The outer surface of the nucleus of a eukaryotic cell is not completely solid. (True/False)
4. Ribosomes are surrounded by a membrane. (True/False)

Answers:

1. d. Both A and B
2.

1. The ***nucleus*** contains the genetic instructions for the production of proteins.
2. The ***centrioles*** organize chromosomes before cell division.
3. The ***rough ER*** is covered in attached ribosomes.

4. The ***Golgi apparatus*** packages and modifies proteins.
5. The ***nucleolus*** assembles ribosomes.
6. The ***mitochondria*** use energy from glucose to make molecules of ATP.
7. The ***smooth ER*** synthesizes lipids.

3. True
4. True
5. False

4.4 PASSIVE TRANSPORT

Transport Across Membranes

If a cell were a house, the plasma membrane would be the walls with windows and doors. Moving things in and out of the cell is an important function of the plasma membrane. It controls everything that enters and leaves the cell. There are two basic ways substances can cross the plasma membrane: passive transport — which requires no energy expenditure by the cell — and active transport — which requires energy from the cell.

Transport Without Energy Expenditure By The Cell

Passive transport occurs when substances cross the plasma membrane without any energy input from the cell. No energy is required because the substances move from an area with a higher concentration to an area with a lower concentration. Concentration refers to the number of particles of a substance per unit of volume. The more particles of a substance in a given volume, the higher the concentration. A substance always moves from an area where it is more concentrated to an area where it is less concentrated. This is referred to as "down the concentration gradient".

There are several different types of passive transport, including simple diffusion, osmosis, and facilitated diffusion. Each type is described below.

Simple Diffusion

Diffusion is the movement of a substance due to a difference in concentration. It happens without any help from other molecules. The substance moves from where it is more concentrated to where it is less concentrated. Picture someone spraying perfume in the corner of a room. Do the perfume molecules stay in the corner? No, they spread out or diffuse throughout the room until they are evenly spread out. Figure 4.4.1 shows how diffusion works across a cell membrane. Substances that can squeeze between the lipid molecules in the plasma membrane by simple diffusion are generally very small, hydrophobic molecules, such as oxygen and carbon dioxide molecules.

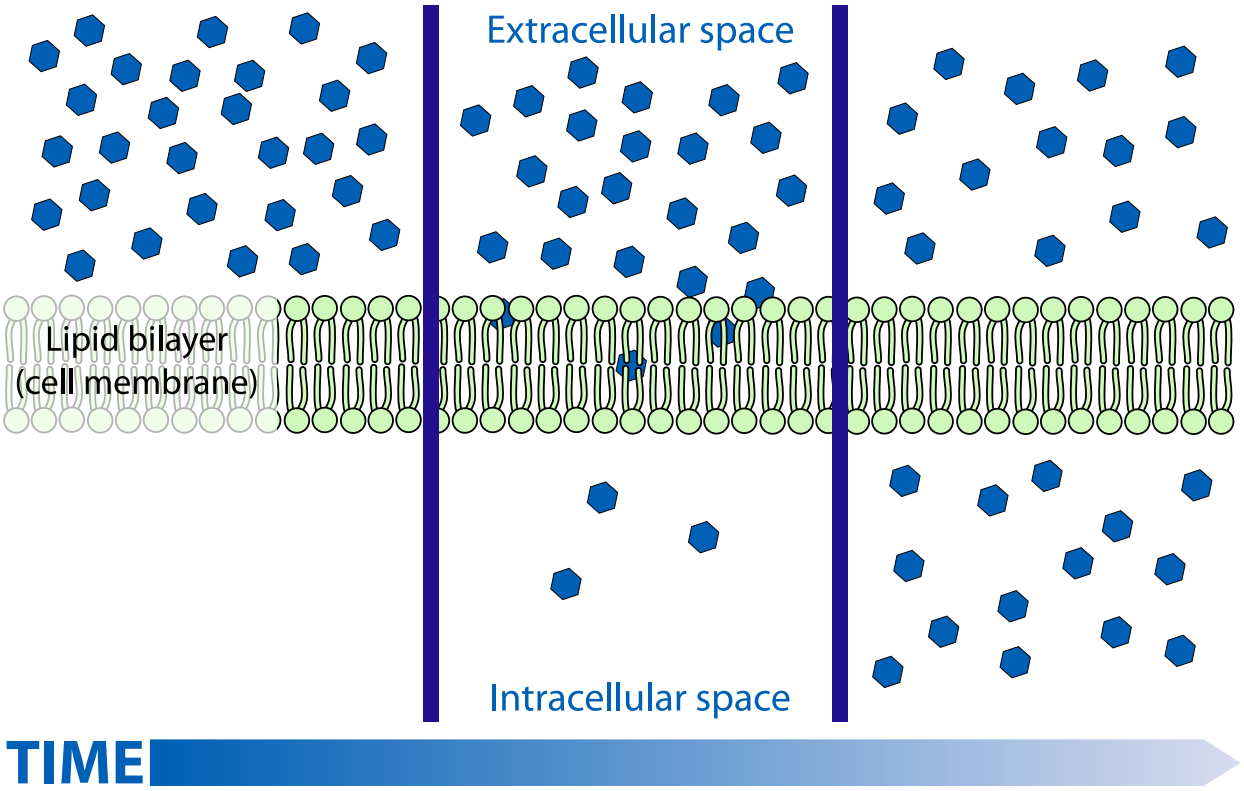


Figure 4.4.1 Diffusion. Image by Mariana Ruiz Villarreal, Public Domain

Osmosis

Osmosis is a special type of diffusion — the diffusion of water molecules across a membrane. Like other molecules, water moves from an area of higher concentration to an area of lower concentration. Water moves in or out of a cell until its concentration is the same on both sides of the plasma membrane. In Figure 4.4.2, the dotted red line shows a semi-permeable membrane. In the first beaker, there is an uneven concentration of solutes on either side of the membrane, but the solute cannot cross, so diffusion of the solute can't occur. In this case, water will move to even out the concentration, as has happened on the beaker on the right side. The water levels are uneven, but the osmosis process has evened the concentration gradient.

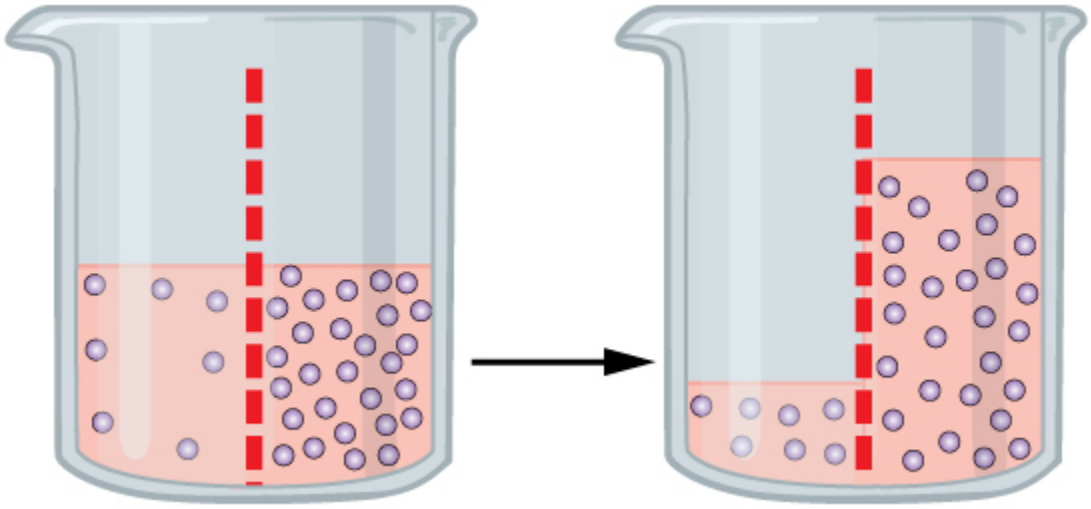


Figure 4.4.2 Osmosis. Image by OpenStax, CC BY 3.0

Facilitated Diffusion

Many substances cannot simply diffuse across a membrane. Hydrophilic molecules, charged ions, and relatively large molecules (such as glucose) all need help with diffusion. This help comes from special proteins in the membrane known as **transport proteins**. Diffusion with the help of transport proteins is called **facilitated diffusion**. Several types of transport proteins exist, including channel and carrier proteins. Both are shown in Figure 4.4.3.

Channel proteins form pores (or tiny holes) in the membrane. This allows water molecules and small ions to pass through the membrane without contacting the lipid molecules' hydrophobic tails in the membrane's interior.

Carrier proteins bind with specific ions or molecules. In doing so, they change shape. Carrier proteins carry the ions or molecules across the membrane as they change shape.

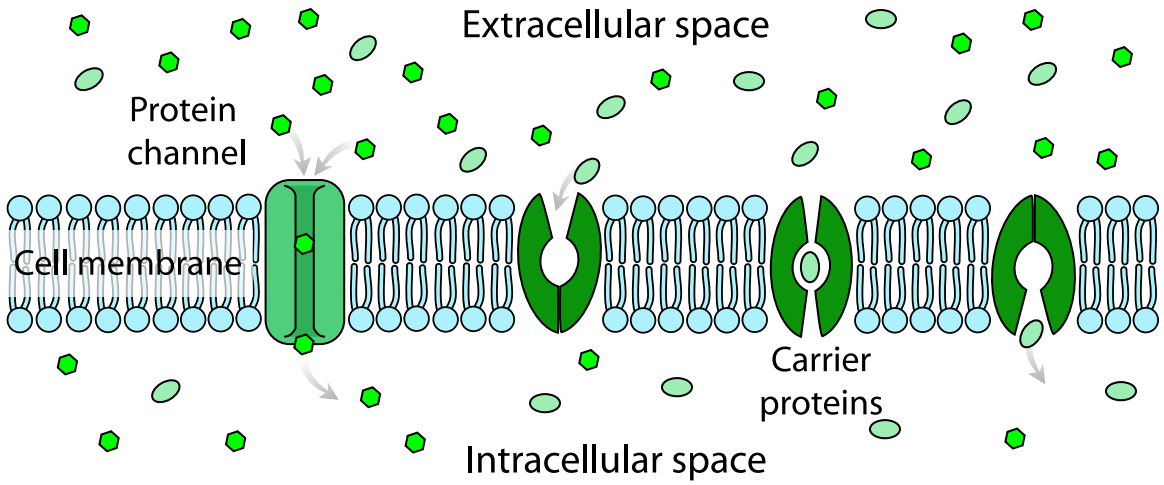


Figure 4.4.3 Facilitated diffusion. "Scheme facilitated diffusion in cell membrane" by Mariana Ruiz Villarreal [LadyofHats], Public Domain.

Transport and Homeostasis

For a cell to function normally, the inside of it must maintain a stable state. The concentrations of salts, nutrients, and other substances must be kept within certain ranges. The state in which stable conditions are maintained inside a cell (or an entire organism) is called **homeostasis**. Homeostasis requires constant adjustments because conditions always change inside and outside the cell. As described in this section, the transport of substances into and out of cells plays an important role in homeostasis. By allowing the movement of substances into and out of cells, transport keeps conditions within normal ranges inside the cells and throughout the organism as a whole.

Exercises 4.4.1

Text Description

1. Only active transport, not passive transport, involves transport proteins. (True/False)

2. Oxygen and carbon dioxide can squeeze between the lipid molecules in the plasma membrane. (True/False)

3. Ions easily diffuse across the cell membrane by simple diffusion. (True/False)

4. Controlling what enters and leaves the cell is an important function of the:

a. Plasma membrane
b. Vesicle
c. Golgi apparatus
d. Nucleus

5. If a doctor injects a patient with what is thought to be an isotonic saline solution and the patient dies, and an autopsy reveals that many red blood cells have been destroyed. Was the solution isotonic?

a. No, it must have been hypotonic, as a hypotonic solution would cause water to enter the cells, thereby making them burst.
b. Yes, it must have been isotonic, as an isotonic solution would cause water to enter the cells, thereby making them burst.

6. Why does osmosis occur in cells?

a. Water moves through a semipermeable membrane in osmosis because there is a concentration gradient across the membrane of solute and solvent. The solute cannot effectively move to balance the concentration on both sides of the membrane, so water moves to achieve this balance.
b. Water moves through a permeable membrane in osmosis because there is a balanced concentration gradient across the membrane of solute and solvent. The solute has moved to balance the concentration on both sides of the membrane to achieve this balance.

7. How does water move via osmosis in cells?

a. Water moves from an area with a low concentration of solutes to an area with a higher one
b. Water moves throughout the cytoplasm
c. Water moves from an area with a high concentration of other solutes to a lower one
d. Water moves from an area with a high concentration of other solutes to a lower one

8. What is the principal force driving movement in diffusion?

a. particle size
b. concentration gradient
c. membrane surface area
d. temperature

Answers:

1. False
2. True
3. False
4. Plasma membrane
5. No, it must have been hypotonic, as a hypotonic solution would cause water to enter the cells, thereby making them burst.
6. Water moves through a semipermeable membrane in osmosis because there is a concentration gradient across the membrane of solute and solvent. The solute cannot effectively move to balance the concentration on both sides of the membrane, so water moves to achieve this balance.
7. Water moves from an area with a low concentration of solutes to an area with a higher one.
8. Concentration gradient.

Tonicity

Tonicity describes the concentration of solutes in a solution outside the cell compared to inside the cell. Different tonicities affect the cell's volume and pressure. There are three types of tonicity: hypotonic, isotonic, and hypertonic.

In a **hypotonic** solution, such as tap water, the extracellular fluid has a lower concentration of solutes than the fluid inside the cell, and water enters the cell. (In living systems, the point of reference is always the cytoplasm, so the prefix hypo– means that the extracellular fluid has a lower concentration of solutes than the cell cytoplasm.) It also means that the extracellular fluid has a higher water concentration than the cell. Water will follow its concentration gradient and enter the cell in this situation. This may cause an animal cell to burst or lyse.

In a **hypertonic** solution (the prefix hyper– refers to the extracellular fluid having a higher concentration of solutes than the cell's cytoplasm), the fluid contains less water than the cell does, such as seawater. Because the cell has a lower concentration of solutes, the water will leave the cell. In effect, the solute is drawing the water out of the cell. This may cause an animal cell to shrivel or crenate.

In an **isotonic** solution, the extracellular fluid has the same osmolarity as the cell. If the concentration of solutes in the cell matches that of the extracellular fluid, there will be no net movement of water into or out of the cell. In hypertonic, isotonic, and hypotonic solutions, blood cells take on characteristic appearances (Figure 4.4.4).

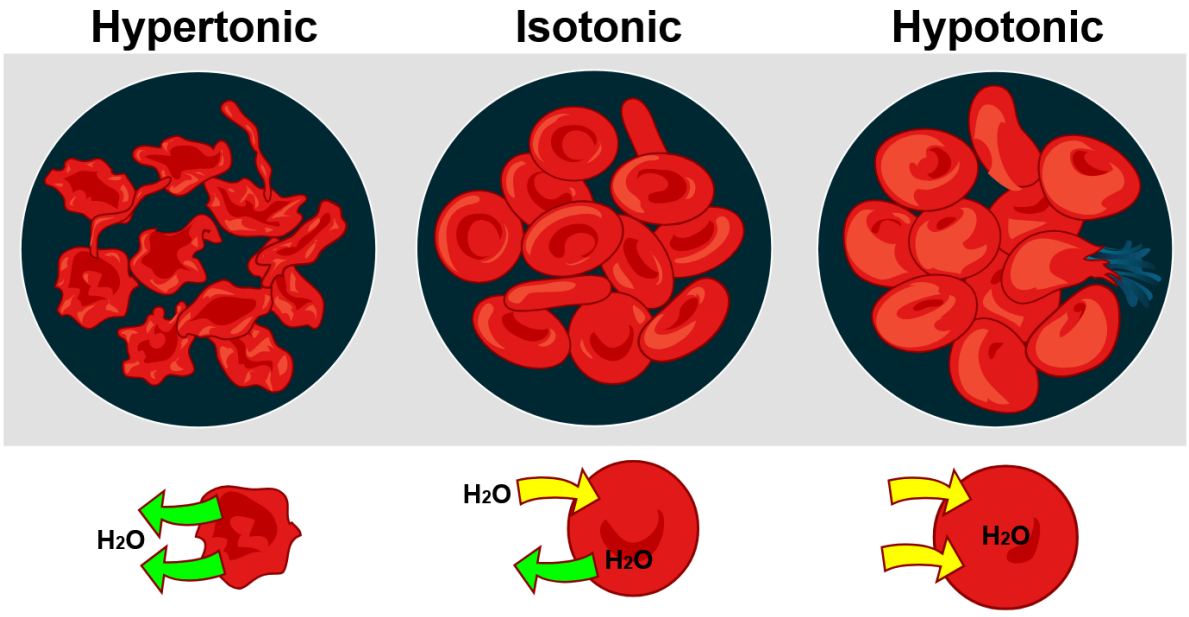


Figure 4.4.4 Osmotic pressure changes the shape of red blood cells in hypertonic, isotonic, and hypotonic solutions. Image by Mariana Ruiz Villarreal, Public Domain

A doctor injects a patient with what the doctor thinks is an isotonic saline solution. The patient dies, and an autopsy reveals that many red blood cells have been destroyed. Do you think the solution the doctor injected was really isotonic?

(Answer: No, it must have been hypotonic, as a hypotonic solution would cause water to enter the cells, thereby making them burst.)

Some organisms, such as plants, fungi, bacteria, and protists, have cell walls surrounding the plasma membrane and preventing cell lysis. The plasma membrane can only expand to the limit of the cell wall, so the cell will not lyse. In fact, the cytoplasm in plants is always slightly hypertonic compared to the cellular environment, and water will always enter a cell if water is available. This influx of water produces **turgor** pressure, which stiffens the cell walls of the plant (Figure 4.4.5). In nonwoody plants, turgor pressure supports the plant. If the plant cells become hypertonic, as occurs in drought, or if a plant is not watered adequately, water will leave the cell. Plants lose turgor pressure in this condition and wilt.

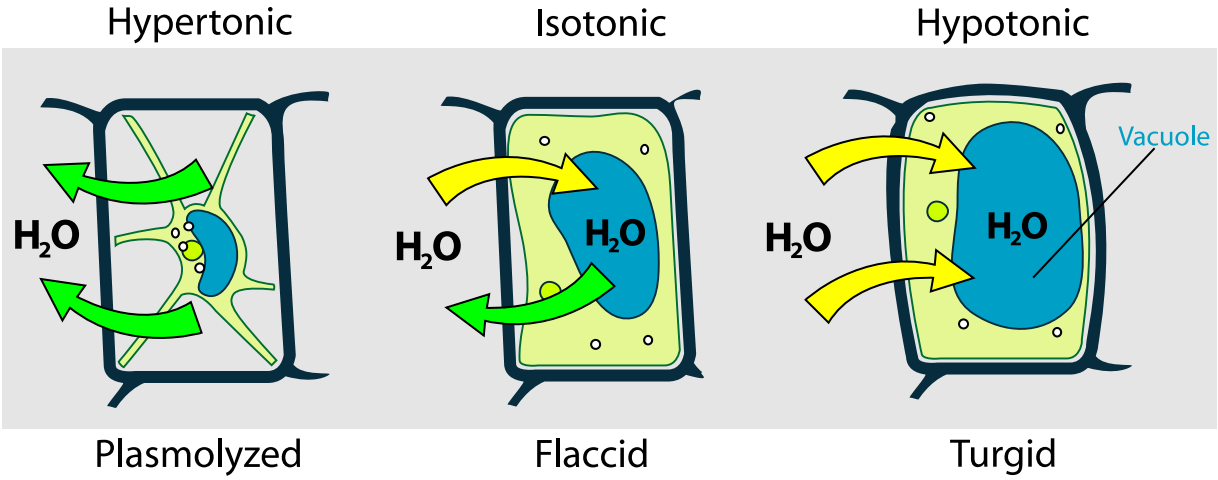


Figure 4.4.5 The turgor pressure within a plant cell depends on tonicity. Image by Mariana Ruiz Villarreal, Public Domain

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4.5 ACTIVE TRANSPORT

What Is Active Transport?

Active transport requires energy, usually from ATP, to move substances across a membrane *against* their concentration gradient (from lower to higher concentration). This process often involves proteins called pumps embedded in the plasma membrane. In cells, substances naturally flow from high to low concentration, so active transport is needed to continually pump substances in order to maintain a concentration gradient.

Think of a ski lift at a mountain resort. Skiers naturally glide downhill (passive transport), but to get back up the mountain, they need the powered ski lift (active transport), which requires energy to move them back uphill.

The **sodium-potassium pump** is a mechanism of active transport that moves sodium ions out of the cell and potassium ions into the cells — in all the trillions of cells in the body! Both ions are moved from lower to higher concentration areas, so energy is needed for this "uphill" process. ATP provides the energy. The sodium-potassium pump also requires carrier proteins. Figure 4.5.1 shows in greater detail how the sodium-potassium pump works. First, three sodium ions bind with a carrier protein in the cell membrane. The carrier protein then changes shape, powered by energy from ATP, and as it does, it pumps the three sodium ions out of the cell. At that point, two potassium ions bind to the carrier protein. The process is reversed, and the potassium ions are pumped into the cell.

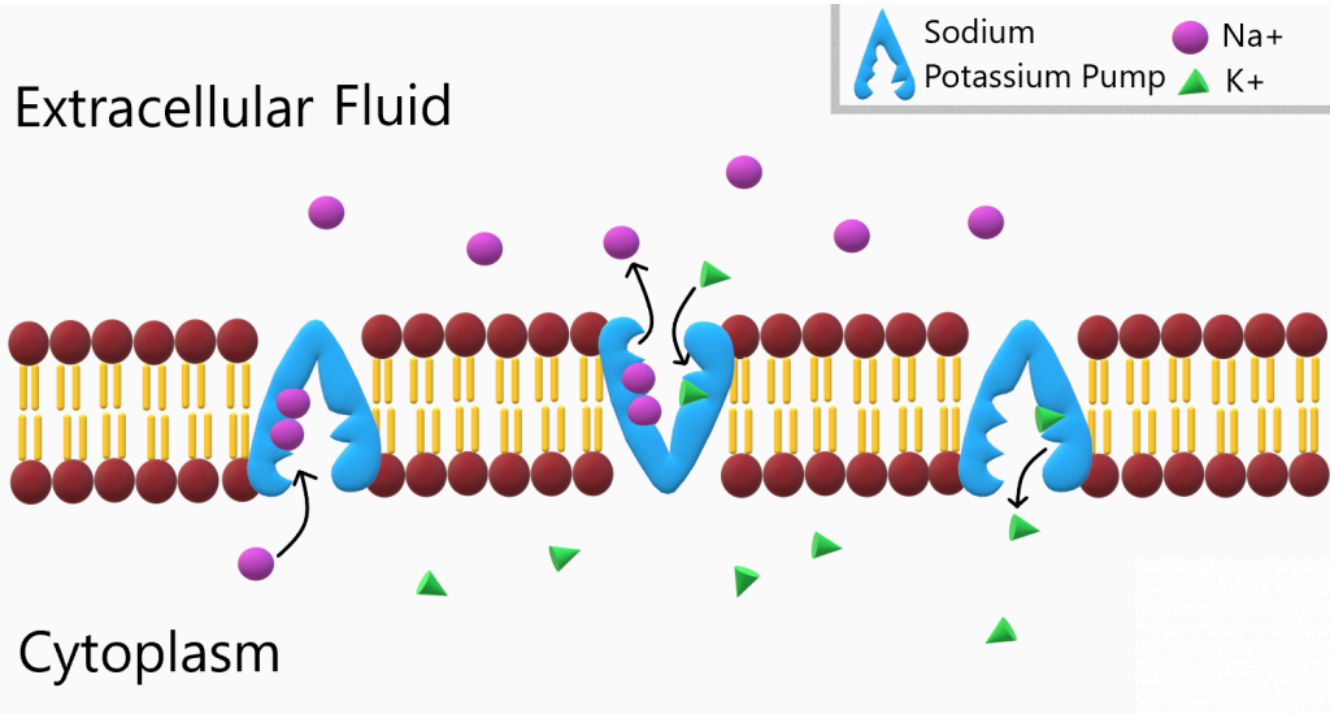

Figure 4.5.1 The sodium-potassium pump moves sodium ions (Na+) out of the cell and potassium ions (K+) into the cell. First, three sodium ions bind with a carrier protein in the cell membrane. The carrier protein then changes shape, powered by energy from ATP, and as it does, it pumps the three sodium ions out of the cell. At that point, two potassium ions bind to the carrier protein. The process is reversed, and the potassium ions are pumped into the cell. Image by Christine Miller, CC BY 4.0

Normal body functions require a very narrow range of sodium and potassium ions concentrations in body fluids, both inside and outside of cells. Normal sodium concentrations are about ten times higher outside of cells than inside. Normal potassium concentrations are about 30 times higher inside of cells than outside. Maintaining these gradients are critical for vital body functions, including the transmission of nerve impulses and contraction of muscles. As sodium and potassium ions naturally diffuse from high to low concentration, our body needs to pump them back across the membrane to maintain the proper concentration gradient.

Vesicle Transport

Some molecules, such as proteins, are too large to pass through the plasma membrane, regardless of their concentration inside and outside the cell. Very large molecules cross the plasma membrane with different help called **vesicle transport**. Vesicle transport requires energy input from the cell, which is also a form of active transport. There are two types of vesicle transport: endocytosis and exocytosis.

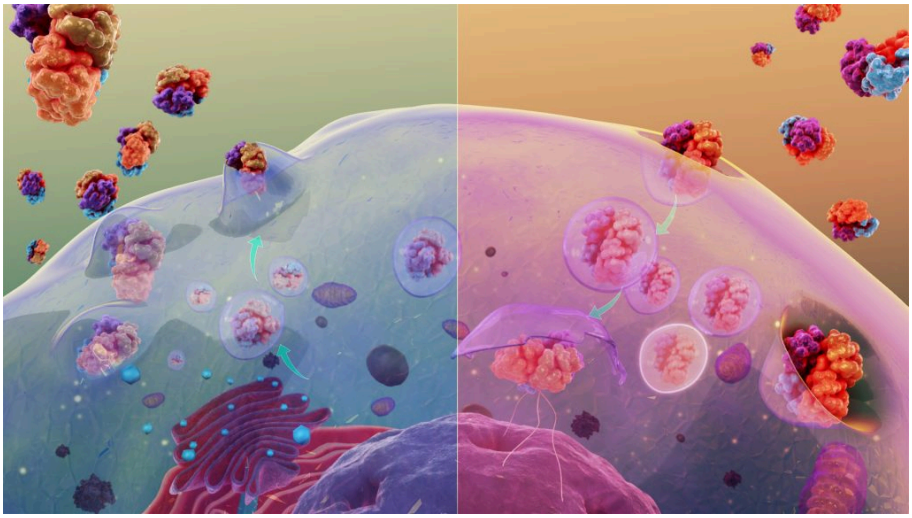

Figure 4.5.2 Vesicle transport includes exocytosis (left) and endocytosis (right). Image by ScientificAnimations, CC BY-SA 4.0

Endocytosis and Exocytosis

Endocytosis is a type of vesicle transport that moves a substance into the cell. The plasma membrane completely engulfs the substance, a vesicle pinches off from the membrane, and the vesicle carries the substance into the cell. The process is called **phagocytosis,** when an entire cell or other solid particle is engulfed. When fluid is engulfed, the process is called **pinocytosis**.

Exocytosis is a type of vesicle transport that moves a substance out of the cell (exo-, like "exit"). A vesicle containing the substance moves through the cytoplasm to the cell membrane. Because the vesicle membrane is a phospholipid bilayer like the plasma membrane, the vesicle membrane fuses with the cell membrane and the substance is released outside the cell.

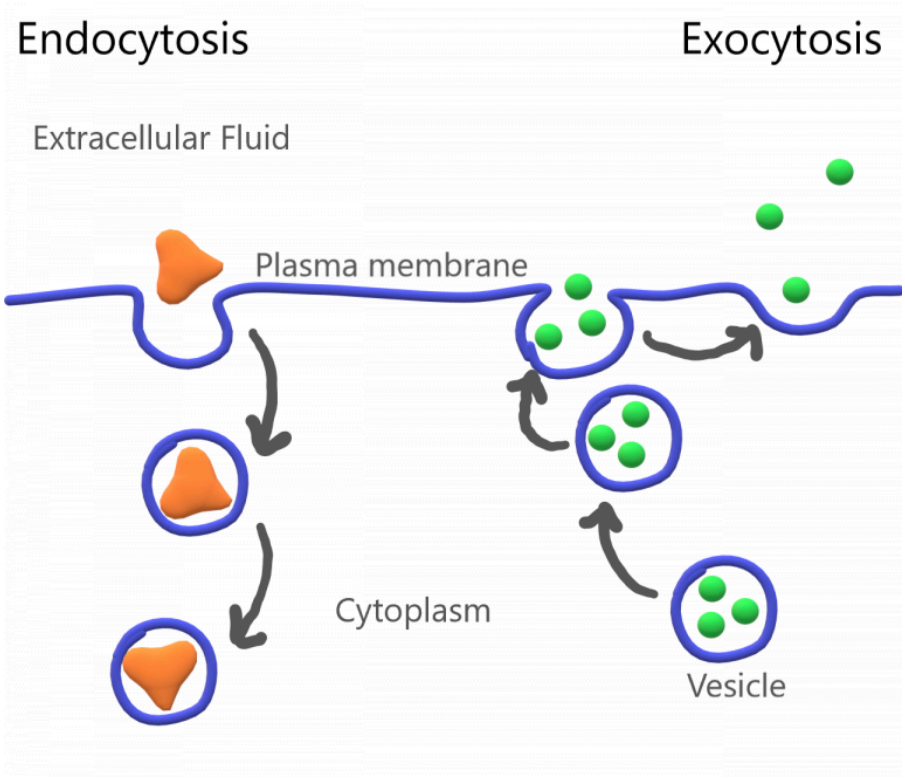

Figure 4.5.3 Endocytosis brings substances into the cell via vesicle formation. Exocytosis allows substances to exit the cell by merging a transport vesicle with the cell membrane. "Endocytosis and Exocytosis" by Christine Miller, CC BY 4.0

Exercises 4.5.1

Text Description

1. Exocytosis moves substances out of the cell, and endocytosis moves substances into the cell. (True/False)

2. The sodium-potassium pump is a:

a. Phospholipid
b. Ion
c. Protein
d. Carbohydrate

3. The sodium-potassium pump uses one protein to pump both sodium and potassium. (True/False)

4. Vesicles are made of nuclear membrane. (True/False)

5. Chemical signalling molecules called neurotransmitters are released from nerve cells (neurons) through vesicles. This is an example of:

a. Pinocytosis
b. Exocytosis
c. Endocytosis
d. Phagocytosis

6. The energy for active transport comes from:

a. Sodium ions
b. ATP
c. Carrier proteins
d. RNA

7. Drag the words into the correct boxes

- An electrical gradient across the cell membrane is called a _____.
- Transport proteins that move substances into and out of a cell are located in the _____.
- When a cell engulfs a solid particle, this is called _____.

- When a cell engulfs fluid, this is called _____.

Possible answers:

- phagocytosis
- plasma membrane
- pinocytosis
- membrane potential

Answers:

1. True

2. Protein

3. True

4. False

5. Exocytosis

6. ATP

7.

- An electrical gradient across the cell membrane is called a ***membrane potential***.
- Transport proteins that move substances into and out of a cell are located in the ***plasma membrane***.
- When a cell engulfs a solid particle, this is called ***phagocytosis***.
- When a cell engulfs fluid, this is called ***pinocytosis***.

CHAPTER 4 SUMMARY

Key Takeaways

- **Diversity and Function of Cells**: The human body is composed of various specialized cells, each performing essential functions such as protection (epithelial cells), structural support (bone cells), immune defense (white blood cells), and oxygen transport (red blood cells). Despite their differences, all cells share fundamental characteristics, including a plasma membrane, cytoplasm, DNA, and ribosomes.
- **Cell Theory and Classification**: Cell theory states that all living organisms consist of cells, life processes occur within cells, and new cells arise from existing ones. Cells are classified into two types: prokaryotic cells, which lack a nucleus and are simpler in structure (found in bacteria and archaea), and eukaryotic cells, which have a nucleus and complex organelles (found in protists, plants, fungi, and animals). The size of cells remains small to efficiently exchange materials with their environment.
- **Each Cell Component Plays a Vital Role in Maintaining the Cell's Integrity and Function:** The plasma membrane regulates material exchange, the cytoplasm supports organelles and facilitates metabolism, the cytoskeleton provides structural support, and flagella and cilia enable movement. These elements work together to ensure cellular function and overall organismal health.
- **Cell Organelles Perform Specialized Functions That are Essential for Cell Survival and Efficiency.** The nucleus controls gene expression, mitochondria generate energy, the endoplasmic reticulum and Golgi apparatus process and transport proteins, and vesicles and vacuoles store and transport materials. Unique organelles in plant cells, like chloroplasts for photosynthesis and the central vacuole for water regulation, highlight structural and functional differences between plant and animal cells.
- **Passive Transport Moves Substances Without Energy:** Passive transport allows substances to move across the plasma membrane without cellular energy input, following their concentration gradient. This includes simple diffusion (movement of small molecules), osmosis (water diffusion), and facilitated diffusion (assisted transport of larger or charged

molecules via proteins). These processes help regulate the movement of essential molecules and maintain cellular function.

- **Active Transport:** This occurs when substances require energy to cross a plasma membrane, often because they move from an area of lower concentration to an area of higher concentration against the concentration gradient using ATP Energy. This process includes membrane pumps (such as the sodium-potassium pump, which maintains ion balance for nerve and muscle function) and vesicle transport (endocytosis for taking in substances and exocytosis for expelling them). These mechanisms are essential for maintaining cellular homeostasis and enabling critical biological processes.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into six key takeaways.

Flashcards

Text Description

1. **Microscope**: An instrument that magnifies and visualizes very small objects, such as cells and microorganisms.
2. **Light microscope:** Uses visible light and lenses to magnify small objects, allowing observation of specimens like cells and tissues
3. **Electron microscope:** Use beam of electrons to achieve much higher magnification and resolution than light microscopes; allow detailed visualization of structures at the molecular and atomic levels
4. **Scanning electron microscope:** Used to see the details of cell surfaces
5. **Transmission electron microscope:** Used to see the details of a cell's internal structures
6. **Cell theory:** All organisms are made of one or more cells; All the life functions of organisms occur within cells; All cells come from existing cells.

7. **Prokaryotic cells**: Simple cells lacking a nucleus and membrane-bound organelles (e.g. bacteria)
8. **Eukaryotic cells**: Complex cells containing a nucleus and membrane-bound organelles (e.g. plant and animal cells).
9. **Plasma membrane**: A selectively permeable barrier surrounding cells, controlling the passage of substances in and out
10. **Phospholipid bilayer**: Double-layered arrangement of phospholipids creating the fundamental structure of cell membranes.
11. **Intracellular**: Located or occurring inside a cell
12. **Extracellular**: Located or occurring outside a cell
13. **Fluid Mosaic**: A model describing the plasma membrane as a fluid structure composed of lipids, proteins, and carbohydrates that move freely within it
14. **Cytoplasm**: All cellular material inside the plasma membrane, excluding the nucleus
15. **Cytosol**: The fluid component of the cytoplasm
16. **Cytoskeleton**: Framework of protein fibres within cells that provides structural support
17. **Extracellular matrix:** A network of proteins and polysaccharides outside cells that holds cells together in a tissue
18. **Flagella**: Long, whip-like structures that extend from the plasma membrane and help in movement
19. **Cilia:** short, hair-like structures that extend from the plasma membrane and help in movement
20. **Organelle**: A specialized structure within a cell performing specific functions (e.g. mitochondria)
21. **Nucleus:** The cell's control centre; contains the cell's DNA
22. **Nuclear envelope**: Double-layered membrane surrounding the nucleus, protecting genetic material.
23. **Nuclear pores**: Channels in the nuclear envelope that regulate the passage of molecules between the nucleus and cytoplasm.
24. **Nucleolus:** A dense region within the nucleus where ribosomes are synthesized
25. **Mitochondrion**: Organelle responsible for producing cellular energy (ATP) through cellular respiration
26. **ATP (adenosine triphosphate)**: The primary energy-carrying molecule cells use for metabolic processes
27. **Endoplasmic Reticulum (ER)**: Membranous organelle involved in protein synthesis and lipid synthesis; composed of smooth ER and rough ER

28. **Rough ER:** Membranous organelle studded with ribosomes, which gives it a "rough" appearance; involved in protein synthesis
29. **Smooth ER:** Membranous organelle that looks smooth because it lacks ribosomes; makes lipids
30. **Golgi Apparatus**: Organelle that modifies, sorts, and packages proteins and lipids for transport within or outside the cell
31. **Vesicle**: Small sac-like organelle that stores and transports materials in the cell
32. **Lysosomes**: Vesicles containing digestive enzymes to break down foreign matter and dead cells
33. **Centrioles**: Organelles aiding in cell division by organizing microtubules in animal cells
34. **Ribosomes:** Sites of protein synthesis; composed of rRNA and proteins; found in cytoplasm or attached to rER
35. **Cell wall**: Provides structural support and protection to plant cells, fungi and some protists
36. **Chloroplast**: Organelle found in plant cells and some protists that conducts photosynthesis, converting light energy into chemical energy stored in glucose
37. **Large central vacuole**: Organelle in plant cells that stores water, nutrients, and waste products
38. **Endosymbiotic Theory:** Suggests that eukaryotic cells originated through a symbiotic relationship where one free-living cell engulfed another, leading to the development of organelles like mitochondria and chloroplasts
39. **Passive Transport**: Movement of substances across membranes without energy input; moving down a concentration gradient
40. **Diffusion**: Passive movement of molecules from high to low concentration until evenly spread out
41. **Osmosis**: Diffusion of water molecules across a membrane
42. **Facilitated diffusion:** Diffusion with the help of transport proteins
43. **Transport proteins**: Proteins that facilitate the movement of molecules across membranes
44. **Homeostasis:** A state in which stable conditions are maintained inside a cell or organism
45. **Tonicity:** Relative concentration of solutes in a solution outside a cell compared to inside; affects cell water movement
46. **Hypotonic**: A solution with a lower solute concentration causes water to enter cells and potentially cause swelling
47. **Isotonic**: A solution with equal solute concentration to the cell, maintaining equilibrium with no net water movement
48. **Hypertonic**: A solution with a higher solute concentration causes water to exit cells,

potentially causing shrinkage

49. **Active Transport**: Movement of substances across membranes requiring energy input (ATP); moving substances against their concentration gradient
50. **Sodium-Potassium Pump**: Protein pump using ATP to actively transport sodium ions out and potassium ions into the cell, maintaining concentration gradients essential for cell functions
51. **Vesicle Transport**: Movement of materials inside membrane-bound vesicles, either into or out of a cell
52. **Endocytosis**: A type of vesicle transport that moves a substance into the cell
53. **Phagocytosis**: A type of endocytosis where large particles are engulfed; "cell-eating"
54. **Pinocytosis: A type of** endocytosis where cells ingest extracellular fluids and dissolved substances; "cell-drinking"
55. **Exocytosis**: A type of vesicle transport that moves substances out of the cell
56. **Types of microscopes:** light microscope, electron microscopes (scanning and transmission)
57. **Who coined the term "cell":** Robert Hooke, after observing the structure of cork under a microscope in 1665
58. **2 basic types of cells:** prokaryotic and eukaryotic
59. **Characteristics of prokaryotic cells:** evolved ~3.5 BYA; smaller, simple cells; most have cell walls; have a plasma membrane; no membrane-bound organelles; have a nucleoid; have ribosomes
60. **Characteristics of eukaryotic cells:** evolved ~2.1 BYA; larger, more complex; plant cells have cell walls while animal cells have an extracellular matrix; have a plasma membrane; have membrane-bound organelles; have a nucleus; have ribosomes
61. **Why do cells remain small?** Cells remain small and multiply to maintain efficient nutrient and waste exchange through their surface area-to-volume ratio.
62. **What type of molecules pass through the phospholipid bilayer?** Small hydrophobic molecules, because they are water-hating, like the interior of the membrane. Hydrophilic molecules cannot pass through without help
63. **3 types of passive transport:** diffusion, osmosis, facilitated diffusion
64. **Types of vesicle transport:** Endocytosis (phagocytosis and pinocytosis) and exocytosis

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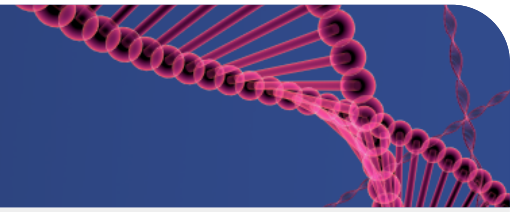
OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms

CHAPTER 5: PHOTOSYNTHESIS

Chapter Overview

Learning Objectives



By the end of this chapter, you will be able to:

- Explain how plants absorb energy from sunlight.
- Describe how the wavelength of light affects its energy and colour.
- Describe how and where photosynthesis takes place within a plant.
- Describe the Calvin cycle.
- Define carbon fixation.
- Explain how photosynthesis works in the energy cycle of all living organisms.

5.1 ENERGY

Chemical reactions that take place inside living things are called **biochemical reactions**. The sum of all the biochemical reactions in an organism is called **metabolism**. Metabolism includes **catabolic** and **anabolic** chemical reactions.

Catabolic Reactions

Catabolic reactions are processes that release energy. In organisms, these reactions involve breaking down molecules into smaller units and releasing energy. An example of a catabolic reaction is the breakdown of glucose during cellular respiration, which releases the energy necessary for cells to perform vital functions.

Anabolic Reactions

Anabolic reactions are processes that absorb energy. In organisms, these reactions involve building complex molecules from simpler ones, requiring an input of energy. A prime example of an anabolic reaction is photosynthesis, where plants use energy from sunlight convert carbon dioxide and water into glucose and oxygen.

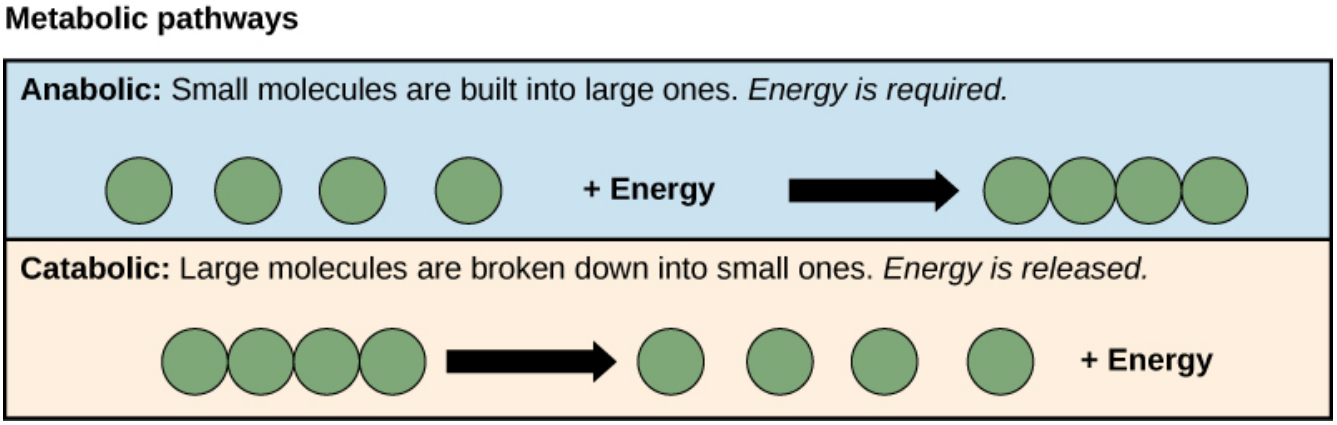


Figure 5.1.1. Catabolic pathways are those that generate energy by breaking down larger molecules. Anabolic pathways are those that require energy to synthesize larger molecules. Both types of pathways are required for maintaining the cell's energy balance. Image by Mary Ann Clark, Matthew Douglas, Jung Choi, Open Stax, CC BY 4.0

Activation Energy

All chemical reactions require energy to get started. Even exothermic reactions that release energy need a boost of energy to begin. The energy required to start a chemical reaction is called **activation energy**. Activation energy is like a child's push to start going down a playground slide. The push gives the child enough energy to start moving, but once she starts, she keeps moving without being pushed again.

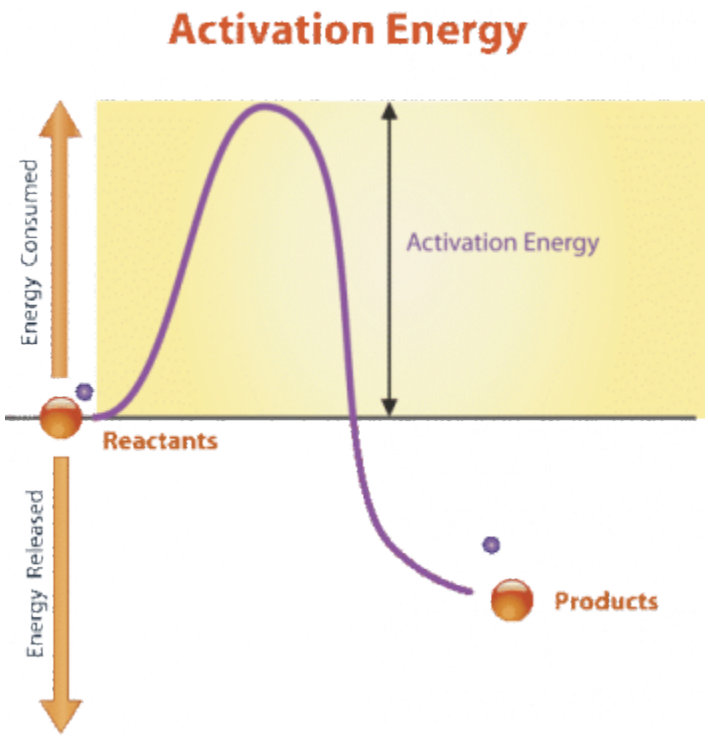


Figure 5.1.2. This reaction is exothermic but requires "help" to start. This "help" is the activation energy. Image by CK12, CC BY-NC 3.0.

Figure 5.1.2 Description

A diagram illustrating activation energy in a chemical reaction. The graph has energy on the vertical axis and progress of response on the horizontal axis. A curved purple line represents the energy change during the reaction. It starts at a point labelled 'Reactants,' rises to a peak (the activation energy barrier), and then falls to a lower energy level labelled 'Products.' A vertical double-headed arrow labelled 'Activation Energy' indicates the energy required to reach the peak. The left side of the graph is labelled 'Energy Consumed,' and the lower portion is labelled 'Energy Released.'

Why do chemical reactions need energy to get started? For reactions to begin, reactant molecules must bump into each other, so they must be moving, and movement requires energy. When reactant molecules bump together, they may repel each other because intermolecular forces push them apart. Energy is also needed to overcome these forces so the molecules can come together and react.

Enzymes

Most of the biochemical reactions that happen inside living organisms require help. Why is this the case? For one thing, temperatures inside living things are usually too low for biochemical reactions to occur quickly

enough to maintain life. The concentrations of reactants may also be too low for them to come together and react. Where do the biochemical reactions get the help they need to proceed? From the enzymes.

An **enzyme** is a protein that catalyzes (speeds up) a biochemical reaction. An enzyme generally reduces the activation energy needed to start the reaction. The graph in Figure 5.1.3 shows the activation energy required for glucose to combine with oxygen. Less activation energy is required when the correct enzyme is present than when it is not.

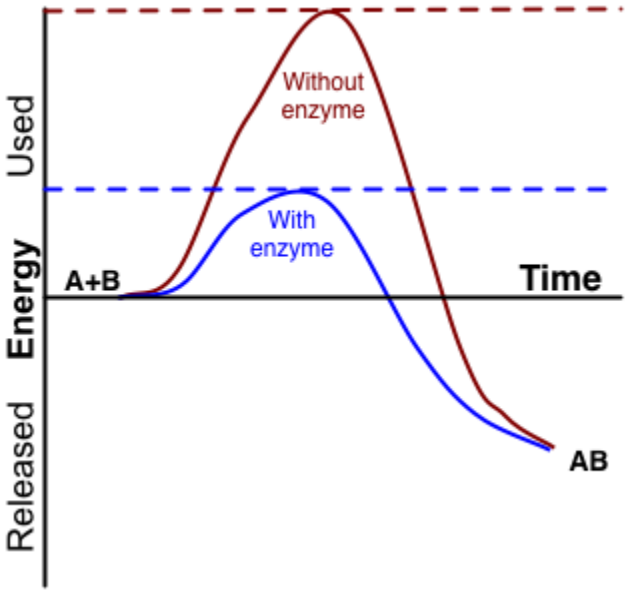


Figure 5.1.3 The activation energy for a reaction is lowered in the presence of an enzyme. Image by G. Andruk, CC BY-SA 3.0

Figure 5.1.3 Description

A graph compares a chemical reaction's activation energy with and without an enzyme. The x-axis represents time, and the y-axis represents energy, with 'Used' at the top and 'Released' at the bottom. Two curves illustrate the energy changes: a red curve labelled 'Without enzyme' rises to a higher peak, indicating a more significant activation energy requirement. A lower blue curve labelled 'With enzyme' shows a reduced activation energy requirement. The reaction starts at 'A + B' and ends at 'AB.' Dashed horizontal lines indicate the peak energy levels for each reaction path.

Enzymes function by binding to the reactant molecules and holding them in such a way as to make the chemical bond-breaking and forming processes take place more easily. It is important to remember that enzymes do not change whether a reaction is catabolic or anabolic. They only reduce the activation energy required for the response to go forward. In addition, an enzyme itself is unchanged by the reaction it catalyzes. Once one reaction has been catalyzed, the enzyme can participate in other reactions.

Enzymes are involved in most biochemical reactions and do their jobs well. A typical biochemical response that would take several days or even centuries without an enzyme will likely occur in just a split second with the proper enzyme! Without enzymes to speed up biochemical reactions, most organisms could not survive.

Enzymes are substrate-specific. The **substrate** of an enzyme is the specific substance it binds with. Each enzyme works only with a particular substrate, which explains why many different enzymes exist. The enzyme's **active site** is located within the enzyme where the substrate binds. The active site is where the "action" happens. Since enzymes are proteins, there is a unique combination of amino acid side chains within the active site. Different properties characterize each side chain. They can be large or small, weakly acidic or basic, hydrophilic or hydrophobic, positively or negatively charged, or neutral. The unique combination of side chains creates a particular chemical environment within the active site. This specific environment is suited to bind to a certain chemical substrate.

As the enzyme and substrate come together, their interaction causes a mild shift in the enzyme's structure, forming an ideal binding arrangement between enzyme and substrate. This dynamic binding is called **induced fit** and forms an enzyme-substrate complex.

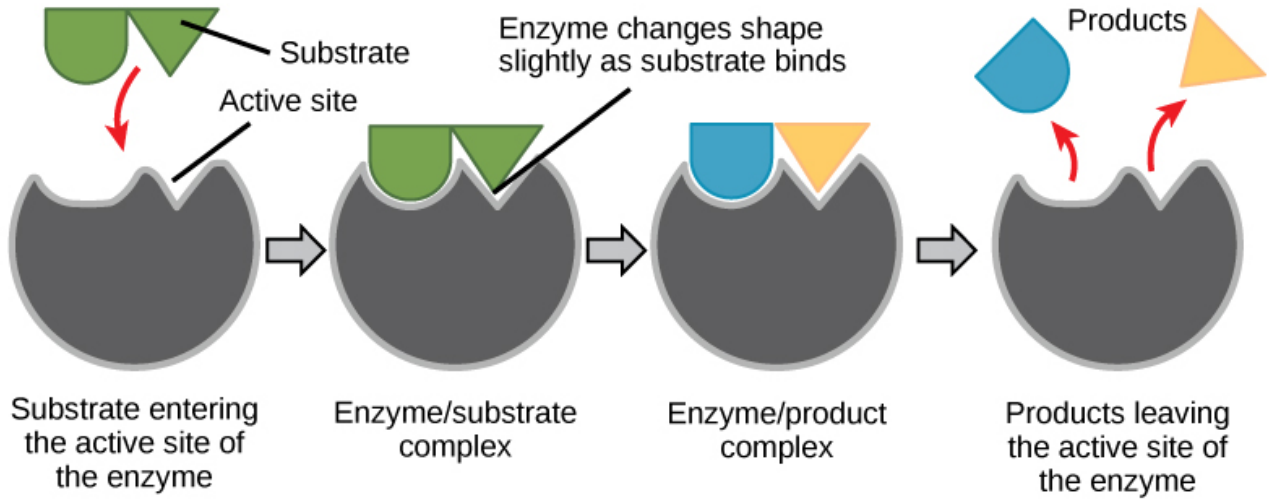


Figure 5.1.4 The induced-fit model shows how substrates bind with enzymes. Image by OpenStax, CC BY 4.0

Figure 5.1.4 Description

A step-by-step diagram illustrating the enzyme-substrate interaction process. The first stage shows a substrate (a green shape) approaching the active site of an enzyme (a gray structure with an indentation). In the second stage, the substrate binds to the enzyme's active site, forming an enzyme-substrate complex. The third stage shows the enzyme changing shape slightly as it catalyzes the reaction, resulting in an enzyme-product complex. In the final stage, the products (a blue and a yellow shape) are released from the enzyme, which

remains unchanged and ready for another reaction cycle. Red arrows indicate movement throughout the process.

Enzyme Inhibitors

Enzymes can be regulated to reduce enzyme activity. An **enzyme inhibitor** is a molecule that binds to an enzyme and blocks its function. In **competitive inhibition**, an inhibitor binds to the active site and blocks the substrate from binding. In **allosteric inhibition** (non-competitive inhibition), an inhibitor binds to a site on the enzyme that is not the active site. This binding alters the enzyme's overall shape, preventing the substrate from binding to the active site.

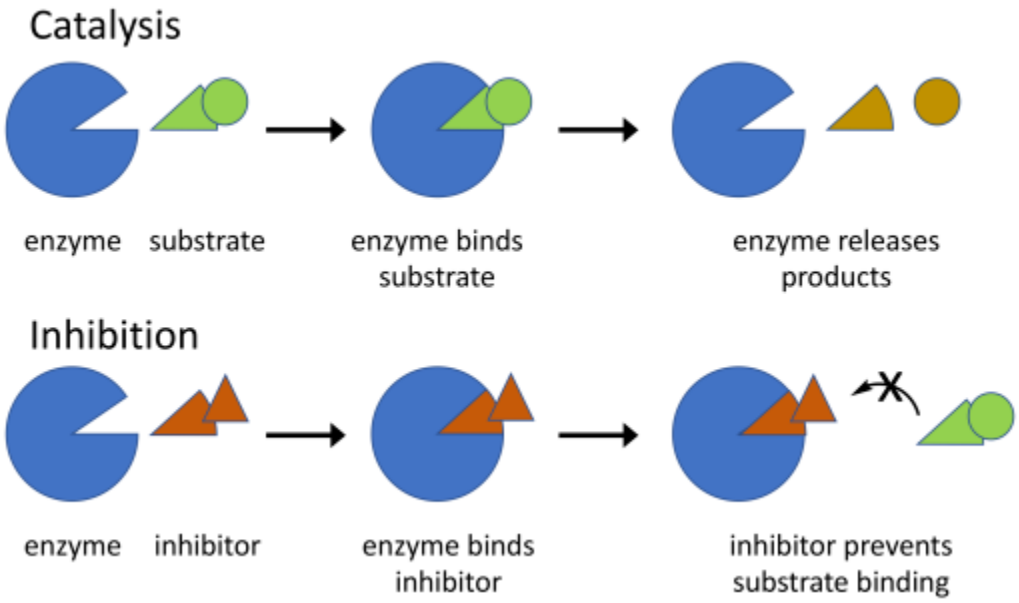


Figure 5.1.5 Image by Boghog, CC BY-SA 4.0

Figure 5.1.5 Description

The image illustrates two biochemical processes: Catalysis and Inhibition, using a simplified enzyme-substrate model.

- Catalysis Process: The enzyme (blue shape) is shown separately from the substrate (green shape). The substrate binds to the enzyme, fitting into its active site. The enzyme facilitates a reaction, breaking the substrate into smaller products (a yellow triangle and a yellow circle). The products are released, and the enzyme is free to catalyze another reaction.
- Inhibition Process: The enzyme is shown separately from an inhibitor (brown triangle). The inhibitor binds to the enzyme, occupying the active site. This binding prevents the substrate from attaching, blocking the enzyme's catalytic function. This diagram visually represents how enzymes catalyze

reactions and how inhibitors can regulate or block enzyme activity by preventing substrate binding.

Energy Transformations

In the scientific world, energy is the ability to do work. You can often see energy at work in living things — a bird flies through the air, a firefly glows in the dark, a dog wags its tail. Living organisms constantly use energy in less obvious ways, as well. Inside every cell of all living things, energy is needed to carry out life processes. Energy is required to break down, build up molecules, and transport many molecules across plasma membranes. All of life's work needs energy.

There are two main categories of energy:

Kinetic Energy

Kinetic energy is the energy associated with objects in motion. For example, a moving wrecking ball, a speeding bullet, a walking person, and the rapid movement of molecules in the air all have kinetic energy.

Figure 5.1.6 Moving water, such as in a waterfall, has kinetic energy. Image by APK, CC BY-SA 4.0

Potential Energy

Potential energy is stored in an object due to its position or state. For instance, a motionless wrecking ball lifted two stories high has potential energy because of its position and the force of gravity acting on it. Other examples include water held behind a dam, a compressed spring, or a pulled rubber band.

Figure 5.1.7 Still water behind a dam has potential energy.
Image by Mario Roberto Durán Ortiz, CC BY-SA 4.0

A principle known as the **conservation of energy** explains that energy can change forms or move from place to place, but it cannot be created or destroyed. For example, light bulbs convert electrical energy into light and heat, and plants convert sunlight into chemical energy.

The principle of conservation of energy is shown in the energy transformations of a wrecking ball. Imagine a wrecking ball lifted two stories high by a crane. When the ball is lifted, energy is used to raise it against the force of gravity. This energy doesn't disappear; instead, it is stored in the wrecking ball as potential energy due to its elevated position.

Now, if the wrecking ball is released, it starts to fall. As it falls, the potential energy is converted into kinetic energy, which is the energy of motion. When the wrecking ball reaches the ground, all the potential energy has been transformed into kinetic energy.

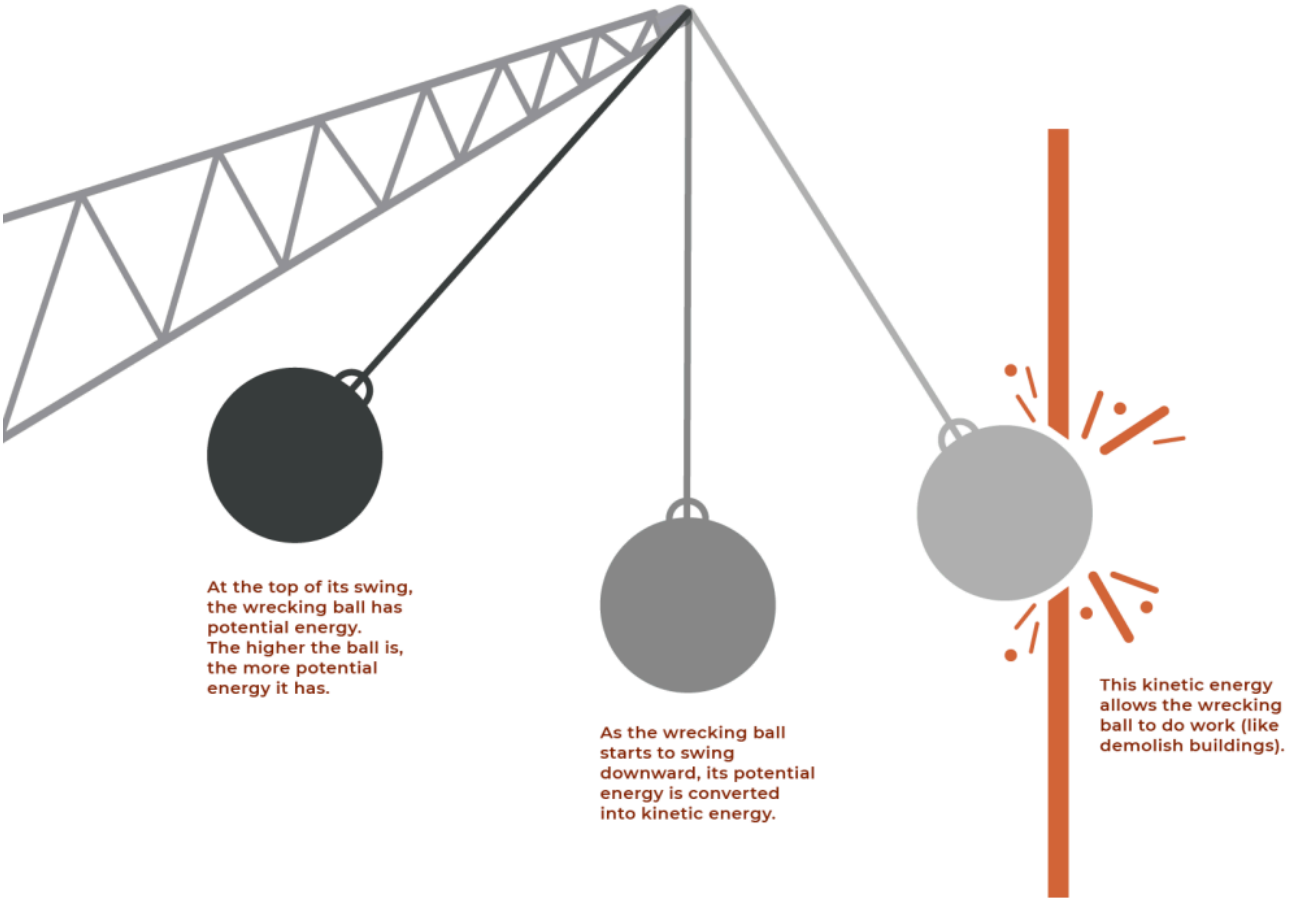


Figure 5.1.8 Energy transformations of a wrecking ball. Image by Freddy Vale, CC BY-NC-SA 4.0

Figure 5.1.8 Description

At the top of its swing, the wrecking ball has potential energy. The higher the ball is, the more potential energy it has. As the wrecking ball starts to swing downward, its potential energy is converted into kinetic energy. This kinetic energy allows the wrecking ball to do work (like demolish buildings).

Energy in Living Organisms

Living cells use chemical energy to provide energy for various cellular processes. **Chemical energy** is a type of potential energy stored within the bonds of chemical compounds, such as food molecules. When these bonds are broken, the stored energy is released and can be used to perform work.

Organisms mainly use two types of molecules for chemical energy: glucose and ATP. Both molecules are used as fuels throughout the living world.

Glucose

Glucose is a simple carbohydrate with the chemical formula $C_6H_{12}O_6$. It stores chemical energy in a concentrated, stable form. In your body, glucose is the form of energy that is carried in your blood and taken up by each of your trillions of cells. Glucose is the end product of photosynthesis and the nearly universal food for life.

ATP

ATP (adenosine triphosphate) is often referred to as the *energy currency* in the cell. It is the energy-carrying molecule that cells directly use to power most cellular processes (e.g., nerve impulse conduction, protein synthesis, and active transport).

ATP consists of adenosine (adenine + ribose) and a tail of three phosphate groups. Each phosphate group is negatively charged. These negative charges repel each other, which gives the tail potential energy. ATP releases energy when it gives up one of its three phosphate groups (P_i) and changes to ADP (adenosine diphosphate, which has two phosphate groups).

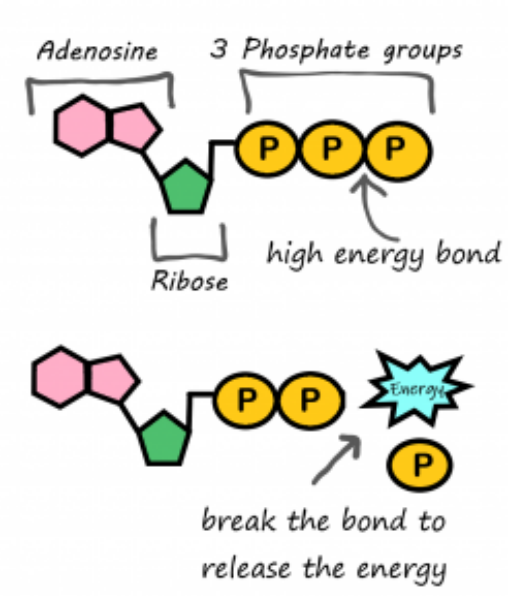


Figure 5.1.9 The breakdown of ATP into ADP + P_i is a catabolic reaction that releases energy. "ATP for energy" by Christine Miller, CC BY 4.0

Figure 5.1.9 Description

A diagram illustrating the structure and function of ATP (adenosine triphosphate) in energy release. The top

portion shows ATP with three phosphate groups (represented as yellow circles labelled 'P'), a ribose sugar (green pentagon), and an adenosine molecule (two pink hexagons). A label indicates a high-energy bond between the last phosphate group. The bottom portion shows the ATP molecule after breaking the bond between the previous phosphate group, forming ADP (adenosine diphosphate) and releasing energy, represented by a blue burst labelled "Energy." The diagram includes handwritten-style annotations explaining the process.

Exercise 5.1.1

Drag each item to its corresponding energy type

Text Description
Energy Types: Kinetic or Potential

Draggable items:

- A raised weight
- A stretched rubber band
- A baseball thrown by a pitcher
- An asteroid falling towards Earth
- Energy in ATP

Answers:

- Kinetic energy: A baseball thrown by a pitcher, An asteroid falling toward Earth
- Potential energy: A raised weight, A stretched rubber band, Energy in ATP

5.2 OVERVIEW OF PHOTOSYNTHESIS

Life runs on chemical energy. Most ecosystems get this energy from photosynthesis. **Photosynthesis** stores energy from sunlight in the chemical bonds of glucose. **Cellular respiration** is then used to break the chemical bonds in glucose to release energy and make ATP.

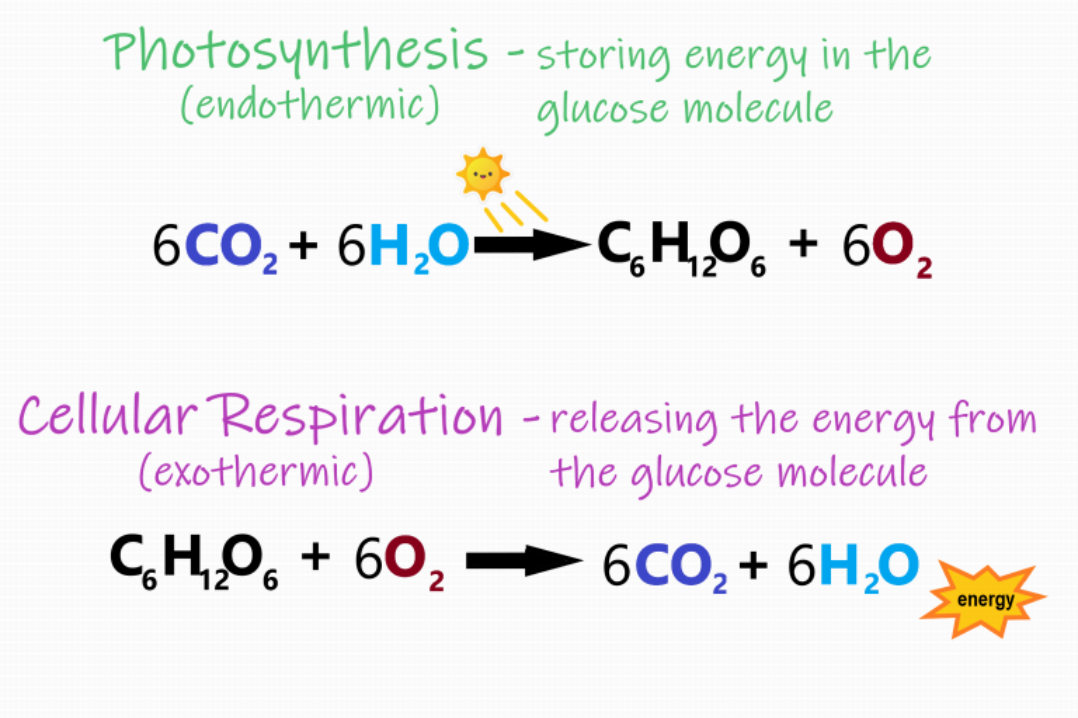


Figure 5.2.1 Energy transfer in photosynthesis and cellular respiration. Image by Christine Miller, CC BY 4.0

Figure 5.2.1 Description

A diagram comparing photosynthesis and cellular respiration with their respective chemical equations. The top section, labelled 'Photosynthesis (endothermic) – storing energy in the glucose molecule' in green text, shows the photosynthesis equation:
$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$.
A small sun icon with rays represents the energy input from sunlight.

The bottom section, labelled 'Cellular Respiration (exothermic) – releasing the energy from the glucose molecule' in purple text, shows the cellular respiration equation:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$.
A small yellow explosion-like shape labelled 'energy' represents the energy released during the process.

The colour-coded text highlights key elements in the equations: carbon dioxide (CO_2) in blue, water (H_2O) in light blue, oxygen (O_2) in red, and glucose ($C_6H_{12}O_6$) in black.

Not all organisms can make their own food. Organisms are divided into two categories based on how they obtain their chemical energy:

Autotrophs

An **autotroph** is an organism that can produce its own food. The Greek roots of the word autotroph mean "self" (auto) and "feeder" (troph). Most autotrophs use the energy in sunlight to make food during photosynthesis. Plants are the best-known autotrophs, but others exist, including algae and certain types of bacteria. Autotrophs are also called **producers**. They produce food for themselves and all other living things (consumers).

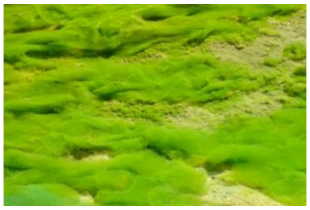
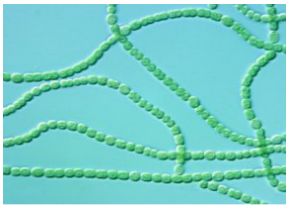




Figure 5.2.2 Photosynthetic autotrophs, which make food using the energy in sunlight, include plants (left), algae (middle), and certain bacteria (right). Plant by Ren Ran, Unsplash License, Green Algae by Tristan Schmurr, CC BY 2.0, and, Cyanobacteria by Argon National Laboratory, CC BY-NC-SA 2.0

Heterotrophs

Heterotrophs cannot make their own food, so they must get their food by consuming other organisms. The Greek roots of the word heterotroph mean "other" (hetero) and "feeder" (trophy), meaning that their food comes from consuming other organisms. Heterotrophs are also called **consumers**. Even if the food organism is another animal, this food traces its origins back to autotrophs and photosynthesis. Heterotrophs include all animals and fungi, as well as many single-celled organisms.

Energy Flow

Energy flows through an ecosystem. It enters as sunlight and exits as heat. In contrast, chemical elements are recycled within an ecosystem. Photosynthesis uses carbon dioxide (CO_2), a gas absorbed from the atmosphere, and water (H_2O), which is absorbed from the soil through the roots. Using the energy from sunlight, these molecules are rearranged to form glucose ($C_6H_{12}O_6$) and oxygen (O_2), a waste product that is released into the atmosphere. The products from photosynthesis are then used in cellular respiration. In the presence of oxygen, the chemical bonds in glucose are broken to release energy, which is harnessed to create ATP. Carbon dioxide and water are then produced as by-products.

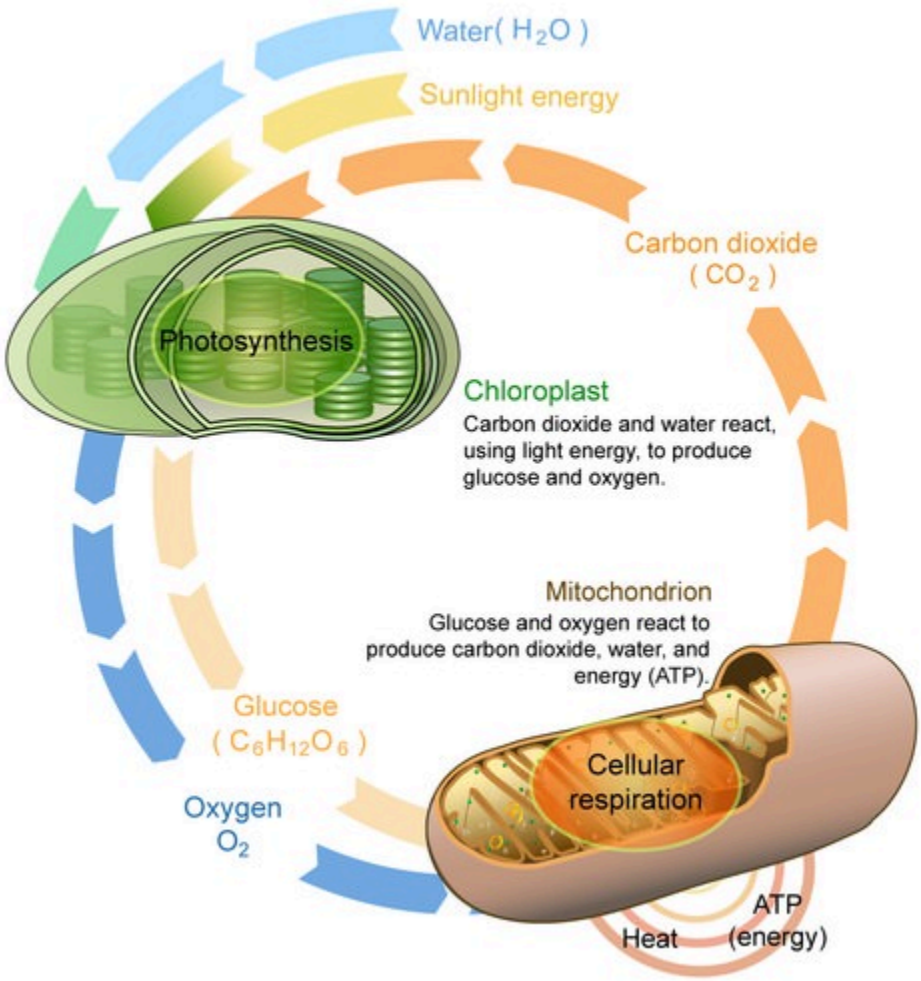


Figure 5.2.3 Photosynthesis and cellular respiration are related. The products of one process are the reactants of the other. Image, LadyofHats & CK-12 Foundation, CC BY-NC 3.0.

Figure 5.2.3 Description

This diagram visually explains how photosynthesis and cellular respiration are interconnected, forming a biological energy cycle that sustains life. Photosynthesis captures solar energy and stores it in glucose, while cellular respiration releases this energy for cellular activities.

Located inside the chloroplast, photosynthesis is depicted as the process where carbon dioxide (CO_2) and water (H_2O) react using sunlight energy to produce glucose ($C_6H_{12}O_6$) and oxygen (O_2). The photosynthesis reaction is labelled with green text.

Located inside the mitochondrion, cellular respiration occurs where glucose and oxygen are used to produce carbon dioxide, water, and ATP (energy). The cellular respiration reaction is labelled in orange text.

Circular Flow of Matter and Energy: The image uses arrows forming a continuous cycle to represent the exchange of materials between the two processes. Blue arrows indicate the movement of oxygen and glucose from photosynthesis to cellular respiration. Orange arrows show the transfer of carbon dioxide and water back to photosynthesis.
Sunlight energy is absorbed for photosynthesis, while heat and ATP energy are released during respiration.

Location of Photosynthesis

In plants, photosynthesis takes place primarily in leaves, which consist of many layers of cells and have differentiated top and bottom sides. The process of photosynthesis occurs not on the surface layers of the leaf but rather in a middle layer called the **mesophyll**. The gas exchange of carbon dioxide and oxygen occurs through small, regulated openings called **stomata**.

In all autotrophic eukaryotes, photosynthesis takes place inside an organelle called a **chloroplast**. In plants, chloroplast-containing cells exist in the mesophyll. Chloroplasts have a double (inner and outer) membrane. Within the chloroplast, there are stacked, disc-shaped structures called **thylakoids**. **Chlorophyll** molecules are embedded in the thylakoid membrane, a pigment (a molecule that absorbs light) through which the entire process of photosynthesis begins. Chlorophyll is responsible for the green colour of plants. The thylakoid membrane encloses an internal space called the thylakoid space. Other types of pigments are also involved in photosynthesis, but chlorophyll is by far the most important. A stack of thylakoids is called a granum, and the space surrounding the granum is called stroma (not to be confused with stomata, the openings on the leaves).

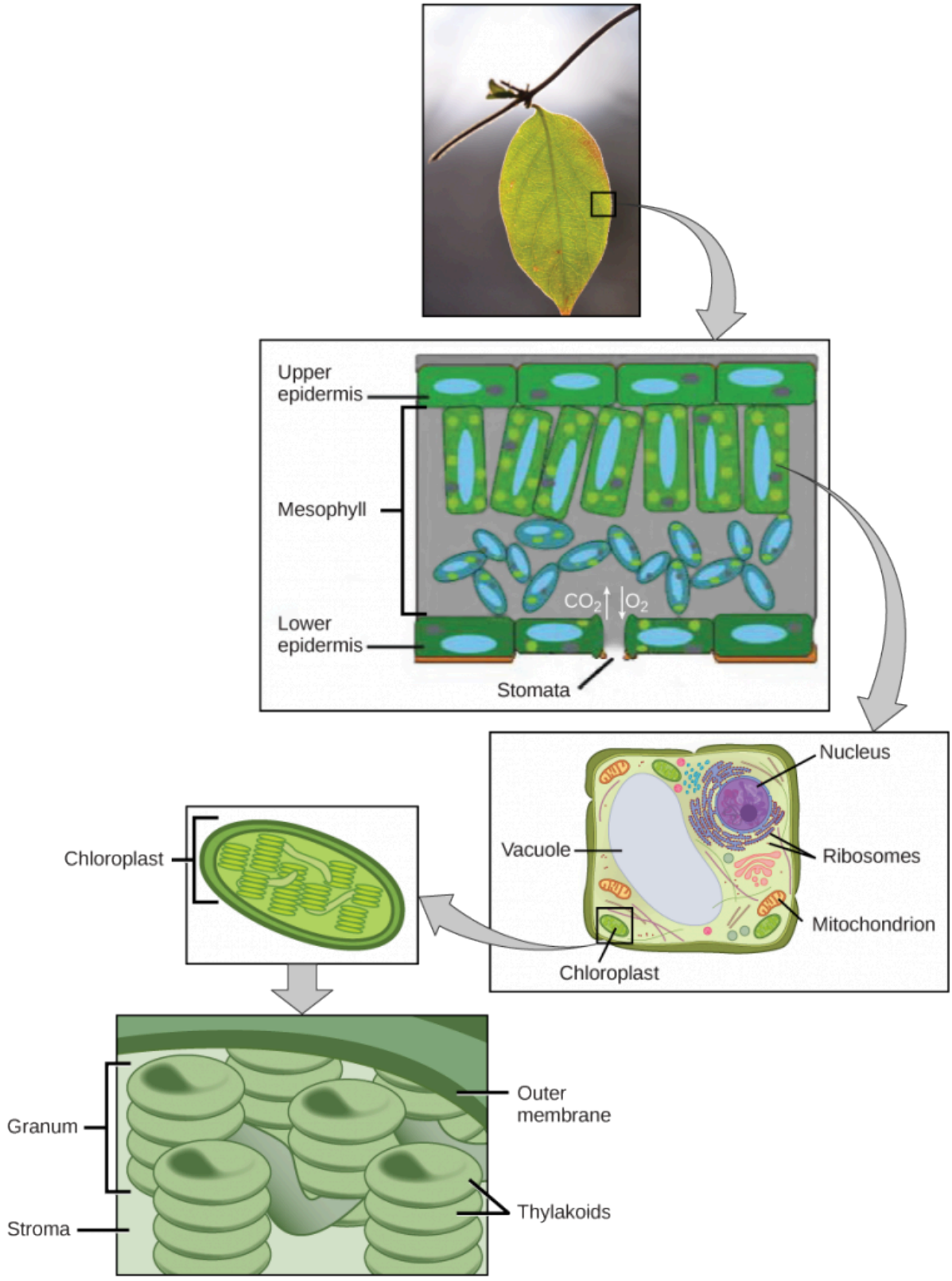


Figure 5.2.4 Not all cells of a leaf carry out photosynthesis. Cells within the middle layer of a leaf have chloroplasts, which contain the photosynthetic apparatus. Image by OpenStax, based on a work by Cory Zanker, CC BY 4.0

Figure 5.2.4 Description

A detailed diagram illustrates a leaf's structure and its internal components, focusing on photosynthesis. At the top, a photograph of a green leaf on a branch is shown, with a small section highlighted for magnification. Below, a cross-section of the leaf displays its layers: the upper epidermis, mesophyll, and lower epidermis. The mesophyll contains chloroplasts, where photosynthesis occurs, and stomata, which facilitate gas exchange (CO_2 intake and O_2 release). Another magnified section highlights a plant cell, showing organelles such as the nucleus, vacuole, ribosomes, mitochondrion, and chloroplast. Further zooming in, a chloroplast diagram is displayed, labelling its internal structures, including the outer membrane, stroma, granum, and thylakoids, where light-dependent photosynthesis reactions occur. Arrows indicate the progressive zooming in from the whole leaf to its cellular and organelle components.

Stages of Photosynthesis

Photosynthesis occurs in two stages: the light-dependent reactions and the Calvin cycle. In the light-dependent reactions, which take place at the thylakoid membrane, chlorophyll absorbs energy from sunlight and then converts it into chemical energy using water. The light-dependent reactions release oxygen from the hydrolysis of water as a byproduct. In the Calvin cycle, which takes place in the stroma, the chemical energy derived from the light-dependent reactions drives both the capture of carbon in carbon dioxide molecules and the subsequent assembly of sugar molecules. The two reactions use carrier molecules to transport the energy from one to the other. The carriers that move energy from the light-dependent reactions to the Calvin cycle reactions can be considered "full" because they bring energy. After the energy is released, the "empty" energy carriers return to the light-dependent reactions to obtain more energy.

Exercises 5.2.1

Text Description

1. On a hot, dry day, plants close their stomata to conserve water. What impact will this have on photosynthesis?

a. The rate of photosynthesis will slow down
b. The rate of photosynthesis will speed up
c. The rate of photosynthesis will stop
d. The rate of photosynthesis will stay the same

2. What two products result from photosynthesis?

a. Glucose and oxygen
b. Water and carbon dioxide
c. Water and oxygen
d. Glucose and carbon dioxide

3. All of the statements about thylakoids are correct EXCEPT...

a. Thylakoids exist as a maze of folded membranes
b. Thylakoids contain chlorophyll
c. The space surrounding thylakoids is called stroma
d. Thylakoids are assembled into stacks

4. From where does a heterotroph directly obtain its energy?

a. The sun and eating other organisms
b. Eating other organisms
c. The sun
d. Simple chemicals in the environment

5. The overall purpose of the light reactions in photosynthesis is to convert solar energy into kinetic energy that cells can use to do work. True or false?

6. Carnivores, such as lions, are dependent on photosynthesis to survive because lions eat animals

that eat plants. True or false?

Answers:

1. a. The rate of photosynthesis will slow down

2. a. Glucose and oxygen

3. a. Thylakoids exist as a maze of folded membranes

4. b. Eating other organisms

5. False

6. True

5.3 LIGHT-DEPENDENT REACTIONS

How can light be used to make food? It is easy to think of light as something that exists and allows living organisms, such as humans, to see, but light is a form of energy. Like all energy, light can travel, change form, and be harnessed to do work. In the case of photosynthesis, light energy is transformed into chemical energy, which autotrophs use to build carbohydrate molecules.

Figure 5.3.1 Autotrophs capture light energy from the sun. Image modification of work by Gerry Atwell, U.S. Fish and Wildlife Service, CC BY 4.0

What Is Light Energy?

The sun emits an enormous amount of solar energy. The manner in which solar energy travels can be described and measured as waves. Scientists can determine a wave's energy amount by measuring its **wavelength**, the distance between two consecutive, similar points in a series of waves, such as from crest to

crest or trough to trough (5.3.2). Shorter wavelengths correspond to higher energy, while longer wavelengths have lower energy.

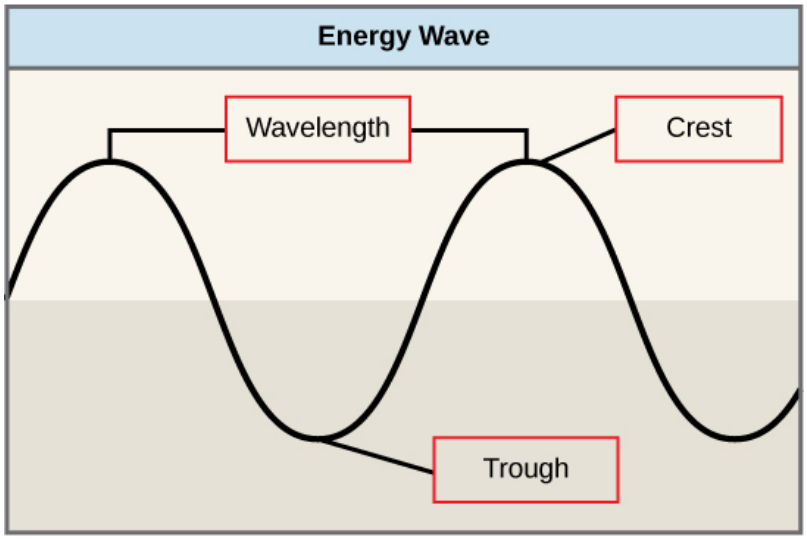


Figure 5.3.2 The wavelength of a single wave. Image by OpenStax, CC BY 4.0

Figure 5.3.2 Description

This diagram visually represents fundamental wave properties, often used in physics and energy-related concepts such as sound, light, and water waves.

- Wavelength – Indicated as the horizontal distance between two successive crests (peaks) of the wave.
- Crest – Marked at the highest point of the wave.
- Trough – Marked at the lowest point of the wave.

The electromagnetic spectrum is the range of all possible wavelengths of radiation (Figure 5.3.3). Each wavelength corresponds to a different amount of energy carried. **Visible light** is a small portion of the electromagnetic spectrum that is detectable by the human eye, ranging from approximately 380 to 750 nanometers in wavelength. The visible light seen by humans as white light actually exists in a rainbow of colours. Certain objects, such as a prism or a drop of water, disperse white light to reveal these colours to the human eye – violet, blue, green, yellow, orange and red. Violet and blue have shorter wavelengths and, therefore, higher energy. At the other end of the spectrum, toward red, the wavelengths are longer and have lower energy.

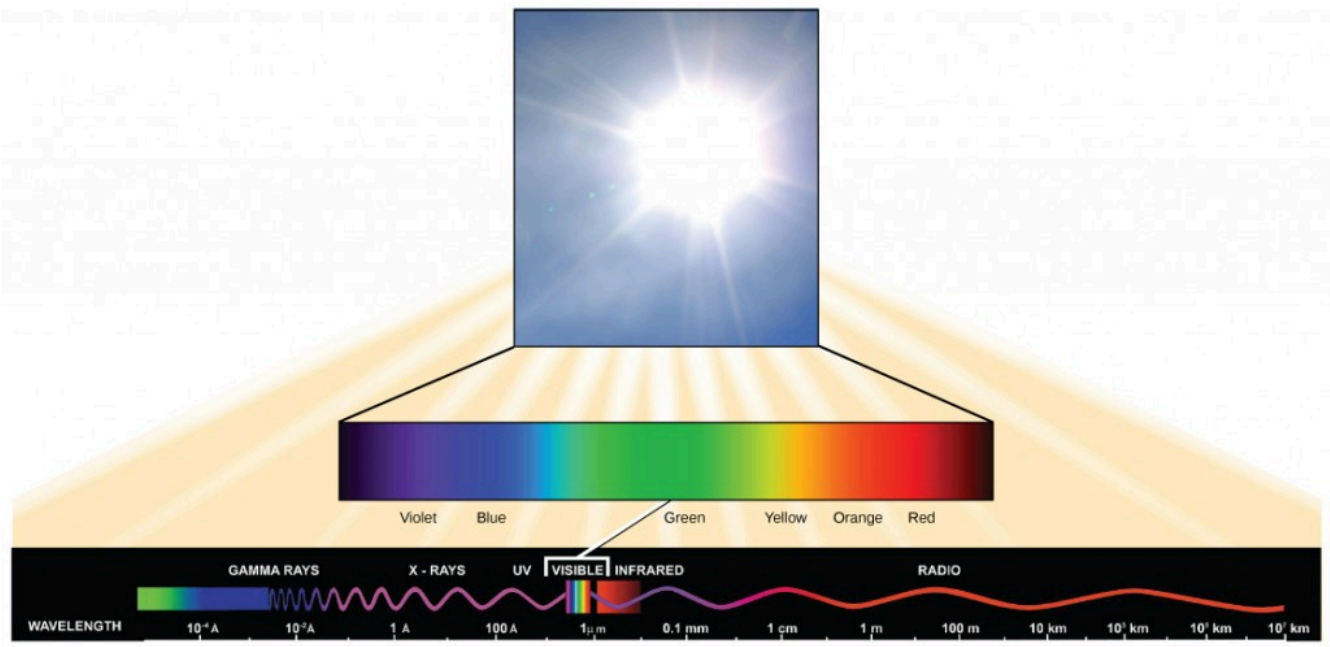


Figure 5.3.3 The sun emits energy in the form of electromagnetic radiation. Visible light is one type of energy emitted from the sun. Image by OpenStax, CC BY 4.0

Figure 5.3.3 Description

The diagram visually explains how sunlight contains a full spectrum of electromagnetic waves, but only a small portion is visible to humans. The illustration suggests that visible light is just a tiny segment of the vast electromagnetic spectrum. The diagram consists of three main components:

- A photograph of bright sunlight in the top section, illustrating the source of visible light.
- A colour spectrum bar beneath the image of the sun, transitioning smoothly from violet to red, representing the visible spectrum of light.
- The electromagnetic spectrum at the bottom showing different types of electromagnetic waves arranged by wavelength: Gamma Rays (shortest wavelength, highest energy), X-rays, Ultraviolet (UV), Visible Light (highlighted in a small band), Infrared (IR), Radio Waves (longest wavelength, lowest energy), The wavelength scale increases from left to right, starting at 10^{-10} meters (angstroms) for gamma rays and extending to 10^{7} kilometers for radio waves. A small "VISIBLE" section is marked in the spectrum to show the tiny range of wavelengths that human eyes can detect.

Understanding Pigments

Light energy enters the process of photosynthesis when pigments absorb the light. A **pigment** is a substance that absorbs light and gives colour to plants, animals, and other materials. In plants, pigment molecules absorb only visible light for photosynthesis. Different kinds of pigments exist, each absorbing only certain wavelengths (colours) of visible light. Pigments reflect the colour of the wavelengths that they cannot absorb.

All photosynthetic organisms contain a pigment called chlorophyll, which humans see as the common green colour associated with plants. *Chlorophyll a* absorbs wavelengths from either end of the visible spectrum (blue and red) but not from green. Because green is reflected, chlorophyll appears green.

Other pigment types include *chlorophyll b* (which absorbs blue and red-orange light) and carotenoids. Each type of pigment can be identified by the specific pattern of wavelengths it absorbs from visible light, which is its absorption spectrum.

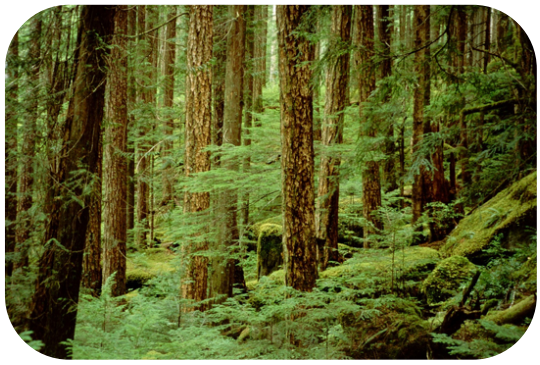


Figure 5.3.4 Plants that grow in the shade benefit from having a variety of light-absorbing pigments. Image by Jason Hollinger, CC BY 4.0

Many photosynthetic organisms have a mixture of pigments; between them, they can absorb energy from a broader range of visible-light wavelengths. Not all photosynthetic organisms have full access to sunlight. Some organisms grow underwater where light intensity decreases with depth, and the water absorbs certain wavelengths. Other organisms grow in competition for light. Plants on the rainforest floor must be able to absorb any bit of light that comes through because the taller trees block most of the sunlight (Figure 5.3.4).

Location of Light-Dependent Reactions

The light-dependent reactions occur in the thylakoid membrane of chloroplasts. Studded in the thylakoid membrane are **photosystems**, clusters of pigments and proteins that absorb sunlight. In the photosystem, a **photon** (a quantity or "packet" of light energy) is absorbed by a chlorophyll molecule and bounced around to other chlorophyll molecules until it eventually hits the *chlorophyll a* found in the reaction centre. The photon causes an electron in the chlorophyll to become "excited." The energy given to the electron allows it to break free from an atom of the chlorophyll molecule. Chlorophyll is therefore said to "donate" an electron. In eukaryotes and some prokaryotes, there are two photosystems – photosystem II (PSII) and photosystem I (PSI) – which were named for the order of their discovery rather than for the order of the function.

How Light-Dependent Reactions Work

The overall purpose of the **light-dependent reactions** is to convert light energy into chemical energy. The chemical energy is stored by two types of energy-carrier molecules: ATP and NADPH. This chemical energy will be used by the Calvin cycle to fuel the assembly of sugar molecules.

The Light-Dependent Reactions start with PSII where a photon excites an electron in the reaction centre chlorophyll (Figure 5.3.5). This electron then passes to the next step in the light reactions, which we'll discuss soon. For PSII to absorb more energy, that donated electron must be replaced. To do so, a water molecule is split to release the electrons, oxygen (O_2) and hydrogen ions (H^+). The electrons replace the donated electron from chlorophyll. The oxygen produced is a waste product that simply diffuses out of the cell and into the surrounding environment. The hydrogen ions produced play critical roles in the next step in the light-dependent reactions.

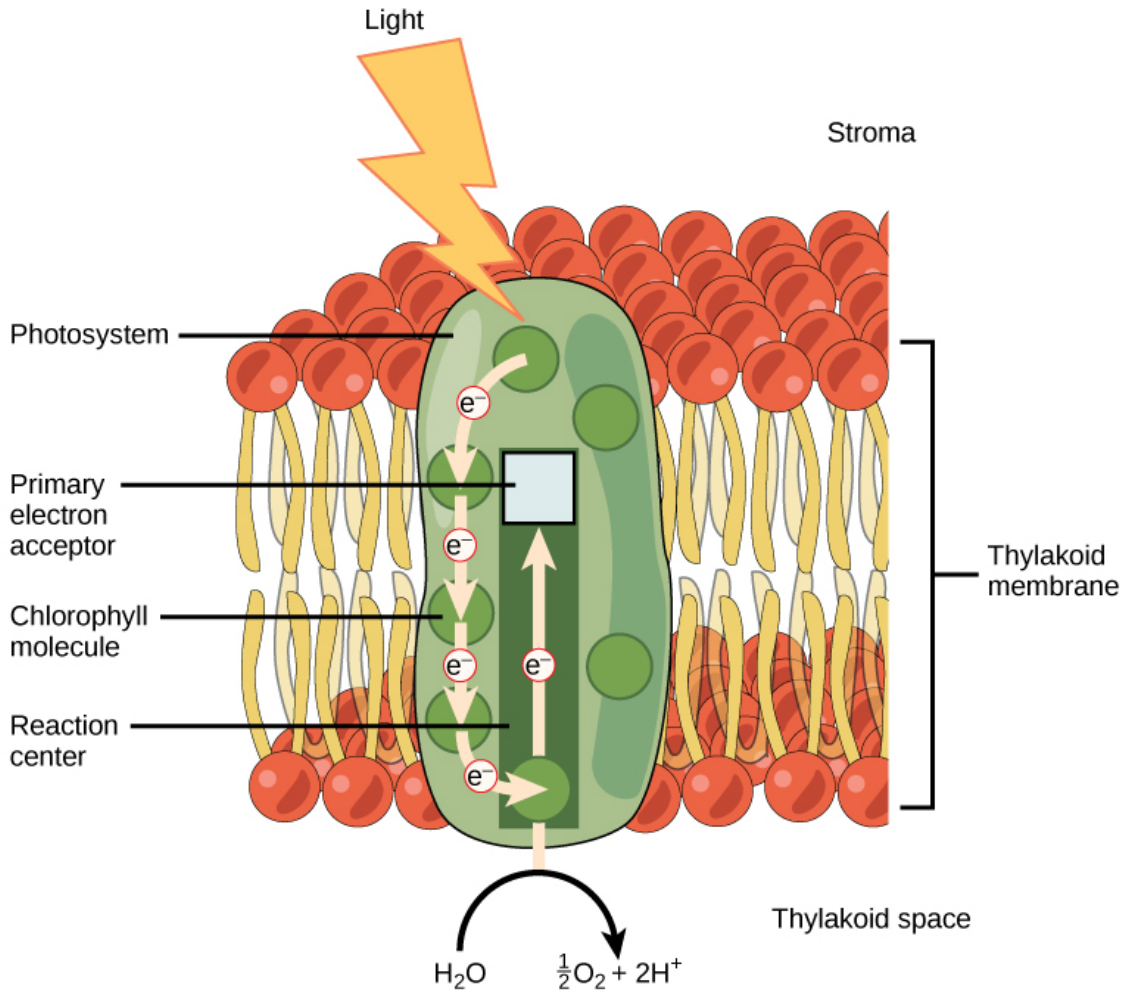


Figure 5.3.5 Light energy is absorbed by a chlorophyll molecule in Photosystem II. Image by OpenStax, CC BY 4.0

Figure 5.3.5 Description

This diagram represents the first stage of photosynthesis that occurs in the thylakoid membrane, helping convert light energy into chemical energy for use in the Calvin cycle.

- Key Components and Labels:
  Light Energy (Lightning Bolt): Light energy strikes the photosystem, initiating the process of electron excitation.
- Thylakoid Membrane Structure: The thylakoid membrane is shown as a bilayer composed of phospholipids (red and yellow structures).
  The stroma (fluid-filled space outside the thylakoid) is labelled at the top. The thylakoid space (interior of the thylakoid) is labelled at the bottom.
- Photosystem and Electron Flow: The photosystem (green, oval-shaped structure) contains chlorophyll molecules that absorb light energy.
  The reaction center (bottom of the photosystem) is where electrons are excited. The primary electron acceptor (top of the photosystem) captures excited electrons. Arrows show the electron transport chain, where electrons (e^-) move upward through different molecules.

Water Splitting (Photolysis): At the bottom, H_2O is split into oxygen (O_2) and protons (H^+), contributing to the electron supply. Overall Process Depicted: Light energy excites electrons in the chlorophyll molecules. Electrons move through the electron transport chain. Water molecules (H_2O) split, producing oxygen (O_2) and protons (H^+). The excited electrons continue through the electron transport chain, leading to the production of ATP and NADPH in subsequent steps.

Photosystem II transfers the excited electron to the electron transport chain (ETC). The electron transport chain is a series of proteins inside the thylakoid membrane (Figure 5.3.6). As the electron passes along these proteins, energy from the electron fuels membrane pumps that actively move hydrogen ions against their concentration gradient. After the energy is used, the electron is accepted by a pigment molecule in the next photosystem (PSI).

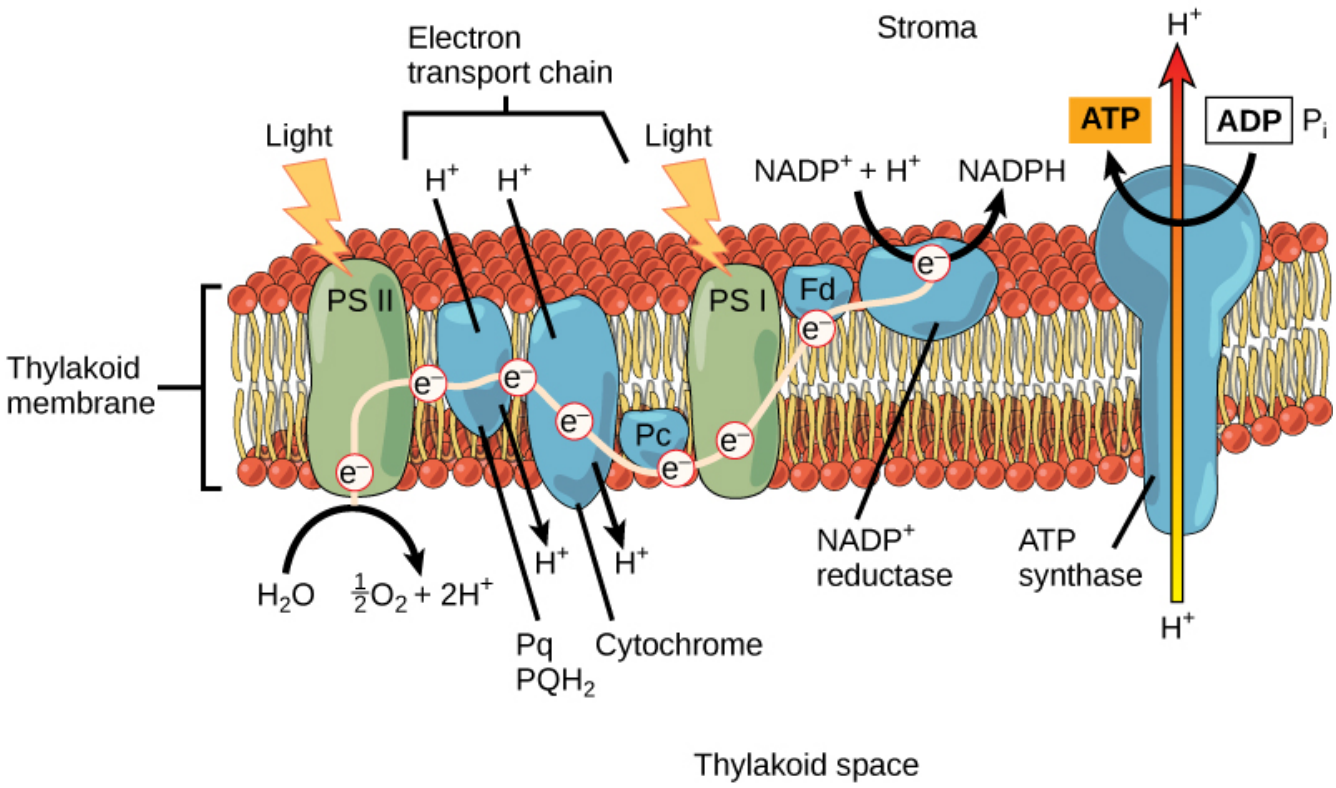


Figure 5.3.6 Electrons flow from water, to PSII, to the ETC, to PSI and ultimately to NADPH for transport to the Calvin Cycle. Image by OpenStax, CC BY 4.0

Figure 5.3.6 Description

This diagram represents the light-dependent reactions of photosynthesis, which occur in the thylakoid membrane and generate ATP and NADPH for the Calvin cycle.

Key Components and Labels:

- Thylakoid Membrane: The diagram shows the thylakoid membrane as a lipid bilayer embedded with proteins involved in the electron transport chain. The stroma (fluid-filled space outside the thylakoid) is labelled at the top. The thylakoid space (interior of the thylakoid) is labelled at the bottom.
- Photosystem II (PS II) – First Light Reaction: Light energy (lightning bolt) excites electrons in Photosystem II (PS II). Water (H_2O) is split, producing oxygen (O_2) and protons (H^+). Excited electrons (e^-) move to Plastoquinone (Pq/PQH_2) and then to Cytochrome complex.
- Electron Transport Chain (ETC) and Proton Gradient: As electrons move through the cytochrome complex, protons (H^+) are pumped from the stroma into the thylakoid space, creating a proton gradient.
- Photosystem I (PS I) – Second Light Reaction: Light energy (lightning bolt) excites electrons in Photosystem I (PS I). Electrons move through Ferredoxin (Fd) to $NADP^+$ reductase, reducing $NADP^+$ to NADPH, which is used in the Calvin cycle.

- ATP Synthase and ATP Production: Protons (H^+) flow down their gradient from the thylakoid space to the stroma through ATP synthase. This flow drives ADP + P_i → ATP synthesis, providing energy for the Calvin cycle.

Overall Process Depicted:
Water is split, generating oxygen, protons, and electrons. Light excites electrons in PS II, starting the electron transport chain. Protons are pumped, creating a proton gradient. Electrons are re-energized in PS I and transferred to $NADP^+$, forming NADPH. ATP synthase produces ATP using the proton gradient.

Generating an Energy Carrier: ATP

The electron transport chains create a higher concentration of H^+ in the thylakoid space than in the stroma. This buildup of H^+ has potential energy, similar to water behind a dam. The gradient causes H^+ to flow back across the membrane into the stroma, where their concentration is lower. H^+ pass through a channel protein and enzyme called **ATP synthase**. The flow of H^+ through ATP synthase causes it to spin. This rotary motion generates kinetic energy, which is used to attach an inorganic phosphate (P) to a molecule of ADP, forming ATP.

Generating another Energy Carrier: NADPH

The final function of the **light-dependent reactions** is to generate the energy-carrier molecule **NADPH** from **NADP+** (Nicotinamide Adenine Dinucleotide Phosphate). NADPH is an **electron carrier**, a molecule that transports high-energy electrons and hydrogen ions to other parts of the cell (to the Calvin cycle).

You can think of $NADP^+$ as an empty Uber – ready to pick up passengers (electrons and hydrogen ions). Once it collects them, it becomes NADPH, the full Uber, which then carries the energy to its next destination.

As electrons move through the electron transport chain of the light-dependent reactions, they eventually arrive at Photosystem I. Here, they are re-energized by another photon absorbed by chlorophyll. These high-energy electrons, along with a hydrogen ion (H^+), are then picked up by $NADP^+$, converting it into NADPH.

Now that the solar energy is stored in energy carriers (ATP and NADPH), it can be used in the Calvin cycle to make a sugar molecule.

Exercises 5.3.1

Text Description

1. What is the energy of a photon first used to do in photosynthesis?

a. Energize an electron
b. Produce ATP
c. Split a water molecule
d. Synthesize glucose

2. Which molecule absorbs the energy of a photon in photosynthesis?

a. ATP
b. Water
c. Glucose
d. Chlorophyll

3. Plants produce oxygen when they photosynthesize. Where does the oxygen come from?

a. Chlorophyll
b. Splitting water molecules
c. The electron transport chain
d. ATP synthesis

4. Which colour (s) of light does chlorophyll *a* reflect?

a. Red and blue
b. Red
c. Blue
d. Green

5. Drag the words into the correct boxes to describe the pathway of energy in light-dependent reactions.

The energy is present initially as light. A _____ of light hits _____, causing an _____ to be energized. The free _____ travels through the _____ chain, and the energy is used to pump _____ into the _____ space, transferring the energy into the _____ gradient. The energy of the gradient

is used to power ATP _____, and the energy is transferred into a bond in the ATP _____. In addition, energy from another photon can be used to create a high-energy _____ in the molecule _____.
Possible answers:

- bond
- electron
- electron
- synthase
- photon
- thylakoid
- electrochemical
- hydrogen ions
- electron transport
- NADPH
- molecule
- chlorophyll

6. Categories: Requires (goes in) and Produces (goes out)

Draggable items: ATD, ADP, NADPH, Oxygen gas, Water, Photons

Answers:

1. a. Energize an electron

2. d. Chlorophyll

3. b. Splitting water molecules

4. d. Green

5. The energy is present initially as light. A ***photon*** of light hits ***chlorophyll***, causing an ***electron*** to be energized. The free ***electron*** travels through the ***electron transport*** chain, and the energy is used to pump ***hydrogen ions*** into the ***thylakoid*** space, transferring the energy into the ***electrochemical*** gradient. The energy of the gradient is used to power ATP ***synthase***, and the energy is transferred into a bond in the ATP ***molecule***. In addition, energy from another photon can be used to create a high-energy ***bond*** in the molecule ***NADPH***.

6. Requires (goes in): Photons, ADP, Water
Produces (goes out): Oxygen Gas, ATP, NADPH

5.4 THE CALVIN CYCLE

After the energy from the sun is converted and packaged into ATP and NADPH, the cell has the fuel needed to build food in the form of carbohydrate molecules. The carbohydrate molecules made will have a backbone of carbon atoms. Where does the carbon come from? The carbon atoms used to build carbohydrate molecules come from carbon dioxide, the gas animals exhale with each breath. The Calvin cycle is the term used for the reactions of photosynthesis that use the energy stored by the light-dependent reactions to form glucose and other carbohydrate molecules.

Location of the Calvin Cycle

In plants, carbon dioxide (CO_2) enters the chloroplast through the stomata and diffuses into the stroma of the chloroplast—the site of the Calvin cycle reactions where sugar is synthesized (5.4.1). The reaction is named after the scientist who discovered it and references the fact that the reactions function as a cycle.

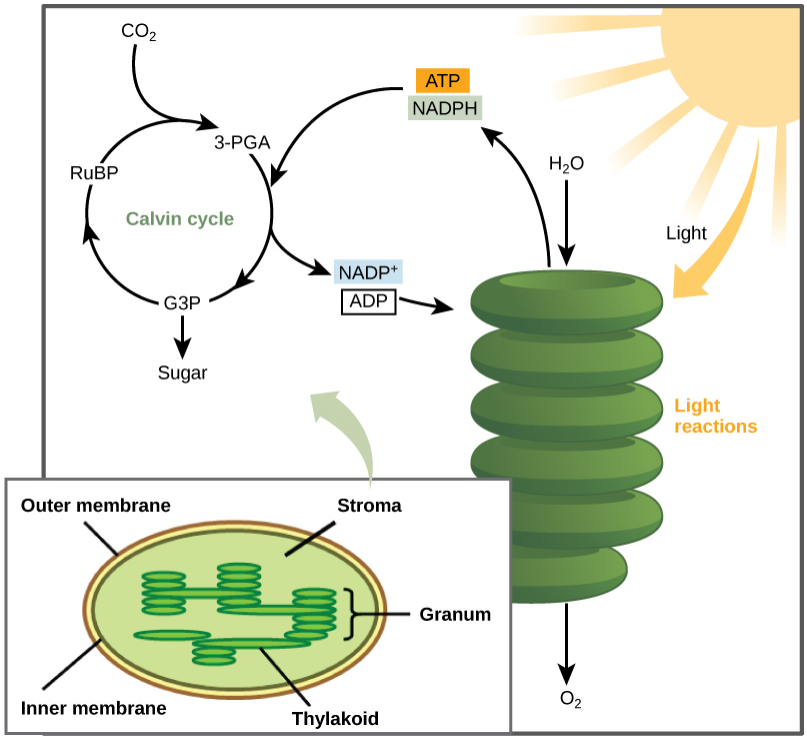


Figure 5.4.1 The Calvin cycle occurs in the stroma. Image by OpenStax, CC BY 4.0

Figure 5.4.1 Description

This diagram effectively conveys the key steps of photosynthesis and the relationship between light-dependent and light-independent reactions.

Main Components and Processes:

- Light Reactions (Right Side of the Image): Sunlight provides energy for photosynthesis. Water (H_2O) is split into oxygen (O_2), which is released. The light reactions take place in the thylakoid membranes of the chloroplast. ATP (adenosine triphosphate) and NADPH (nicotinamide adenine dinucleotide phosphate) are produced.
- Calvin Cycle (Left Side of the Image): Occurs in the stroma of the chloroplast. CO_2 (carbon dioxide) is incorporated into the cycle. The molecule RuBP (ribulose bisphosphate) is involved in carbon fixation. 3-PGA (3-phosphoglycerate) is an intermediate molecule. G3P (glyceraldehyde-3-phosphate) is formed, which can be used to produce sugars. ATP and NADPH from the light reactions provide energy and reducing power.
- Chloroplast Structure (Inset Diagram): Shows the outer and inner membranes. The stroma is the fluid-filled space where the Calvin cycle occurs. Grana are stacks of thylakoids where the light reactions take place.

Overall Process:

- Light reactions convert light energy into chemical energy (ATP and NADPH).
- The Calvin cycle uses ATP and NADPH to fix carbon dioxide and produce glucose.

Stages of the Calvin Cycle

The Calvin cycle reactions (Figure 5.4.2) can be organized into three basic stages: fixation, reduction, and regeneration. In the stroma, in addition to CO_2, two other chemicals are present to initiate the Calvin cycle: an enzyme abbreviated RuBisCO and the molecule ribulose bisphosphate (RuBP). RuBP has five atoms of carbon and a phosphate group on each end.

RuBisCO catalyzes a reaction between CO_2 and RuBP, which forms a six-carbon compound that is immediately converted into two three-carbon compounds (3-Phosphoglycerate, 3-PGA). This process is called **carbon fixation** because CO_2 is "fixed" from its inorganic form into organic molecules.

ATP and NADPH use their stored energy to convert the three-carbon compound, 3-PGA, into another three-carbon compound called glyceraldehyde-3-phosphate (G3P). This type of reaction is called a **reduction** reaction because it involves the gain of electrons. A reduction is the gain of an electron by an atom or

molecule. The molecules of ADP and NAD^+, resulting from the reduction reaction, return to the light-dependent reactions to re-energize.

One of the G3P molecules leaves the Calvin cycle to contribute to the formation of glucose ($C_6H_{12}O_6$). Because glucose has six carbon atoms, it takes six turns of the Calvin cycle to make one molecule of glucose (one for each carbon dioxide molecule fixed). The remaining G3Ps are used in the **regeneration of RuBP**, which allows the cycle to start again. ATP from the light-dependent reactions provides the necessary energy for this regeneration process.

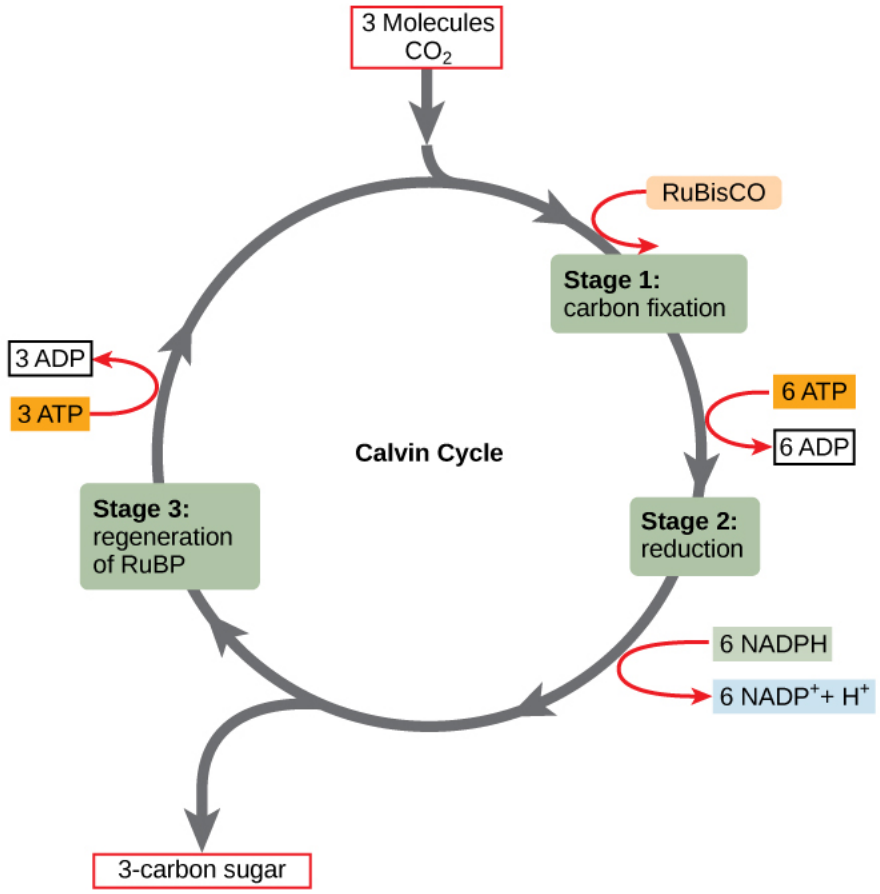


Figure 5.4.2 The Calvin cycle. Image by OpenStax, CC BY 4.0

Exercises 5.4.1

Text Description

1. Where in plant cells does the Calvin cycle take place?

a. Stroma
b. Granum
c. Thylakoid space
d. Thylakoid membrane

2. Which statement correctly describes carbon fixation?

a. The production of carbohydrate molecules from G3P
b. The formation of RuBP from G3P molecules
c. The use of RUBISCO to form 3-PGA
d. The conversion of CO₂ to an organic compound

3. What is the molecule that leaves the Calvin cycle to be converted into glucose?

a. RuBP
b. ADP
c. 3-PGA
d. G3P

4. Which part of the Calvin cycle would be affected if a cell could not produce the enzyme RuBisCO?

a. The middle part of the Calvin cycle could take place.
b. None of the parts of the Calvin cycle could take place.
c. All parts of the Calvin cycle could take place.
d. The last part of the Calvin cycle could not take place.

5. Drag the words into the correct boxes to explain the reciprocal nature of the net chemical reactions for photosynthesis and respiration.

The process of _____ takes the energy of sunlight and combines _____ and _____ to produce _____ and _____ as a waste product. The reactions of _____ take _____ and consume _____ to break it down into _____ and _____, releasing energy. Thus, the reactants of _____ are the _____

of respiration, and vice versa.
Possible answers:

- sugar
- products
- water
- respiration
- photosynthesis
- oxygen
- photosynthesis
- water
- carbon dioxide
- oxygen
- sugar
- carbon dioxide

Answers:

1. a. Stroma

2. d. The conversion of CO_2 to an organic compound

3. d. G3P

4. b. None of the parts of the Calvin cycle could take place.

5. The process of ***photosynthesis*** takes the energy of sunlight and combines ***water*** and ***carbon dioxide*** to produce ***sugar*** and ***oxygen*** as a waste product. The reactions of ***respiration*** take ***sugar*** and consume ***oxygen*** to break it down into ***carbon dioxide*** and ***water***, releasing energy. Thus, the reactants of ***photosynthesis*** are the ***products*** of respiration, and vice versa.

CHAPTER 5 SUMMARY

Key Takeaways

- **Energy and Its Role in Living Organisms:** Living organisms rely on chemical energy, stored in molecules like glucose and ATP, to fuel cellular processes. Glucose is a stable form of stored energy, while ATP is the immediate energy currency, releasing energy when converted to ADP. Energy exists in two main forms: kinetic energy (movement) and potential energy (stored energy). The conservation of energy principle states that energy can change forms but cannot be created or destroyed, as seen in energy transformations in both physical and biological systems.
- **Metabolism and Enzymes in Biochemical Reactions**: Metabolism encompasses all biochemical reactions in living organisms, including catabolic reactions (which break down molecules and release energy, e.g., cellular respiration) and anabolic reactions (which build molecules and absorb energy, e.g., protein synthesis). Enzymes are biological catalysts that speed up these reactions by lowering activation energy, ensuring life-sustaining processes occur efficiently.
- **Photosynthesis and Cellular Respiration:** Autotrophs (producers), such as plants, algae, and some bacteria, capture sunlight and store energy in glucose through photosynthesis. Heterotrophs (consumers), including animals and fungi, rely on autotrophs for food. Energy is transferred as glucose is broken down through cellular respiration to produce ATP, the energy currency of life. This cycle sustains all living organisms, recycling carbon and oxygen while maintaining the energy balance in ecosystems.
- **Light-Dependent Reactions:** Photosynthesis converts light energy into chemical energy through light-dependent reactions, which occur in the thylakoid membrane. Pigments like chlorophyll absorb sunlight, exciting electrons that move through the electron transport chain, driving the production of ATP and NADPH. These energy carriers fuel the Calvin cycle, where sugar molecules are synthesized. This process enables autotrophs to produce food, supporting life and energy flow in ecosystems.
- **The Calvin Cycle:** The Calvin cycle uses ATP and NADPH from light-dependent reactions to

fix CO^2 into organic molecules, ultimately forming glucose. This process occurs in the stroma and involves three stages: carbon fixation, reduction, and regeneration. Photosynthesis and cellular respiration form a biological energy cycle, where photosynthesis stores solar energy in carbohydrates, and respiration releases this energy for cellular functions. This cycle sustains life by continuously transforming and recycling energy and matter in ecosystems.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into six key takeaways.

Flashcards

Text Description

1. **Biochemical reactions:** Chemical reactions occurring within living organisms
2. **Metabolism**: All chemical reactions in an organism; includes catabolism and anabolism
3. **Catabolic reactions:** Processes that break down molecules into simpler ones; releases energy
4. **Anabolic reactions:** Processes that build complex molecules from simpler ones; requires energy
5. **Activation energy**: Minimum energy required to start a chemical reaction
6. **Enzyme**: Protein that catalyzes (speeds up) a biochemical reaction by lowering activation energy
7. **Substrate**: Specific substance that an enzyme binds with
8. **Active site**: Region on an enzyme where the substrate binds and the chemical reaction occurs
9. **Induced fit**: Model describing how an enzyme changes shape to better fit the substrate upon binding
10. **Enzyme inhibitor**: Molecule that binds to an enzyme and blocks its function
11. **Competitive inhibition**: Inhibitor binds to the active site and blocks the substrate from

binding

12. **Allosteric inhibition**: Inhibitor binds to site on the enzyme that is not the active site (allosteric site); causes change to enzyme shape so prevents substrate from binding
13. **Kinetic energy**: Energy of motion (e.g. moving objects, molecules in motion)
14. **Potential energy**: Stored energy based on position or structure (e.g. water behind a dam, ATP)
15. **Conservation of energy:** The principle stating that energy cannot be created or destroyed, only transformed from one form to another
16. **Chemical Energy**: Potential energy stored in chemical bonds (e.g. glucose)
17. **ATP (Adenosine Triphosphate)**: Primary energy carrier in cells, supplying energy for cellular processes
18. **Photosynthesis**: Process where producers convert sunlight into chemical energy stored as glucose
19. **Cellular Respiration**: Process by which organisms convert chemical energy (glucose) into usable ATP energy
20. **Autotroph:** Organism that can produce its own food; producers
21. **Heterotrophs**: Organisms that get their food by consuming other organisms; consumers
22. **Mesophyll**: Leaf tissue containing chloroplasts, specialized for photosynthesis
23. **Stomata**: Small pores on leaves allowing gas exchange (CO^2 and O^2) and water vapour release
24. **Chloroplast**: Organelle within plant cells where photosynthesis takes place
25. **Thylakoids**: Stacked, disc-shaped structures in chloroplasts; site of the light-dependent reactions of photosynthesis
26. **Chlorophyll**: Green pigment in chloroplasts that absorbs sunlight
27. **Wavelength:** the distance between consecutive points of a wave
28. **Visible light:** portion of the electromagnetic spectrum that is detectable by the human eye,
29. **Pigment**: A substance that absorbs light and gives colour to plants, animals, and other materials; reflects the colour that they cannot absorb
30. **Photosystem:** clusters of pigments and proteins that absorb sunlight; studded in the thylakoid membrane and used in the light-dependent reactions
31. **Photon:** a distinct quantity or "packet" of light energy
32. **Light-dependent reactions**: First stage of photosynthesis; Light energy is converted into chemical energy in the form of ATP and NADPH
33. **ATP synthase:** An enzyme that produces ATP from ADP and inorganic phosphate
34. **Electron carrier:** Molecule that shuttles high-energy electrons between compounds in

biochemical pathways

35. **Calvin cycle:** Second stage of photosynthesis; Uses the energy stored by the light-dependent reactions and carbon dioxide to form glucose
36. **Carbon fixation:** process of converting inorganic carbon dioxide into organic compounds during photosynthesis; first stage of the Calvin Cycle
37. **Reduction:** A chemical reaction that involves the gain of electrons by an atom or molecule; 3-PGA is reduced to G3P during the second stage of the Calvin cycle
38. **Regeneration of RuBP:** Final phase in the Calvin cycle; G3P is used to regenerate RuBP, enabling the cycle to continue
39. **2 main categories of energy**: kinetic energy and potential energy
40. **Most ecosystems get energy from:** Photosynthesis
41. **Equation for photosynthesis:** $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
42. **How are photosynthesis and cellular respiration related?** The products of one process are the reactants of the other
43. **2 categories based on how organisms get their food:** autotrophs (producers) and heterotrophs (consumers)
44. **2 stages of photosynthesis:** light-dependent reactions and the Calvin cycle
45. **Location of light-dependent reactions:** Thylakoid membrane of chloroplasts
46. **How does PSII replenish donated electrons?** Splits a molecule of water to access the electrons
47. **Explain the path of electrons through the light-dependent reactions:** Water > PSII > ETC > PSI > NADPH
48. **What happens to energy in electrons as they pass through the ETC?** Energy from the electron is used to pump H+ into thylakoid, producing potential energy
49. **What is the purpose of the light-dependent reactions:** Convert light energy into chemical energy (ATP and NADPH)
50. **2 types of energy-carrier molecules produced in light-dependent reactions:** ATP and NADPH
51. **Location of Calvin cycle:** the stroma of chloroplasts
52. **Stages of the Calvin cycle:** carbon fixation, reduction, regeneration of RuBP

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms.

CHAPTER 6: CELLULAR RESPIRATION

Chapter Overview

Learning Objectives

By the end of this chapter, you will be able to:

- Explain the role of redox reactions in cellular respiration.
- Identify the locations of the three main stages of cellular respiration.
- Describe the process of aerobic respiration.
- Discuss the fundamental difference between anaerobic cellular respiration and fermentation.
- Describe the type of fermentation that readily occurs in animal cells and the conditions that initiate that fermentation.

6.1 OVERVIEW OF CELLULAR RESPIRATION

Cellular respiration is the process by which living cells break down glucose molecules and release energy.

Redox Reactions

Most of the energy stored in molecules is in the form of **high-energy electrons**. The shift of an electron from one molecule to another removes some potential energy from the first molecule and increases the potential energy of the second molecule. In cellular respiration, the high-energy electrons from glucose are passed through a series of redox reactions, ultimately leading to the production of ATP. **Redox (reduction-oxidation) reactions** are chemical processes involving the transfer of electrons between two substances. An **oxidation** reaction strips an electron from a molecule, and the addition of this electron to another molecule is a **reduction** reaction. The transfer of energy in the form of electrons allows the cell to transfer and use energy in an incremental fashion—in small packages rather than in a single, destructive burst.

Stages of Cellular Respiration

Cellular respiration involves many chemical reactions, but they can all be summed up with this chemical equation:

$$\mathbf{C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Chemical\ Energy\ (in\ ATP)}$$

In other words, the equation shows that glucose ($C_6H_{12}O_6$) and oxygen (O_2) react to form carbon dioxide (CO_2) and water (H_2O), releasing energy in the process. Because oxygen is required for cellular respiration, it is an **aerobic process**. This is the reason why we breathe oxygen in from the air. This type of respiration releases a large amount of energy from glucose that can be stored as ATP. Most animals, plants, and even some prokaryotes rely on aerobic respiration for their energy needs.

The reactions of cellular respiration can be grouped into three stages: glycolysis, the citric acid cycle, and the

electron transport (ETC). As we dive into the details for each stage, you will see that to track the path of the energy transfers, we are tracking the path of electrons moving through metabolic pathways.

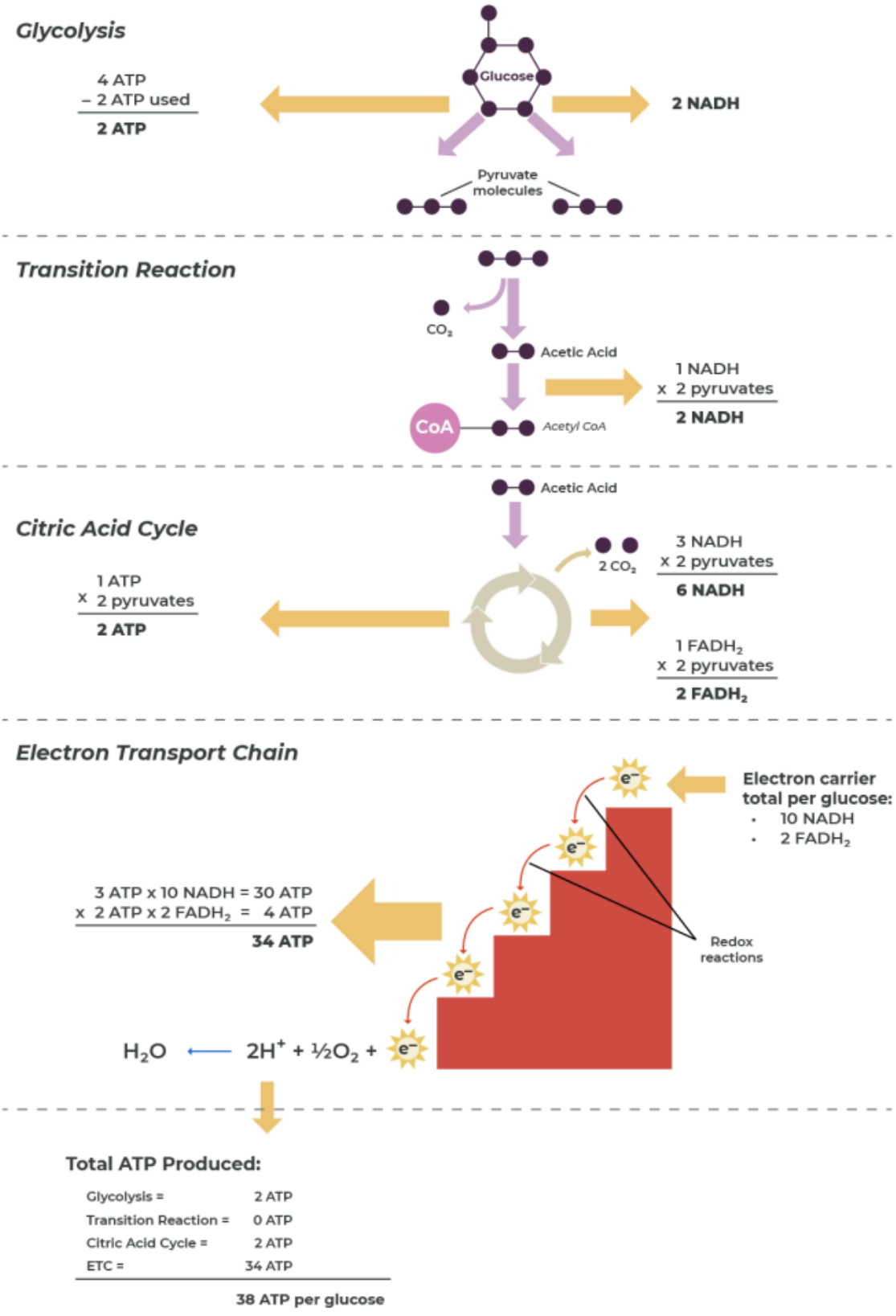

Glycolysis
4 ATP
– 2 ATP used
2 ATP
Glucose
2 NADH
Pyruvate molecules
Transition Reaction
CO₂
Acetic Acid
1 NADH
x 2 pyruvates
2 NADH
CoA
Acetyl CoA
Acetic Acid
Citric Acid Cycle
1 ATP
x 2 pyruvates
2 ATP
2 CO₂
3 NADH
x 2 pyruvates
6 NADH
1 FADH₂
x 2 pyruvates
2 FADH₂
Electron Transport Chain
Electron carrier total per glucose:
• 10 NADH
• 2 FADH₂
3 ATP x 10 NADH = 30 ATP
x 2 ATP x 2 FADH₂ = 4 ATP
34 ATP
Redox reactions
H₂O ← 2H⁺ + ½O₂ +
e⁻
Total ATP Produced:
Glycolysis = 2 ATP
Transition Reaction = 0 ATP
Citric Acid Cycle = 2 ATP
ETC = 34 ATP
38 ATP per glucose

Figure 6.1.1 Cellular respiration takes place in the stages shown here. The process begins with a molecule of glucose, which has six carbon atoms. What happens to each of these atoms of carbon?
"Carbohydrate_Metabolism" by OpenStax College, CC BY 3.0. Modifications: Minor text changes and revised glucose and pyruvate illustrations

Figure 6.1.1 Description

The four main stages involved in breaking down glucose to produce ATP are glycolysis, Transition Reaction, Citric Acid Cycle, and the Electron Transport Chain. Each stage is separated by dashed lines and includes visual diagrams and labelled outputs.

Glycolysis:

- Glucose is broken down into two pyruvate molecules
- Produces 4 ATP but uses 2 ATP, resulting in a net gain of 2 ATP
- Also produces 2 NADH

Transition Reaction:

- Each pyruvate is converted into acetic acid, releasing CO_2
- Acetic acid combines with CoA to form Acetyl CoA
- Produces 2 NADH (1 NADH per pyruvate, two pyruvates total)
- No ATP is produced in this stage

Citric Acid Cycle (Krebs Cycle):

- Each Acetyl CoA enters the cycle, releasing 2 CO_2 per turn
- Produces 6 NADH, 2 $FADH_2$, and 2 ATP per glucose molecule (accounting for two cycles, one per pyruvate)

Electron Transport Chain (ETC):

- Utilizes 10 NADH and 2 $FADH_2$ from previous stages
- Each NADH yields 3 ATP ($10 \times 3 = 30$ ATP)
- Each $FADH_2$ yields 2 ATP ($2 \times 2 = 4$ ATP)
- A total of 34 ATP produced through redox reactions
- Final reaction produces water (H_2O) from oxygen, hydrogen ions, and electrons

Total ATP Produced per Glucose:

- Glycolysis: 2 ATP
- Transition Reaction: 0 ATP
- Citric Acid Cycle: 2 ATP
- Electron Transport Chain: 34 ATP
- Total: 38 ATP per glucose molecule

The illustration uses arrows and molecule representations to depict chemical conversions and energy flow, with NADH and $FADH_2$ acting as electron carriers leading into the ETC.

Location of Cellular Respiration

The different stages of cellular respiration occur in different parts of the cell. Glycolysis happens in the cytosol. The remainder of the stages occur in the mitochondria. A mitochondrion has an inner and outer membrane. The space between the inner and outer membrane is called the intermembrane space. The space enclosed by the inner membrane is called the matrix. The citric acid cycle takes place in the matrix. The electron transport chain happens on the inner membrane.

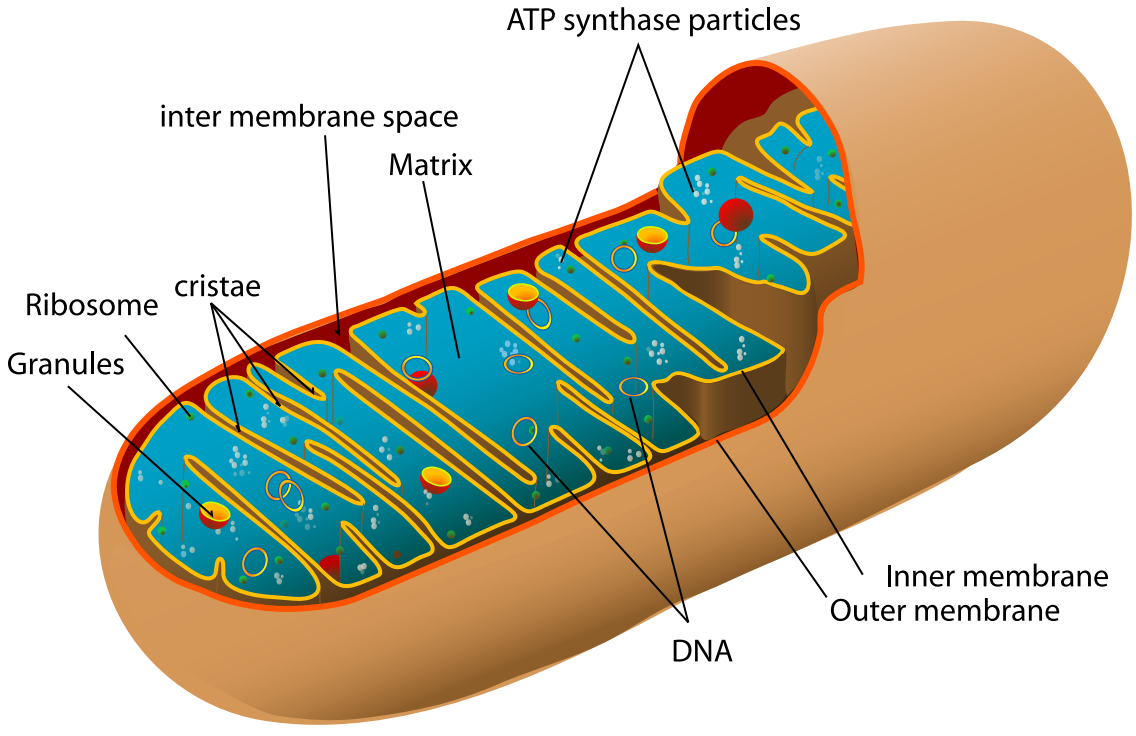


Figure 6.1.2 Labelled mitochondrion structure. Image by LadyofHats, Public Domain

Figure 6.1.2 Description

A detailed diagram of a mitochondrion, the organelle responsible for energy production in animal cells. The illustration shows a mitochondrion with a cutaway section revealing its internal structures. Labels identify key components, including:

- Outer membrane: The smooth outer layer that encases the mitochondrion.
- Inner membrane: A highly folded structure forming cristae, which increases the surface area for biochemical reactions.
- Cristae: The folds of the inner membrane where the electron transport chain takes place.
- Matrix: The fluid-filled space inside the inner membrane, containing enzymes, mitochondrial DNA, and ribosomes.
- Intermembrane space: The region between the outer and inner membranes, where certain metabolic processes occur.

The diagram uses colour coding to distinguish these structures, with the outer membrane in a brownish shade, the inner membrane and cristae in yellow, and the matrix in blue with various molecular structures inside. The mitochondrion plays a crucial role in ATP production through cellular respiration.

6.2 AEROBIC RESPIRATION

Stage I: Glycolysis

The word **glycolysis** literally means "glucose splitting," which is exactly what happens in this stage. Enzymes split a molecule of glucose into two molecules of pyruvate (also known as pyruvic acid). Glycolysis is a complex reaction involving ten steps, each requiring a different enzyme. We will not review all of the details but will summarize the key steps involved.

To start glycolysis, energy is needed to split the glucose molecule into two 3-carbon molecules. This energy is provided by two molecules of ATP in what's called the *energy investment phase*. As glycolysis continues, energy is released and used to make four molecules of ATP – this is the *energy harvesting phase*. The result is a net gain of two ATP molecules. During this stage, high-energy electrons are also transferred to molecules of **NAD+** (Nicotinamide Adenine Dinucleotide), forming two molecules of **NADH**, another important energy carrier. Similar to NADPH in photosynthesis, NADH acts as an electron shuttle. NAD+ (empty Uber) gains electrons and becomes NADH (full Uber), which carries the electrons to stage III of cellular respiration to make more ATP. At the end of glycolysis, there are two 3-carbon pyruvate molecules which go on to stage II of cellular respiration.

Reactants and Products of Glycolysis

Glycolysis converts glucose into two molecules of pyruvate. This releases energy, which is transferred to ATP. Click on the hotspots to learn more.

Image Description
Glycolysis:

- Two Pyruvate: Two pyruvates move to the next stage of cellular respiration.
- Glucose Molecule: The 6-carbon glucose molecule is split into 2 separate 3-carbon pyruvate molecules.
- Net gain of 2 ATP: Produces 4 ATP but uses 2 ATP, resulting in a net gain of 2 ATP released into the cell for energy use.
- 2 NADH: Produces 2 NADH that travel to the mitochondria, carrying high-energy electrons to the ETC.

Exercises 6.2.1

Text Description

1. What bond and molecule store and provide energy to perform work?

a. Bonds of glucose and an ATP molecule
b. Bonds of ATP and a glucose molecule
c. Bonds of a catabolic molecule and an anabolic molecule
d. Bonds of an anabolic molecule and a catabolic molecule

2. What is the energy currency that is used by cells?

a. ADP
b. ATP
c. Adenosine
d. AMP

3. What type of molecule is the glucose that enters the glycolysis pathway split into?

a. NADH
b. ATP
c. Pyruvate
d. Phosphate

4. Used during glycolysis or produced during glycolysis?

Draggable options: ADP-used, ADP-produced, ATP-harvest, ATP-investment, Glucose, Pyruvate, NAD+, NADH

Answers:

1. b. Bonds of ATP and a glucose molecule

2. b. ATP

3. c. Pyruvate

4. Used during glycolysis: ADP-used, ATP-investment, Glucose, NAD+
Produced during glycolysis: ADP-produced, ATP-harvest, Pyruvate, NADH

Transition Reaction

Before pyruvate can enter the next stage of cellular respiration, it needs to be modified slightly. The **transition reaction** is a very short reaction which converts pyruvate into a form that the citric acid cycle can process. Each pyruvate loses a carbon in the form of a molecule of carbon dioxide, which is released as a waste product. The remaining 2-carbon molecule is called acetic acid. High energy electrons are removed from acetic acid and transferred to NAD+, converting it to NADH. NADH carries the high-energy electrons to the Electron Transport Chain (stage III). Coenzyme A binds with acetic acid, forming acetyl coA, which acts as a shuttle to transport acetic acid to the mitochondria for the Citric Acid Cycle (stage II).

Note that Glycolysis (stage I) produced two molecules of pyruvate. That means that the Transition Reaction will have to occur two times, once for each pyruvate molecule.

Reactants and Products of the Transition Reaction

In the transition reaction, pyruvate is converted to a 2-carbon molecule of acetyl CoA and a molecule of carbon dioxide. This reaction occurs twice (once for each pyruvate from Glycolysis). No ATP is produced in this stage. Click on the hotspots below to learn more.

Image Description
Transition Reaction:

- Two Carbon Dioxide: Each pyruvate is converted into acetic acid, releasing CO^2. Two carbon dioxide diffuse out of the cell.
- Acetyl CoA: Acetic acid combines with CoA to form Acetyl CoA. Two acetyl CoA move to the next stage of cellular respiration.
- Two NADH: Produces two NADH (1 NADH per pyruvate, two pyruvates total). Two NADH bring high-energy electrons to the ETC.

Stage II: The Citric Acid Cycle

The **citric acid cycle**, also known as the Krebs cycle, consists of 8 steps which are each catalyzed by a specific enzyme. We will only summarize the key steps involved.

Acetyl coA travels to the matrix of the mitochondria for the citric acid cycle. The coA drops acetic acid off in the cycle. CoA is then reused for cellular respiration or other metabolic processes.

In the cycle, the acetic acid combines with a four-carbon molecule called OAA (oxaloacetate). This produces citric acid, which has six carbon atoms. The citric acid goes through a series of reactions that release energy. Each of the carbons from acetic acid are stripped off OAA and released as carbon dioxide. The resulting energy is captured in molecules of NADH, ATP, and $FADH_2$, another energy-carrying coenzyme. The final step of the Citric Acid Cycle regenerates OAA, the molecule that began the cycle. This molecule is needed for the next turn through the cycle.

Two turns of the cycle are needed because glycolysis produces two pyruvic acid molecules when it splits glucose.

Reactants and Products of the Citric Acid Cycle

In the Citric Acid Cycle, acetyl CoA is converted to two molecules of carbon dioxide. This stage occurs twice (once for each acetyl coA produced in the Transition Reaction).

Image Description
Citric Acid Cycle:

- 4 Carbon Dioxide: Each Acetyl CoA enters the cycle, releasing 2 CO^2. Four carbon dioxide diffuse out of the cell.
- Two ATP: Two ATP (1 ATP per pyruvate, two pyruvates total) are released into the cell for energy use.
- Oxaloacetate: Acetyl CoA drops the acetic acid off onto oxaloacetate. These 2 carbons get released as 2 CO^2 and oxaloacetate remains in the cycle to be reused. This repeats for the 2nd acetyl coA, producing a total of 4 CO^2).
- 6 NADH and 2 $FADH^2$: Produces 6 NADH, 2 $FADH^2$ (3 NADH and 1 $FADH^2$ per pyruvate, two pyruvates total), that bring high-energy electrons to the ETC.

Exercises 6.2.2

Text Description
Used or produced during the Citric Acid Cycle?

Draggable items: ADP, ATP, FAD, FADH2, NAD+, NADH, Acetic Acid, Carbon Dioxide

---

Correct Answers:

Used during the Citric Acid Cycle: ADP, NAD+, acetic acid, FAD

Produced during the Citric Acid Cycle: ATP, NADH, Carbon Dioxide, FADH2

Results of Glycolysis, Transition Reaction and Citric Acid Cycle

After glycolysis, the transition reaction, and the citric acid cycle, the glucose molecule has been broken down completely. All six of its carbon atoms have combined with oxygen to form carbon dioxide. The energy from its chemical bonds has been harvested but there have only been 4 ATP produced (2 from glycolysis, 2 from the citric acid cycle).

The rest of the energy is currently stored in the electron carriers:

- 10 NADH (2 from glycolysis, 2 from transition reaction, and 6 from the citric acid cycle)
- 2 $FADH_2$ (from the citric acid cycle)

This energy will be transferred to the third and final stage of cellular respiration: the Electron Transport Chain (ETC). The ETC will use the energy from the high energy electrons to create significantly more ATP.

Stage III: Electron Transport Chain

The **Electron Transport Chain** (ETC) is the final stage of cellular respiration. In this stage, energy being transported by NADH and $FADH_2$ is transferred to ATP. Oxygen acts as the final electron acceptor. It pulls the electrons out of the electron transport chain, then combines with the hydrogens released from all the

NADH and $FADH_2$, and forms water molecules. The image below summarizes the ETC. Click on the hotspots below to learn more.

Reactants and Products of the Electron Transport Chain

Image Description
Electron Transport Chain (ETC):

- NADH and $FADH^2$: NADH and $FADH^2$ from previous stages drop high-energy electrons off at ETC, becoming NAD^+ and FAD for reuse.
- ATP: Each NADH yields 3 ATP (10 x 3 = 30 ATP), each $FADH^2$ yields 2 ATP (2 x 2 = 4 ATP), total of 34 ATP produced through redox reactions
- H^2O: O^2 serves as the final electron acceptor in the ETC, facilitating ATP production and generating water as a waste product.

Making ATP

During the ETC, high-energy electrons are released from NADH and $FADH_2$, and they move along electron transport chains on the inner membrane of the mitochondrion. An electron transport chain is a series of molecules that transfer electrons from molecule to molecule by chemical reactions. Some of the energy from the electrons is used to pump hydrogen ions (H^+) against their concentration gradient, from the matrix into the intermembrane space. Similar to what we saw in photosynthesis, this buildup of H+ has potential energy. This gradient, known as an **electrochemical gradient**, drives the synthesis of ATP.

This gradient causes the ions to flow back across the membrane into the matrix, where their concentration is lower. ATP synthase acts as a channel protein, helping the hydrogen ions cross the membrane. It also acts as an enzyme, forming ATP from ADP and inorganic phosphate in a process called **oxidative phosphorylation**. After passing through the electron transport chain, the "spent" electrons combine with oxygen and hydrogen ions to form water.

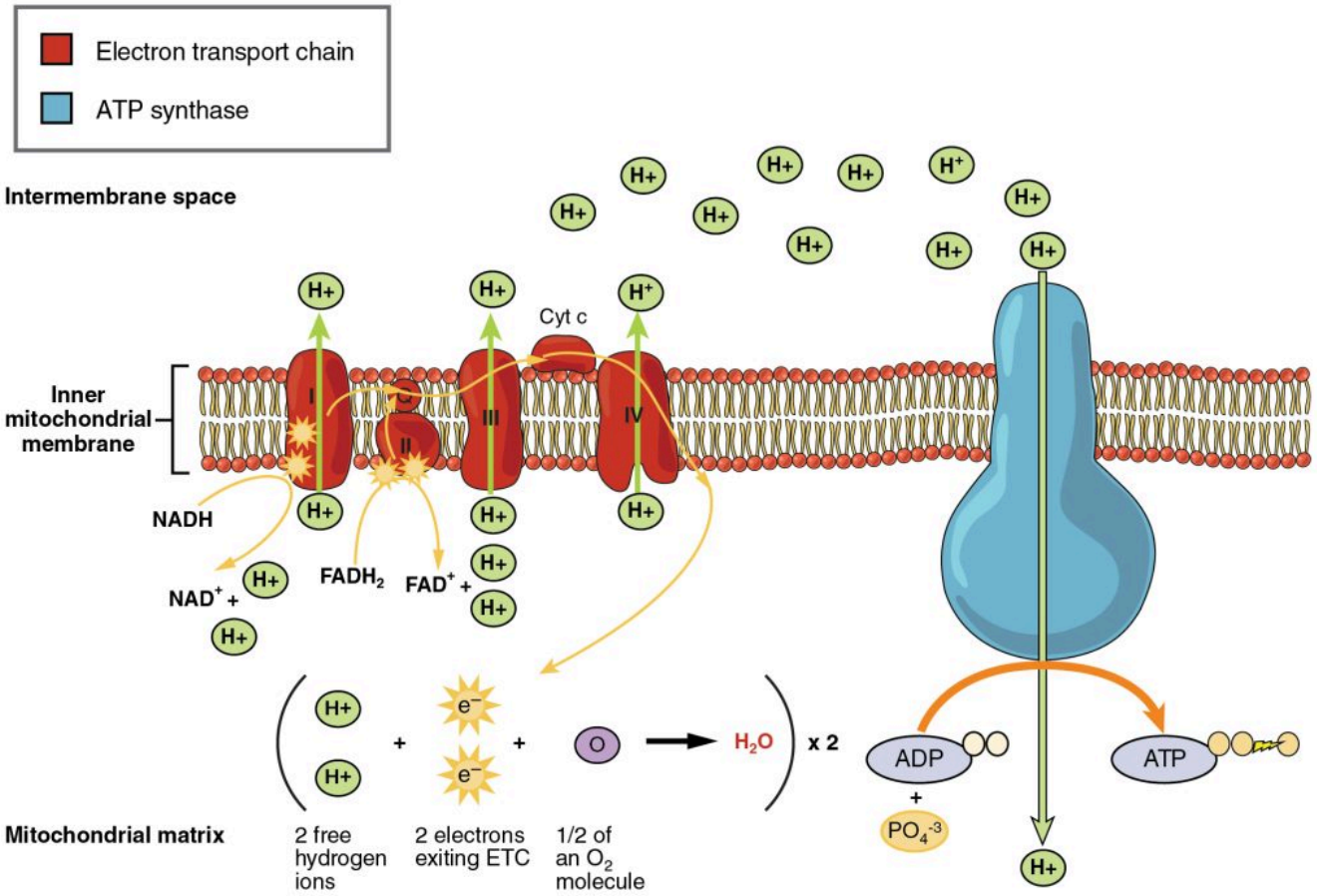


Figure 6.2.1 Electron transport chains on the inner membrane of the mitochondrion carry out the last stage of cellular respiration. Image by OpenStax, CC BY 3.0

Figure 6.2.1 Description

A detailed diagram of the electron transport chain (ETC) in cellular respiration, showing the movement of electrons and protons across the inner mitochondrial membrane.

Key components in the diagram:

- **Electron transport chain (ETC) complexes (red structures):** Embedded in the inner mitochondrial membrane, facilitating the transfer of electrons and pumping hydrogen ions (H^+) into the intermembrane space.
- **ATP synthase (blue structure):** A protein complex that uses the proton gradient to convert ADP and inorganic phosphate (PO_4^{3-}) into ATP.
- **NADH and $FADH_2$:** High-energy electron carriers donating electrons to the ETC.
- **Flow of electrons (e^-):** Represented by yellow arrows, moving through the complexes and ultimately reducing oxygen (O_2) to form water (H_2O).

- **Proton gradient (H^+ ions):** Hydrogen ions are pumped into the intermembrane space, creating a gradient that drives ATP production.
- **ATP synthesis:** ATP synthase allows H^+ ions to flow back into the mitochondrial matrix, catalyzing the formation of ATP from ADP and phosphate.

The diagram visually represents oxidative phosphorylation, highlighting how the ETC powers ATP production through a series of redox reactions.

Exercises 6.2.3

Text description
Drag each item to its corresponding section.

- Section 1: What is used during oxidative phosphorylation?
- Section 2: What is produced during oxidative phosphorylation?

Draggable items: ADP, NAD+ and FAD, Oxygen gas, ATP, Water, NADH and $FADH_2$

Answers:

- Used during oxidative phosphorylation: ADP, Oxygen gas, NADH and $FADH_2$
- Produced during oxidative phosphorylation: ATP, Water, NAD+ and FAD

How Much ATP?

In theory, 38 molecules of ATP can be produced from the catabolism of just one molecule of glucose in aerobic respiration. Glycolysis produces two ATP molecules, and the citric acid cycle produces two more. Electron transport begins with several molecules of NADH and $FADH_2$ and transfers their energy into as many as 34 more ATP molecules. In reality, the exact number of ATP molecules varies. Different species and even different tissues within one organism will produce different quantities of ATP.

Metabolism of molecules other than glucose

We have learned about the catabolism of glucose, which provides energy to living cells. But living things consume more than just glucose for food.

Basically, all molecules from food can enter the cellular respiration pathway somewhere. Some molecules enter at glycolysis, while others enter at the citric acid cycle. Carbohydrates, proteins, and lipids can all be converted into forms that eventually connect into glycolysis and the citric acid cycle pathways to be used for ATP production.

Exercises 6.2.4

Text Description
Place the molecules into the correct sequence of the breakdown of glucose during cellular respiration: 2 Acetyl CoA & 2 CO_2, 4 Carbon Dioxide, Glucose, 2 Pyruvate.

Correct Sequence: 1. Glucose, 2. 2 Pyruvate, 3. 2 Acetyl CoA + 2 CO2, 4. 4 Carbon Dioxide

Text Description

1. During cellular respiration, NADH and ATP are used to make glucose. (True/False)

2. ATP synthase acts as both an enzyme and a channel protein. (True/False)

3. The carbons from glucose end up in ATP molecules at the end of cellular respiration. (True/False)

4. Energy is stored within the chemical bonds within the glucose molecule. (True/False)

5. Cyanide inhibits cytochrome c oxidase, a component of the electron transport chain. If cyanide poisoning occurs, the pH of the intermembrane space becomes more basic. The electron transport chain can no longer pump hydrogen ions into the intermembrane space and ATP synthesis stops. (True/False)

6. What is the function of the electrons added to NAD^+?

a. They become part of a fermentation pathway.
b. They go to another pathway for ATP production.
c. They energize the entry of the acetyl group into the citric acid cycle.
d. They are converted into NADP.

7. Drag the words into the correct boxes

We inhale oxygen when we breathe and exhale carbon dioxide. The oxygen we inhale is the _____ _____ _____ in the electron transport chain and allows _____ _____ to proceed, which is the most efficient pathway for harvesting energy in the form of _____ from food _____. The carbon dioxide we breathe out is _____ during the _____ when the bonds in carbon compounds are _____.
Possible answers:

- formed
- molecules
- citric acid cycle
- respiration
- acceptor
- ATP
- aerobic
- final
- broken
- electron

Answers:

1. False
2. True
3. False
4. True
5. True
6. b. They go to another pathway for ATP production.
7. We inhale oxygen when we breathe and exhale carbon dioxide. The oxygen we inhale is the ***final electron acceptor*** in the electron transport chain and allows ***aerobic respiration*** to proceed, which is the most efficient pathway for harvesting energy in the form of ***ATP*** from food ***molecules***. The carbon dioxide we breathe out is ***formed*** during the ***citric acid cycle*** when the bonds in carbon compounds are ***broken***.

6.3 FERMENTATION

Anaerobic respiration enables organisms to convert energy for their use without oxygen. With oxygen, organisms can use aerobic cellular respiration to produce up to 38 molecules of ATP from just one glucose molecule. Without oxygen, organisms only produce two molecules of ATP per glucose molecule. Anaerobic respiration starts with glycolysis, the first stage of cellular respiration. Glycolysis does not require oxygen but produces two molecules of ATP for each glucose molecule. For glycolysis to work, NAD^+ must accept electrons. For glycolysis to continue, NADH must be converted back to NAD^+ for reuse. Since no oxygen is present, the ETC is not functioning, so the NADH needs to drop its electrons elsewhere. Different organisms do this step in different ways. **Fermentation** is a type of anaerobic respiration that regenerates NAD^+ by adding the electrons from NADH to an organic molecule. There are two main types of fermentation:

Lactic Acid Fermentation

Animals and certain bacteria, including those in yogurt, use **lactic acid fermentation**. During intense exercise, your muscle cells rely on this process for short periods when your muscles use ATP faster than your cardiovascular system can deliver oxygen. In this process, NADH transfers electrons back onto pyruvate (pyruvic acid), which converts it into lactic acid. The NAD+ cycles back to allow glycolysis to continue, so more ATP is made.

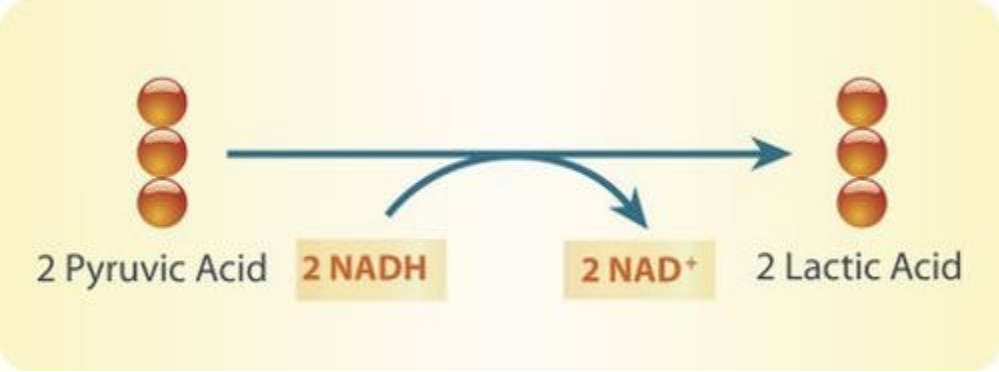


Figure 6.3.1 Lactic acid fermentation produces lactic acid and NAD+. The NAD+ cycles back to allow glycolysis to continue so more ATP is made. Each circle represents a carbon atom. Image by Hana Zavadska, CC BY-NC 3.0

Alcohol Fermentation

Alcohol fermentation produces ethanol, an alcohol. It is carried out by single-celled fungi (called yeasts) and

some bacteria. Pyruvate is broken down to release a carbon dioxide molecule, resulting in a 2-carbon molecule (acetaldehyde) remaining. NADH drops its electrons onto the acetaldehyde, which converts it into ethanol. The resulting NAD+ is reused in glycolysis to continue making ATP. We use alcoholic fermentation to make bread, wine, beer, and even biofuels.

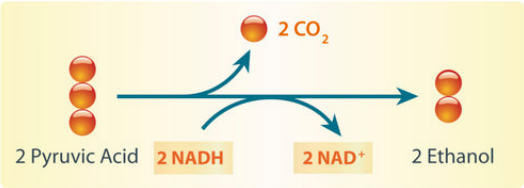


Figure 6.3.2 Alcohol fermentation produces ethanol. Image by Hana Zavadska, CC BY-NC 3.0

Figure 6.3.3 CO_2 from fermentation causes bubbles in bread dough and explains why the dough rises. Image by Orlova Maria, Unsplash License

Table 6.3.1 Aerobic vs Anaerobic Respiration

Feature	Aerobic Respiration	Anaerobic Respiration
Requires oxygen?	Yes	No
Glucose breakdown	Complete	Incomplete
End products	CO_2 and H_2O	Animal cells: lactic acid Plant cells and yeast: carbon dioxide and ethanol
ATP produced	About 38	2

Exercises 6.3.1

Text Description

1. What is the purpose of fermentation?

a. To generate about 32 ATP in the presence of oxygen.
b. To allow cells to survive without using ATP.
c. To regenerate NAD+ so glycolysis can continue to happen.

2. The fermentation pathway starts after which part of cellular respiration?

a. The citric acid cycle
b. Oxidative phosphorylation
c. Glycolysis

3. Drag the words to explain how the following fact supports or does not support the assertion that glycolysis is one of the oldest metabolic pathways. Fact: Both prokaryotic and eukaryotic organisms carry out some form of glycolysis.

If glycolysis evolved relatively _____, it likely _____ be as _____ in organisms as it is. It probably evolved in very _____ organisms and _____, with the _____ of other pathways of carbohydrate metabolism that evolved _____.
Possible answers:

- addition
- wouldn't
- later
- persisted
- primitive
- late
- universal

4. Aerobic or Anaerobic?

Draggable options: Requires oxygen, Lactic acid produced, Ethanol produced, Is less efficient, Incomplete breakdown of glucose, Makes more ATP per glucose, Does not require oxygen, Complete breakdown of glucose, 2 ATP produced, About 36 ATP produced, H_2O and CO_2 produced.

Answers:

1. c. To regenerate NAD+ so glycolysis can continue to happen.

2. c. Glycolysis

3. If glycolysis evolved relatively ***late***, it likely ***wouldn't*** be as ***universal*** in organisms as it is. It probably evolved in very ***primitive*** organisms and ***persisted***, with the ***addition*** of other pathways of carbohydrate metabolism that evolved ***later***.

4. Aerobic: Requires oxygen, About 36 ATP produced, Complete breakdown of glucose, H_20 and $C0_2$ produced, Makes more ATP per glucose

Anaerobic: Does not require oxygen, Incomplete breakdown of glucose, Ethanol produced, Lactic acid produced, 2 ATP produced, Is less efficient.

Anaerobic Cellular Respiration in Prokaryotes

Ancient prokaryotes likely generated ATP exclusively from glycolysis before oxygen was abundant in Earth's atmosphere. Since nearly all organisms complete glycolysis, it suggests that it evolved in primitive organisms and persisted, with the addition of other metabolic pathways that evolved later.

Some prokaryotes use different ways to convert NADH back into NAD+. The group of Archaea called methanogens reduces carbon dioxide to methane to oxidize NADH. These microorganisms are found in soil and the digestive tracts of ruminants, such as cows. Similarly, sulphate-reducing bacteria and Archaea, most of which are anaerobic, reduce sulphate to hydrogen sulphide to regenerate NAD+ from NADH.

CHAPTER 6 SUMMARY

Key Takeaways

- **Cellular respiration:** An aerobic process that systematically extracts energy from glucose through redox reactions, ultimately producing ATP. This process occurs in distinct stages—glycolysis, the citric acid cycle, and the electron transport chain—each taking place in specific cellular locations, primarily the cytosol and mitochondria.
- **Aerobic Respiration:** Cellular respiration systematically extracts energy from glucose in three stages—glycolysis, the citric acid cycle, and the electron transport chain (ETC)—to produce ATP. Glycolysis splits glucose into two pyruvate molecules, yielding a net gain of two ATP and generating NADH. The citric acid cycle further processes pyruvate, releasing carbon dioxide and producing ATP, NADH, and $FADH^2$. The ETC then transfers electrons from NADH and $FADH^2$, ultimately producing the majority of ATP through oxidative phosphorylation.
- **Fermentation**: Anaerobic respiration allows organisms to generate ATP without oxygen by relying on glycolysis and alternative pathways, such as fermentation, to regenerate NAD+ for continued ATP production. Different organisms utilize lactic acid fermentation, alcohol fermentation, or unique prokaryotic pathways to sustain energy production in oxygen-limited environments.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into three key takeaways.

Flash Cards

Text Description

1. **Cellular respiration**: Process cells use to convert glucose and oxygen into energy (ATP), producing carbon dioxide and water as byproducts
2. **High-energy electrons**: Electrons carrying significant energy, often used in cellular processes like the electron transport chain
3. **Redox reactions:** Reduction-oxidation reactions; Chemical reactions involving electron transfers, where oxidation (loss of electrons) and reduction (gain of electrons) occur simultaneously
4. **Oxidation:** Substance loses electrons during a chemical reaction
5. **Reduction:** Substance gains electrons during chemical reaction
6. **Aerobic process**: Metabolic process requiring oxygen to generate ATP efficiently (e.g., aerobic cellular respiration)
7. **Glycolysis:** Converts glucose into pyruvate; Stage I of cellular respiration
8. **Transition reaction:** Converts pyruvate to acetyl-CoA before the citric acid cycle
9. **Citric acid cycle**: Converts acetyl coA to CO_2; Stage II of cellular respiration
10. **Electron transport chain**: Series of proteins in the inner mitochondrial membrane that transfer electrons from NADH and $FADH^2$ to oxygen, producing ATP; Stage III of cellular respiration
11. **Electrochemical gradient:** A gradient created by differences in charge and chemical concentration across a membrane, driving ion movement essential for ATP production
12. **Oxidative phosphorylation**: The process of producing ATP using energy from electrons transferred through the electron transport chain
13. **Anaerobic respiration:** A form of cellular respiration that occurs without oxygen, producing energy by breaking down glucose through pathways like fermentation.
14. **Fermentation**: Anaerobic process that allows cells to produce energy from glucose without using oxygen
15. **Lactic acid fermentation**: Form of anaerobic respiration that produces lactic acid; Used by muscle cells during intense exercise and by certain bacteria
16. **Alcohol fermentation:** Form of anaerobic respiration that produces ethanol and carbon dioxide; Used by yeast and some bacteria
17. **What is the main function of cellular respiration?** To produce ATP for cellular work

18. **Equation for cellular respiration**: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + Chemical Energy (in ATP)
19. **Stages of cellular respiration:** Glycolysis, Citric Acid Cycle, Electron Transport Chain
20. **Location of cellular respiration:** Cytosol (glycolysis), mitochondrial matrix (citric acid cycle), inner mitochondrial membrane (ETC)
21. **Reactants and products of glycolysis:** Reactants: Glucose, NAD+, ATP, ADP. Products: Pyruvate, NADH, ADP, ATP (net gain of 2 ATP)
22. **Reactants and products of transition reaction:** Reactants: Pyruvate, NAD+, coenzyme A, Products: Acetyl coA, CO_2, NADH
23. **Where is most of the energy from glucose stored after the citric acid cycle?** Stored in high-energy electrons transported by electron carriers (NADH, $FADH_2$)
24. **Reactants and products of citric acid cycle:** Reactants: Acetic acid, NAD+, FAD, ADP, Products: Carbon dioxide, NADH, $FADH_2$, ATP
25. **Reactants and products of electron transport chain:** Reactants: NADH, $FADH_2$, ADP, O_2, Products: NAD+, FAD, ATP, H_2O
26. **Which stage of cellular respiration produces the most ATP?** Electron transport chain
27. **What is the source of potential energy that drives the production of ATP in the ETC?** Electrochemical gradient; Concentration gradient of H+ across the inner membrane of a mitochondrion
28. **Enzyme that creates ATP by adding a phosphate group to ADP as hydrogen ions flow through it:** ATP synthase
29. **Max energy yield from 1 glucose in cellular respiration?** 38 ATP
30. **Two main types of fermentation:** Lactic acid fermentation and Alcohol fermentation
31. **Energy yield from 1 glucose in anaerobic respiration?** 2 ATP
32. **How many ATP are produced in each stage of cellular respiration?**Glycolysis – 2, Transition Reaction – 0, Citric Acid Cycle – 2, Electron Transport Chain – max 34
33. **Why is oxygen needed in cellular respiration?** Acts as final electron acceptor; Pulls electrons out of the electron transport chain, forming water
34. **Which stage of cellular respiration occurs in fermentation?** Glycolysis

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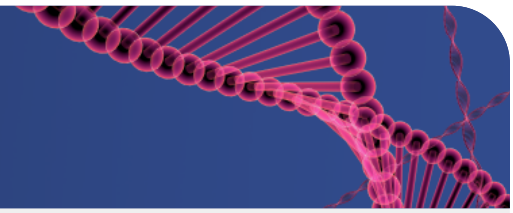
OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms.

CHAPTER 7: CELLULAR REPRODUCTION

Chapter Overview

Learning Objectives



By the end of this Chapter, you will be able to:

- Describe the prokaryotic and eukaryotic genome.
- Describe the three stages of interphase.
- Discuss the behaviour of chromosomes during mitosis and how the cytoplasmic content divides during cytokinesis.
- Discuss the behaviour of chromosomes during meiosis and how it differs from mitosis.

7.1 THE GENOME

A cell's complete complement of DNA is called its **genome**. Prokaryotes' genome comprises a single, double-stranded DNA molecule as a loop or circle. The region in the cell containing this genetic material is called a nucleoid.

In eukaryotes, the nuclear DNA exists as thin fibres called **chromatin**. Once a cell is ready to divide, the chromatin coils around proteins to compact into **chromosomes**. Chromosomes are encoded with genetic instructions for making RNA and proteins. These instructions are organized into units called genes. Hundreds (or even thousands!) of genes may be on a single chromosome. **Genes** are segments of DNA that code for particular pieces of RNA, which act as blueprints for building proteins. Humans have an estimated 20 thousand to 22 thousand genes.

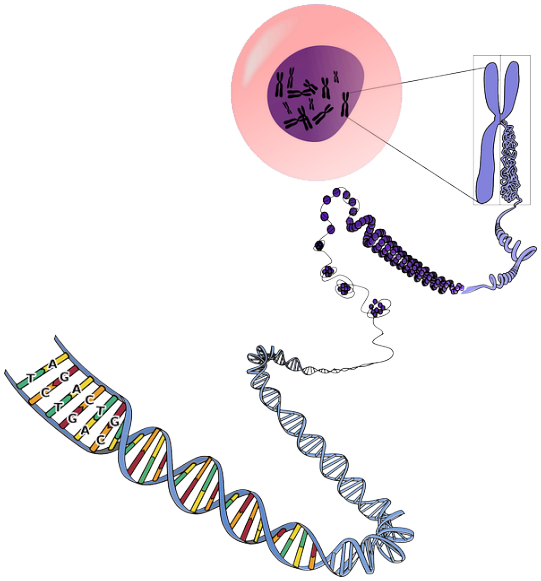


Figure 7.1.1 Hierarchical organization of DNA, starting from its most compact form within the nucleus to its fundamental molecular structure. Image by OpenClipart-Vectors, Pixabay License

Each chromosome consists of two identical structures called **sister chromatids**. Sister chromatids are joined together at a region called a **centromere**. Sister chromatids get separated during cell division.

A set number of chromosomes characterizes each species. Human body cells (**somatic cells**) have two sets of chromosomes in each cell, one set inherited from each parent. Because chromosomes occur in pairs, these cells are called **diploid** or 2n. There are 23 chromosomes in each set, for a total of 46 chromosomes per diploid cell. Each chromosome in one set is matched by a chromosome of the same type in the other set, so there are 23 pairs of chromosomes per cell. Each pair consists of chromosomes of the same size and shape and contains the same genes. The chromosomes in a pair are known as **homologous chromosomes**.

Human cells that contain one set of 23 chromosomes are called **gametes**, or sex cells; these eggs and sperm are designated n, or **haploid**.

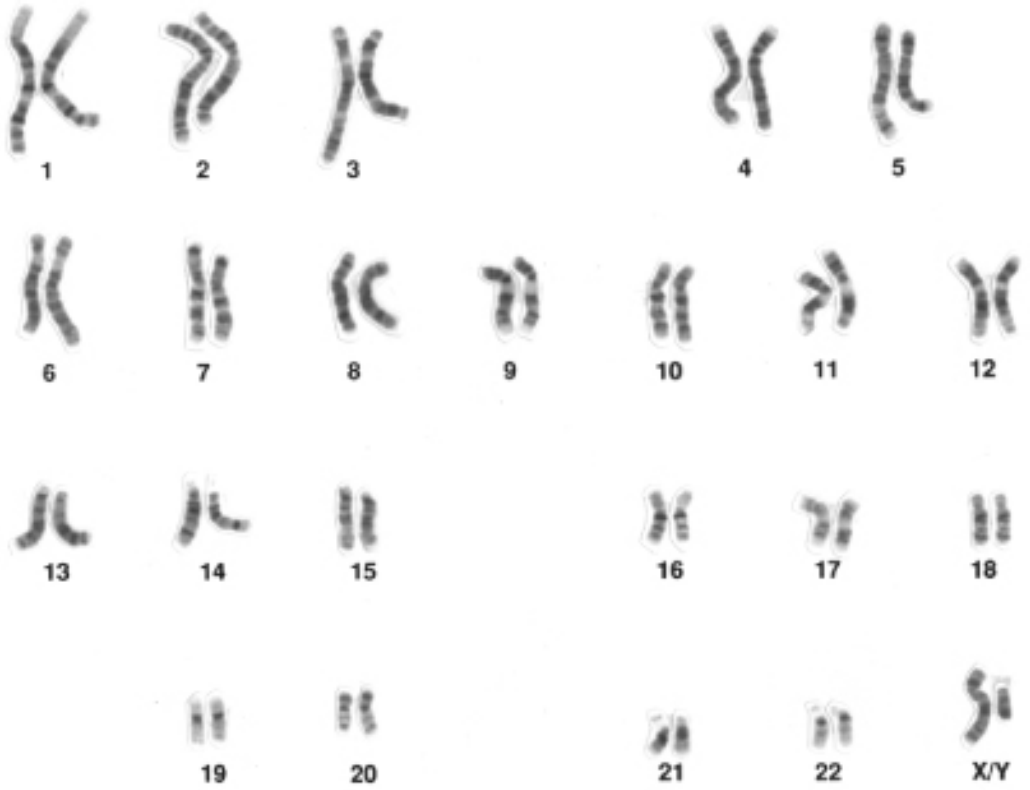


Figure 7.1.2 Human male karyotype. There are 23 pairs of chromosomes per cell. Image by National Human Genome Research Institute, Public Domain

Types of Chromosomes

Human cells contain two types of chromosomes: autosomes and sex chromosomes.

Autosomes

Autosomes are chromosomes containing genes for characteristics unrelated to biological sex. These chromosomes are the same in males and females. The great majority of human genes are located on autosomes. Of the 23 pairs of human chromosomes, 22 pairs are called autosomes (pairs 1-22 in Figure 7.1.2).

Sex Chromosomes

The remaining pair of human chromosomes consists of the sex chromosomes X and Y (pair 23 in Figure 7.1.3). **Sex chromosomes** determine the sex of an individual. Females have two X chromosomes (XX), and males have one X and one Y chromosome (XY).

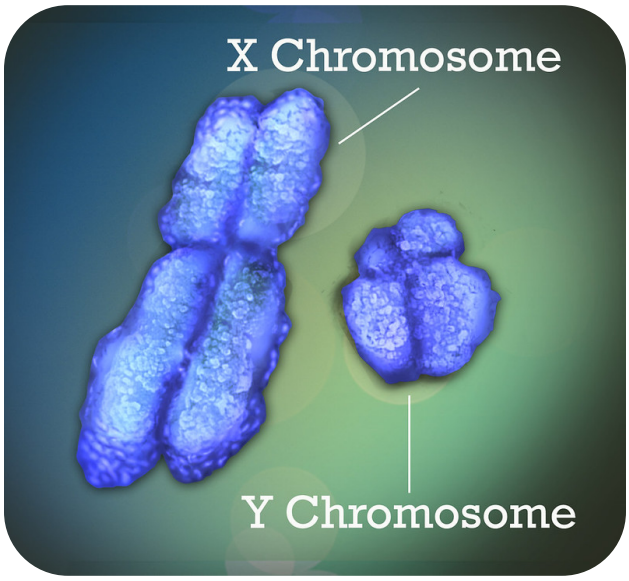


Figure 7.1.3 The sex chromosomes. Image by Jonathan Bailey, National Human Genome Research Institute, National Institutes of Health [NIH] Image Gallery, CC BY-NC 2.0

Exercise 7.1.1

Text Description

1. The familiar X-shaped chromosome represents:

- How DNA always looks in eukaryotic cells
- How DNA in eukaryotic cells looks once it is replicated and the cell is about to divide
- Female sex chromosomes only
- How DNA appears immediately after cytokinesis

2. Chromosomes In Eukaryotic Cells

- centriole
- centromere
- chromatid
- DNA

3. Humans have 46 chromosomes. (True/False)
4. Autosomes refer to any chromosome that is not a sex chromosome. (True/False)
5. The X chromosome determines biological sex. (True/False)
6. Alleles for the same types of traits are found on homologous pairs of chromosomes. (True/False)
7. Which of the following is considered a homologous chromosome:

- chromosome 22 and the X chromosome
- the two copies of chromosome 22 that make up a pair
- all of the chromosomes in a skin cell and all of the chromosomes in a muscle cell
- chromosomes 21 and 22

Answers:

1. How does DNA in eukaryotic cells looks once it is replicated and the cell is about to divide
2. centriole
3. True
4. True

5. False
6. True
7. The two copies of chromosome 22 that make up a pair

Text Description
Place the terms related to DNA in order of structure size from largest to smallest

1. Homologous Pair
2. Nucleotide
3. Nucleus
4. Gene/Allele
5. Chromosome

Answers:

1. Nucleus
2. Homologous Pair
3. Chromosome
4. Gene/Allele
5. Nucleotide

7.2 THE CELL CYCLE

The continuity of life from one cell to another has its foundation in the reproduction of cells by way of the cell cycle. The **cell cycle** is a repeating series of events that includes growth, DNA synthesis, and cell division. The cell cycle in prokaryotes is quite simple: the cell grows, its DNA replicates, and the cell divides. In eukaryotes, the cell cycle is more complicated.

The eukaryotic cell cycle has several phases. The mitotic phase (M) includes both mitosis and cytokinesis. This is when the nucleus and then the cytoplasm divide. The other three phases (G1, S, and G2) are generally grouped together as interphase. During **interphase**, the cell grows, performs routine life processes, and prepares to divide.

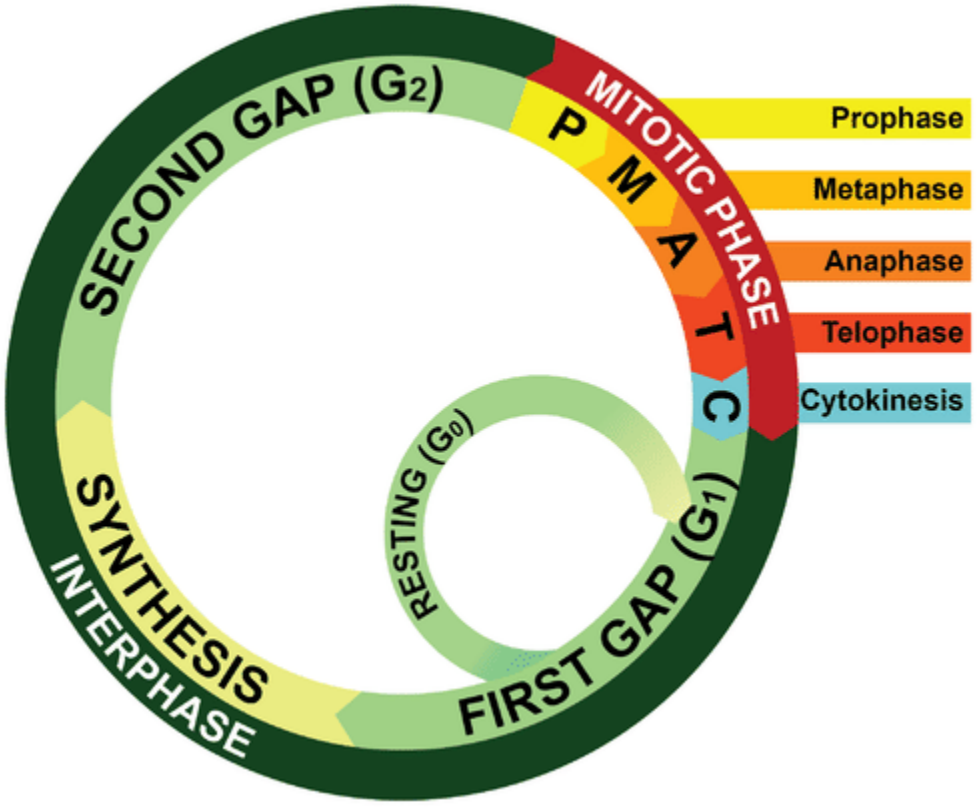


Figure 7.2.1 Eukaryotic Cell Cycle. Image by LadyofHats, CC BY-NC 3.0

Interphase

The interphase of the eukaryotic cell cycle can be subdivided into the three phases:

- **Gap 1 (G1):** During this phase, the cell grows rapidly while performing routine metabolic processes. It also makes proteins needed for DNA replication and copies some organelles in preparation for cell division. A cell typically spends most of its life in this phase.
- **Synthesis Phase (S):** During this phase, the cell's DNA is copied in the process of DNA replication to prepare for the upcoming mitotic phase.
- **Gap 2 (G2):** During this phase, the cell makes final preparations to divide. For example, it makes additional proteins and organelles.

Not all cells adhere to the classic cell-cycle pattern in which a newly formed daughter cell immediately enters interphase, closely followed by the mitotic phase. Cells in the G0 phase are inactive, having exited the cell cycle. Some cells enter G0 temporarily until an external signal triggers the onset of G1. Other cells that never or rarely divide, such as mature cardiac muscle and nerve cells, remain in G0 permanently.

Control of the Cell Cycle

If the cell cycle occurred without regulation, cells might go from one phase to the next before they were ready. What controls the cell cycle? How does the cell know when to grow, synthesize DNA, and divide? The cell cycle is controlled mainly by regulatory proteins. These proteins control the cycle by signalling the cell to either start or delay the cycle's next phase. They ensure that the cell completes the previous phase before moving on. Regulatory proteins control the cell cycle at key checkpoints.

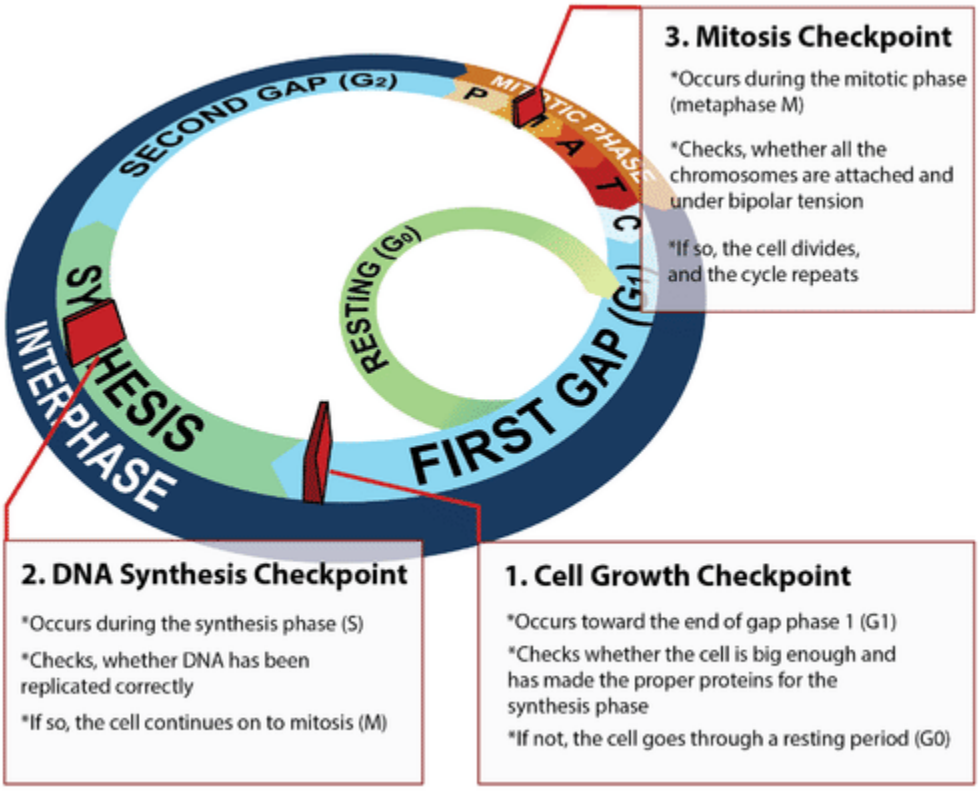


Figure 7.2.2 Checkpoints in the eukaryotic cell cycle ensure that the cell is ready to proceed before moving on to the next phase. Image by LadyofHats, CC BY-NC 3.0

Figure 7.2.2 Description

The image is a diagram of the cell cycle, illustrating the different phases of cell growth and division, along with key checkpoints that regulate the process.

Description: Circular Representation of the Cell Cycle:

The cycle is divided into distinct phases: Interphase (G1, S, G2) and Mitosis (M).
Interphase includes:

- First Gap (G1) – Cell growth phase.
- Synthesis (S) – DNA replication occurs.
- Second Gap (G2) – Preparation for mitosis.
- The Mitotic Phase (M) represents cell division.
- A Resting Phase (G0) is also indicated for cells that do not proceed with division.

Checkpoints in the Cell Cycle:

1. Cell Growth Checkpoint (G1 Checkpoint): Occurs at the end of the G1 phase. Checks if the cell has grown sufficiently and has the necessary proteins for DNA synthesis. If conditions are not met, the cell enters G0 (resting phase).
2. DNA Synthesis Checkpoint (G2 Checkpoint): Occurs during the S phase. Ensures that DNA has been replicated correctly before proceeding to mitosis.
3. Mitosis Checkpoint (Metaphase Checkpoint): Occurs during the M phase. Checks whether chromosomes are properly attached to the mitotic spindle before cell division continues.

Checkpoints in the eukaryotic cell cycle ensure the cell is ready to proceed before it moves on to the next phase.

- Cell Growth Checkpoint – Occurs in G1 just before entry into the S phase, decides whether the cell should divide.
- DNA Synthesis Checkpoint – Determines if the DNA has been replicated properly.
- Mitosis Checkpoint – Occurs during metaphase and ensures that all the chromosomes are properly aligned before the cell is allowed to divide.

Cancer and the Cell Cycle

Cancer is a disease that occurs when the cell cycle is no longer regulated. This happens because a cell's DNA becomes damaged. Damage can occur due to exposure to hazards, such as radiation or toxic chemicals. Cancerous cells generally divide much faster than normal cells, which may end up forming a mass of abnormal cells called a tumour (see Figure 7.2.3). The rapidly dividing cells take up nutrients and space that normal cells need. This can damage tissues and organs and eventually lead to death.

Figure 7.2.3 These cells are cancer cells that grow out of control and form a tumour. Image by Ed Uthman, MD, Public Domain

Cell Division

Cell division is the process in which one cell, called the **parent cell**, divides to form two new cells or **daughter cells**. How this happens depends on whether the cell is prokaryotic or eukaryotic.

Prokaryotic cells have a single circular chromosome, no nucleus, and few other organelles. The cell division process used by prokaryotes is called **binary fission**. It is a less complicated and much quicker process than cell division in eukaryotes. The resulting daughter cells are whole individual organisms. Because of the speed of binary fission, populations of prokaryotes (like bacteria) can grow very rapidly.

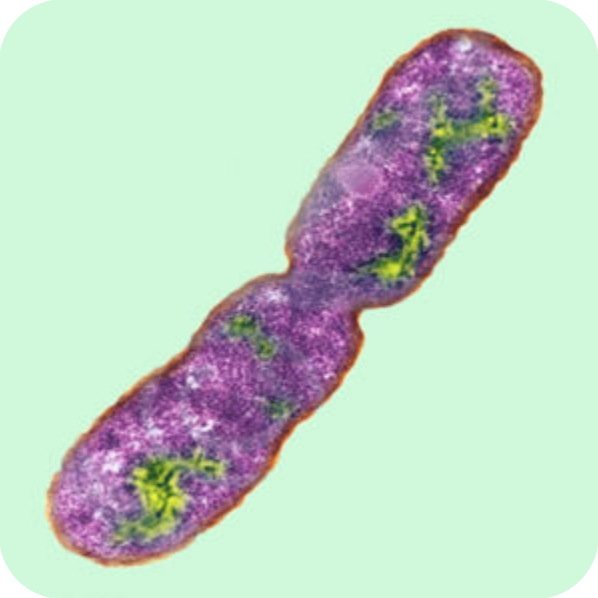


Figure 7.2.4 E. coli bacteria dividing into two identical daughter cells. Image by OpenStax, CC-BY 4.0

In contrast, Eukaryotic cells have multiple chromosomes within a nucleus and many other organelles. All these cell parts must be duplicated and separated when the cell divides. Cell division occurs during the mitotic phase of the cell cycle. The next section of the chapter takes a closer look at the steps involved.

Exercise 7.2.1

Text Description

1. The two main phases in the eukaryotic cell cycle are mitosis and interkinesis. (True/False)

2. A cell splits into two daughter cells during part of interphase. (True/False)

3. Cells may move into Synthesis (S-phase) if they pass the G1 checkpoint. (True/False)

4. Cytokinesis occurs in both prokaryotes and eukaryotes. (True/False)

5. Which is the correct order of the cell cycle?

a. First growth, second growth, synthesis, mitotic phase
b. First growth, synthesis, second growth, mitotic phase
c. First growth, synthesis, mitotic phase, second growth
d. First growth, mitotic phase, second growth, synthesis

6. Drag the words into the correct boxes

The cell spends most of its time in growth phase _____. During _____ the cell replicates its DNA. Growth phase can also be referred to as _____ phase. In the second growth phase, the cell makes final preparations to divide by making additional proteins and _____.
Possible answers:

- gap
- synthesis
- 1
- organelles

7. Drag the words into the correct boxes.

1. The cell cycle is controlled by regulatory _____, which signal the cell to start or _____ the next phase of the cycle.
2.
3. The cell cycle is controlled at key _____; occurring in the first gap phase, _____, and mitotic phase.
4.

5. If the cell cycle control system is damaged, it may result in _____ cells forming a _____.

Possible answers:

- delay
- proteins
- cancer
- checkpoints
- synthesis
- tumor

Answers:

1. False

2. False

3. True

4. True

5. b. First growth, synthesis, second growth, mitotic phase

6. The cell spends most of its time in growth phase ***1***. During ***synthesis*** the cell replicates its DNA. Growth phase can also be referred to as ***gap*** phase. In the second growth phase, the cell makes final preparations to divide by making additional proteins and ***organelles***.

7. The cell cycle is controlled by regulatory ***proteins***, which signal the cell to start or ***delay*** the next phase of the cycle.

The cell cycle is controlled at key ***checkpoints***, occurring in the first gap phase, ***synthesis***, and mitotic phase.

If the cell cycle control system is damaged, it may result in ***cancer*** cells forming a ***tumor***.

7.3 MITOSIS AND CYTOKINESIS

The **mitotic phase** is the part of the eukaryotic cell cycle when the cell is dividing. It is a multistep process during which the duplicated chromosomes are aligned, separated, and moved to opposite poles of the cell. Then, the cell is divided into two new identical daughter cells. The mitotic phase consists of two overlapping processes: mitosis and cytokinesis.

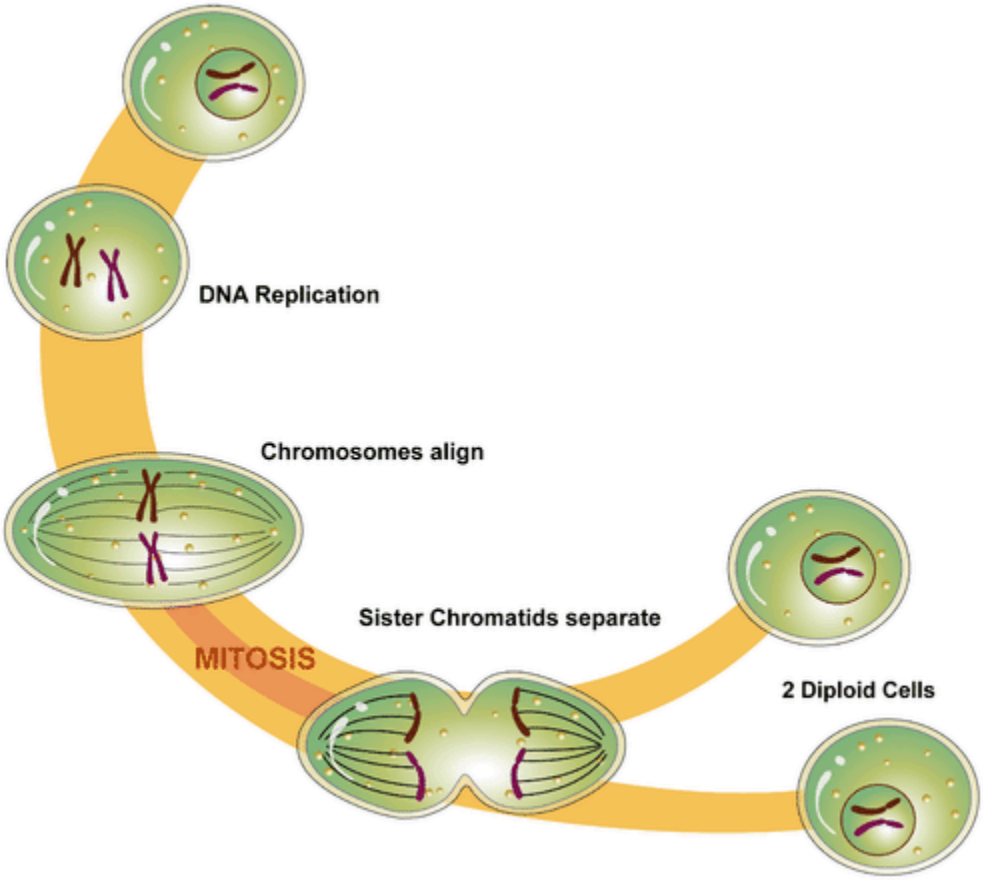


Figure 7.3.1 Mitosis is the phase of the eukaryotic cell cycle that occurs between DNA replication and the formation of two daughter cells. Image by LadyofHats, CC BY-NC 3.0

Figure 7.3.1 Description

The image is a diagram illustrating the process of mitosis, the type of cell division that results in two genetically identical diploid daughter cells.

1. Starting Cell (Interphase): The diagram begins with a single diploid cell containing a nucleus with uncondensed chromatin.DNA Replication occurs, and chromosomes duplicate, each consisting of two sister chromatids.
2. Chromosomes Align (Metaphase): The chromosomes, now condensed and visible, align at the center of the cell on the metaphase plate. The spindle fibres are attached to the centromeres of the chromosomes.
3. Sister Chromatids Separate (Anaphase-Telophase): The sister chromatids are pulled apart by spindle fibres and move towards opposite poles of the cell. The cell starts to elongate, and the nuclear envelope begins to reform.
4. Formation of Two Diploid Cells (Cytokinesis): The cell membrane pinches in, leading to the formation of two genetically identical diploid daughter cells. Each daughter cell has the same chromosome number as the original parent cell.

Mitosis

Mitosis is the process in which the nucleus of a eukaryotic cell divides. During mitosis, the two sister chromatids that make up each chromosome separate from each other and move to opposite poles of the cell. This type of cell division begins with one diploid cell and results in two identical diploid daughter cells. Mitosis is used for growth and replacing dead or damaged cells. It can also be used for asexual reproduction in some organisms.

Mitosis occurs in four phases: prophase, metaphase, anaphase, and telophase. Expand each phase below to learn more.

Phase 1: Prophase

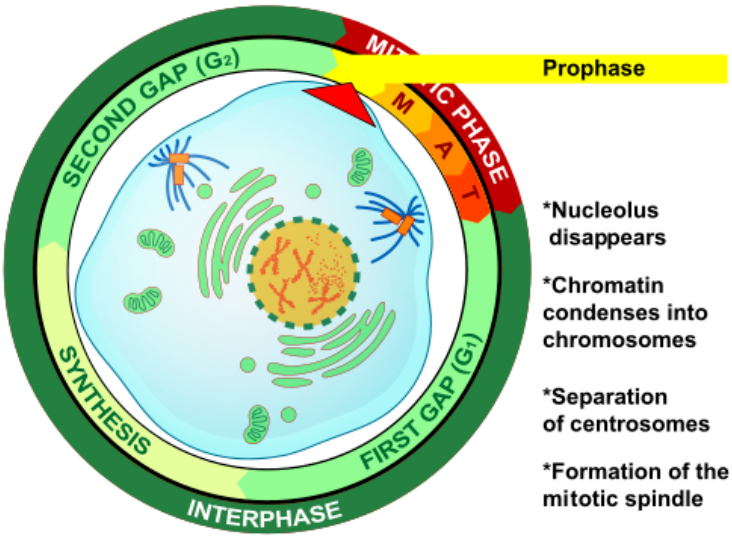


Figure 7.3.2 Prophase of mitosis. Image by LadyofHats, Public Domain

The first and longest phase of mitosis is **prophase**. During this phase, chromatin condenses into distinct chromosomes, each consisting of two sister chromatids joined at the centromere. Centrosomes move to opposite ends of the cell, initiating the formation of the spindle fibers. These fibers, composed of microtubules, are crucial for the subsequent steps of mitosis. The centrosomes play a key role in ensuring that the new cells formed after cell division contain a complete set of chromosomes. The nuclear envelope breaks down, allowing the spindle fibers to attach to the chromosomes.

Phase 2: Metaphase

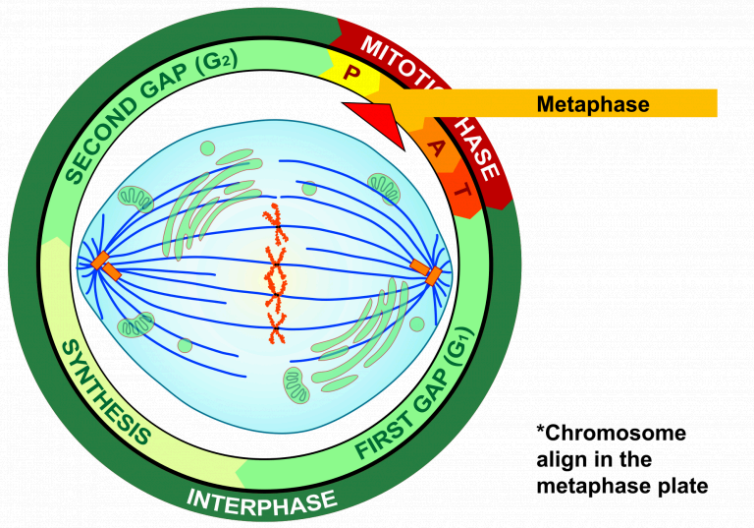


Figure 7.3.3 *Metaphase of mitosis.* Image by LadyofHats, Public Domain

During **metaphase**, spindle fibers from opposite poles attach to the centromere of each chromosome, creating a "tug of war" effect. This tension ensures chromosomes align at the cell's equator, known as the metaphase plate. The spindle fibres ensure that sister chromatids separate and go to different daughter cells when the cell divides.

Phase 3: Anaphase

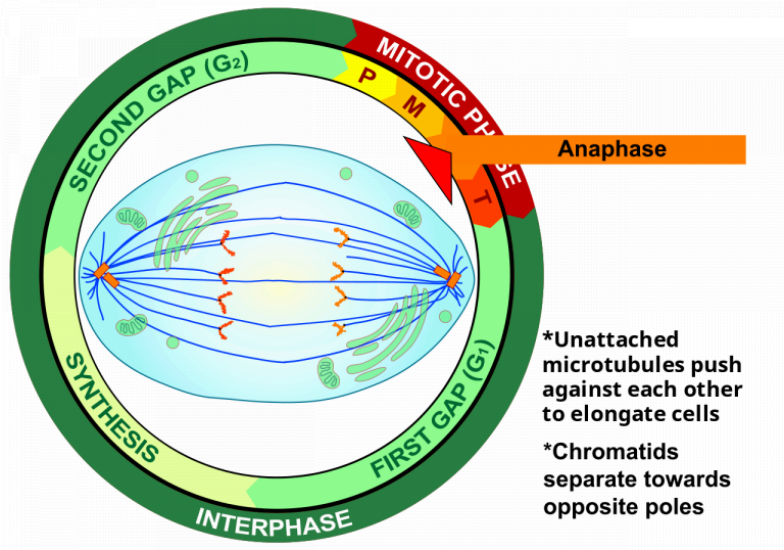


Figure 7.3.4 Anaphase of mitosis. Image by LadyofHats, Public Domain

During **anaphase**, sister chromatids are pulled apart by the spindle fibers. Each chromatid, now an individual chromosome, moves toward opposite poles of the cell. This separation ensures that each new cell will receive an identical set of chromosomes. Spindle fibers not attached to chromosomes elongate, pushing the poles further apart and helping to stretch the cell.

Phase 4: Telophase

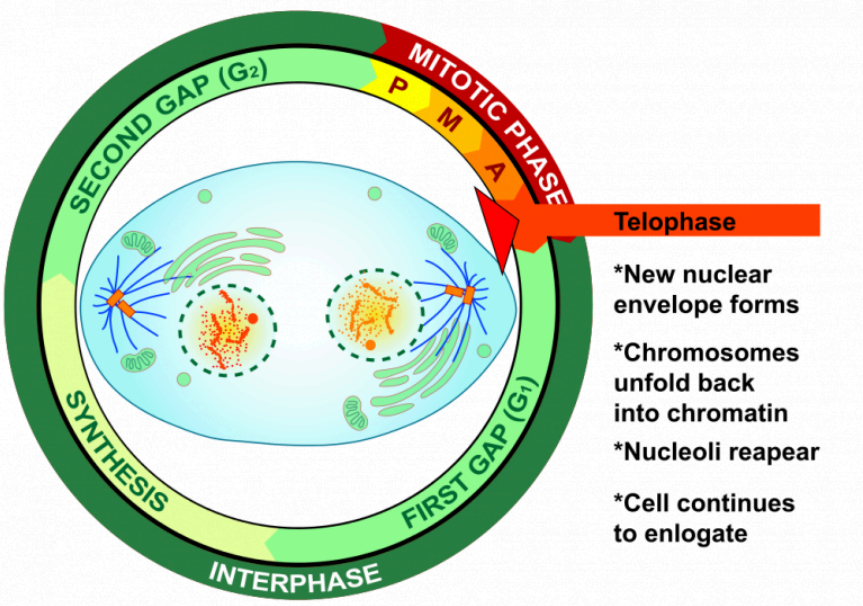


Figure 7.3.5 Telophase in mitosis. Image by LadyofHats, Public Domain

During **telophase**, the separated chromosomes reach the opposite poles of the cell. Telophase is the reverse of prophase. The spindle fibers begin to disassemble, and the nuclear envelope re-forms around each set of chromosomes, creating two distinct nuclei. The chromosomes start to decondense back into chromatin. Cytokinesis often starts during this phase, to split the cytoplasm into two daughter cells.

Cytokinesis

Cytokinesis is the second part of the mitotic phase, during which cell division is completed by the physical separation of the cytoplasmic components into two daughter cells. Although the stages of mitosis are similar for most eukaryotes, the process of cytokinesis is quite different for eukaryotes with cell walls, such as plant cells.

In cells such as animal cells that lack cell walls, cytokinesis begins following the onset of anaphase. A contractile ring composed of actin filaments forms inside the plasma membrane at the former metaphase plate. The actin filaments pull the cell's equator inward, forming an indentation called the **cleavage furrow**. The furrow deepens as the actin ring contracts, and eventually, the membrane and cell are split in two (Figure 7.3.6).

A cleavage furrow is impossible in plant cells because of the rigid cell walls surrounding the plasma

membrane. A new cell wall must form between the daughter cells. During interphase, the Golgi apparatus accumulates enzymes, structural proteins, and glucose molecules prior to breaking up into vesicles and dispersing throughout the dividing cell. These Golgi vesicles move on microtubules to collect at the metaphase plate during telophase. There, the vesicles fuse from the centre toward the cell walls; this structure is called a **cell plate**. As more vesicles fuse, the cell plate enlarges until it merges with the cell wall at the cell's periphery. Enzymes use the glucose that has accumulated between the membrane layers to build a new cell wall of cellulose. The Golgi membranes become the plasma membrane on either side of the new cell wall (Figure 7.3.6).

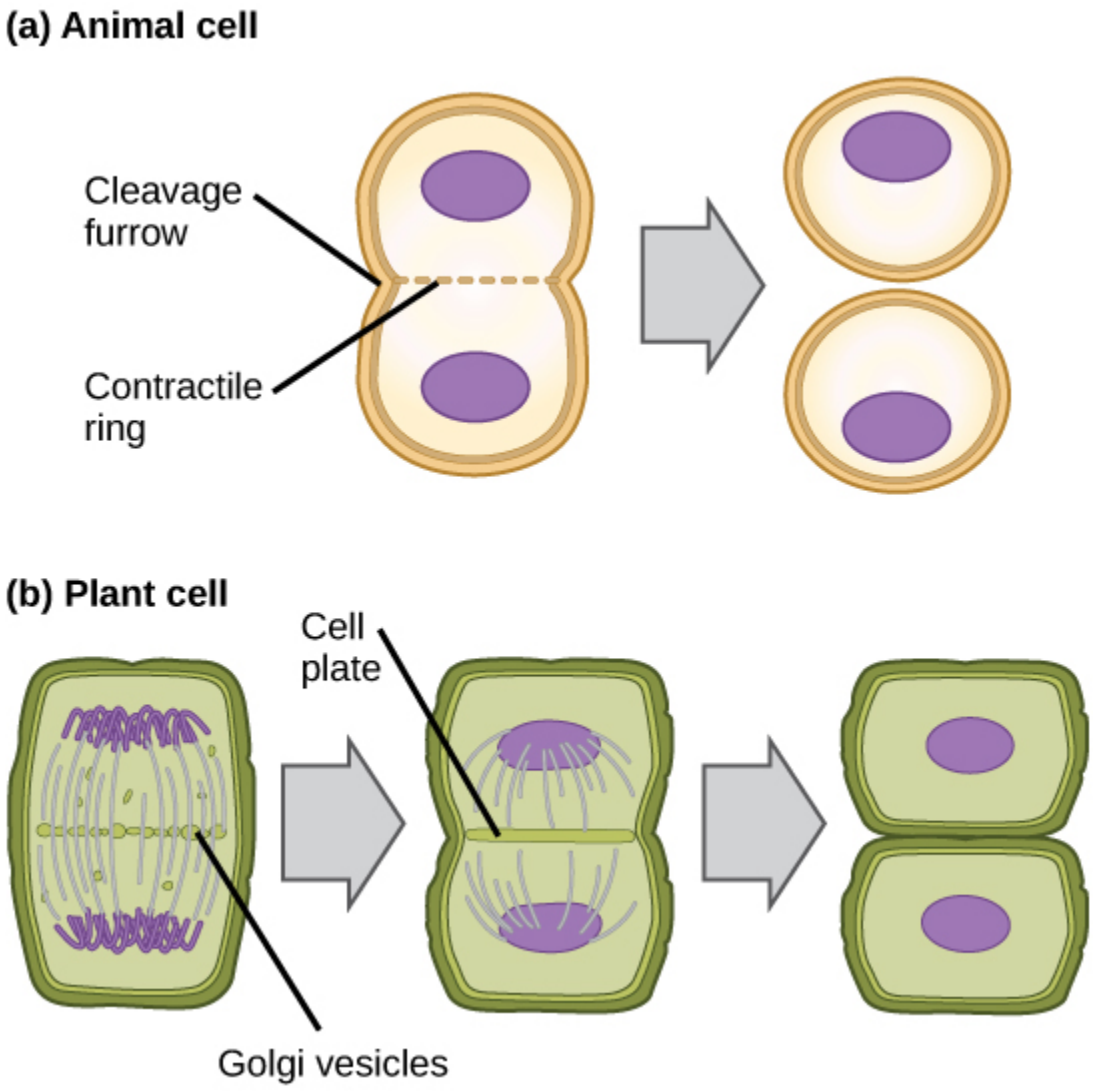


Figure 7.3.6 (a) A cleavage furrow divides animals cell. (b) A cell plate divides plant cells
Image by OpenStax, CC BY 4.0

Exercise 7.3.1

Text Description
Drag to arrange the images in the correct sequence

1. An image illustrating telophase and cytokinesis
2. An image illustrating anaphase
3. An image illustrating metaphase
4. An image illustrating prophase

Answers:

1. An image illustrating prophase
2. An image illustrating metaphase
3. An image illustrating anaphase
4. An image illustrating telophase and cytokinesis

Text Description

1. Fibres called centrioles attach to the centromeres during mitosis. (True/False)

2. Chromosomes begin to uncoil during anaphase. (True/False)

3. During metaphase, sister chromatids line up along the equator of the cell. (True/False)

4. After mitosis, the result is typically two daughter cells with identical DNA to each other. (True/False)

Answers:

1. False

2. False

3. True

4. True

7.4 MEIOSIS

Sexual Reproduction

Reproduction is the process by which organisms give rise to offspring. It is one of the defining characteristics of living things. Like many other organisms, human beings reproduce sexually. **Sexual reproduction** involves two parents. As you can see from Figure 7.4.1, in sexual reproduction, parents produce reproductive (sex) cells — called **gametes** — that unite to form offspring. Gametes are haploid (or n) cells. This means they contain one copy of each chromosome in the nucleus. Gametes are produced by a type of cell division called meiosis, which is described in detail below. The process in which two gametes unite is called **fertilization**. The fertilized cell that results is referred to as a zygote. A **zygote** is a diploid (or 2n) cell which contains two copies of each chromosome. Thus, it has twice the number of chromosomes as a gamete.

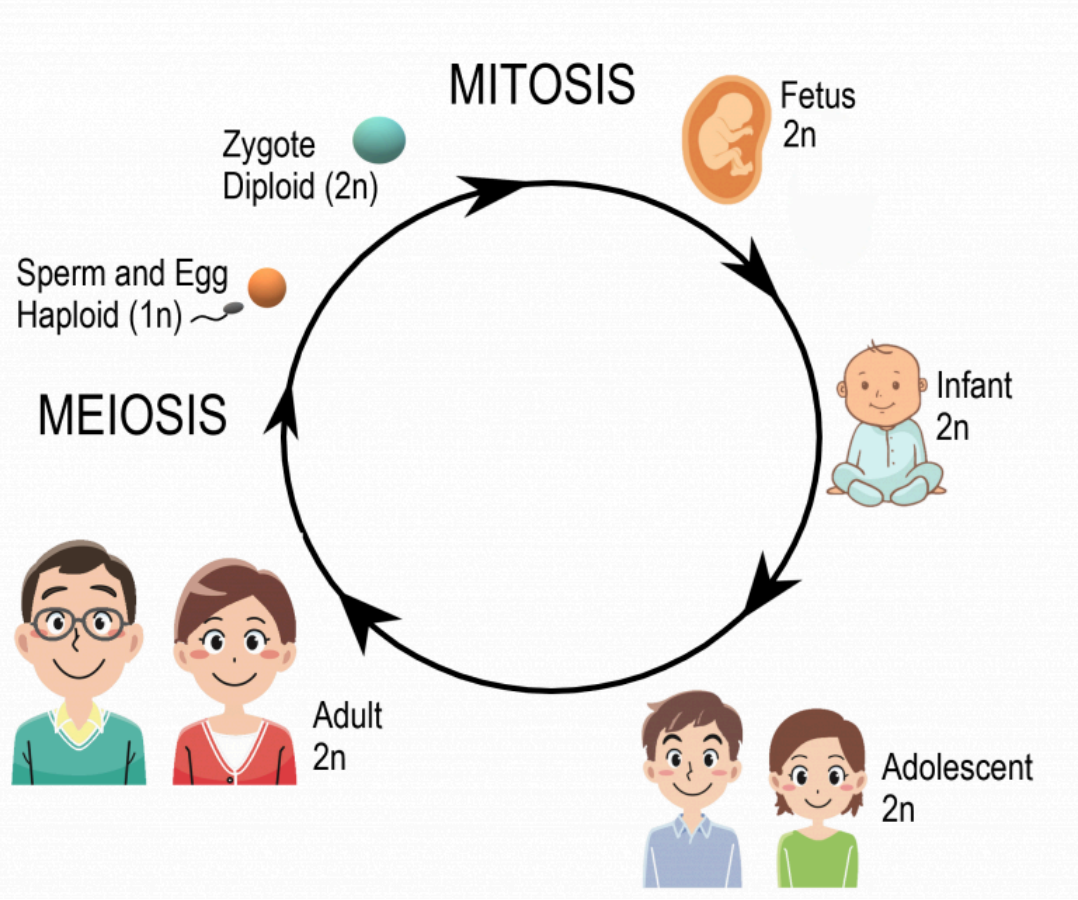


Figure 7.4.1 Sexual reproduction involves the production of haploid gametes by meiosis, followed by fertilization and forming a diploid zygote. The number of chromosomes in a gamete is represented by the letter N. Why does the zygote have 2N, or twice as many, chromosomes? Image by Christine Miller, CC BY-NC-SA 4.0

Meiosis

The process that produces haploid gametes is called meiosis. **Meiosis** is a type of cell division in which the number of chromosomes is reduced by half. During meiosis, **homologous chromosomes** (paired chromosomes — one from each parent) separate in the first division (meiosis I), so the resulting cells only have one chromosome from each pair. These cells then go through a second division (meiosis II), where the sister chromatids of each chromosome are then separated, ensuring that each gamete ends up with a single copy of each chromosome.

This type of cell division starts with one diploid cell and finishes with four genetically different haploid cells. Meiosis is only used to produce gametes for sexual reproduction.

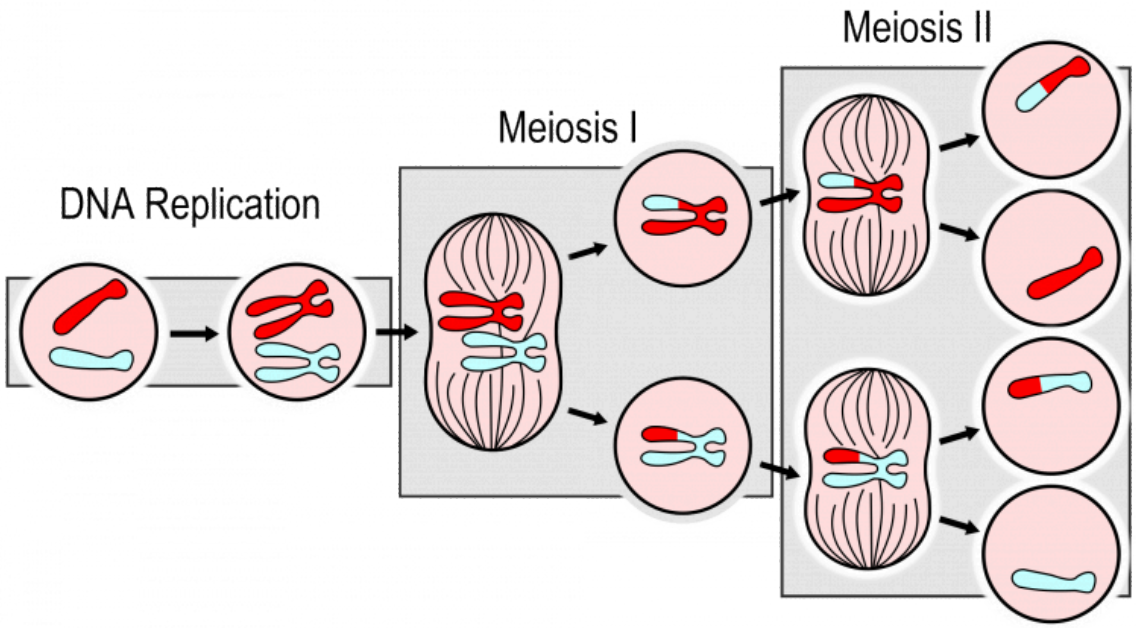


Figure 7.4.2 Overview of Meiosis. During meiosis, homologous chromosomes separate and go to different daughter cells. Image by PatríciaR. Original image from NCBI; original vector version by Jakov, Public Domain

As you can see in the meiosis diagram, the two cell divisions are called meiosis I and meiosis II. Meiosis I begins after DNA replicates during interphase. Meiosis II follows meiosis I without DNA replicating again. Both meiosis I and meiosis II occur in four phases: prophase, metaphase, anaphase, and telophase. You may recognize these four phases from mitosis, the division of the nucleus that takes place during routine cell division of eukaryotic cells.

Meiosis I- Increasing Genetic Variation

The phases of Meiosis I are:

1. **Prophase I**: The nuclear envelope begins to break down, and the chromosomes condense. Centrosomes start moving to opposite cell poles, and spindle fibers form. Importantly, homologous chromosomes pair up, which is unique to prophase I. In the prophase of mitosis and meiosis II, homologous chromosomes do not form pairs in this way. During prophase I, crossing-over occurs. The significance of crossing over is discussed below.
2. **Metaphase I**: Spindle fibres attach to the paired homologous chromosomes. The paired chromosomes line up along the cell's equator, randomly aligning in a process called independent assortment (discussed below). This occurs only in metaphase I. In the metaphase of mitosis and meiosis II, sister chromatids

line up along the cell's equator.

3. **Anaphase I**: Spindle fibres shorten, and the chromosomes of each homologous pair start to separate from each other. One chromosome of each pair moves toward one pole of the cell, and the other chromosome moves toward the opposite pole.
4. **Telophase I and Cytokinesis**: The spindle breaks down, and new nuclear membranes form. The cytoplasm of the cell divides, and two haploid daughter cells result. The daughter cells each have a random assortment of chromosomes, with one from each homologous pair. Both daughter cells go on to meiosis II.

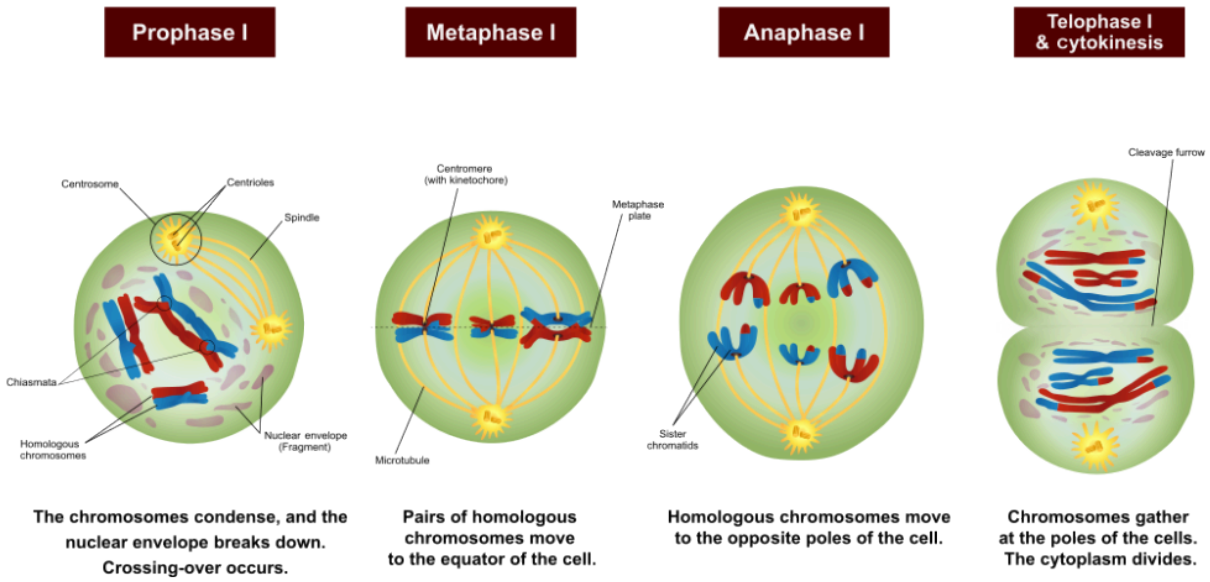


Figure 7.4.3 Meiosis I is critical in creating genetic diversity in resulting gametes. Crossing over in Prophase I and independent alignment in Metaphase I ensure that each resulting gamete is unique. Image by Ali Zifan, CC BY-SA 4.0

Figure 7.4.3 Description

Diagram showing the stages of Meiosis I: Prophase I, Metaphase I, Anaphase I, and Telophase I with cytokinesis. In Prophase I, chromosomes condense, the nuclear envelope breaks down, and crossing-over occurs. In Metaphase I, homologous chromosomes align at the equator. In Anaphase I, homologous chromosomes move to opposite poles. In Telophase I and cytokinesis, chromosomes gather at the poles, and the cytoplasm divides, forming two cells.

Meiosis II- Halving the DNA

The phases of Meiosis II are:

1. Prophase II: The nuclear envelope breaks down, and the spindle forms in each haploid daughter cell from meiosis I. The centrosomes also start to separate.
2. Metaphase II: Spindle fibres line up the sister chromatids of each chromosome along the cell's equator.
3. Anaphase II: Sister chromatids separate and move to opposite poles.
4. Telophase II and Cytokinesis: The spindle breaks down, forming new nuclear membranes. The cytoplasm of each cell divides, and four haploid cells result. Each cell has a unique combination of chromosomes.

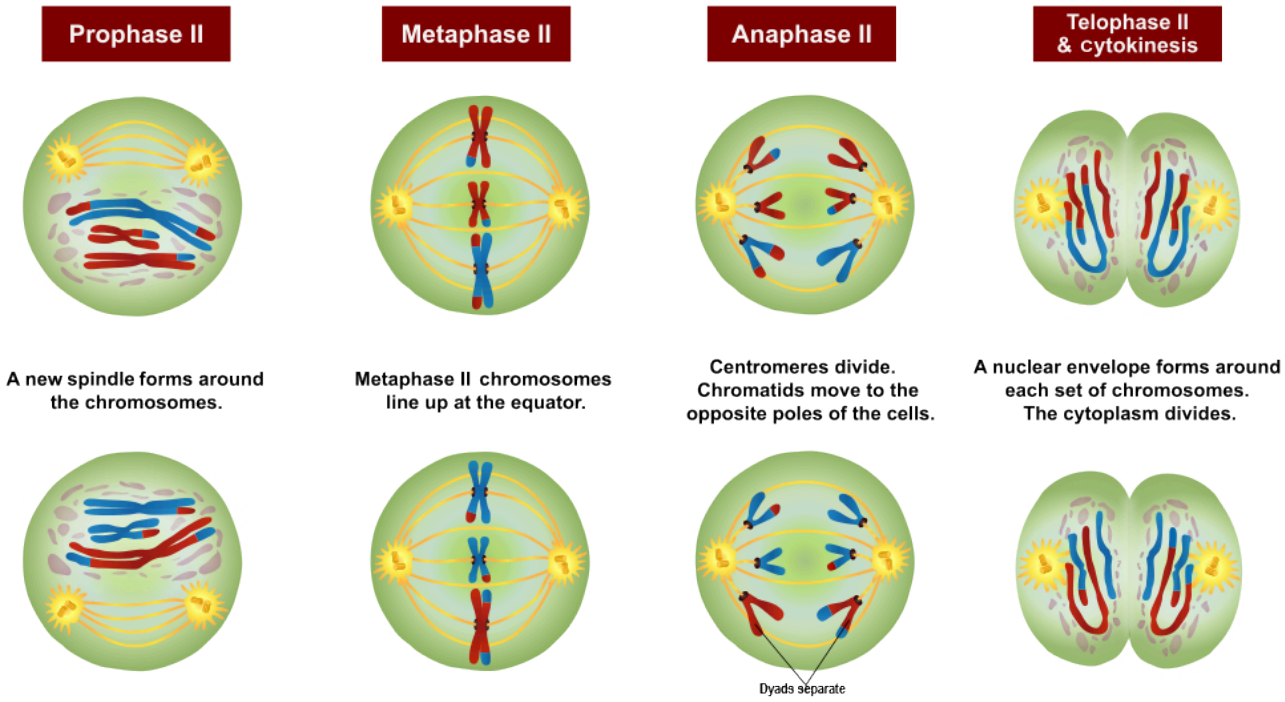


Figure 7.4.4 In Meiosis II, sister chromatids are separated to create four unique haploid cells. Image by Ali Zifan, CC BY-SA 4.0

Figure 7.4.4 Description

Diagram showing the stages of Meiosis II: Prophase II, Metaphase II, Anaphase II, and Telophase II with cytokinesis. In Prophase II, a new spindle forms around the chromosomes. In Metaphase II, chromosomes align at the cell equator. In Anaphase II, centromeres divide, and chromatids move to opposite poles. In

Telophase II and cytokinesis, nuclear envelopes form around each set of chromosomes, and the cytoplasm divides, resulting in four genetically unique haploid cells.

Comparing Mitosis and Meiosis

Mitosis and meiosis are both processes of nuclear division in eukaryotic cells. They have many similarities and distinct differences that lead to very different outcomes.

Mitosis involves a single division, resulting in two new cells. These cells are genetically identical to the original and have the same number of chromosome sets. For humans, mitosis starts with one diploid cell, resulting in two diploid cells. This type of cell division is used for growth and replacing dead or damaged cells. It can also be used for asexual reproduction in some organisms.

Meiosis, on the other hand, involves two divisions, resulting in four cells. These cells are genetically diverse and contain half the number of chromosomes. In humans, meiosis starts with one diploid cell and results in four haploid cells. This type of cell division is used to produce gametes for sexual reproduction.

The differences in outcomes between mitosis and meiosis are primarily a result of the behaviour of chromosomes in meiosis I. In mitosis, chromosomes line up along the metaphase plate *individually* (or "single file"). This configuration results in each chromosome getting split, with one sister chromatid going to either pole. In contrast, in meiosis I, homologous chromosome pairs bind together, crossover, and line up along the metaphase plate in *tetrads* (or "double file"). This configuration results in the tetrad splitting with one entire chromosome from each pair going to either pole (sister chromatids remain intact).

Meiosis II is more similar to mitosis. Chromosomes line up along the metaphase plate individually (or "single file"), dividing sister chromatids.

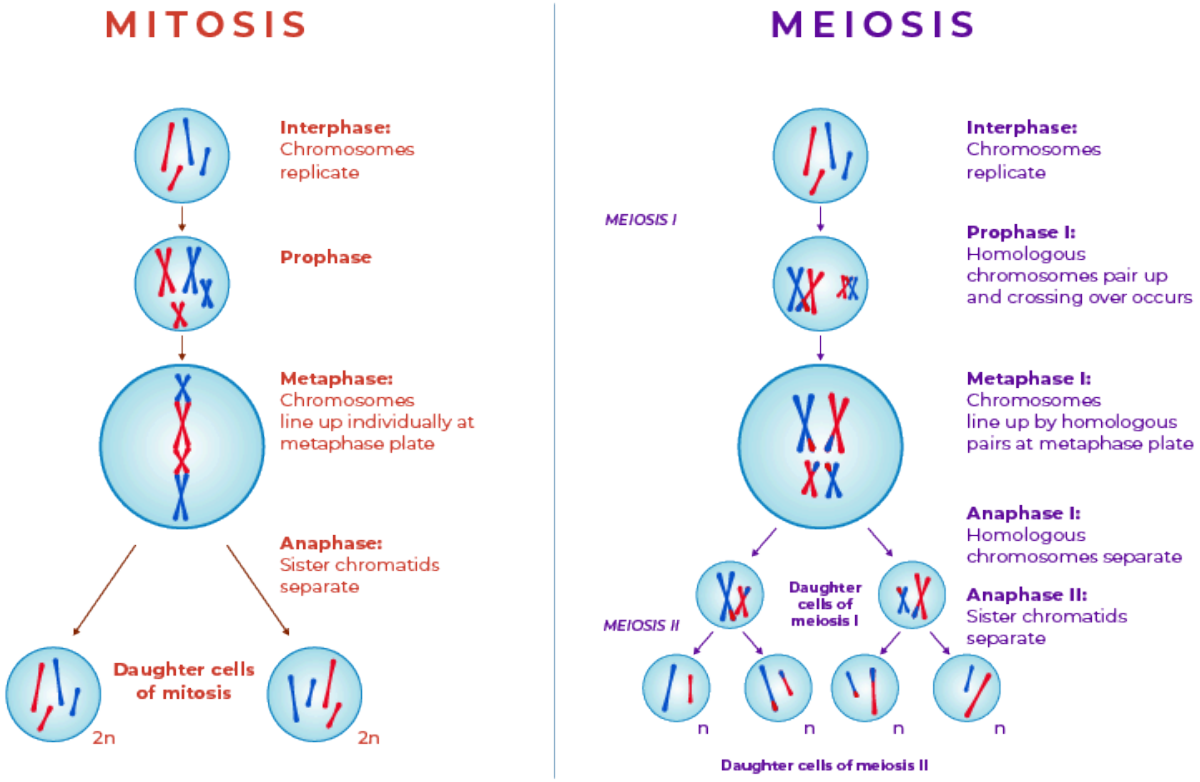


Figure 7.4.5 Meiosis and mitosis are preceded by one DNA replication round; however, meiosis includes two nuclear divisions. The four daughter cells resulting from meiosis are haploid and genetically distinct. The daughter cells resulting from mitosis are diploid and identical to the parent cell. Mitosis vs. Meiosis by Dr. Katherine Harris is licensed under a CC BY-NC-SA 3.0 Mods: recoloured.

Figure 7.4.5 Description

Side-by-side comparison of Mitosis and Meiosis. On the left, the Mitosis process is shown: chromosomes replicate during interphase, align individually at the metaphase plate, and sister chromatids separate in anaphase, resulting in two diploid (2n) daughter cells. On the right, Meiosis is shown: chromosomes replicate during interphase, homologous chromosomes pair and undergo crossing over during Prophase I, align as pairs in Metaphase I, separate in Anaphase I, and then sister chromatids separate in Anaphase II. Meiosis results in four haploid (n) daughter cells, each genetically unique.

Sexual Reproduction and Genetic Variation

"It takes two to tango" might be a euphemism for sexual reproduction. Requiring two individuals to produce offspring, however, is also the main drawback of this way of reproducing because it requires extra steps — and often a certain amount of luck — to produce with a partner successfully. On the other hand, sexual reproduction greatly increases the potential for genetic variation in offspring, which increases the likelihood

that the resulting offspring will have genetic advantages. In fact, each offspring produced is almost guaranteed to be genetically unique, differing from both parents and from any other offspring.

Sexual reproduction increases genetic variation in a number of ways:

Crossing Over

When homologous chromosomes pair up during meiosis I, crossing over can occur. **Crossing over** is the exchange of genetic material between non-sister chromatids of homologous chromosomes. It results in new combinations of genes on each chromosome.

Once crossing over has occurred, we can no longer call them sister chromatids since they are no longer identical; we term them dyads. In addition, once crossing over has occurred, the pair of homologous chromosomes can be referred to as tetrads.

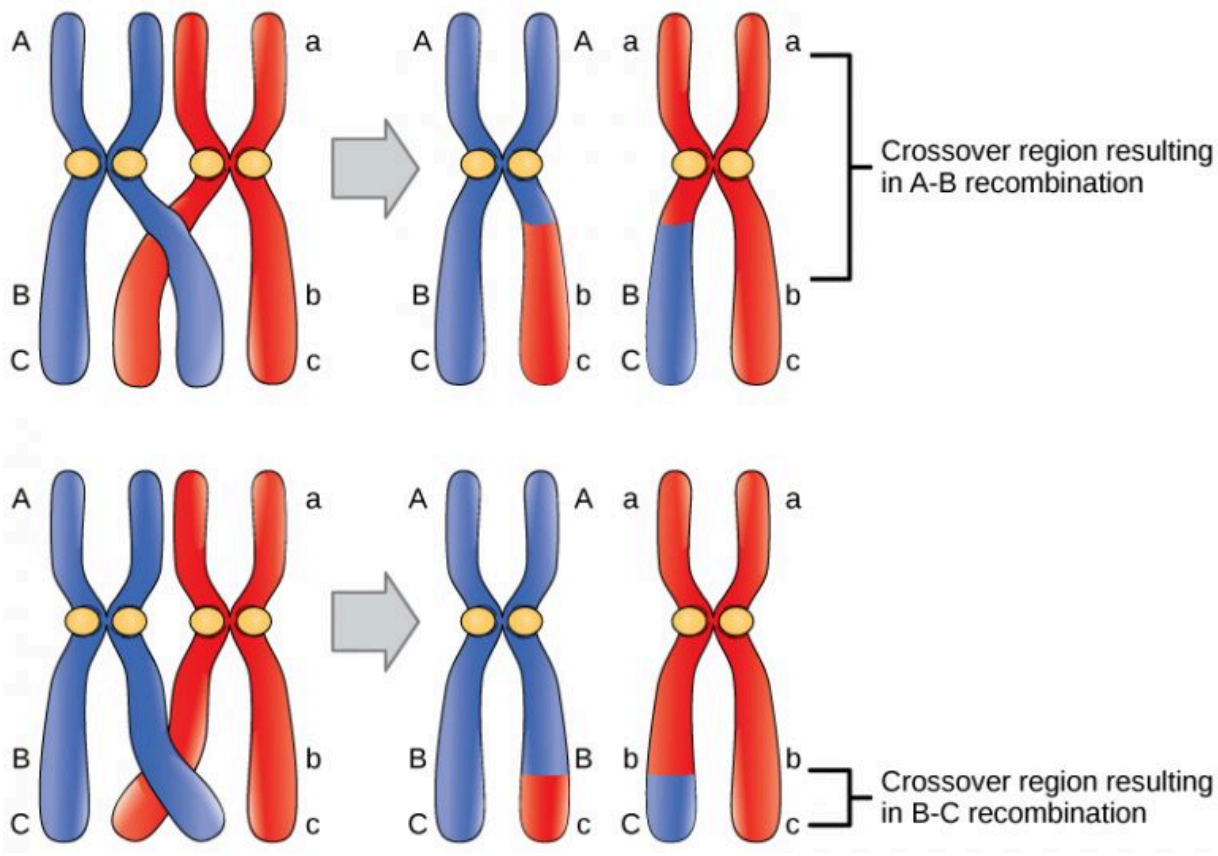


Figure 7.4.6 Crossing over results in an exchange of sections of DNA between homologous pairs of chromosomes. Image by OpenStax, CC BY 4.0

Figure 7.4.5 Description

Diagram showing crossing over between homologous chromosomes. The top panel shows A-B recombination, where a crossover occurs between regions labelled A and B on homologous chromosomes, resulting in an exchange of genetic material. The bottom panel shows B-C

recombination, where the crossover occurs between regions B and C. Each results in chromosomes with mixed genetic segments, illustrating how recombination increases genetic diversity. Labelled regions A, B, C and their lowercase counterparts mark chromosome segments from different parents.

Independent Assortment

During metaphase I of meiosis, the orientation of each homologous pair of chromosomes is random. This means that either the maternal (red) or paternal (blue) chromosome can be on the left or right side. This is called **independent assortmen**t. It results in gametes that have unique combinations of chromosomes. For humans, independent assortment results in over 8 million different combinations of chromosomes!

For example, in Figure 7.4.7, there are 8 possible ways the chromosome pairs can align. In the first possibility, all 3 blue chromosomes are on the same side which would result in gametes with only red or only blue chromosomes. In the second possibility, the pairs are oriented differently, producing gametes with a mix of red and blue chromosomes. These different arrangements will result in gametes with different combinations of chromosomes.

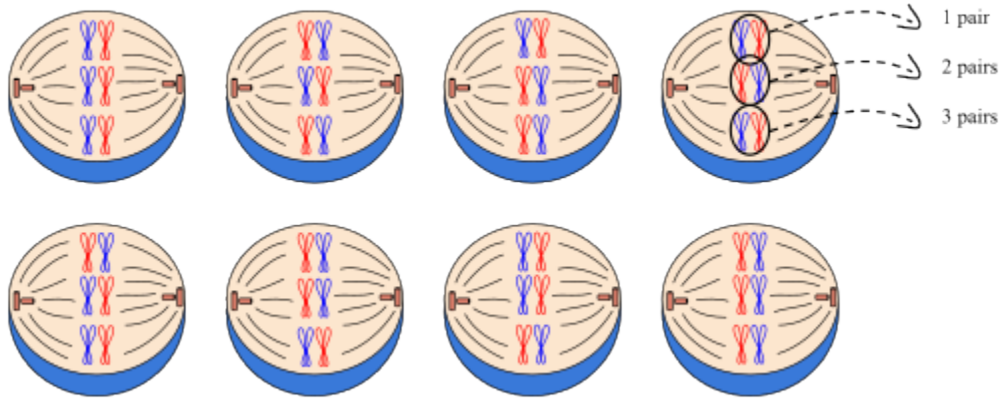


Figure 7.4.7 The way that homologous pairs align (with paternal or maternal DNA on the left or right side) determines which mix of genes will end up in gametes. Image by Mtian20, CC BY-SA 4.0

Random Fertilization

In sexual reproduction, two gametes unite to produce an offspring. However, which two of the millions of potential gametes will combine is a matter of chance. Given that a human egg cell, with approximately 8 million possible genetic combinations, is **randomly fertilized** by a human sperm cell which also has about 8 million possibilities, a single man and woman can produce zygotes with 64 trillion combinations of chromosomes!

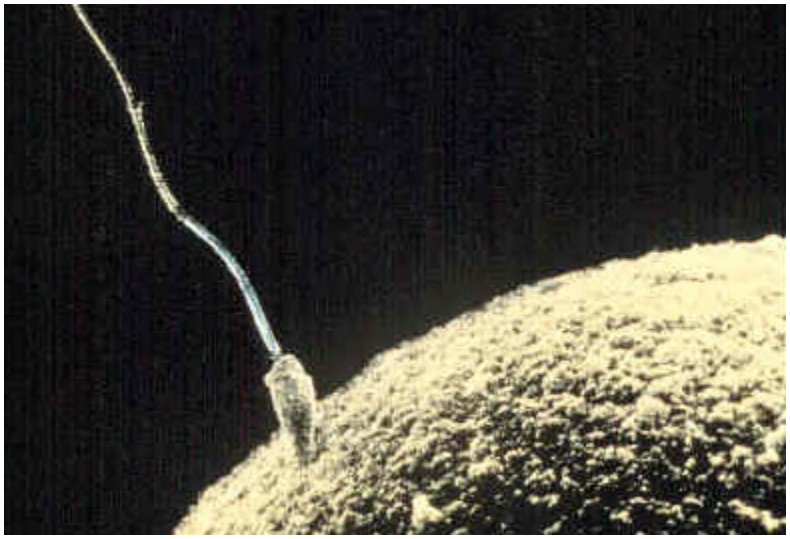


Figure 7.4.8 Fertilization. Image by Andrea Laurel, CC BY 2.0

Errors in Meiosis

Mistakes may occur during meiosis that results in **nondisjunction**. This is the failure of replicated chromosomes to separate properly during meiosis. Some of the resulting gametes will be missing all or part of a chromosome, while others will have an extra copy of all or part of the chromosome. If such gametes are fertilized and form zygotes, they usually do not survive. If they do survive, the individuals are likely to have serious genetic disorders.

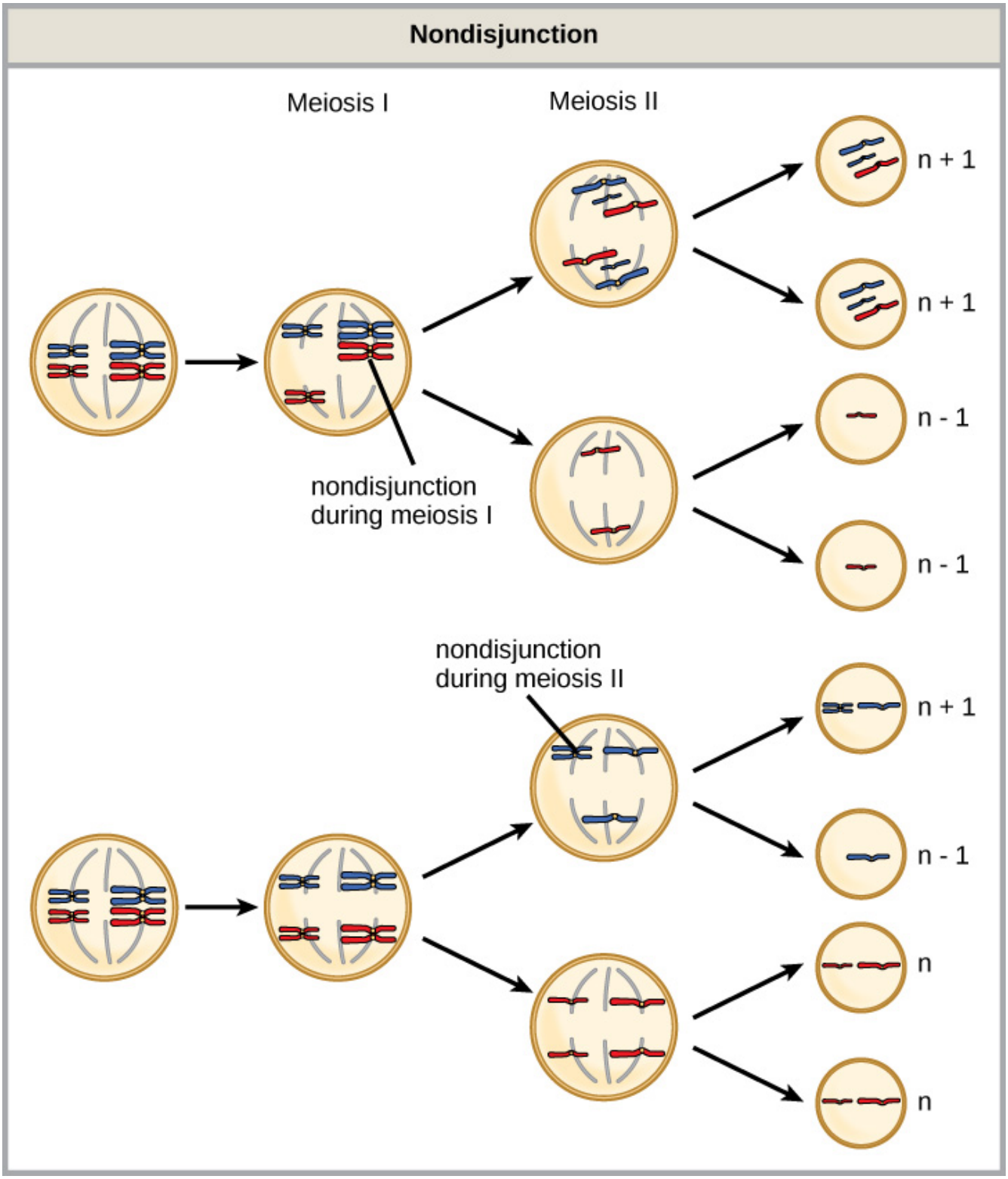


Figure 7.4.9 Following meiosis, each gamete has one copy of each chromosome. Nondisjunction occurs when homologous chromosomes (meiosis I) or sister chromatids (meiosis II) fail to separate during meiosis. Image by OpenStax, CC BY 4.0

Figure 7.4.8 Description

Diagram illustrating nondisjunction during meiosis. In the top half, nondisjunction occurs during Meiosis I, where homologous chromosomes fail to separate, resulting in two gametes with an extra chromosome (n+1) and two with one missing chromosome (n−1). In the bottom half, nondisjunction occurs during Meiosis II, where sister chromatids fail to separate in one of the cells, producing one gamete with an extra chromosome (n+1), one with a missing chromosome (n−1), and two normal gametes (n).

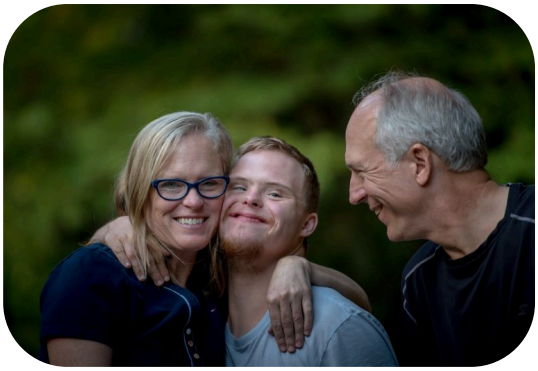


Figure 7.4.10 Family with Down syndrome child. Image by Nathan Anderson, Unsplash License

Down syndrome is a genetic disorder where an individual has an extra copy of chromosome 21. People with Down syndrome often have distinct facial features and developmental delays and may have other health issues.

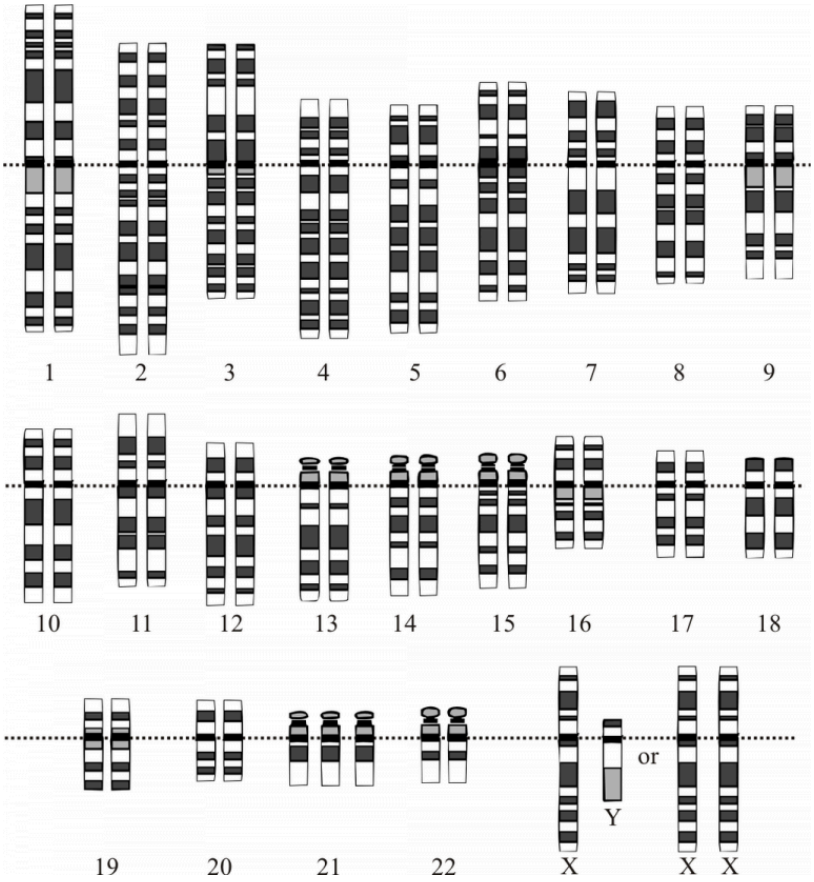


Figure 7.4.11 Trisomy 21 (Down Syndrome) Karyotype. Image by National Human Genome Research Institute, CC BY-SA 4.0

Exercise 7.4.1

Text Description

1. Crossing over is the exchange of genetic material between sister chromatids. (True/False)

2. Human sperm are haploid. (True/False)

3. Drag the words into the correct boxes

In ____ crossing over occurs between homologous pairs of chromosomes.

In ____ independent alignment increases the genetic diversity that will occur once Meiosis is complete.

In ____ of mitosis, sister chromatids separate. In ____ of Meiosis, dyads separate. In ____ of Meiosis, tetrads separate.
Possible Answers:

- Anaphase I
- Prophase I
- Metaphase I
- Anaphase II
- Telophase I
- Anaphase
- Telophase II

4. Drag and drop the images in the correct zone for the stages of meiosis

Possible Drop Zones:

- Prophase 1
- Metaphase 1
- Anaphase 1
- Telophase 1
- Prophase 2
- Metaphase 2
- Anaphase 2

- Telophase 2

Possible Images:

- Image Illustrating Cells in Prophase 1
- Image Illustrating Cells in Metaphase 1
- Image Illustrating Cells in Anaphase 1
- Image Illustrating Cells in Telophase 1
- Image Illustrating Cells in Prophase 2
- Image Illustrating Cells in Metaphase 2
- Image Illustrating Cells in Anaphase 2
- Image Illustrating Cells in Telophase 2

5. How many daughter cells does meiosis produce?

- Four Haploids
- Two Haploids
- Two Diploids
- Four Diploids

6. At which stage of meiosis are sister chromatids separated from each other?

- Prophase I
- Anaphase II
- Prophase II
- Anaphase I

7. What is the part of meiosis that is similar to mitosis?

- Meiosis II
- Anaphase I
- Meiosis I
- Interkinesis

8. If a muscle cell of a typical organism has 32 chromosomes, how many chromosomes will be in a gamete of that same organism?

- 16
- 64
- 32

- 8

9. Drag the words into the correct boxes

Random alignment leads to new combinations of traits. The chromosomes that were originally inherited by the gamete-producing individual came equally from the ____ and the ____. In ____, the duplicated copies of these maternal and paternal homologous chromosomes line up across the ____ of the cell to form a tetrad. The ____ of each tetrad is ____. There is an ____ chance that the maternally derived chromosomes will be facing either pole. The same is true of the paternally derived chromosomes. The alignment should occur ____ in almost every meiosis. As the homologous chromosomes are pulled apart in ____, any combination of maternal and paternal chromosomes will move toward each pole. The gametes formed from these two groups of chromosomes will have a mixture of traits from the individual's parents. Each gamete is ____.

Possible Answers:

- differently
- anaphase I
- egg
- sperm
- center
- orientation
- unique
- metaphase I
- random
- equal

10. Drag the words into the correct boxes to describe the ways meiosis II is similar to and different from mitosis of a diploid cell.

The two divisions are similar in that the chromosomes line up along the metaphase plate ____, meaning unpaired with other chromosomes (as in meiosis I). In addition, each chromosome consists of ____ sister ____ that will be pulled apart. The two divisions are different because in meiosis II there are ____ the number of chromosomes that are present in a diploid cell of the same species undergoing mitosis. This is because ____ reduced the number of chromosomes to a haploid state.

Possible Answers:

- half
- individually

- meiosis I
- chromatids
- two

Answers:

1. False

2. True

3. In ***Prophase I*** crossing over occurs between homologous pairs of chromosomes.

In ***Metaphase I*** independent alignment increases the genetic diversity that will occur once Meiosis is complete.

In ***Anaphase*** of mitosis, sister chromatids separate. In ***Anaphase II*** of Meiosis, dyads separate. In ***Anaphase I*** of Meiosis, tetrads separate.

At the end of ***Telophase I*** there are two cells, and at the end of ***Telophase II*** there are four unique haploid cells.

4. Images match description

5. Four Haploids

6. Anaphase II

7. Meiosis II

8. Meiosis II

9. Random alignment leads to new combinations of traits. The chromosomes that were originally inherited by the gamete-producing individual came equally from the ***egg*** and the ***sperm***. In ***metaphase I***, the duplicated copies of these maternal and paternal homologous chromosomes line up across the ***center*** of the cell to form a tetrad. The ***orientation*** of each tetrad is ***random***. There is an ***equal*** chance that the maternally derived chromosomes will be facing either pole. The same is true of the paternally derived chromosomes. The alignment should occur ***differently*** in almost every meiosis. As the homologous chromosomes are pulled apart in ***anaphase I***, any combination of maternal and paternal chromosomes will move toward each pole. The gametes formed from

these two groups of chromosomes will have a mixture of traits from the individual's parents. Each gamete is ***unique***.

10. The two divisions are similar in that the chromosomes line up along the metaphase plate ***individually***, meaning unpaired with other chromosomes (as in meiosis I). In addition, each chromosome consists of ***two*** sister ***chromatids*** that will be pulled apart. The two divisions are different because in meiosis II there are ***half*** the number of chromosomes that are present in a diploid cell of the same species undergoing mitosis. This is because ***meiosis I*** reduced the number of chromosomes to a haploid state.

CHAPTER 7 SUMMARY

Key Takeaways

- **The Genome:** All cells have a genome, complete DNA instructions. Eukaryotic DNA is stored in chromosomes inside a nucleus, while prokaryotic DNA forms a single circular loop.
- **Chromosomes and Genes:** Human body cells have 46 chromosomes (23 pairs), including autosomes and sex chromosomes. Genes on these chromosomes code for proteins and are inherited in pairs (diploid), except in gametes (haploid).
- **The Cell Cycle:** The cell cycle includes phases for growth (G1, G2), DNA replication (S), and Mitotic (M phase). Checkpoints regulate the cycle to prevent errors; uncontrolled growth can lead to cancer.
- **Mitosis:** Mitosis produces two identical diploid cells, used for growth, repair, and asexual reproduction. It involves four phases: prophase, metaphase, anaphase, and telophase, followed by cytokinesis.
- **Meiosis and Sexual Reproduction:** Meiosis creates four unique haploid gametes for sexual reproduction. It includes two divisions and increases genetic diversity through crossing over, independent assortment, and random fertilization.
- **Errors in Meiosis:** Mistakes like nondisjunction can result in extra or missing chromosomes, potentially causing genetic disorders such as Down syndrome.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into six key takeaways.

Flash Cards

Text Description

1. **Genome**: The complete genetic material (DNA) set in an organism
2. **Chromatin**: DNA and associated proteins loosely packed within the nucleus; condenses to form chromosomes during cell division
3. **Chromosomes:** Structures of tightly coiled DNA and proteins that carry genetic information in cells
4. **Genes**: Segments of DNA encoding specific proteins, determining inherited characteristics
5. **Sister chromatids**: Identical copies of a chromosome joined together after DNA replication; separate during cell division
6. **Centromere**: Region where sister chromatids are attached, essential for their proper separation during cell division
7. **Somatic cells**: Non-reproductive cells of an organism's body, typically diploid
8. **Diploid:** A cell containing a two complete sets of chromosomes (2n), one from each parent
9. **Homologous chromosomes**: Pairs of chromosomes (one from each parent) carrying genes for the same traits in similar positions
10. **Gametes**: Sex cells (sperm and egg) containing half the genetic material of somatic cells; involved in reproduction
11. **Haploid**: A cell containing a single set of chromosomes (n), such as gametes
12. **Autosomes**: Chromosomes that do not determine sex; humans have 22 pairs of autosomes
13. **Sex chromosomes**: Chromosomes determine biological sex; Females (XX) and males (XY)
14. **Cell cycle:** Series of stages that cells go through to grow and divide, consisting of interphase (G1, S, and G2 phases) and mitotic phase (mitosis and cytokinesis)
15. **Interphase:** Phase of the cell cycle during which the cell grows, duplicates its DNA, and prepares for mitosis; Consists of three stages – G1, S, G2
16. **Gap 1:** First stage of interphase in the cell cycle; cell grows rapidly while performing routine metabolic processes

17. **Synthesis:** Second stage of interphase in the cell cycle; DNA replication occurs to prepare for the mitotic phase
18. **Gap 2:** Final stage of interphase; makes final preparations to divide
19. **Cancer:** Disease of the cell cycle where the cells do not respond properly to the cell cycle control system; Cancerous cells divide faster than normal cells and may form a tumour
20. **Cell division:** Process in which a parent cell divides to form two daughter cells
21. **Parent cell**: The original cell that divides to produce new cells during cell division
22. **Daughter cells**: New cells produced after a cell divides; genetically identical after mitosis, varied after meiosis
23. **Binary fission**: A form of asexual reproduction in prokaryotes where one cell divides into two identical daughter cells
24. **Mitotic phase**: Stage of the cell cycle when the cell is dividing; Consists of mitosis and cytokinesis
25. **Mitosis**: Cell division producing genetically identical daughter cells; essential for growth, repair, and asexual reproduction
26. **Cytokinesis:** Process during cell division where the cytoplasm of a parent cell is divided into two daughter cells
27. **Cleavage furrow:** Indentation that forms during cytokinesis in animal cells; Caused by a contractile ring that tightens and pinches the cell into two daughter cells
28. **Cell plate:** Structure that forms during cytokinesis in plant cells; Vesicles fuse in the centre of the cell and expand outward dividing the cell into two daughter cells
29. **Reproduction**: The biological process by which organisms produce new offspring
30. **Sexual reproduction**: Reproduction involving two parents, combining genetic material through gamete fusion to create genetically unique offspring
31. **Gametes:** Reproductive cells (sperm in males and eggs in females); Haploid (n); Unite during fertilization to form a new organism
32. **Fertilization**: Fusion of two gametes (sperm and egg), forming a zygote
33. **Zygote**: Diploid (2n) cell formed when two gametes fuse; first cell of a new organism
34. **Meiosis**: Type of cell division producing haploid gametes; reduces chromosome number by half, creating genetic diversity
35. **Crossing-over**: Exchange of genetic material between homologous chromosomes during meiosis; Increases genetic variation in the offspring

36. **Independent assortment**: The random distribution of homologous chromosomes into gametes during meiosis; Contributes to genetic variation in the offspring
37. **Random fertilization:** The two gametes that unite to produce an offspring is a matter of chance; Contributes to genetic variation in the offspring
38. **Nondisjunction:** Failure of chromosomes to separate properly during meiosis, leading to an abnormal number of chromosomes in the daughter cells
39. **Two types of chromosomes:** Autosomes and sex chromosomes
40. **Stages in the Cell Cycle:** Interphase – G1, S, G2, Mitotic Phase – Mitosis (Prophase, Metaphase, Anaphase, Telophase) and Cytokinesis
41. **Checkpoints in Cell Cycle:** Cell Growth Checkpoint, DNA Synthesis Checkpoint, Mitosis Checkpoint
42. **Functions of Mitosis:** Growth, repair and asexual reproduction (in some organisms)
43. **Steps in Prophase**: Chromatin condenses into chromosomes. Nuclear envelope disintegrates. Centrosomes migrate to opposite poles. Spindle fibers form and connect to chromosomes.
44. **Steps in Metaphase:** Spindle fibers "tug of war". Chromosomes line up at metaphase plate.
45. **Steps in Anaphase**: Sister chromatids pulled apart. Chromosomes pulled to opposite poles as spindles shorten. Spindles not attached to chromosomes lengthen and elongate cell
46. **Steps in Telophase**: Spindle fibers disassemble. Nuclear envelope re-forms. Chromosomes decondense back into chromatin (reverse of prophase).
47. **Types of cytokinesis:** Cleavage furrow (animal cells) and cell plate (plant cells)
48. **Life cycle of sexually reproducing organisms:** Adult (2n) > Sperm and egg (n) produced by meiosis > Zygote (formed through fertilization) > Growth using mitosis (from zygote to fetus, infant, adolescent, adult)
49. **Function of meiosis:** Produce gametes for sexual reproduction; Reduce the chromosome number by half
50. **Key differences between Mitosis and Meiosis I:**
    Mitosis: chromosomes line up along the metaphase plate *individually* (or "single file").
    Meiosis I: homologous chromosome pairs line up along the metaphase plate in *tetrads* (or "double file") which allows number of chromosomes to get cut in half in daughter cells; crossing over also occurs which increases genetic variation.
51. **Three causes of genetic variation in sexual reproduction:** Crossing over, independent assortment, random fertilization

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms.

CHAPTER 8: PATTERNS OF INHERITANCE

Chapter Overview

Learning Objectives

By the end of this Chapter, you will be able to:

- Describe how Gregor Mendel's experiments with pea plants challenged the blending theory of inheritance.
- Describe Mendel's monohybrid experiments, including the P, F1, and F2 generations, using diagrams or Punnett squares.
- Explain the Law of Segregation, relating it to modern concepts of alleles and gamete formation.
- Explain the Law of Independent Assortment.
- Apply Mendel's laws of inheritance to predict simple inheritance patterns through Punnett squares.
- Explain how Mendel's discoveries about heredity apply broadly to sexually reproducing

organisms, including humans.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Produce learning goals from this content.

8.1 LAWS OF INHERITANCE

Figure 8.1.1 Mendel conducted his research using pea plants. Image by Yana Ray, CC0 1.0

These purple-flowered plants are not just pretty to look at. Plants like these led to a giant leap forward in biology. They're common garden peas, and they were studied in the mid-1800s by an Austrian monk named Gregor Mendel. Through careful experimentation, Mendel uncovered the secrets of **heredity**, or how parents pass characteristics to their offspring. You may not care much about heredity in pea plants, but you probably care about your own heredity. Mendel's discoveries apply to people, as well as to peas, and to all other living things that reproduce sexually. In this concept, you will read about Mendel's experiments and the secrets of heredity that he discovered.

Mendel and His Pea Plants

Figure 8.1.2 Gregor Mendel. Image by Unknown, Public Domain

Gregor Mendel (Figure 8.1.2) was born in 1822. He grew up on his parents' farm in Austria. He did well in school and became a friar (and later an abbot) at St. Thomas' Abbey. Through sponsorship from the monastery, he went to the University of Vienna, where he studied science and math. His professors encouraged him to learn science through experimentation and to use math to make sense of his results. Mendel is best known for his experiments with pea plants (like the purple flower pictured in Figure 8.1.1).

During Mendel's time, the blending theory of inheritance was popular. According to this theory, offspring have a blend (or mix) of their parents' characteristics. However, Mendel noticed plants that weren't a blend of the parents in his garden. For example, a tall and short plant had either tall or short offspring, not medium in height. Observations such as these led Mendel to question the blending theory. He wondered if there was a different underlying principle that could explain how characteristics are inherited. He decided to experiment with pea plants to find out. In fact, Mendel experimented with almost 30 thousand pea plants over the next several years!

Why Study Pea Plants?

Why did Mendel choose common, garden-variety pea plants for his experiments? Pea plants are a good choice because they are fast-growing and easy to raise. They also have several different characters. A **character** is a heritable feature that varies among individuals. Pea plants have seven characteristics: seed shape and colour, flower colour, pod shape and colour, flower position, and stem height. Each of these characters has two contrasting traits. A **trait** is a specific variation of a character. For example, the seed shape may be round or wrinkled, and the flower colour may be white or purple.

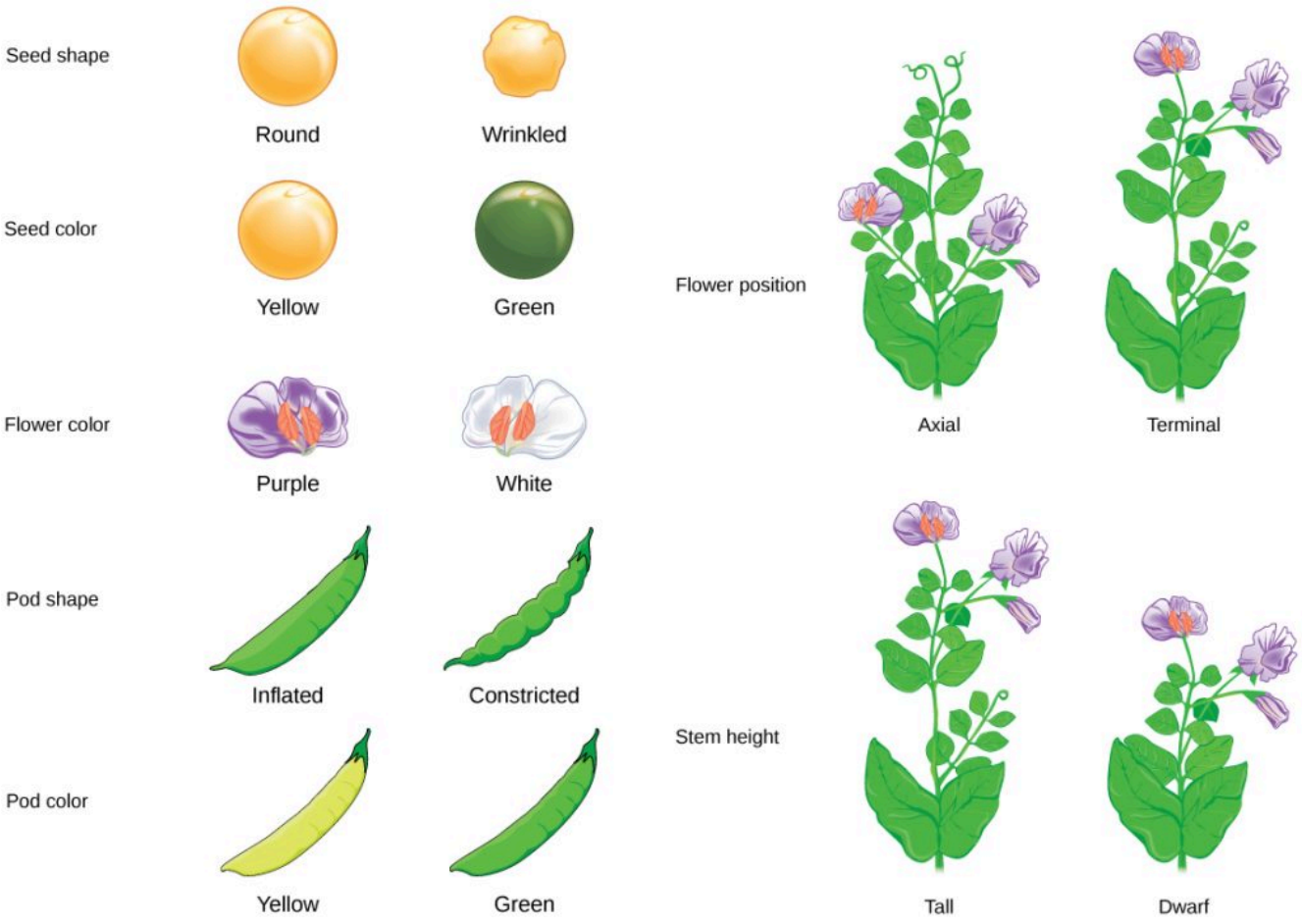


Figure 8.1.3 Mendel identified seven pea plant characteristics. Image by OpenStax, CC BY 4.0

Figure 8.1.3 Description

This image illustrates the different traits studied by Gregor Mendel in pea plants, showing pairs of contrasting characteristics for each trait. The image is organized into different sections, each depicting a specific trait with its two variations.

Traits and Their Variations

- Seed Shape:
  - Round – Smooth and spherical pea seeds.
  - Wrinkled – Irregularly shaped and wrinkled pea seeds.
- Seed Colour:
  - Yellow – Bright yellow-coloured peas.
  - Green – Deep green-coloured peas.
- Flower Colour:
  - Purple – Flowers with purple petals.
  - White – Flowers with white petals.
- Pod Shape:
  - Inflated – Smooth and full pea pods.
  - Constricted – Pea pods that appear pinched and uneven.
- Pod Colour:
  - Yellow – Light yellow-green coloured pods.
  - Green – Standard green-coloured pods.
- Flower Position:
  - Axial – Flowers growing along the sides of the stem.
  - Terminal – Flowers growing at the ends of the plant's stem.
- Stem Height:
  - Tall – Pea plants with long stems.
  - Dwarf – Pea plants with short stems.

To research how characteristics are passed from parents to offspring, Mendel needed to control **pollination**, which is the fertilization step in the sexual reproduction of plants. Pollen consists of tiny grains that are the male sex cells (or sperm) of plants. A male flower part called the anther produces them. Pollination occurs when pollen is transferred from the anther to the stigma of the same or another flower. The stigma is a female part of a flower, passing pollen grains to female gametes in the ovary.

Pea plants are naturally self-pollinating, which is another reason they are a good choice for genetics experiments. In self-pollination, pollen grains from anthers on one plant are transferred to stigmas of flowers on the same plant. The flower petals remain sealed tightly until pollination is completed to prevent the pollination of other plants. The result is **true-breeding** pea plants, which are plants that always produce offspring that look like the parent. By experimenting with true-breeding pea plants, Mendel avoided the appearance of unexpected traits in offspring that might occur if the plants were not properly bred.

Mendel was interested in the offspring of two different parent plants, so he had to prevent self-pollination. He removed the anthers from the flowers of some of the plants in his experiments. Then, he pollinated them by hand using a small paintbrush with pollen from other parent plants of his choice. When pollen from one

plant fertilizes another plant of the same species, it is called cross-pollination. The offspring that result from such a cross are called hybrids. When the term **hybrid** is used in this context, it refers to any offspring resulting from the breeding of two genetically distinct individuals.

Mendel's First Set of Experiments

At first, Mendel experimented with just one character at a time. He began with flower colour. Mendel cross-pollinated true-breeding purple-flowered and true-breeding white-flowered parent plants. The parent plants in the experiments are called the **P** (for parent) **generation**.

The offspring of the P generation are called the **F1** (for filial, or "offspring") **generation**. As shown in Figure 8.1.4, all of the plants in the F1 generation had purple flowers — none of them had white flowers. Mendel wondered what had happened to the white-flower trait.

He assumed that some type of inherited factor produces white flowers and others produce purple flowers. Did the white-flower factor just disappear in the F1 generation? If so, then the offspring of the F1 generation — called the **F2 generation** — should all have purple flowers like their parents.

To test this prediction, Mendel allowed the F1 generation plants to self-pollinate. He was surprised by the results. Some of the F2 generation plants had white flowers. He studied hundreds of F2 generation plants, and for every three purple-flowered plants, there was an average of one white-flowered plant (75% purple flowers and 25% white flowers). Based on these observations, Mendel proposed that characters are controlled by "unit factors" that exist in pairs, with one being dominant and overpowering the other. In the case of flower colour, purple was dominant over white.

Figure 8.1.4 Description

A diagram showing flower colour inheritance in three generations of orchids. The top section labelled "Parental Generation (P)" shows one purple-flowered plant and one white-flowered plant. The middle section, "First Generation (F1)," shows four purple-flowered plants with a label indicating that 100% of the F1 generation has purple flowers. The bottom section, "Second Generation (F2)," shows three purple-flowered plants and one white-flowered plant, with a label stating that 75% (three out of four) have purple flowers. The diagram illustrates Mendelian inheritance, where the purple trait is dominant, and the white trait is recessive.

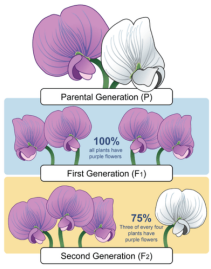


Figure 8.1.4 Mendel's first experiment with pea plants. Image by CK-12 Foundation, CC BY-NC 3.0

Law of Segregation

Mendel did the same experiment for all seven characters. In each case, one trait disappeared in the F1 plants, later reappearing in the F2 plants. In each case, 75% of F2 plants had one trait, while 25% had another. Mendel then formulated his first law of inheritance, the **law of segregation**, which states that unit factors

(now known as **alleles**) separate during the formation of gametes, ensuring that each gamete carries only one allele for each character.

Mendel's Second Set of Experiments

Mendel wondered whether different characters are inherited together. For example, are purple flowers and tall stems always inherited together, or do these two characteristics show up in different combinations in offspring? To answer these questions, Mendel next investigated two characters at a time. For example, he crossed plants with yellow round seeds and plants with green wrinkled seeds. The results of this cross are shown in Figure 8.1.5.

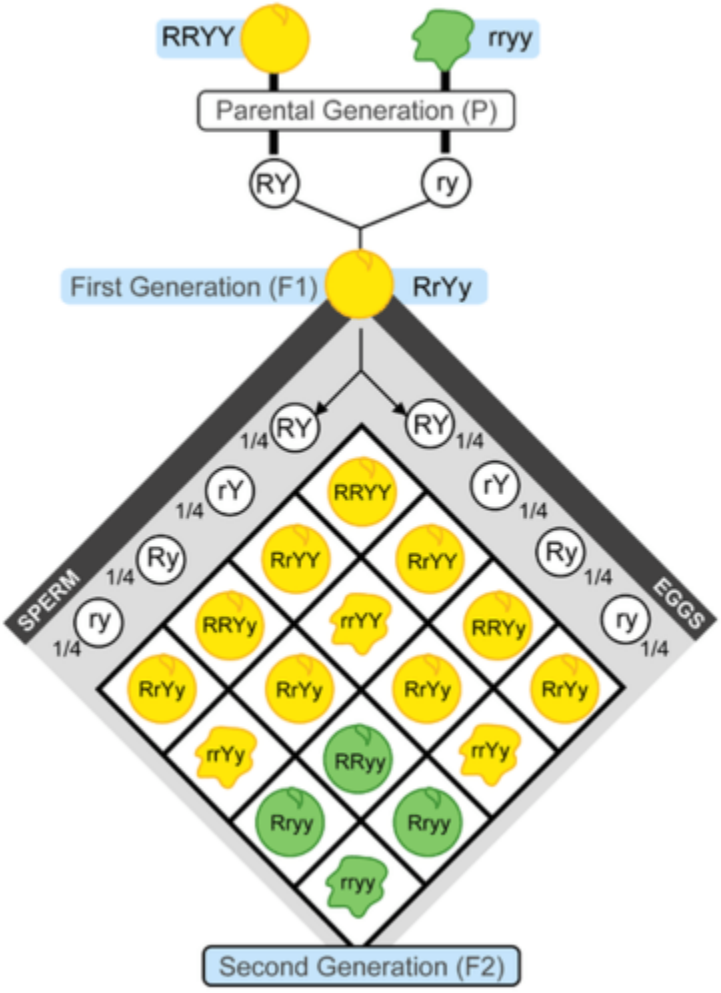


Figure 8.1.5 Mendel's second set of experiments. Image by CK-12 Foundation, CC BY-NC 3.0

Figure 8.1.5 Description

The graphic shows a Punnett square diagram illustrating a dihybrid cross between pea plants with round yellow seeds (genotype RRYY) and wrinkled green seeds (genotype rryy).

- At the Parental Generation (P) level, the cross is between RRYY and rryy. Their gametes (RY and ry) combine to form the First Generation (F1), producing offspring with the heterozygous genotype RrYy (round yellow).
- The Second Generation (F2) is represented by a 4×4 Punnett square showing the combinations of gametes from two RrYy parents.
- Each row and column represents the gametes (RY, Ry, rY, ry), and the 16 squares inside show the resulting genotypes.
- The genotypes include combinations such as RRYY, RRYy, RrYY, RrYy, rrYY, rrYy, Rryy, and rryy.
- The phenotypic outcomes are represented with colors: yellow circles for round yellow seeds and green circles for wrinkled green seeds.

The letters R, r, Y, and y represent genes for the characters Mendel was studying. This experiment demonstrates that, in the F2 generation, nine out of 16 were round yellow seeds, three out of 16 were wrinkled yellow seeds, three out of 16 were round green seeds, and one out of 16 were wrinkled green seeds.

In this set of experiments, Mendel observed that plants in the F1 generation were all alike. All of them had yellow round seeds like one of the two parents. However, when the F1 generation plants self-pollinated, their offspring — the F2 generation — showed all possible combinations of the two characters. Some had green round seeds, for example, and some had yellow wrinkled seeds. These combinations of characteristics were not present in the F1 or P generations.

Law of Independent Assortment

Mendel repeated this experiment with other combinations of characters, such as flower colour and stem height. The results were the same as those shown in Figure 8.1.5 each time. The results of Mendel's second set of experiments led to his second law. This is the **law of independent assortment**, which states that factors (which we now call "alleles") controlling different characters are inherited independently of each other.

Exercise 8.1.1

Text Description
When Mendel was conducting his experiments, the more popular inheritance theory was the ____; which was not supported by his research findings.

Mendel's first set of experiments involved observing pea blossom colours. Using ____ Mendel fertilized flowers with white blossoms using pollen from flowers with purple blossoms, creating ____.

He found that in the first resulting generation, F1, that ____ of the flowers had purple blossoms. However, when he then created an F2 generation, he found ____ of the resulting offspring had white flowers, and only ____ showed the purple blossoms.

From here, Mendel surmised that there were in fact two alleles for flower colour, and that the ____ allele was dominant to, or overpowered, the ____ allele. He also surmised that each plant had two copies of genes for flower colour, but only one of these genes was passed directly on to the offspring.

This led Mendel to develop his first law of genetics, the ____.

Possible Answers:

- white
- purple
- 25%
- 100%
- cross-pollination
- 75%
- law of segregation
- hybrids
- blending theory of inheritance

Answers:

When Mendel was conducting his experiments, the more popular inheritance theory was the ***blending theory of inheritance***; which was not supported by his research findings.

Mendel's first set of experiments involved observing pea blossom colours. Using ***cross-pollination*** Mendel fertilized flowers with white blossoms using pollen from flowers with purple blossoms, creating ***hybrids***.

He found that in the first resulting generation, F1, that ***100%*** of the flowers had purple blossoms. However, when he then created an F2 generation, he found ***25%*** of the resulting offspring had white flowers, and only ***75%*** showed the purple blossoms.

From here, Mendel surmised that there were in fact two alleles for flower colour, and that the ***purple*** allele was dominant to, or overpowered, the ***white*** allele. He also surmised that each plant had two copies of genes for flower colour, but only one of these genes was passed directly on to the offspring.

This led Mendel to develop his first law of genetics, the ***law of segregation***.

8.2 GENETICS

This father-son duo share some similarities. The shape of their faces and their facial features look very similar. You might guess they are father and son if you saw them together. People have long known that the characteristics of living things are similar between parents and their offspring. However, it wasn't until the experiments of Gregor Mendel that scientists understood how those traits are inherited.

Figure 8.2.1 Like Father, Like Son. Image by Kelly Sikkema, Unsplash License

The Father of Genetics

Mendel experimented with pea plants to show how traits such as seed shape and flower colour are inherited. Based on his research, he developed two well-known laws of inheritance: the law of segregation and the law of independent assortment. When Mendel died in 1884, his work was still virtually unknown. In 1900, three other researchers working independently came to the same conclusions Mendel had drawn almost half a century earlier. Only then was Mendel's work rediscovered.

Mendel knew nothing about genes because they were discovered after his death. However, he thought that some "factors" controlled traits and that those "factors" were passed from parents to offspring. We now call these "factors" genes. Mendel's laws of inheritance, now expressed in terms of genes, form the basis of **genetics**, the science of heredity. For this reason, Mendel is often called the father of genetics.

The Language of Genetics

Today, we know that genes on chromosomes control the traits of organisms. To talk about inheritance in terms of genes and chromosomes, you need to know the language of genetics. The terms below serve as a good starting point. They are illustrated in the figure that follows.

- A **gene** is the part of a chromosome containing a given protein's genetic code. For example, in pea plants, a given gene might code for flower colour.
- The position of a given gene on a chromosome is called its **locus** (plural, loci). A gene might be located near the centre or at one end or the other of a chromosome.
- A given gene may have different normal versions, which are called **alleles**. For example, in pea plants,

there is a purple-flower allele (B) and a white-flower allele (b) for the flower-colour gene. Different alleles account for much of the variation in the traits of organisms, including people.

- In sexually reproducing organisms, each individual has two copies of each type of chromosome. Paired chromosomes of the same type are called **homologous chromosomes**. They are about the same size and shape and have all the same genes at the same loci.

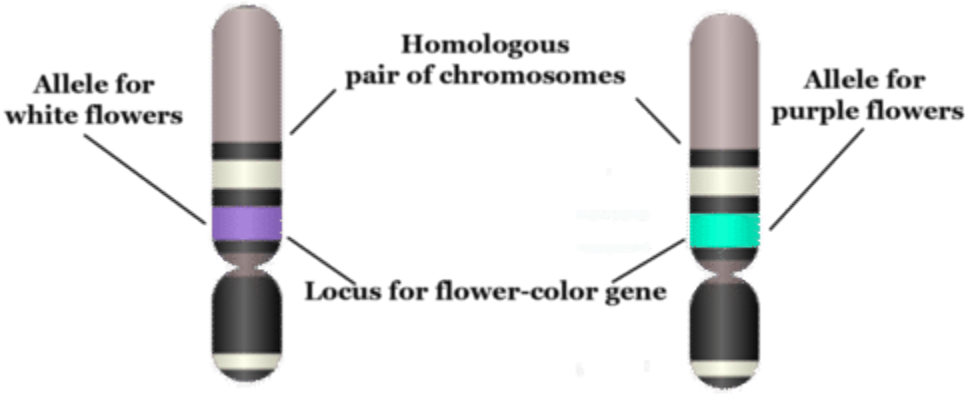


Figure 8.2.2 Chromosome, Gene, Locus, and Allele. "Chromosome, Gene, Locus, and Allele" by CK-12 Foundation, CC BY-NC 3.0

Figure 8.2.2 Description

A diagram comparing two homologous chromosomes to show allele differences. The left chromosome has a purple band representing a **recessive allele** (a), and the right chromosome has a teal band representing a **dominant** allele (A). Each allele is located in the same position (locus) on the chromosome pair, highlighting how different versions of a gene (alleles) can exist at the exact location on homologous chromosomes.

Genotype

When sexual reproduction occurs, sex cells (gametes) unite during fertilization to form a single cell called a zygote. The zygote inherits two of each type of chromosome, with one of each type coming from the father and the other from the mother. Because homologous chromosomes have the same genes at the same loci, each individual also inherits two copies of each gene. The two copies may be the same allele or different alleles. The alleles an individual inherits for a given gene make up the individual's **genotype**. As shown in Table 8.2.1, an organism with two of the same allele (for example, BB or bb) is called a **homozygote**. An organism with two different alleles (in this example, Bb) is called a **heterozygote**.

Phenotype

The expression of an organism's genotype is referred to as its **phenotype**, and it refers to the organism's traits, such as purple or white flowers in pea plants. As you can see from Table 8.2.1, different genotypes may produce the same phenotype. In this example, both BB and Bb genotypes produce plants with the same phenotype, purple flowers. Why does this happen? Only the B allele is expressed in a Bb heterozygote, so the b allele doesn't influence the phenotype. Generally, when only one of two alleles is expressed in the phenotype, the expressed allele is called **dominant**, and the allele that isn't expressed is called **recessive**.

The terms dominant and recessive may also be used to refer to phenotypic traits. For example, purple flower colour in pea plants is a dominant trait. It shows up in the phenotype whenever a plant inherits even one dominant allele for the trait. Similarly, white flower colour is a recessive trait. Like other recessive traits, it shows up in the phenotype only when a plant inherits two recessive alleles for the trait.

Table 8.2.1 Allele Combinations

Alleles	Genotype	Phenotype
PP	Homozygous dominant	Purple flowers
Pp	Heterozygous	Purple flowers
pp	Homozygous recessive	White flowers

Exercise 8.2.1

Text Description

1. The term ____ is used to mean the part of a chromosome that contains the genetic code for a specific protein.

You have two copies of each type of gene, called ____, which are present on 2 chromosomes that code for the same types of traits, called ____.

The specific area on a chromosome that you might find a gene is called a ____.

The two alleles you have determines your ____, which in turn determines what your observable characteristics are, are referred to as ____.

Possible Answers:

- alleles
- locus
- phenotype
- gene
- homologous chromosomes
- genotype

2. If a child has the genotype Dd and he/she inherited the D from their mother, where did the d likely come from?

- Thier Moter
- Their maternal grandparents
- Either their mother or their father
- Their Father

3. A gene for flower colour and a gene for seed shape could be on the same:

- Locus
- Chromosome
- Allele
- All of the above

4. Each phenotype has only one genotype. (True/False)

5. Recessive genes are never expressed in a phenotype. (True/False)

6. An observable physical trait is a phenotype. (True/False

7. A gene usually codes for a given

- Allele
- Protein
- Chromosome
- Amino Acid

Answers

1. The term ***gene*** is used to mean the part of a chromosome that contains the genetic code for a specific protein.

You have two copies of each type of gene, called ***alleles***, which are present on 2 chromosomes that code for the same types of traits, called ***homologous chromosomes***.

The specific area on a chromosome that you might find a gene is called a ***locus***.

The two alleles you have determines your ***genotype***, which in turn determines what your observable characteristics are, are referred to as ***phenotype***.

2. Their father

3. Chromosome

4. False

5. False

6. True

7. Protein

8.3 MENDELIAN INHERITANCE

Monohybrid Cross

A **Punnett Square** chart allows you to easily determine the expected ratios of possible genotypes in the offspring of two parents. You can see a simple example in Figure 8.3.1. This Punnett square is for a **monohybrid cross** when fertilization occurs between two parents that differ by only one character. In this case, both parents are yellow and are heterozygotes (Yy) for the gene controlling pea colour. Half of the gametes produced by each parent will have the Y allele (for yellow), and half will have the y allele (for green). That's because the two alleles are on homologous chromosomes, which always separate and go to separate gametes during meiosis. The alleles in the gametes from each parent are written down the side and across the top of the Punnett square. Filling in the cells of the Punnett square gives the possible genotypes of their offspring. It also shows the most likely ratios of the genotypes, which in this case is 1 YY: 2 Yy: 1 yy (25% YY: 50% Yy: 25% yy). You can then determine the most likely ratios of the phenotypes, which is three yellow: 1 green (75% yellow: 25% green).

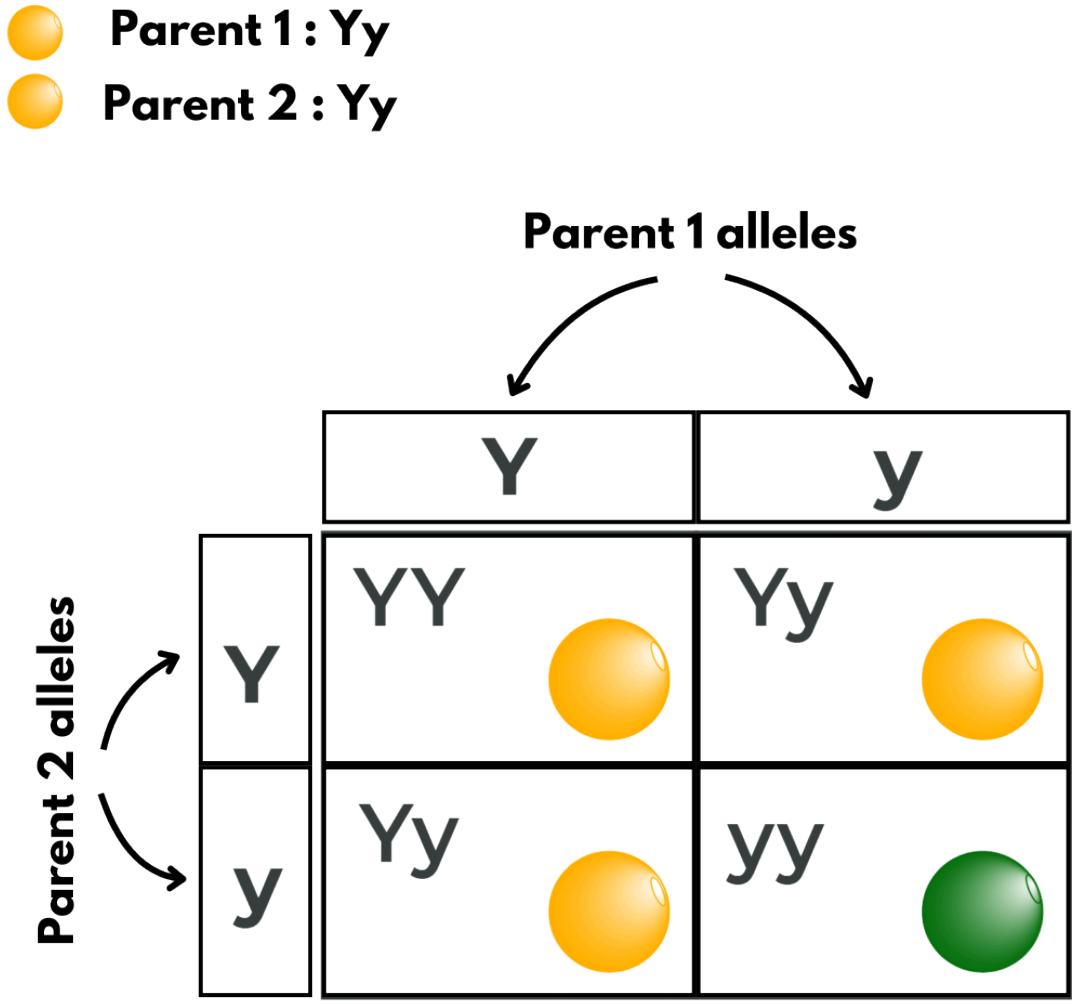


Figure 8.3.1 A Punnett square shows the most likely proportions of offspring by genotype for a particular mating type. Image modification of work by Christine Miller, Public Domain Mods: recoloured, mom/dad changed to parent 1, parent 2

Figure 8.3.1 Description

A Punnett square diagram illustrating a genetic cross between two heterozygous pea plants for seed colour. Each parent has one dominant allele (Y) for yellow seeds and one recessive allele (y) for green seeds. The Punnett square shows four possible combinations of offspring genotypes: YY, Yy, Yy, and yy. Three of the squares result in yellow seeds (YY and Yy), and one results in green seeds (yy). The expected phenotypic ratio is 3 yellow to 1 green. Yellow and green seed images are used to represent the traits.

A Punnett square can also be used to show how the X and Y chromosomes are passed from parents to their

children. Mothers pass only X chromosomes to their children. Fathers always pass their X chromosome to their daughters and their Y chromosome to their sons.

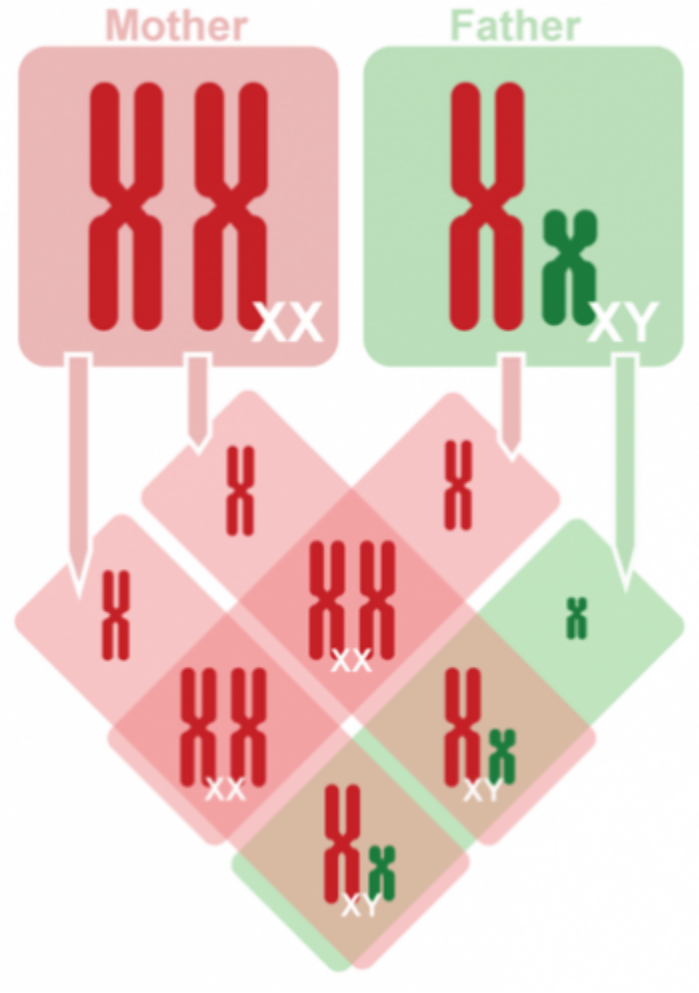


Figure 8.3.2 Inheritance of Sex Chromosomes. Image by CK-12 Foundation, CC BY-NC 3.0

Figure 8.3.2 Description

A diagram showing sex chromosome inheritance using a Punnett square. The mother (XX) contributes only X chromosomes, while the father (XY) contributes either an X or a Y chromosome. The square illustrates four possible combinations: two XX (female) and two XY (male). This results in a 50/50 chance of offspring being female or male. The mother's chromosomes are shown in red and the father's in green, with the resulting offspring combinations displayed in pink and green boxes.

Exercise 8.3.1

Text Description
Drag and drop the genotypes into the correct boxes to complete the Punnett square
Drop Zones:

- Aa
- Aa
- aa
- aa

Genotypes:

- Aa
- aa
- AA

Answers:
From the top left of Punnett Square to the top right

- Aa
- Aa

From the bottom left of Punnett Square to the bottom right

- aa
- aa

Probability Basics

The results of Mendel's research can be explained in terms of probabilities, which are mathematical measures of likelihood. The **probability** of an event is calculated by the number of times the event occurs divided by the total number of opportunities for the event to occur. A probability of one (100 percent) for some event indicates that it is guaranteed to occur. In contrast, a probability of zero (0 percent) indicates that it is

guaranteed not to occur, and a probability of 0.5 (50 percent) means it has an equal chance of occurring or not occurring.

Figure 8.3.1 shows a 25% chance of getting the genotype yy. That does not guarantee that there will be one yy pea plant out of every 4 offspring. Sample size plays a crucial role in observing these probabilities. In smaller sample sizes, the actual outcomes may deviate from the expected probabilities due to random chance. When flipping a coin, you have a 50% chance of getting heads and a 50% chance of tails. If you flip a coin 2 times, you aren't guaranteed to get 1 heads and 1 tail. However, as the sample size increases, the observed ratios align more closely with the predicted probabilities. By flipping a coin 1000 times, you have a much better chance of observing the predicted ratios of 50% heads and 50% tails. Similarly, for genetics, there is a higher likelihood of observing the expected 25% yy genotype when considering a large number of offspring.

Dihybrid Cross

A **dihybrid cross** is when fertilization occurs between parents that differ by two characters. Consider the characteristics of seed colour and seed shape for two pea plants, one that has wrinkled, green seeds (rryy) and another that has round, yellow seeds (RRYY). Because each parent is homozygous, the law of segregation indicates that the gametes for the wrinkled–green plant are all ry, and the gametes for the round–yellow plant are all RY. Therefore, the F1 offspring generation is all RrYy (Figure 8.10).

The gametes produced by the F1 individuals must have one allele from each of the two genes. For example, a gamete could get an R allele for the seed shape gene and either a Y or a y allele for the seed colour gene. It cannot get an R and an r allele; each gamete has only one allele per gene. The law of independent assortment states that a gamete into which an r allele is sorted would be equally likely to contain either a Y or a y allele. Thus, there are four equally likely gametes that can be formed when the RrYy heterozygote is self-crossed: RY, rY, Ry, and ry. Arranging these gametes along the top and left of a 4 × 4 Punnett square gives us 16 equally likely genotypic combinations. These genotypes show a phenotypic ratio of 9 round–yellow: 3 round–green: 3 wrinkled–yellow: 1 wrinkled–green. These are the offspring ratios we would expect, assuming we performed the crosses with a large enough sample size.

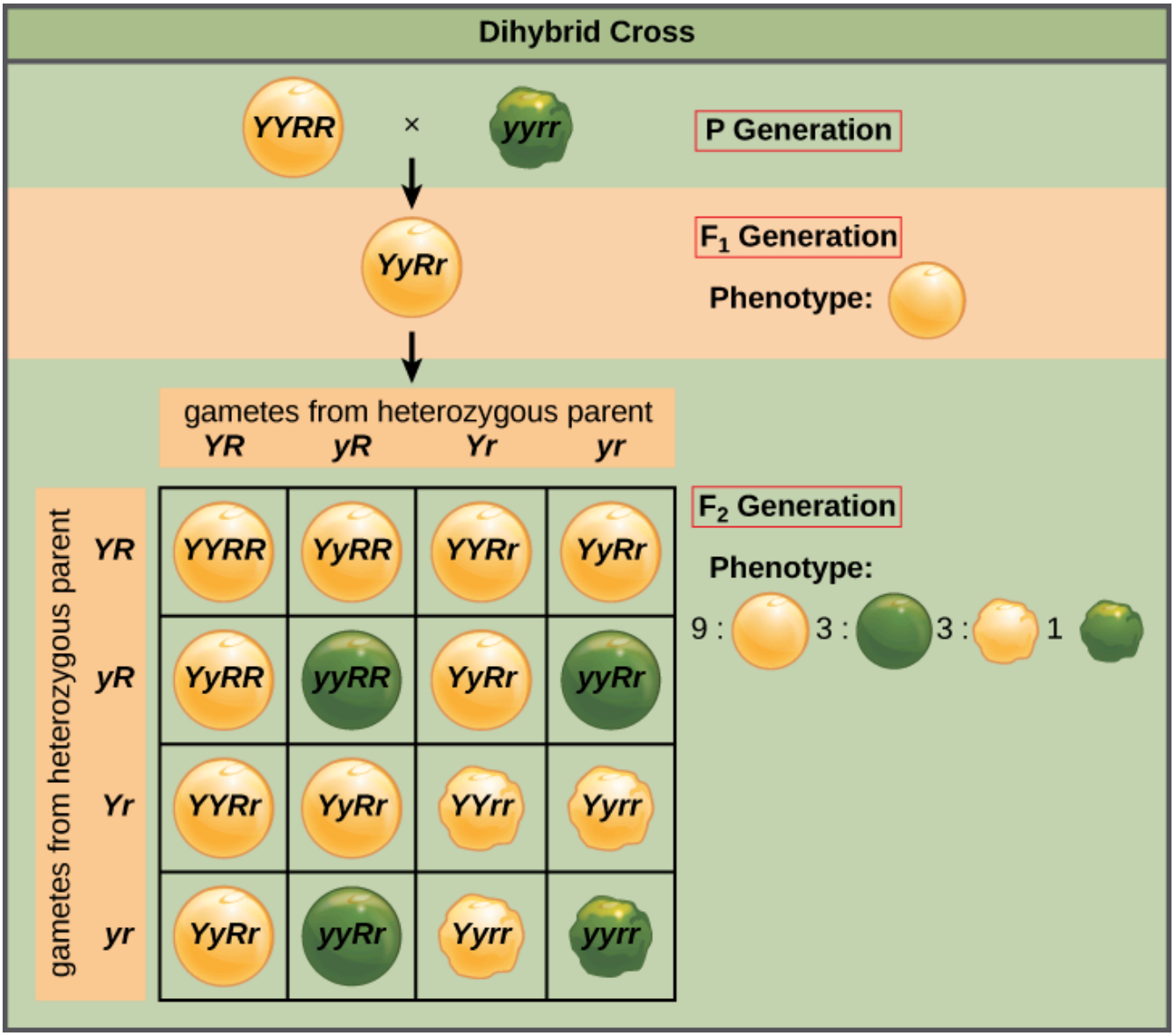


Figure 8.3.3 A dihybrid cross in pea plants involves seed colour and texture genes. The P cross produces F1 offspring that are all heterozygous for both characteristics. The resulting 9:3:3:1 F2 phenotypic ratio is obtained using a Punnett square. Image by OpenStax, CC BY 4.0

Figure 8.3.3 Description

A diagram of a dihybrid cross illustrating the inheritance of two traits in pea plants: seed colour (yellow or green) and seed shape (round or wrinkled). The parental generation (P) consists of a plant with yellow round seeds (YYRR) crossed with one with green wrinkled seeds (yyrr). The first generation (F_1) is entirely heterozygous (YyRr) with yellow round seeds. A Punnett square for the F_2 generation shows the 16 possible offspring combinations from two YyRr parents. The resulting phenotypic ratio is shown as 9:3:3:1 — 9 yellow round, 3 green round, 3 yellow wrinkled, and 1 green wrinkled.

Exercise 8.3.2

Let's create a Punnet Square for the following parents: RrYy x RRYy
Text Description

1. This cross is an example of a dihybrid cross because the parents differ in 2 characters. (True/False)

2. Select all of the possible gametes for a parent that has the genotype RrYy.

- Ry
- ry
- RY
- rY

3. Select all of the possible gametes for a parent that has the genotype RRYy

- RY
- Ry
- ry
- rY

4. Since one of the parents only has 2 possible gametes, that means that we get to make a simplified Punnett square with 4 boxes by 2 boxes. Fill in the genotypes for the offspring

Drop Zones:

- RY, RY
- Ry, RY
- rY, RY
- ry, RY
- RY, Ry
- Ry, Ry
- rY, Ry
- ry, Ry

Possible Options:

- RRYY

- RRYy
- RrYY
- RyYy
- RRYy
- RRyy
- RrYy
- Rryy

5. Drag in the corresponding phenotypes

Drop Zones:

- RY, RY
- RY, Ry
- RY, rY
- RY, ry
- Ry, RY
- Ry, Ry
- Ry, rY
- Ry, ry

Images:

- Smooth Yellow Pea
- Smooth Green Pea
- Wrinkled Yellow Pea
- Wrinkled Green Pea

Answers:
1. True
2. All of these options
3. *RY, Ry*
4.
    Zone RY, RY: RRYY
    Zone Ry, RY: RRYy
    Zone rY, RY: RrYY
    Zone ry, RY: RrYy

Zone RY, Ry: RRYy
Zone Ry, Ry: RRyy
Zone rY, Ry: RrYy
Zone ry, Ry: Rryy

5.

Zone RY, RY: Smooth Yellow Pea
Zone RY, Ry: Smooth Yellow Pea
Zone RY, rY: Smooth Yellow Pea
Zone RY, ry: Smooth Yellow Pea
Zone Ry, RY: Smooth Yellow Pea
Zone Ry, Ry: Smooth Green Pea
Zone Ry, rY: Smooth Yellow Pea
Zone Ry, ry: Smooth Green Pea

6. ***6*** round yellow:***2*** round green: ***0*** wrinkled yellow:***0*** wrinkled green

Mendelian Inheritance in Humans

Mendelian inheritance refers to the inheritance of traits controlled by a single gene with two alleles, one of which may be completely dominant to the other. The inheritance pattern of Mendelian traits depends on whether the traits are controlled by genes on autosomes or by genes on sex chromosomes.

Autosomal Traits

Autosomal traits are controlled by genes on one of the 22 pairs of human autosomes. Autosomes are all the chromosomes except the sex chromosomes (X and Y). Autosomes do not differ between males and females, so autosomal traits are inherited similarly, regardless of the parent's sex or offspring.

Figure 8.3.4 Child with albinism. Image by Felipe Fernandes, CC BY-SA 2.0

Not many human autosomal traits are controlled by a single gene with two alleles, but they are a good starting point for understanding human heredity. Most forms of albinism in humans have a Mendelian inheritance pattern. Albinism is a condition that results from a lack of pigment melanin in the skin, hair, and eyes. It is usually controlled by a single autosomal gene with two alleles. The allele for normal

pigmentation (let's call it R) is dominant to the allele for albinism (r). Individuals with an RR or Rr genotype will not have albinism because the R allele dominates over the recessive r allele.

However, consider what happens if two individuals with the Rr genotype reproduce with each other. The outcome would be similar to the example shown in the Punnett square above for two hypothetical Yy individuals (Figure 8.3.1). Their possible offspring could be RR (normal pigmentation), Rr (normal pigmentation), or rr (albinism). This explains why a child with albinism (rr) can have two parents who do not have albinism. Both unaffected parents must be carriers of the recessive r allele, but they also have a dominant R allele that prevents them from having the condition themselves.

Some other human traits with a Mendelian inheritance pattern are Huntington's disease and wet versus dry earwax. You may have heard about other human traits that were previously thought to be Mendelian, such as dimples, a widow's peak hairline, a hitchhiker's thumb, and the ability to roll your tongue. As science has progressed, it is now understood that these are not actually Mendelian traits. In fact, most human traits are controlled by multiple genes or have more than two alleles, which means they do not have a simple Mendelian inheritance pattern.

Sex-Linked Traits

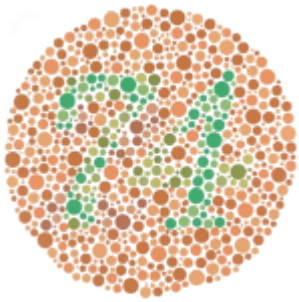


Figure 8.3.5 Colour blindness test. Image by Shinobu Ishihara, Public Domain

Traits controlled by genes on the sex chromosomes are called **sex-linked traits**. Because of the small size of the Y chromosome, most sex-linked traits are controlled by genes on the X chromosome. These traits are called X-linked traits.

Because males have just one X chromosome, they have only one allele for any X-linked trait. Therefore, a recessive X-linked allele is always expressed in males. Because females have two X chromosomes, they have two alleles for any X-linked trait. Therefore, they must inherit two copies of the recessive allele to express an X-linked recessive trait. This explains why X-linked recessive traits are less common in females than males and why they show a different inheritance pattern than autosomal traits.

An example of a recessive X-linked trait is red-green colour blindness. People with this trait cannot distinguish between the colours red and green. More than one recessive gene on the X chromosome codes for this trait, which is fairly common in males but relatively rare in females. Figure 8.3.6 shows a simple pedigree for this trait. A female with one of the recessive alleles for the trait does not have the trait herself but can pass it on to her children. In this case, she is called a carrier of the trait. Half of any sons she has can be expected to have the trait because there is a 50 percent chance that they will inherit the X chromosome with the colour-blindness allele. Having only one X chromosome, the recessive allele will be expressed in the sons who inherit it. However, as long as the father is not affected, none of the woman's daughters will have the trait. The

daughters have a 50 percent chance of inheriting the X chromosome with the colour-blindness allele, but it won't be expressed because it is recessive to the normal allele they inherit from their father.

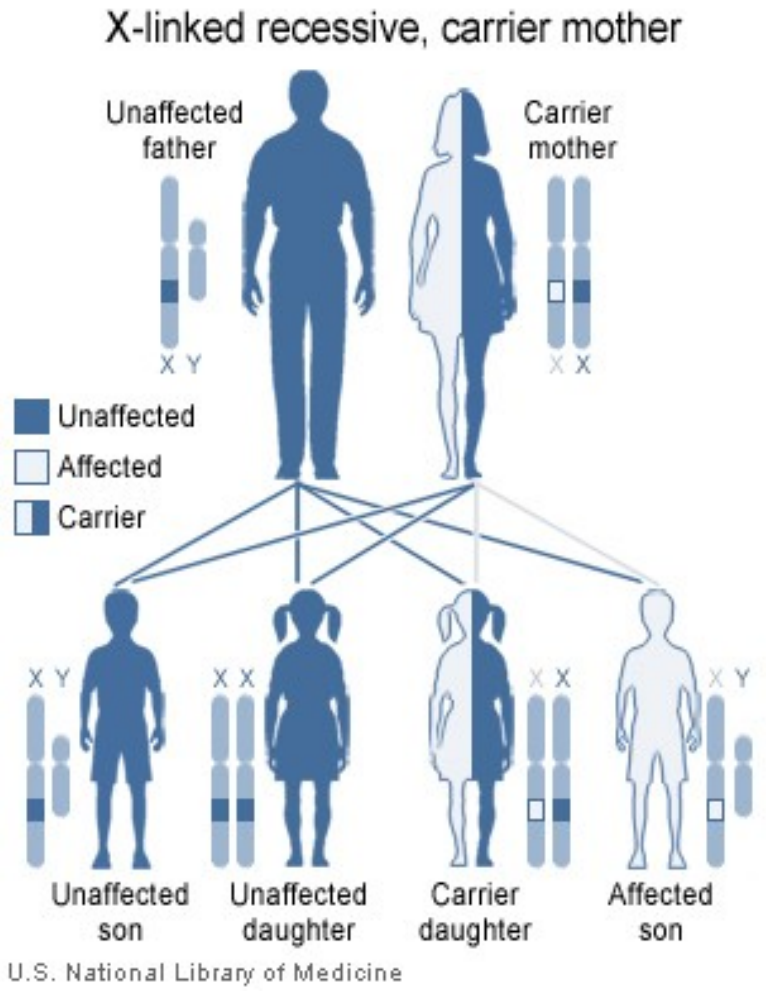


Figure 8.3.6 Heredity implications of an X-linked recessive gene carried by the mother. Image by National Institutes of Health, Public Domain

Figure 8.3.6 Description

A genetic inheritance chart illustrating an X-linked recessive condition passed from a carrier mother and an unaffected father. The father has normal XY chromosomes, and the mother has one affected X chromosome (X*) and one normal X chromosome. The chart shows the four possible children: an unaffected son (XY), an unaffected daughter (XX), a carrier daughter (XX), and an affected son (XY). Sons inherit their X chromosome from their mother and Y from their father, while daughters inherit one X from each parent. The diagram highlights how sons can be affected if they inherit the X* from the carrier mother.

Genetic Disorders

Some human genetic disorders follow Mendelian inheritance patterns. Table 8.3.1 lists several genetic disorders caused by mutations in just one gene. Some of the disorders are caused by mutations in autosomal genes, others by mutations in X-linked genes.

Table 8.3.1 Types of Genetic Disorders, Their Effects, and Mode of Inheritance

Genetic Disorder	Direct Effect of Mutation	Signs and Symptoms of the Disorder	Mode of Inheritance
Marfan syndrome	Defective protein in connective tissue	Heart and bone defects and unusually long, slender limbs and fingers	Autosomal dominant
Sickle cell anemia	Abnormal hemoglobin protein in red blood cells	Sickle-shaped red blood cells that clog tiny blood vessels, causing pain and damaging organs and joints	Autosomal recessive
Hypophosphatemic (Vitamin D-resistant) rickets	Lack of a substance needed for bones to absorb minerals	Soft bones that easily become deformed, leading to bowed legs and other skeletal deformities	X-linked dominant
Hemophilia A	Reduced activity of a protein needed for blood clotting	Internal and external bleeding that occurs easily and is difficult to control	X-linked recessive

A **dominant disorder** is caused by a mutated dominant allele. Very few genetic disorders are controlled by dominant alleles. A dominant allele is expressed in every individual who inherits even one copy of it. If it causes a serious disorder, affected people may die young and fail to reproduce. Therefore, the mutant dominant allele will likely die out of a population.

A **recessive disorder**, such as sickle cell anemia or cystic fibrosis, is not expressed in people who inherit just one copy of it. These people are called **carriers**. They do not have the disorder themselves, but they carry the mutant allele, and their offspring can inherit it. Thus, the allele will likely pass on to the next generation rather than die out.

Figure 8.3.7 Queen Victoria. Image by unknown, Public Domain

Queen Victoria carried hemophilia and passed the hemophilia allele to two of her daughters. When they married royalty in other European countries, they spread the allele across Europe, including the royal families of Spain, Germany, and Russia. Victoria's son, Prince Leopold, also inherited the hemophilia allele from his mother, and he suffered from the disease. Understandably, hemophilia was once popularly called "the royal disease."

Studying Inheritance Patterns

A **pedigree** shows how a trait is passed from generation to generation within a family. A pedigree can show, for example, whether a Mendelian trait is an autosomal or X-linked trait. It can also be used to infer the genotype of different family members. Pedigrees can also be used to track the inheritance of genetic disorders within families.

The trait represented by this chart is a hypothetical autosomal trait controlled by a dominant allele. At the top of the pedigree, you can see symbols representing a married couple. The husband has the trait (affected male), but the wife does not (unaffected female). The next row of the pedigree shows the couple's children, as well as the spouses of three of the children. For example, the first child on the left is an affected male married to an unaffected female. The third row of the pedigree shows the next generation (the couple's grandchildren at the top of the pedigree). One child in this generation — the affected female on the left — is the sibling of an unaffected male.

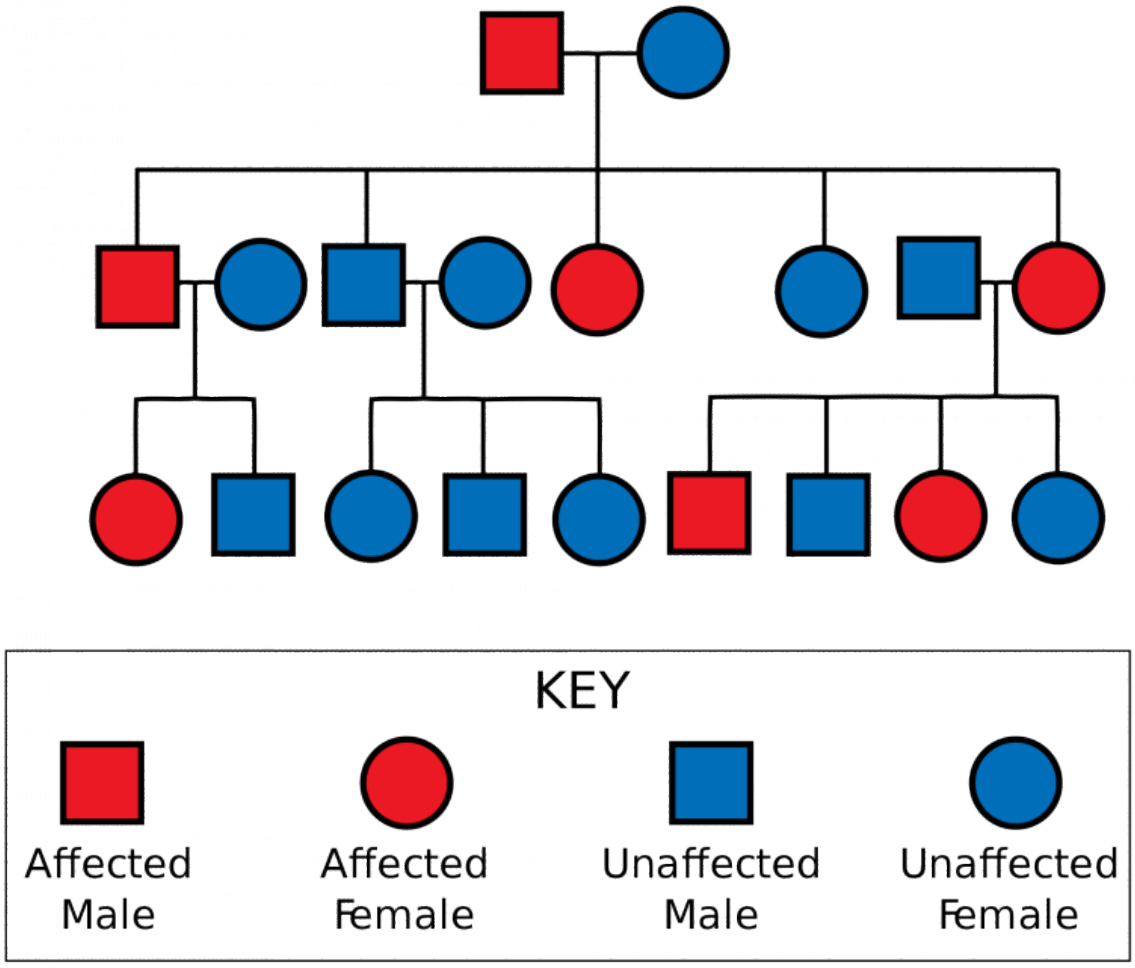


Figure 8.3.8 A pedigree chart shows how a trait is passed from parents to offspring in a family. The trait represented by this pedigree is an autosomal dominant trait. Image by Jerome Walker, CC BY-SA 3.0

Figure 8.3.8 Description

A pedigree chart showing the inheritance of a genetic trait through multiple generations. Squares represent males and circles represent females. Red shapes indicate individuals affected by a genetic condition, and blue shapes represent unaffected individuals. The chart spans four generations, with connecting lines indicating parental relationships and offspring. The trait appears to affect both males and females, suggesting an autosomal (non-sex-linked) inheritance pattern. The condition shows up in every generation, which may indicate a dominant trait.

Exercise 8.3.3

Text Description

1.A chart showing how a trait is passed from one generation to the next is a ____.

A chart that allows you to easily determine the expected ratios of possible genotypes of the offspring of two parents is a ____.

Chromosomes which do not code for gender are called ____.

The X and Y chromosomes are the ____ and these carry sex-linked traits, including ____.

Possible Answers

- pedigree
- sex chromosomes
- hemophilia and colour blindness
- Punnett Square
- autosomal chromosomes

2. Women are more likely than men to have X-linked diseases. (True/False)

3. Most human autosomal traits are controlled by a single gene with two alleles, similar to Mendel's pea plant. (True/False)

4. A man and a woman have known genotypes and you want to predict the possible genotypes of their offspring. Which is the best tool?

- Punnett Square
- Pedigree

5. You want to document which members of your family had or have breast cancer.

- Punnett Square
- Pedigree

Answers:
1. A chart showing how a trait is passed from one generation to the next is a ***pedigree***.

A chart that allows you to easily determine the expected ratios of possible genotypes of the offspring of two parents is a ***Punnett Square***.

Chromosomes which do not code for gender are called ***autosomal chromosomes***.

The X and Y chromosomes are the ***sex chromosomes*** and these carry sex-linked traits, including ***hemophilia and colour blindness***.

2. False

3. False

4. Punnett Square

5. Pedigree

8.4 NON-MENDELIAN INHERITANCE

Figure 8.4.1 Collage of Diverse Faces. From Top Left: Image by Omid Armin. Image by Anastasiya Pavlova. Image by Leonel Hernandez Arteaga. Image by Joseph Gonzalez. Image by Gabriel Silverio. Image by Oladimeji Oduns. All images are licensed under the Unsplash License

This collage shows some of the variations in human skin colour, which can range from very light to very dark, with every possible gradation in between. As you might expect, the skin colour trait has a more complex genetic basis than just one gene with two alleles, which is the type of simple trait that Mendel studied in pea plants. Like skin colour, many other human traits have more complicated modes of inheritance than Mendelian traits. Such modes of inheritance are called **non-Mendelian inheritance**, and they include inheritance of multiple allele traits, traits with codominance or incomplete dominance, and polygenic traits, and pleiotropy. All of these modes are described below.

Multiple Allele Traits

Most human genes are thought to have more than two normal versions or alleles. Traits controlled by a single gene with more than two alleles are called **multiple allele traits**. An example is the ABO blood type. Your blood type refers to which of certain proteins called antigens are found on your red blood cells. There are three common alleles for this trait, which are represented by the letters A, B, and O.

As shown in the table, there are six possible ABO genotypes because the three alleles, taken two at a time, result in six possible combinations. The A and B alleles are dominant to the O allele. As a result, both AA and AO genotypes have the same phenotype, with the A antigen in their blood (type A blood). Similarly, both BB and BO genotypes have the same phenotype, with the B antigen in their blood (type B blood). No antigen is associated with the O allele, so people with the OO genotype have no antigens for ABO blood type in their blood (type O blood).

Codominance

Look at the genotype AB in the ABO blood group table. Alleles A and B for the ABO blood type are neither dominant nor recessive to one another. Instead, they are codominant. **Codominance** occurs when two alleles for a gene are expressed equally in the phenotype of heterozygotes. In the case of ABO blood type, AB heterozygotes have a unique phenotype, with both A and B antigens in their blood (type AB blood).

Knowing your ABO blood type is crucial in emergencies, as it can save your life during a blood transfusion. If you receive blood with an antigen your blood lacks, your antibodies will recognize it as foreign and cause **agglutination**, where the transfused red blood cells clump together. This reaction is serious and potentially fatal. Understanding the antigens and antibodies in each ABO blood type helps determine which blood types you can safely receive.

Figure 8.4.2 Description

A chart showing the relationship between genotypes and phenotypes in the ABO blood group system. It has two columns: "Genotype" and "Phenotype (blood type)." The possible genotypes and their corresponding blood types are:

AA → A

AO → A

BB → B

BO → B

OO → O

AB → AB

Each phenotype is illustrated with a red blood cell icon, with small coloured markers representing antigens on the cell surface, depending on the blood type.

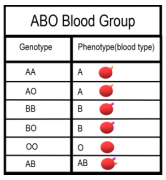


Figure 8.4.2 ABO blood types per genotype. Image by Christine Miller, Public Domain

If you have blood type A, your red blood cells have the A antigen, and your blood plasma contains anti-B antibodies. If you were to receive a transfusion of type B or type AB blood, both of which have the B antigen, your anti-B antibodies would attack the transfused red blood cells, causing agglutination.

People with blood type O are universal donors because their blood lacks A and B antigens, causing no immune reaction when transfused into others. Conversely, individuals with blood type AB are universal recipients since they have no anti-A or anti-B antibodies, allowing them to receive blood from any ABO type.

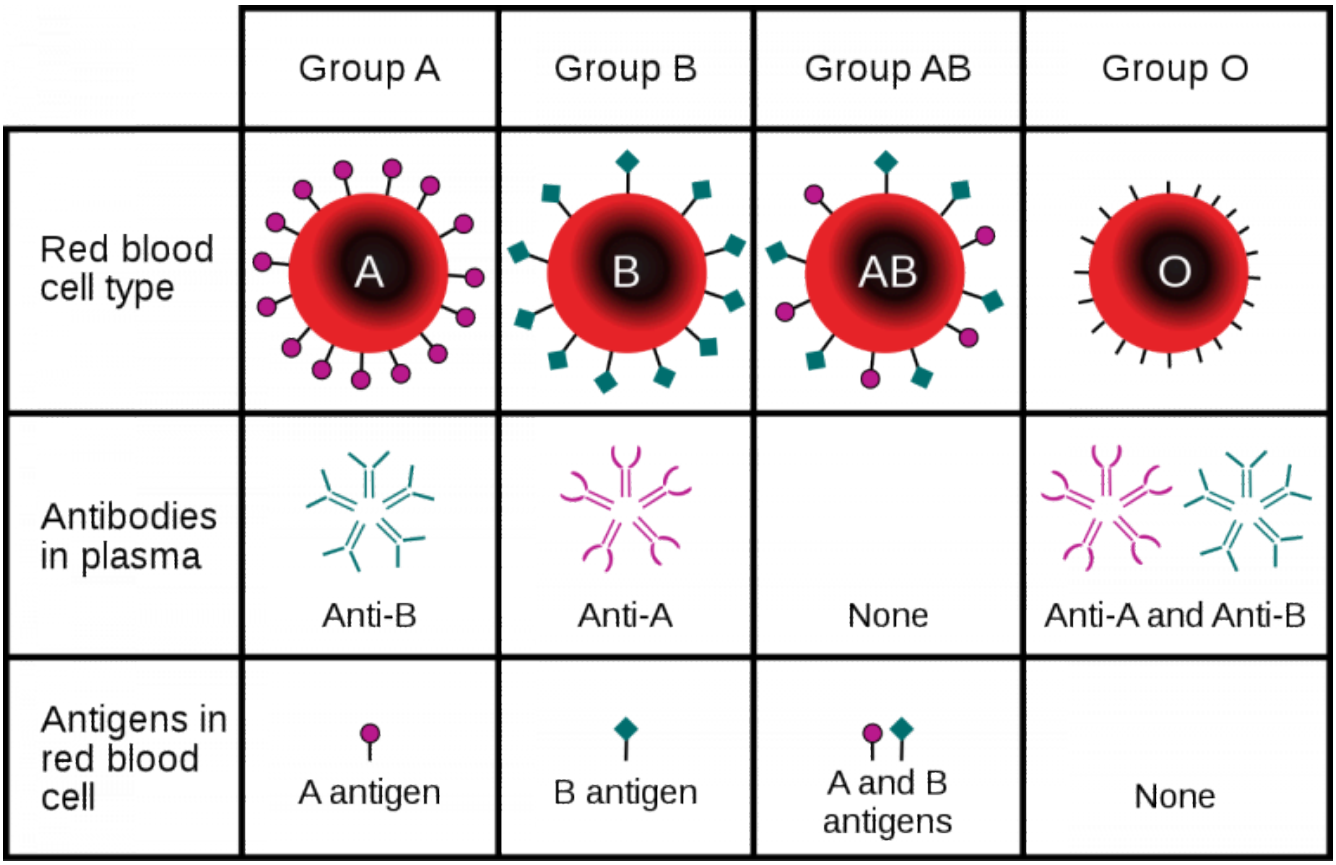


Figure 8.4.3 Antigens and antibodies in ABO blood types. Image by InvictaHOG, Public Domain

Figure 8.4.3 Description

A diagram showing the ABO blood group system based on antigens and antibodies. Four red blood cells are labelled A, B, AB, and O.

Type A cells have A antigens (pink circles) on their surface and anti-B antibodies (blue Y-shaped structures) in the plasma.

Type B cells have B antigens (blue diamonds) and anti-A antibodies (pink Y-shaped structures).

Type AB cells have both A and B antigens and no antibodies, making them universal recipients.

Type O cells have no surface antigens or anti-A and anti-B antibodies, making them universal donors. The diagram explains the compatibility of blood transfusions based on immune responses.

Incomplete Dominance

Another relationship between alleles for the same gene may be **incomplete dominance**. This occurs when the dominant allele is not completely dominant. In this case, an intermediate phenotype results in heterozygotes who inherit both alleles. Generally, this happens when the two alleles for a given gene both produce proteins, but one protein is not functional. As a result, the heterozygote individual produces only half the amount of normal protein as is produced by an individual who is homozygous for the normal allele.

An example of incomplete dominance in humans is Tay Sachs disease. In this case, the normal allele for the gene produces an enzyme responsible for breaking down lipids. A defective allele for the gene results in the production of a nonfunctional enzyme. Heterozygotes who have one normal and one defective allele produce half as much functional enzyme as the normal homozygote, and this is enough for normal development. Homozygotes that have defective alleles, however, produce only nonfunctional enzymes. This leads to the accumulation of lipids in the brain starting in utero, which causes significant brain damage. Most individuals with Tay Sachs disease die at a young age, typically by the age of five years.

Another good example of incomplete dominance in humans is hair type. There are genes for straight and curly hair, and if an individual is heterozygous, they will typically have the phenotype of wavy hair.

Figure 8.4.4 Three phenotypes of hair through the incomplete dominance model. Image by Christine Miller, Public Domain

Figure 8.4.4 Description

An image illustrating incomplete dominance in hair texture inheritance. It shows three side-by-side photos of different hair types. The left panel displays straight hair labelled “Homozygous Straight,” the center panel shows wavy hair labelled “Heterozygous,” and the right panel features tightly curled hair labelled “Homozygous Curly.” This demonstrates how individuals with one straight and one curly hair allele exhibit a blended, intermediate phenotype—wavy hair.

Polygenic Traits

Many human traits are controlled by more than one gene. These traits are called **polygenic traits**. The alleles of each gene have a minor additive effect on the phenotype. There are many possible combinations of alleles, especially if each gene has multiple alleles. Therefore, a whole continuum of phenotypes is possible.

An example of a human polygenic trait is adult height. Several genes, each with more than one allele, contribute to this trait, so there are many possible adult heights. Adult height ranges from less than 5 feet to more than 6 feet, with males, on average, being somewhat taller than females. Most people fall near the middle of the range of heights for their sex, as shown in Figure 8.4.4.

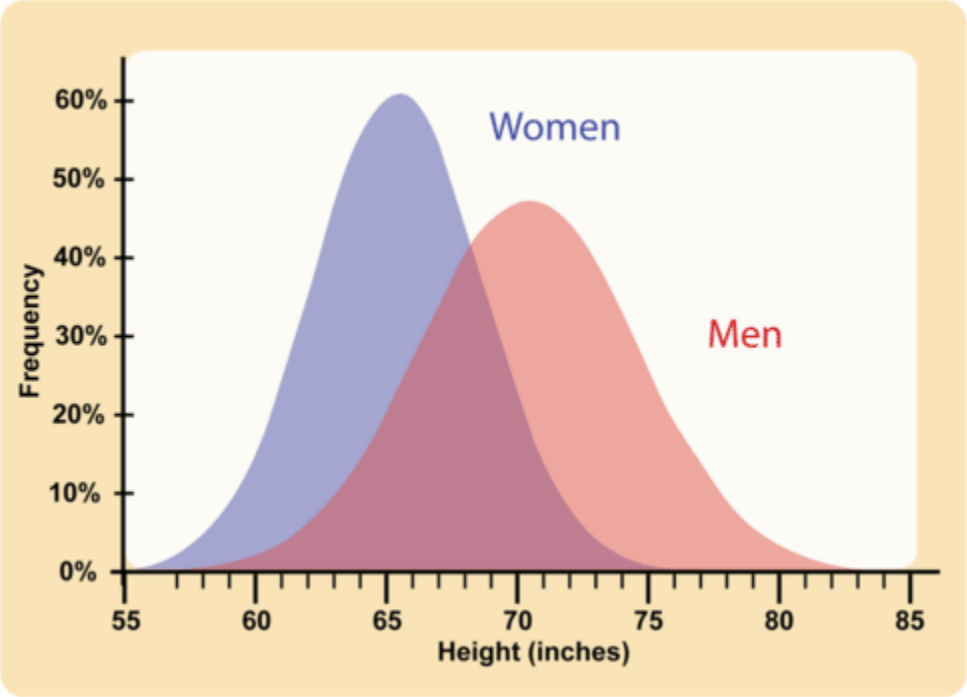


Figure 8.4.5 Human Adult Height. Like many other polygenic traits, adult height has a bell-shaped distribution. Image by CK-12 Foundation, CC BY 3.0

Figure 8.4.5 Description

A bell curve graph comparing the height distributions of men and women. The x-axis represents height in

inches (ranging from 55 to 85), and the y-axis represents frequency as a percentage (0% to 60%). The blue curve represents women, peaking around 64–65 inches, while the red curve represents men, peaking around 69–70 inches. The curves overlap in the middle, showing that some women are taller than some men, but overall, men tend to be taller. The graph illustrates continuous variation in height, a polygenic trait influenced by multiple genes.

Many traits are affected by the environment, as well as by genes. This may be especially true for polygenic traits. Adult height, for example, might be negatively impacted by poor diet or childhood illness. Skin colour is another polygenic trait. There is a wide range of skin colours in people worldwide. In addition to differences in genes, differences in exposure to ultraviolet (UV) light cause some variation. As shown in Figure 8.4.5, exposure to UV light darkens the skin.

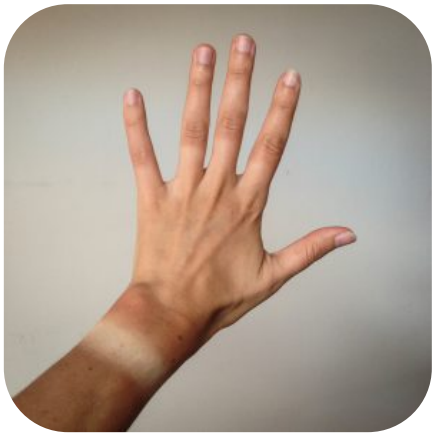


Figure 8.4.6 UV light darkens skin. Image by katiebordner, CC BY 2.0

Pleiotropy

Some genes affect more than one phenotypic trait. This is called **pleiotropy**.

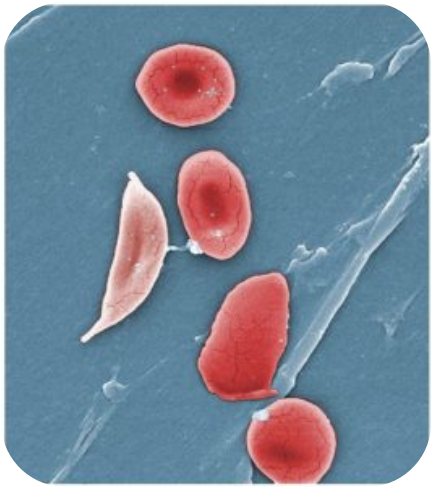


Figure 8.4.7 Sickle-shaped red blood cell on the left is shown next to several normal red blood cells. Image by OpenStax, CC BY 3.0

There are numerous examples of pleiotropy in humans. They generally involve important proteins that are needed for the normal development or functioning of more than one organ system. An example of pleiotropy in humans occurs with the gene that codes for the main protein in collagen, a substance that helps form bones. This protein is also important in the ears and eyes. Mutations in the gene result in problems not only in bones but also in these sensory organs, which is how the gene's pleiotropic effects were discovered.

Another example of pleiotropy occurs with sickle cell anemia. This recessive genetic disorder occurs when there is a mutation in the gene that normally encodes the red blood cell protein called hemoglobin. People with the disorder have two alleles for sickle cell hemoglobin, named for the sickle shape (pictured in Figure 8.4.6) that their red blood cells take on under certain conditions (like physical exertion). The sickle-shaped red blood cells clog small blood vessels, causing multiple phenotypic effects, including stunting physical growth, certain bone deformities, kidney failure, and strokes.

Exercise 8.4.1

Text Description

1. A trait controlled by four genes is most likely a ____.
A trait for which each allele of the heterozygote makes an equal contribution to the phenotype is most likely a ____.
A trait controlled by a single gene that has three different alleles is most likely a ____.
A trait controlled by a single gene where one allele is fully dominant to the only other allele is most likely a ____.

Possible Answers

- codominant trait
- multiple allele trait
- mendelian trait
- polygenic trait

2. People with O type blood cannot receive a blood transfusion from anyone besides others with O type blood. (True/False)

3. People with O type blood can be heterozygous for this trait. (True/False)

4. Human traits can be influenced by the environment. (True/False)

Answers:
1. A trait controlled by four genes is most likely a ***polygenic trait***.
A trait for which each allele of the heterozygote makes an equal contribution to the phenotype is most likely a ***codominant trait.***

A trait controlled by a single gene that has three different alleles is most likely a ***multiple allele trait***.
A trait controlled by a single gene where one allele is fully dominant to the only other allele is most likely a ***Mendelian trait***.

2. True

3. False

4. True

CHAPTER 8 SUMMARY

Key Takeaways

- **Gregor Mendel, the Father of Genetics:** Mendel completed groundbreaking experiments with pea plants in the mid-1800s, revealing fundamental heredity principles and challenging the blending theory of inheritance by showing that traits are inherited as distinct units, not mixed averages of the parents.
- **Experiments on Pea Plants:** Pea plants were ideal for Mendel's experiments because they grow quickly, are easy to control for pollination, and have clear contrasting traits (e.g., purple vs. white flowers). True-breeding plants always produce offspring with the same trait when self-pollinated, making them essential for Mendel's controlled crosses. Cross-pollination between different true-breeding plants led to hybrids in the F1 generation that only showed the dominant trait.
- **Law of Segregation:** In monohybrid crosses, Mendel observed that the trait that disappeared in the F1 generation reappeared in the F2 generation in a 3:1 ratio, leading to the Law of Segregation:
    - Each organism carries two alleles for each trait.
    - These alleles separate during gamete formation, so each gamete gets only one allele.
- **Law of Independent Assortment:** In dihybrid crosses, Mendel found that traits are inherited independently of one another, leading to the Law of Independent Assortment:
    - Alleles for different traits segregate independently during the formation of gametes.
- **Foundations of Modern Genetics:** Mendel's work formed the foundation of modern genetics, although his ideas were not widely accepted until decades later.
- **Non-Mendelian Modes of Inheritance:** Many human traits follow non-Mendelian modes of inheritance, including multiple allele traits, traits with codominance or incomplete dominance, and polygenic traits, and pleiotropy.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into key takeaways.

Flash Cards

Text Description

1. **Heredity:** The passing of traits from parents to offspring
2. **Character:** A heritable feature that varies among individuals (e.g. flower colour)
3. **Trait:** A specific variation of a character (e.g. purple flowers)
4. **Pollination**: The transfer of pollen from the male anther to the female stigma of a flower
5. **True-breeding**: Organisms that produce offspring identical to themselves when self-pollinated
6. **Hybrid**: Offspring resulting from the cross between parents with different traits
7. **P generation**: The parental generation in a genetic cross
8. **F1 generation**: The first filial generation, offspring of the P generation
9. **F2 generation**: The second filial generation, offspring of the F1 generation
10. **Law of segregation**: Mendel's principle stating that two alleles for a trait separate during gamete formation
11. **Law of independent assortment**: Mendel's principle stating that genes for different traits can segregate independently during the formation of gametes
12. **Genetics:** The science of heredity; The study of how traits are passed from parents to offspring
13. **Gene:** A section of DNA on a chromosome that codes for a specific protein; Controls a character
14. **Locus:** The specific physical location of a gene on a chromosome
15. **Allele:** Different versions of a gene; Determines a specific trait

16. **Homologous Chromosomes:** A pair of chromosomes that have the same genes at the same loci; One comes from the father and one from the mother
17. **Dominant Allele:** An allele that is expressed in the phenotype even when only one copy is present in the genotype (e.g. B for purple flowers)
18. **Recessive Allele:** An allele that is only expressed in the phenotype if two copies are present in the genotype (e.g. b for white flowers)
19. **Genotype**: The genetic makeup of an organism, consisting of the alleles inherited from its parents
20. **Heterozygous**: Having two different alleles for a particular gene
21. **Homozygous**: Having two identical alleles for a particular gene
22. **Phenotype**: The observable traits of an organism; Determined by its genotype.
23. **Monohybrid Cross:** A genetic cross between two individuals that differ in only one character (e.g. seed colour)
24. **Punnett Square**: A diagram used to predict the genotype and phenotype ratios of offspring from a genetic cross
25. **Probability:** The measure of the likelihood that an event will occur; Calculated by the number of times the event occurs divided by the total number of opportunities for the event to occur
26. **Dihybrid cross:** A genetic cross between parents that differ by two characters
27. **Mendelian inheritance:** Inheritance of traits controlled by a single gene with two alleles, one of which may be completely dominant to the other
28. **Autosomal traits:** Traits controlled by genes on one of the 22 pairs of human autosomes
29. **Sex-linked traits:** Traits controlled by genes on the sex chromosomes
30. **Dominant disorder:** Genetic disorder caused by a mutated dominant allele; One copy from one parent is sufficient to cause the disorder in the offspring
31. **Recessive disorder:** Genetic disorder that occurs when an individual inherits two recessive mutant alleles for a particular gene
32. **Carrier**: Individual that does not have the disorder themselves, but they carry the recessive mutant allele so their offspring can inherit it
33. **Pedigree**: A diagram that shows the occurrence and appearance of phenotypes of a particular gene or organism and its ancestors across multiple generations
34. **Non-Mendelian inheritance:** Inheritance patterns that do not follow Mendel's laws

35. **Multiple allele traits**: Traits controlled by a single gene with more than two alleles
36. **Codominance**: A type of inheritance where both alleles in a heterozygote are fully expressed
37. **Agglutination**: Clumping of blood cells due to the binding of antigens and antibodies
38. **Incomplete dominance**: A type of inheritance where the phenotype of a heterozygote is intermediate between the phenotypes of the homozygous parents
39. **Polygenic inheritance**: The inheritance of traits controlled by multiple genes, often resulting in a continuous range of phenotypes
40. **Pleiotropy**: A single gene influencing more than one phenotypic trait
41. **Father of Genetics:** Gregor Mendel
42. **Plants Mendel studied?** Pea plants
43. **Why study pea plants?** Fast-growing, easy to raise, have several different characters, self-pollinating
44. **Mendel's Laws:** Law of segregation and law of independent assortment
45. **AA:** Homozygous dominant genotype
46. **Aa:** Heterozygous genotype
47. **aa:** Homozygous recessive genotype
48. **Why are recessive sex-linked traits more common in men?** Men have only one X chromosome, so a single recessive allele will express the trait
49. **Non-Mendelian modes of inheritance**: Multiple alleles traits, codominance, incomplete dominance, polygenic traits, pleiotropy
50. **Blood Type O:** Universal donors because their blood lacks A and B antigens; Causes no immune reaction when transfused into others

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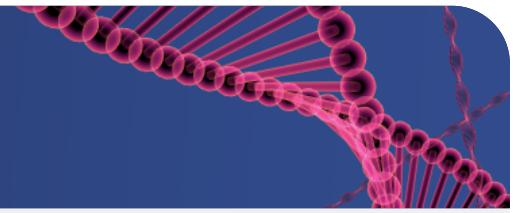
OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms

CHAPTER 9: MOLECULAR BIOLOGY

Chapter Overview

Learning Objectives



By the end of this chapter, you will be able to:

- Explain the historical significance of the discovery of DNA as the genetic material and identify key scientists involved in uncovering DNA's structure.
- Describe the molecular structure of DNA, including the role of nucleotides, sugar-phosphate backbone, nitrogenous bases, and the double helix formation.
- Differentiate between purines and pyrimidines, and identify the rules of complementary base pairing (A-T and G-C).
- Define antiparallel strands and explain the significance of the 3' and 5' ends of DNA.
- Summarize the process of DNA replication, including where and when it occurs in the cell cycle and how the structure of DNA allows it to be copied during DNA replication.
- Identify the roles of key enzymes involved in DNA replication, such as DNA polymerase, and

describe their function.
- Describe how replication bubbles form and expand during the process of DNA replication.
- Relate the importance of accurate DNA replication to growth, development, and cellular function in multicellular organisms.

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Prompt: Produce learning objectives from this content.

9.1 DNA STRUCTURE AND REPLICATION

Discovery of DNA

Determining that DNA is the genetic material on an organism was an important milestone in biology. It took many scientists undertaking creative experiments over several decades to show with certainty that DNA is the molecule that determines the traits of organisms.

One of the most significant scientific achievements of the 20th century was the discovery of the DNA double helix, a twisted ladder-like structure. In the 1950s, James Watson and Francis Crick, with crucial contributions from Rosalind Franklin and Maurice Wilkins, unveiled the double helix model of DNA (see Figure 9.1.1).

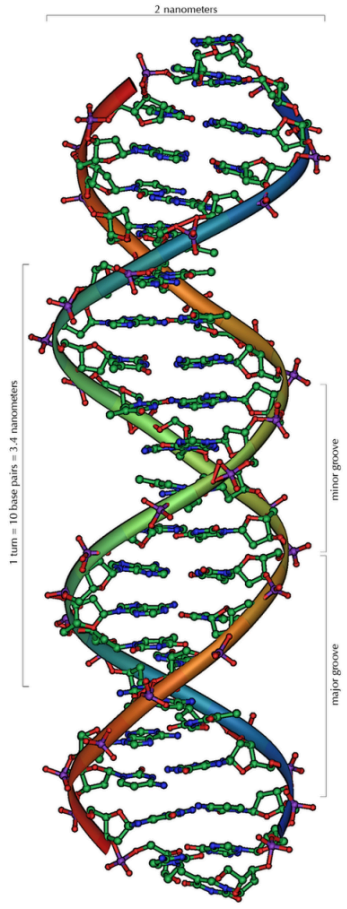

Figure 9.1.1 DNA double helix. Image by Michael Ströck, CC BY-SA 3.0

Figure 9.1.1 Description

3D molecular model of the DNA double helix, showing its twisted ladder-like structure. The image highlights the major and minor grooves, with a full turn of the helix measuring 3.4 nanometers and 10 base pairs per turn. The diameter of the helix is labelled as 2 nanometers.

Building Blocks of DNA

The building blocks of deoxyribonucleic acid (DNA) are **nucleotides**, which are made up of three parts: a deoxyribose (5-carbon sugar), a phosphate group, and a nitrogenous base (Figure 9.1.2).

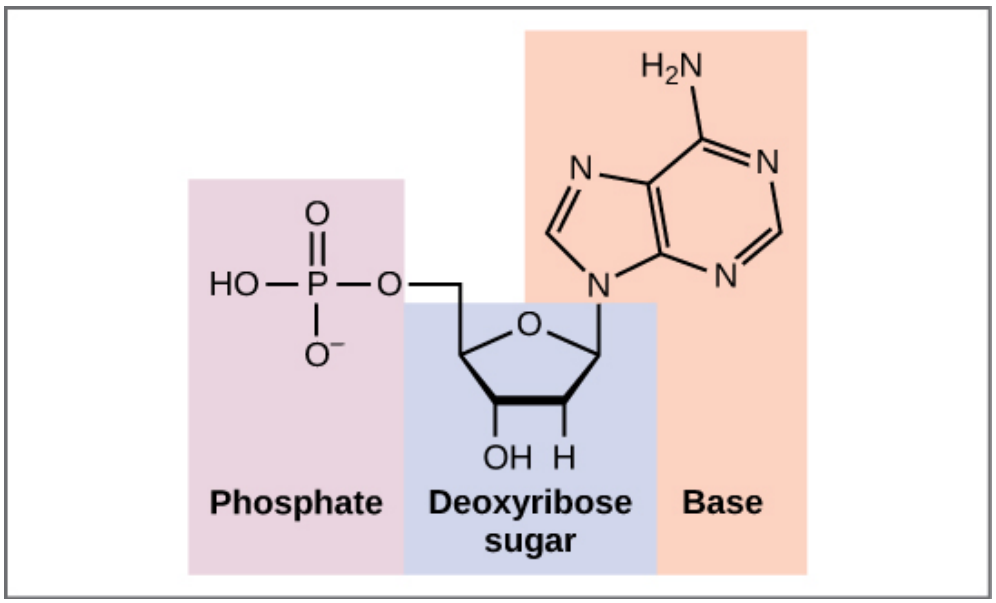

Figure 9.1.2 (a) Each DNA nucleotide comprises a sugar, a phosphate group, and a base. Image by OpenStax, CC BY 4.0

Figure 9.1.2 Description

Diagram of a nucleotide showing its three main components: a phosphate group, a ribose sugar, and a nitrogenous base. The phosphate group is highlighted in purple, the ribose sugar in blue, and the nitrogenous base in orange.

There are four types of nitrogenous bases in DNA. Adenine (A) and guanine (G) are double-ringed purines, and cytosine (C) and thymine (T) are smaller, single-ringed pyrimidines. The nucleotide is named according to the nitrogenous base it contains.

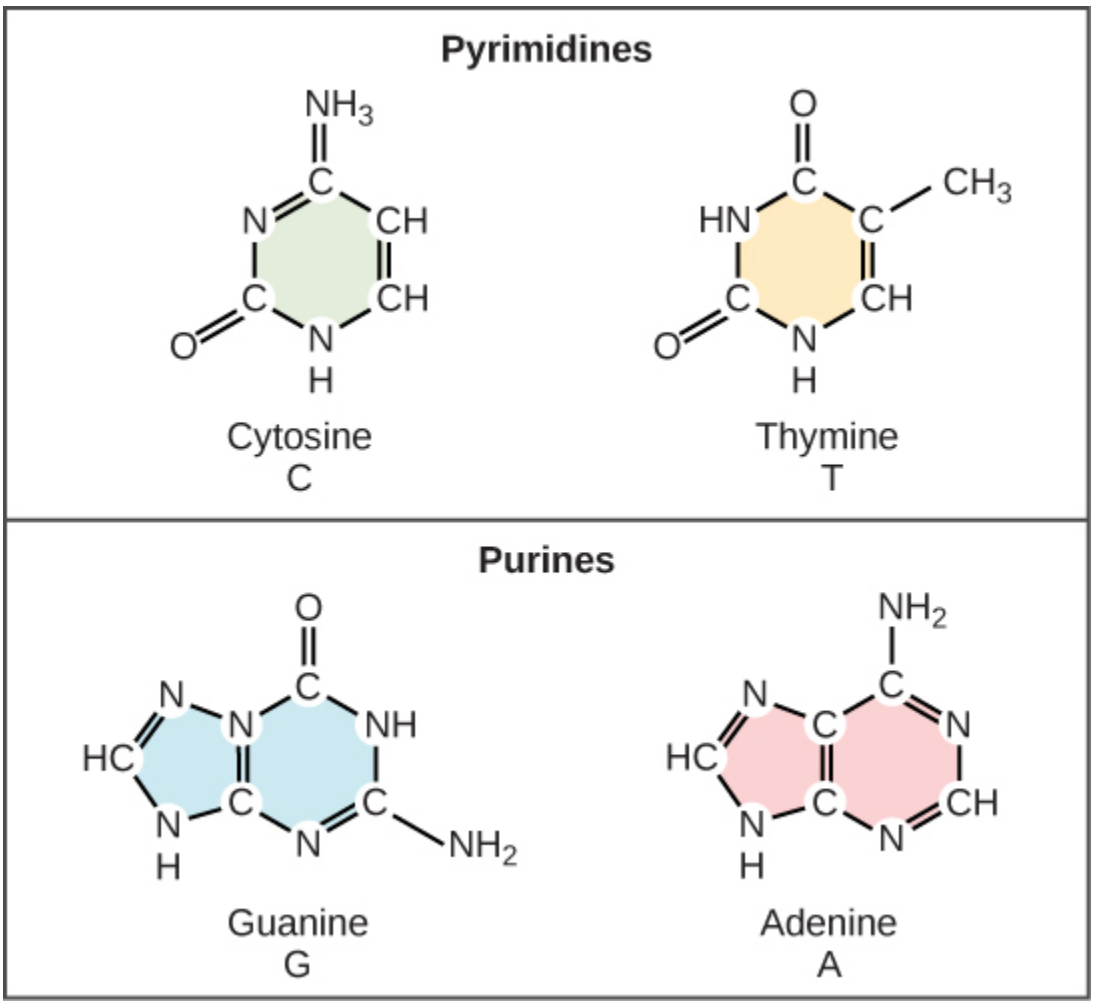

Figure 9.1.3 (b) Cytosine and thymine are pyrimidines. Guanine and adenine are purines. Image by OpenStax, CC BY 4.0

Figure 9.1.3 Description

Diagram showing the chemical structures of the four nitrogenous bases in DNA, categorized into two groups: pyrimidines (cytosine and thymine) and purines (guanine and adenine). Pyrimidines have a single-ring structure, while purines have a double-ring structure. Each base is labelled with its name, abbreviation, and coloured background.

Structure of DNA

The phosphate group of one nucleotide bonds covalently with the sugar molecule of the next nucleotide, and so on, forming a long polymer of nucleotide monomers. The sugar-phosphate groups line up in a "backbone" for every single strand of DNA, and the nitrogenous bases stick out from this backbone. The carbon atoms of the five-carbon sugar are numbered clockwise from the oxygen as 1′, 2′, 3′, 4′, and 5′ (1′ is read as "one prime").

The phosphate group is attached to the 5′ carbon of one nucleotide and the 3′ carbon of the next nucleotide. In its natural state, each DNA molecule is actually composed of two single strands held together along their length with hydrogen bonds between the bases.

DNA comprises two strands twisted around each other to form a helix, called a **double helix**. Base pairing takes place between a purine and pyrimidine: namely, A pairs with T, and G pairs with C. In other words, adenine and thymine are complementary base pairs, and cytosine and guanine are **complementary base pairs**. The two strands are anti-parallel in nature; that is, one strand will have the 3′ carbon of the sugar in the "upward" position, whereas the other strand will have the 5′ carbon in the upward position. The diameter of the DNA double helix is uniform throughout because a purine (two rings) always pairs with a pyrimidine (one ring), and their combined lengths are always equal. (Figure 9.1.3).

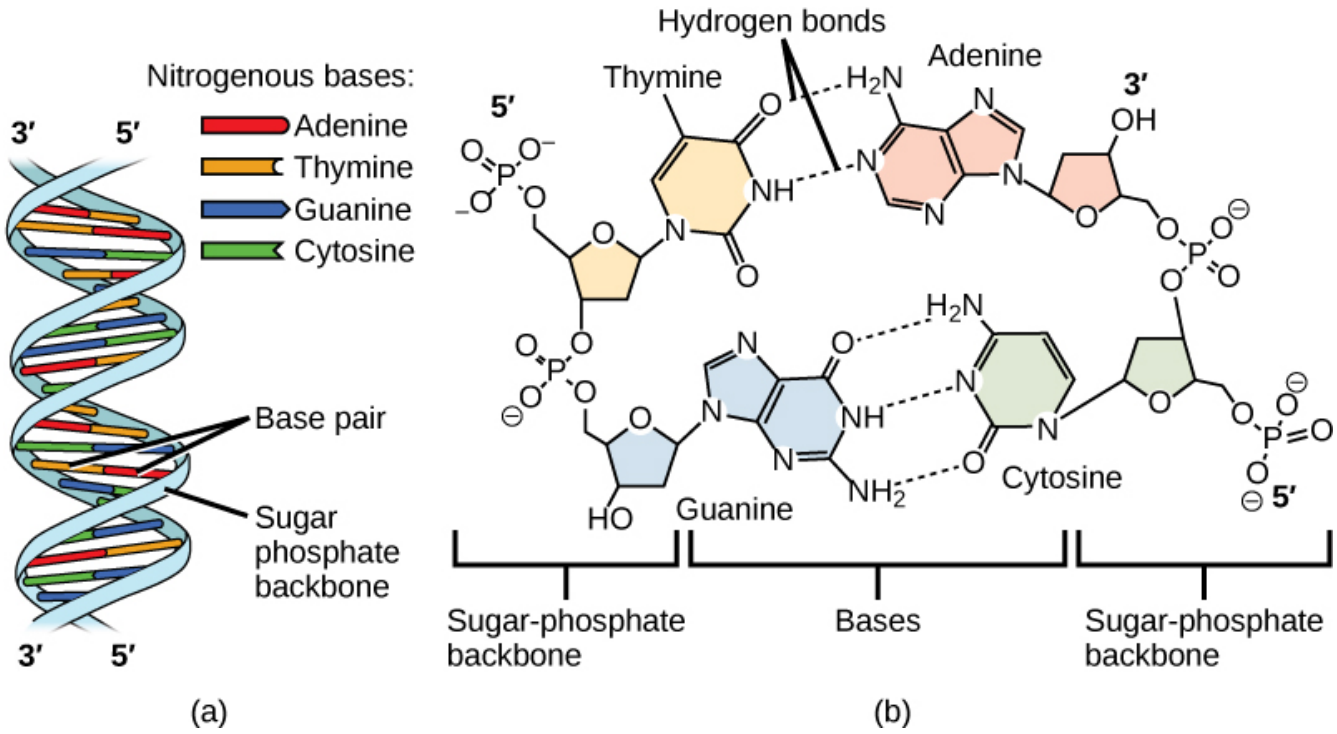

Figure 9.1.4 DNA (a) forms a double-stranded helix, and (b) Complementary base pairs. (credit a: modification of work by Jerome Walker, Dennis Myts). Image by OpenStax, CC BY 4.0

Figure 9.1.4 Description

Illustration of DNA structure. Panel (a) shows a DNA double helix with base pairs colored by type: adenine (red), thymine (yellow), guanine (blue), and cytosine (green), along with the sugar-phosphate backbone. Panel (b) shows a zoomed-in view of DNA base pairing: adenine pairs with thymine via two hydrogen bonds, and

guanine pairs with cytosine via three hydrogen bonds. Sugar-phosphate backbones are shown on both sides of the base pairs with directionality labelled 5′ to 3′.

Exercises 9.1.1

Text Description

1. Two-ring bases always bind to each other (True/False?)

2. In DNA, each nucleotide contains a sugar. (True/False?)

3. Complementary Base Pairing- drag and drop to complete the complementary strand

Drop Zones:

- A
- C
- G
- T
- C
- A

Possible Answers:

- A
- T
- C
- G

4. A single strand of DNA is a polymer of ____ joined ____ between the ____ of one and the ____ of the next to form a “backbone” from which the ____ bases stick out. In its natural state, DNA has ____ wound around each other in a ____. The bases on each strand are bonded to each other with ____ bonds. Only specific bases bond with each other; ____ bonds with ____, and ____ bonds with ____.

Answers

1. False
2. True
3. A: T
   C: G
   G: C
   T: A
   C: G
   A: T
4. A single strand of DNA is a polymer of ***nucleic acids*** joined ***covalently*** between the ***phosphate group*** of one and the ***deoxyribose sugar*** of the next to form a "backbone" from which the ***nitrogenous*** bases stick out. In its natural state, DNA has ***two strands*** wound around each other in a ***double helix***. The bases on each strand are bonded to each other with ***hydrogen*** bonds. Only specific bases bond with each other; ***adenine*** bonds with ***thymine***, and ***cytosine*** bonds with ***guanine***.

DNA Replication

DNA replication is required for the growth or replication of an organism. You started as one single cell and are now made up of approximately 37 trillion cells! Each and every one of these cells contains the exact same copy of DNA, which is only possible because of DNA replication.

DNA replication is the process by which DNA is copied. It occurs during the synthesis (S) phase of the eukaryotic cell cycle. DNA must be copied so that each new daughter cell will have a complete set of chromosomes after cell division occurs.

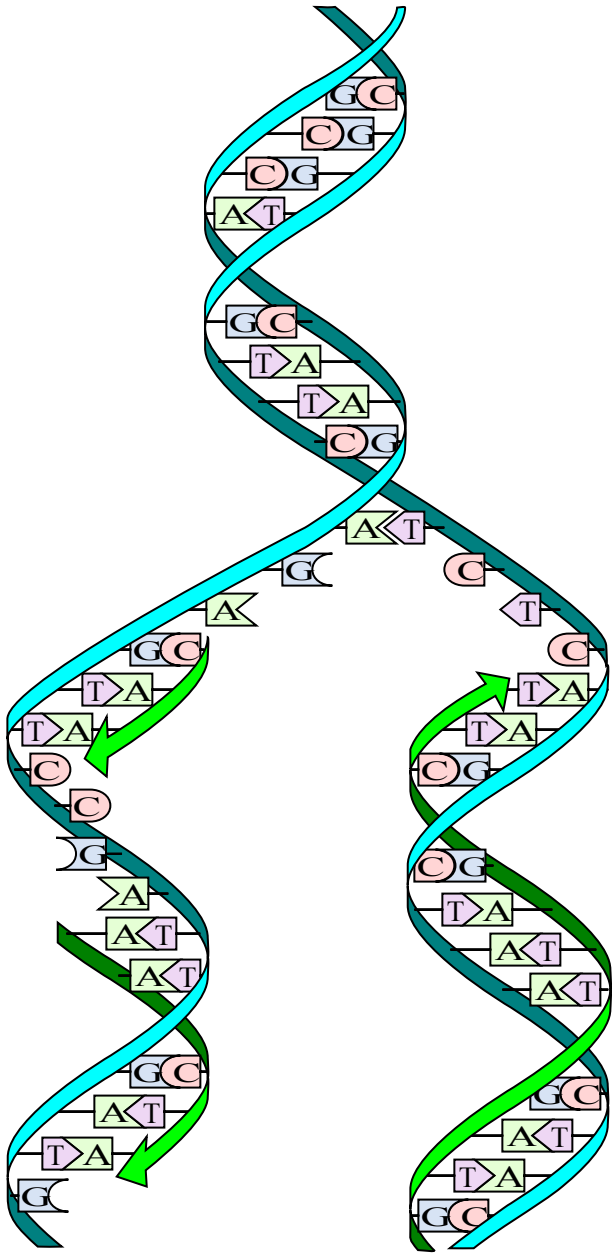

Figure 9.1.5 DNA replication. Image by Madprime, CC0 1.0

Figure 9.1.5 Description

Diagram of DNA replication showing the unwinding of the double helix into two single strands. Each strand serves as a template for synthesizing a new complementary strand. Arrows indicate the direction of replication, and base pairing is shown between the template and new strands.

Knowledge of DNA's structure helped scientists understand how DNA is copied. Recall that adenine nucleotides pair with thymine nucleotides and cytosine with guanine. This means that the two strands are

complementary to each other. For example, a strand of DNA with a nucleotide sequence of AGTCATGA will have a complementary strand with the sequence TCAGTACT.

DNA replication is referred to as **semi-conservative**. This means that when a strand of DNA is replicated, each of the two original strands acts as a template for a new complementary strand. When the replication process is complete, there are two identical sets of DNA, each containing one of the original DNA strands and one newly synthesized strand.

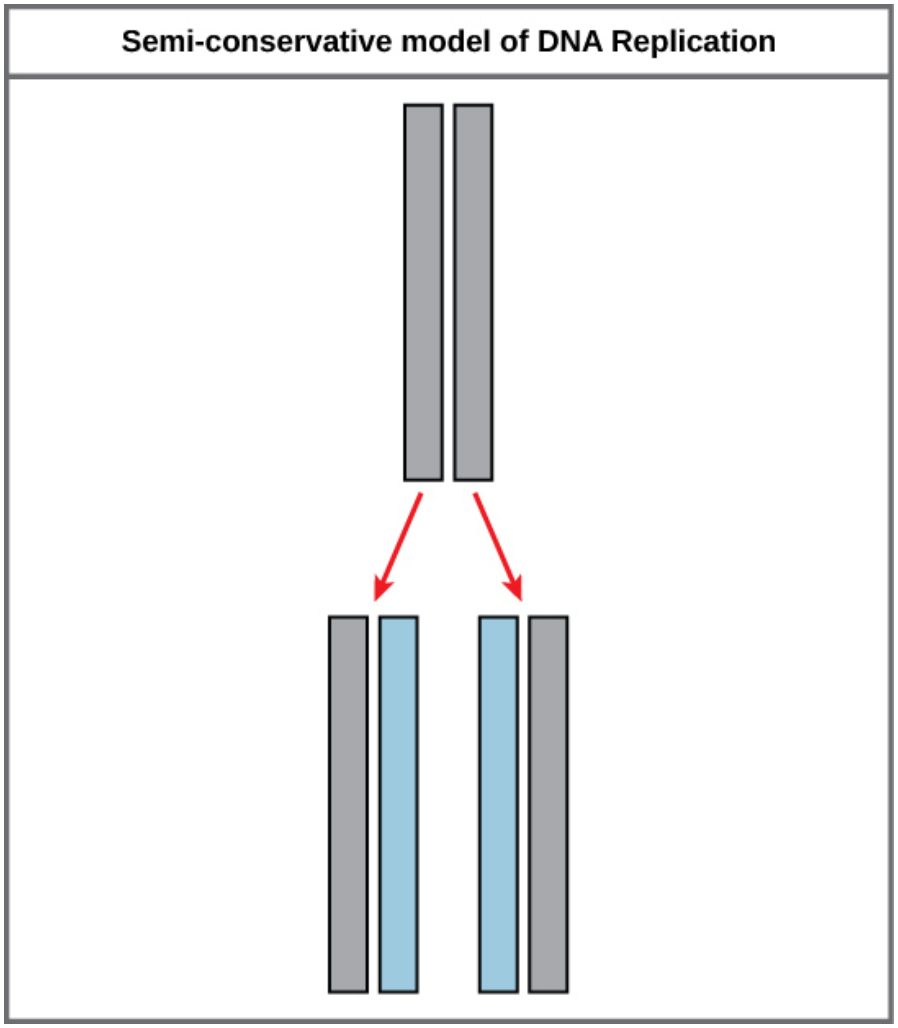

Figure 9.1.6 The semiconservative model of DNA replication. Gray indicates the original DNA strands, and blue indicates newly synthesized DNA. Image by OpenStax, CC BY 4.0

Figure 9.1.6 Description

Diagram illustrating the semi-conservative model of DNA replication. The original DNA molecule, shown as two gray strands, separates, and each strand serves as a template for a new strand. The resulting DNA molecules each contain one original (gray) strand and one newly synthesized (blue) strand.

DNA replication is a complicated process with a specific sequence of events and enzymes that facilitate each step. **DNA polymerases** are key enzymes that form covalent bonds between nucleotides to build a new DNA strand. Replication starts at specific sites called **origins of replication,** where the parental DNA strands start to unwind in both directions, forming replication bubbles. Once the nitrogenous bases from the inside of the parental DNA molecule are exposed, the creation of a new, complementary strand can begin. As each nucleotide pairs with its complementary base on the template strand, DNA polymerase creates a covalent bond to attach to the growing daughter strand. Eventually, all replication bubbles merge, resulting in two complete double-stranded daughter DNA molecules.

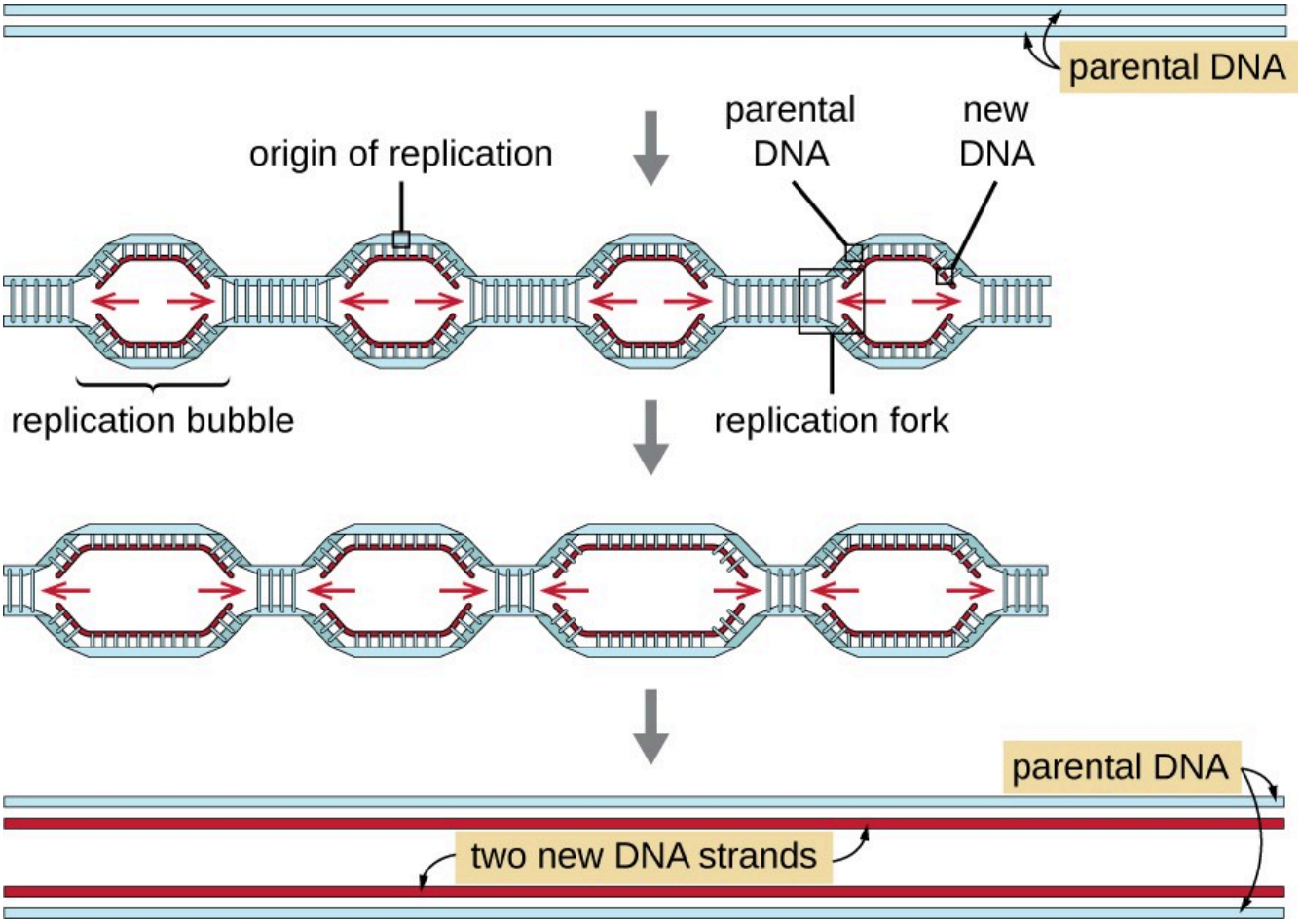

Figure 9.1.7 Eukaryotic chromosomes are typically linear, and each contains multiple origins of replication. Image by OpenStax, CC BY 4.0

Figure 9.1.7 Description

A diagram showing two strands of parental DNA. Then, an arrow shows multiple replication bubbles with an origin of replication in each. Arrows point to the left and right from each origin of replication. New

strands of DNA are shown to be formed. One of the bubbles has the left half of the bubble in a box labelled replication fork. The next image shows the replication bubbles getting longer. The final image shows two new DNA strands, each with one old strand and one new strand.

9.2 TRANSCRIPTION

Central Dogma

Protein synthesis, the production of proteins, occurs in all living things' cells. It uses the information in DNA to make corresponding proteins.

In eukaryotic cells, DNA is found in chromosomes, which always remain in the nucleus. Proteins are made at ribosomes in the cytoplasm. How do the instructions in DNA get to the site of protein synthesis outside the nucleus?

Another type of nucleic acid is responsible – RNA or ribonucleic acid. RNA is a small molecule that can squeeze through pores in the nuclear membrane. It carries the information from DNA in the nucleus to a ribosome in the cytoplasm and then helps assemble the protein.

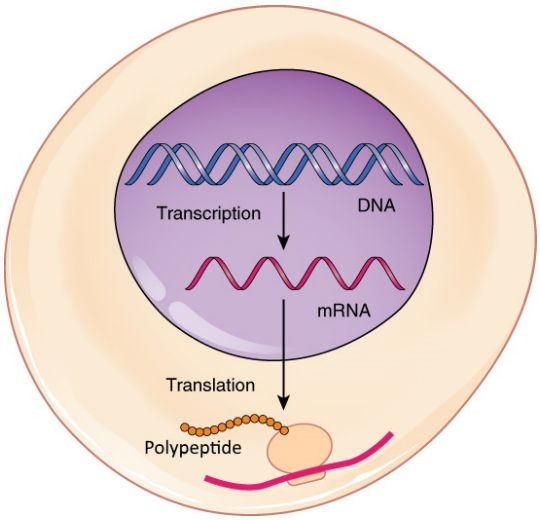

Figure 9.2.1 Basic overview of protein synthesis. Image by OpenStax, CC BY 4.0

In short: **DNA → RNA → Protein**

DNA is used as a template during transcription to make a messenger RNA molecule (mRNA). During translation, mRNA is read and used to link amino acids together to make a polypeptide. This sequence of events is called the **central dogma** of molecular biology.

Figure 9.2.1 Description

Diagram of gene expression in a eukaryotic cell. Inside the nucleus, DNA undergoes transcription to produce mRNA. The mRNA exits the nucleus and is used in the cytoplasm for translation, resulting in the formation of a polypeptide chain.

Structure of RNA

DNA alone cannot "tell" your cells how to make proteins. It needs the help of RNA, the other leading player in the central dogma of molecular biology. Like DNA, RNA is a nucleic acid consisting of repeating nucleotides bonded together to form a polynucleotide chain. RNA differs from DNA in several ways: it exists

as a single-stranded molecule, contains the sugar ribose (as opposed to deoxyribose) and uses the base uracil instead of thymine.

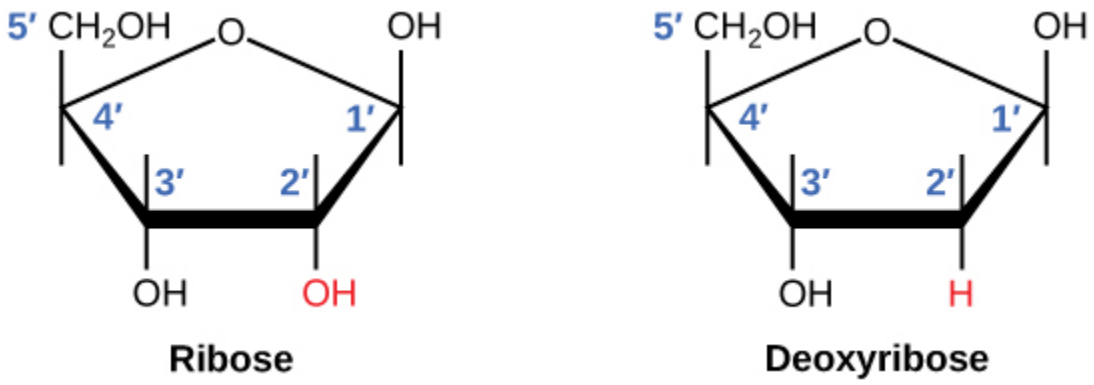

Figure 9.2.2 Ribose has an oxygen at the 2' carbon that is lacking in *deoxy*ribose. Image by OpenStax, CC BY 4.0

Figure 9.2.2 Description

Side-by-side comparison of the chemical structures of ribose and deoxyribose sugars. Both have a five-carbon ring labelled with carbon positions (1′ to 5′), but ribose has a hydroxyl group (OH) at the 2′ carbon, while deoxyribose has only hydrogen (H) at the same position.

Functions of RNA

The main function of RNA is to help make proteins. There are three main types of RNA involved in protein synthesis:

- **Messenger RNA (mRNA)** copies (or transcribes) the genetic instructions from DNA in the nucleus and carries them to the cytoplasm.
- **Ribosomal RNA (rRNA)** helps form ribosomes, where proteins are assembled. Ribosomes also contain proteins.
- **Transfer RNA (tRNA)** brings amino acids to ribosomes, where rRNA catalyzes the formation of chemical bonds between them to form a protein.

The diversity of roles that RNA molecules play has led to their being called the Swiss Army knives of the cellular world.

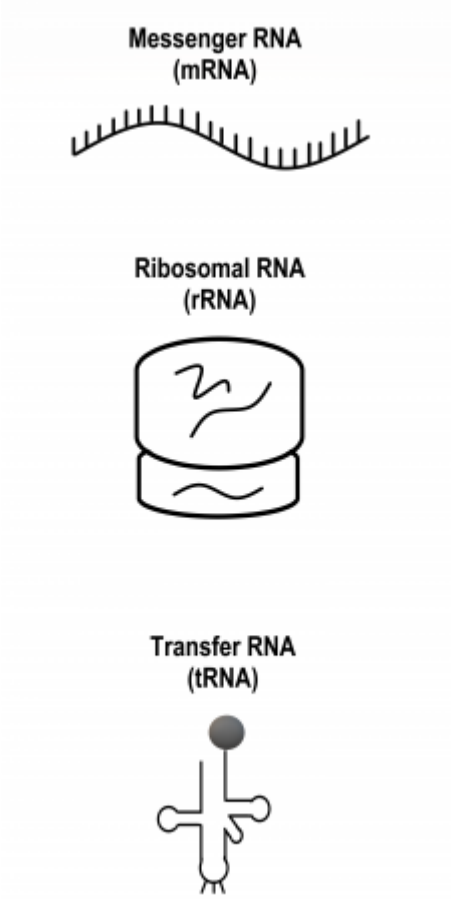

Figure 9.2.3 Three types of RNA. Image by Christine Miller, CC BY-NC 4.0

Figure 9.2.3 Description

Diagram showing the three main types of RNA. At the top is messenger RNA (mRNA), represented as a squiggly single strand. In the middle is ribosomal RNA (rRNA), illustrated as part of a ribosome complex with two subunits. At the bottom is transfer RNA (tRNA), shown as a cloverleaf structure with an attached amino acid.

Exercises 9.2.1

Text Description
Comparison of DNA and RNA

Drop Zones:

- DNA
- RNA

Possible Answers

- Stores genetic information
- Can be found throughout the cell
- Can be used to carry information, carry amino acids, make up ribosomes
- Contains ribose
- Double stranded
- Single stranded
- Contains deoxyribose
- Contains thymine
- Contains uracil
- Remains in the nucleus

Answers

DNA:

- Double stranded
- Contains deoxyribose
- Contains thymine
- Remains in the nucleus
- Stores genetic information

RNA:

- Single stranded

- Contains ribose
- Contains uracil
- Can be found throughout the cell
- Can be used to carry information, carry amino acids, make up ribosomes

Text Description
mRNA is ____ from DNA, and then is ____ into a protein.

____ exits the nucleus through a nuclear pore. ____ helps form the structure where proteins are assembled. ____ transports amino acids to the ribosome.

Answers

mRNA is ***transcribed*** from DNA, and then is ***translated*** into a protein.

mRNA exits the nucleus through a nuclear pore. ***rRNA*** helps form the structure where proteins are assembled. ***tRNA*** transports amino acids to the ribosome.

Transcription

Transcription is the first part of the central dogma of molecular biology: **DNA → RNA**. It is the transfer of genetic instructions in DNA to mRNA. During transcription, a strand of mRNA is made to complement a strand of DNA.

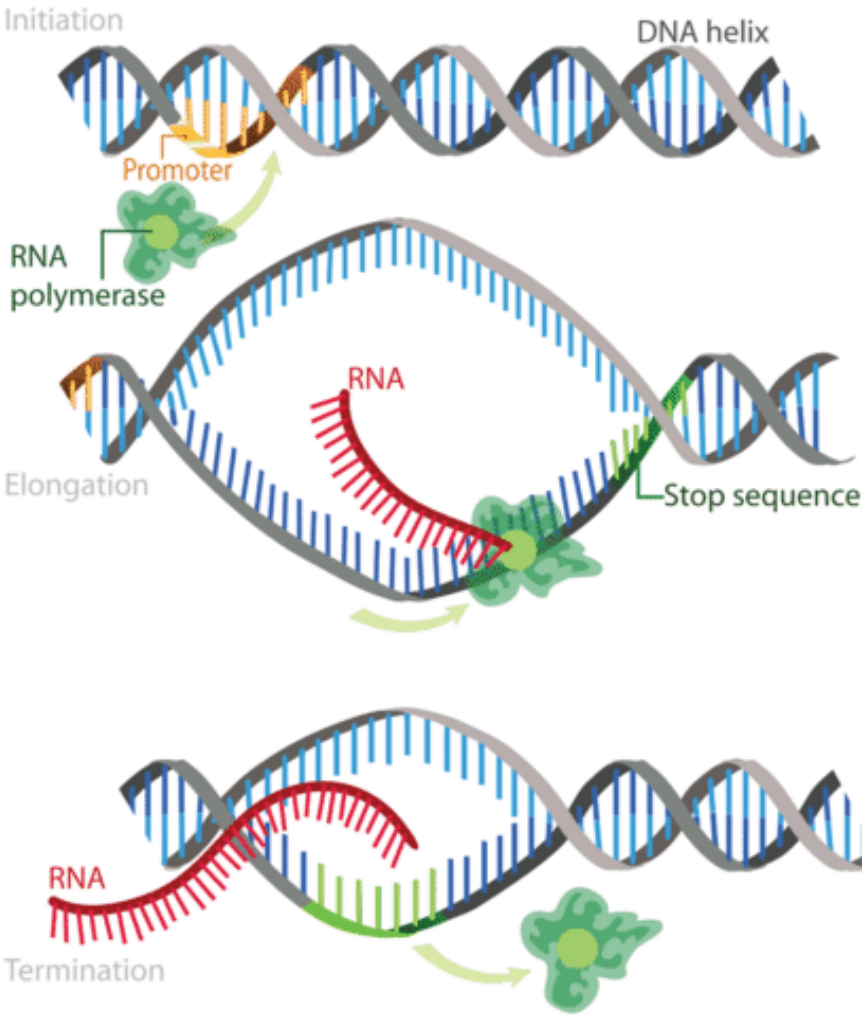

Figure 9.2.4 Transcription occurs in three steps—initiation, elongation, and termination. Image by Mariana Ruiz Villarreal, CC BY-NC 3.0

Figure 9.2.4 Description

Illustration of the transcription process in three stages: initiation, elongation, and termination. In initiation, RNA polymerase binds to the promoter region of DNA. In elongation, the DNA unwinds, and RNA polymerase synthesizes a complementary RNA strand. In termination, the RNA strand detaches and the DNA rewinds.

Transcription occurs in three main steps:

1. Initiation

Transcription begins when the enzyme **RNA polymerase** binds to a gene region called the **promoter**

sequence. This signals the DNA to unwind so the enzyme can "read" the bases of DNA. The region of unwinding is called a transcription bubble.

In most cases, promoters exist upstream of the genes they regulate. The specific sequence of a promoter is very important because it determines whether the corresponding gene is transcribed all of the time, some of the time, or hardly at all.

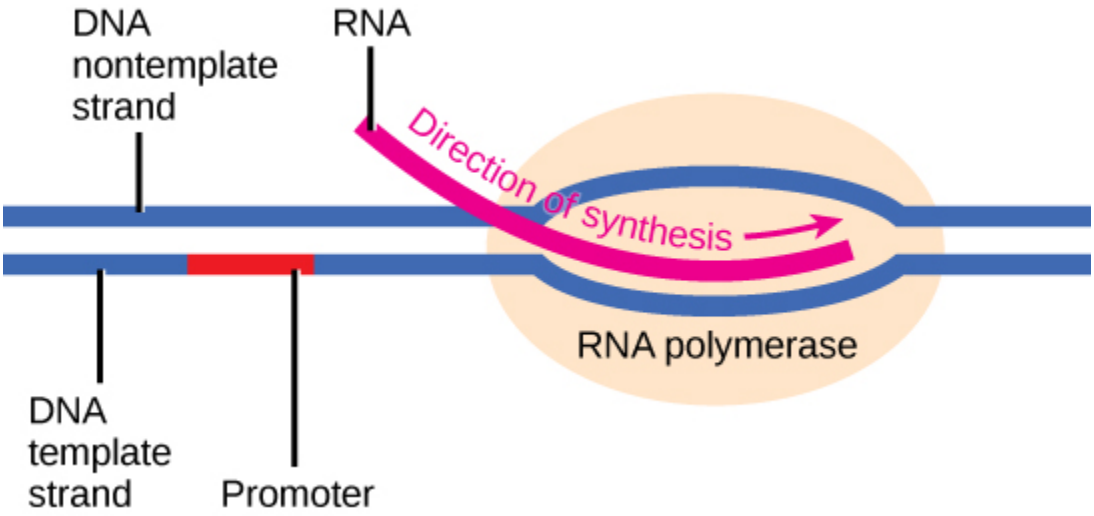

Figure 9.2.5 Initiation of transcription. Image by OpenStax, CC BY 4.0

Figure 9.2.5 Description

Diagram of transcription initiation showing RNA polymerase binding to the DNA template strand at the promoter region. The DNA non-template strand is also shown. RNA synthesis begins at the promoter, and the RNA strand is elongated in the 5′ to 3′ direction.

2. Elongation

RNA polymerase moves along the template strand of DNA, unwinds the double helix, synthesizes mRNA, and then rewinds the DNA. RNA polymerase adds RNA nucleotides to the growing mRNA strand through complementary base pairing. When the RNA has "T", RNA polymerase adds in "A". "C" in the DNA corresponds to "G" in RNA. "G" in DNA to "C" in RNA. When RNA polymerase reaches "A" in the DNA, it adds in "U" (because there is no "T" in RNA).

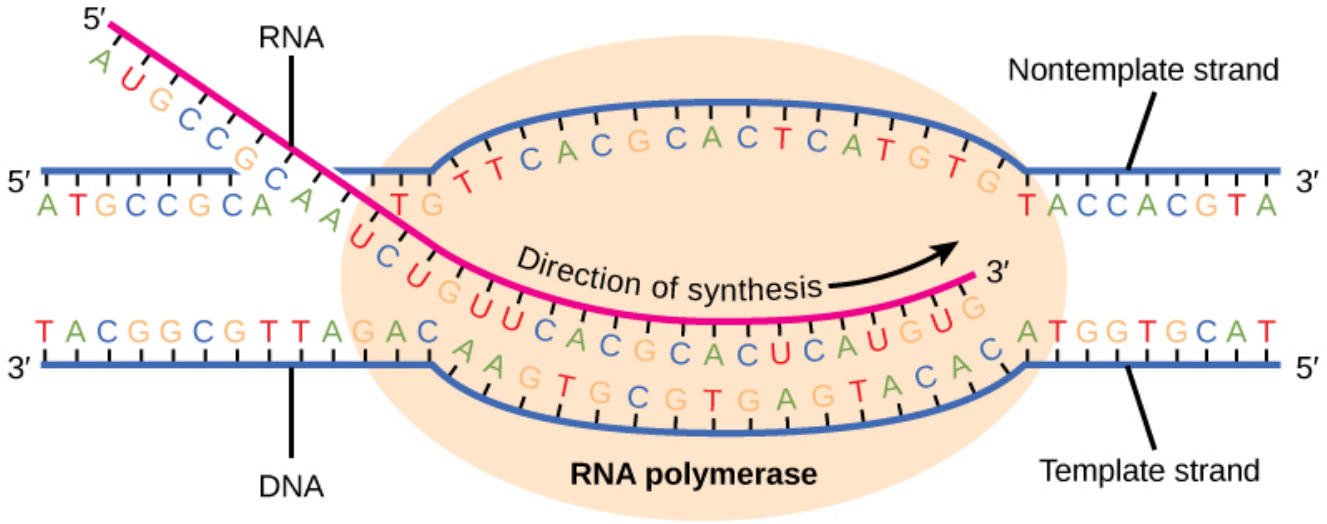

Figure 9.2.6 Elongation of transcription. Image by OpenStax, CC BY 4.0

Figure 9.2.6 Description

Diagram of RNA transcription showing RNA polymerase moving along the DNA template strand in the 3′ to 5′ direction. The RNA strand is synthesized in the 5′ to 3′ direction, complementary to the DNA template strand. The DNA non-template strand is also shown, with all base pairs labelled.

3. Termination

RNA polymerase reaches a special region in the DNA called the **terminator** sequence, which signals the end of the gene. At this point, RNA polymerase stops transcription, detaches from the DNA template, and releases the mRNA transcript. The result is a strand of mRNA that is complementary to the DNA template strand and nearly identical to the nontemplate strand – the only difference being that DNA uses the base thymine (“T”), and the mRNA uses uracil (“U”) instead.

Processing mRNA

The newly transcribed eukaryotic mRNAs must undergo several processing steps before they can be transferred from the nucleus to the cytoplasm and translated into a protein. The additional steps involved in eukaryotic mRNA maturation create a molecule that is much more stable than a prokaryotic mRNA. For example, eukaryotic mRNAs last for several hours, whereas the typical prokaryotic mRNA lasts no more than five seconds.

The processing may include splicing, adding a cap, and adding a tail, among other possible modifications.

- **Splicing**: Eukaryotic genes comprise **exons** (protein-coding sequences) and **introns** (regions that do not code for the protein). Splicing removes introns from mRNA. It is essential that all of a pre-mRNA's introns are completely and precisely removed before protein synthesis so that the exons join together to code for the correct amino acids. If the process errs by even a single nucleotide, the sequence of the rejoined exons will be shifted, and the resulting protein will be nonfunctional.
- **Capping**: A special nucleotide cap is added to the "head" (5' end) of the mRNA. This cap protects the mRNA from breaking down and helps the ribosomes know where to bind to the mRNA.
- **Polyadenylation**: A **poly-A tail**, consisting of approximately 200 adenine bases, is added to the "tail" (3' end) of the mRNA. It signals the end of mRNA, exports mRNA from the nucleus, and protects mRNA from enzymes that might break it down.

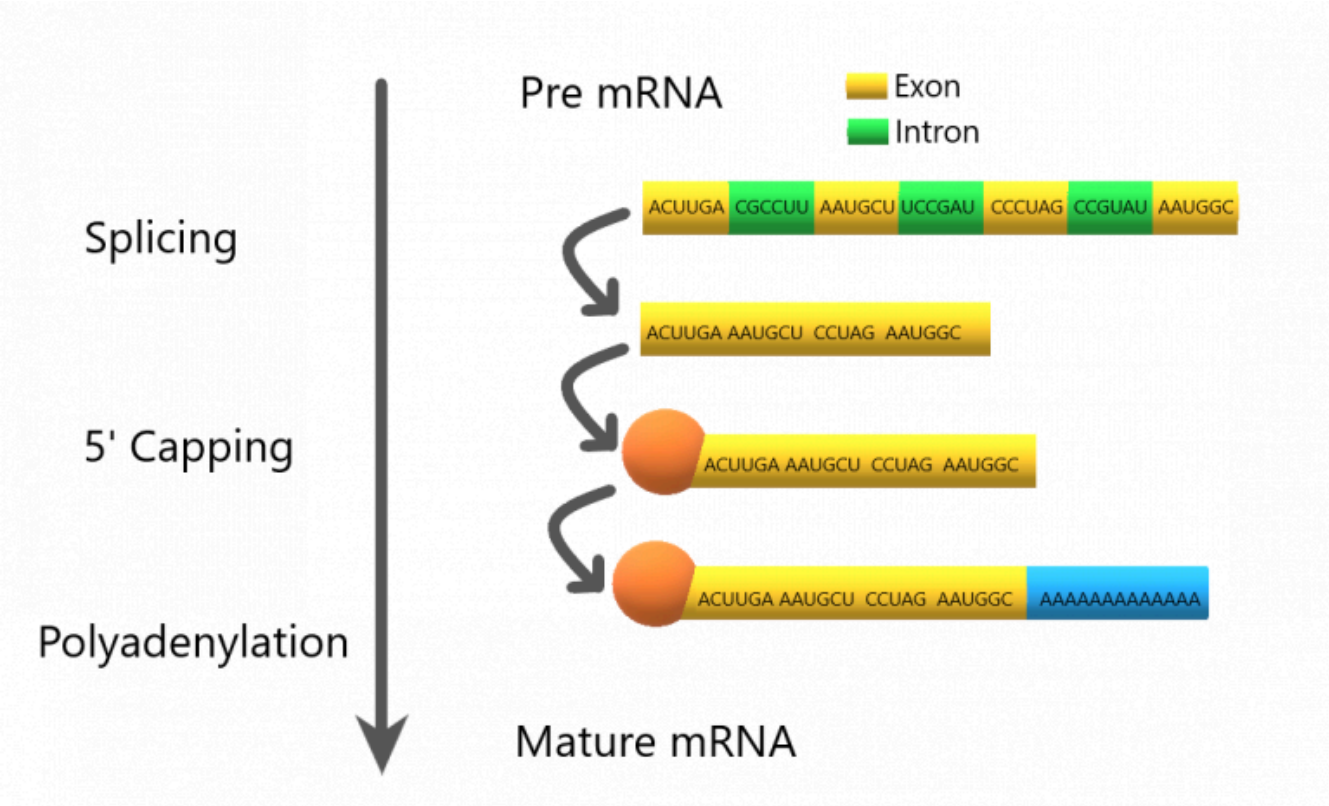

Figure 9.2.7 mRNA processing. Image by Christine Miller, CC BY-NC-SA 4.0

Figure 9.2.7 Description

Diagram illustrating the processing of pre-mRNA into mature mRNA. The pre-mRNA contains both exons (yellow) and introns (green). The first step is splicing, where introns are removed. Next, a 5′ cap is added to the beginning of the mRNA. Finally, a poly-A tail is added to the 3′ end. The result is mature mRNA ready for translation.

Exercise 9.2.2

Text Description

1. What is a promoter?

- a specific sequence of DNA nucleotides
- a specific sequence of RNA nucleotides
- a protein that binds to DNA
- an enzyme that synthesizes RNA

2. What portions of eukaryotic mRNA sequence that are removed during RNA processing?

- exons
- caps
- poly-A tails
- introns

Answers

1. a specific sequence of DNA nucleotides
2. introns

9.3 TRANSLATION

Translation refers to the process by which a ribosome reads the genetic message in mRNA to synthesize a protein. This involves decoding the sequence of nucleotides in mRNA to assemble amino acids in the correct order, forming a protein.

Relating this to translating languages, think of mRNA as a message written in one language (nucleotides) that needs to be translated into another language (amino acids). Just as a translator may use a French-English dictionary to convert text from one language to another, the ribosome uses the genetic code to translate the sequence of nucleotides in mRNA into a sequence of amino acids to build a protein.

Genetic Code

The **genetic code** consists of the sequence of nitrogen bases in a chain of DNA or RNA. The bases are adenine (A), cytosine (C), guanine (G), and thymine (T) (or uracil, U, in RNA). The four bases make up the "letters" of the genetic code. The letters are combined in groups of 3 to form code "words," called **codons**. Each codon stands for (encodes) one amino acid unless it codes for a start or stop signal. There are 20 common amino acids in proteins. With four bases forming three-base codons, there are 64 possible codons. This is more than enough to code for the 20 amino acids.

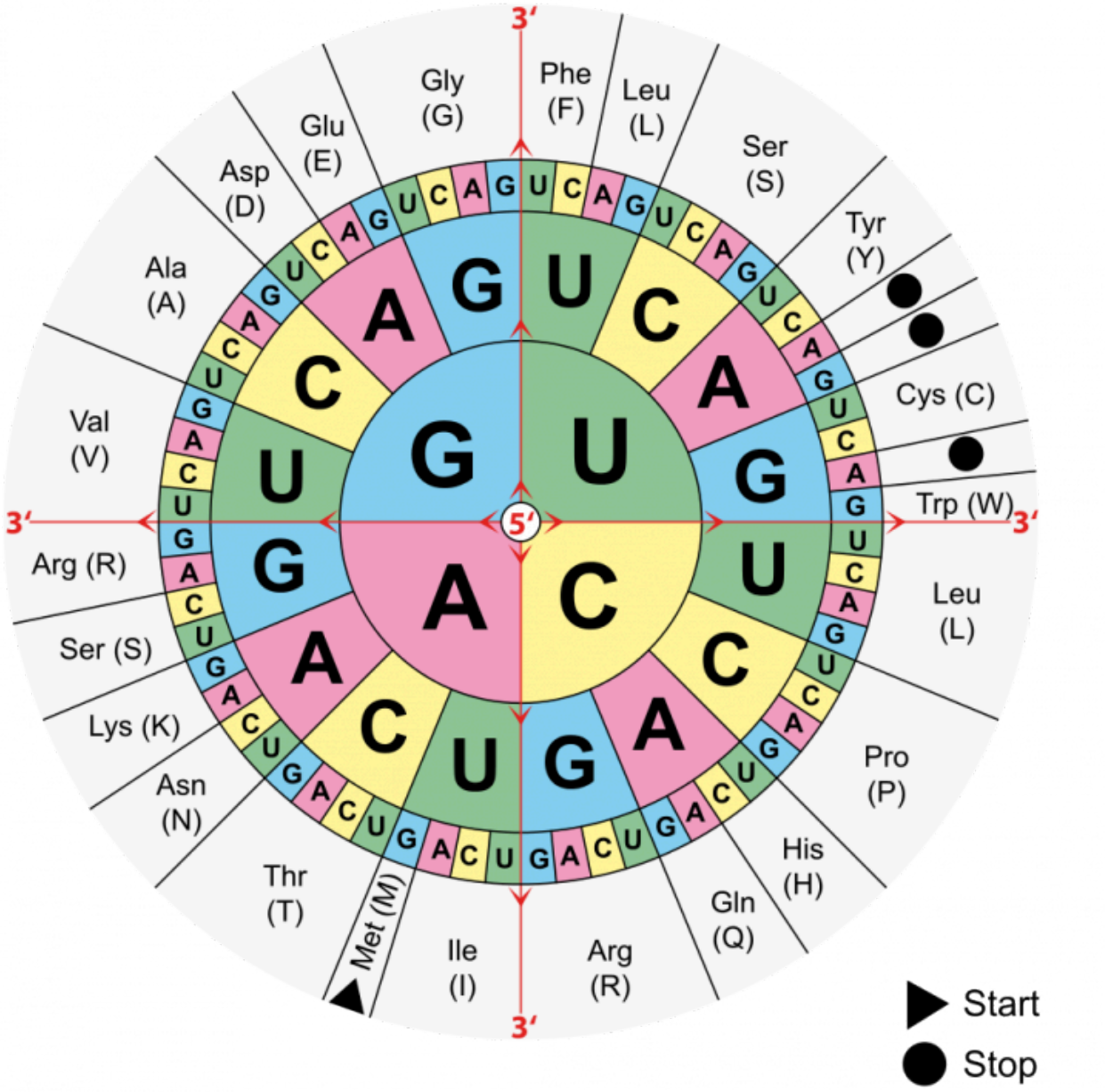

Figure 9.3.1 The Genetic Code (decoder). Image by Mouagip, Public Domain

Figure 9.3.1 Description

Circular codon chart showing the genetic code. It is read from the center outward, starting with the first nucleotide of an mRNA codon at the center, followed by the second and third nucleotides. The chart maps mRNA codons to their corresponding amino acids, using one-letter and three-letter abbreviations. Start codon (AUG) is indicated for methionine (Met), and three-stop codons are marked with black dots.

To find the amino acid for a particular codon, find the first base in the codon in the circle's centre in Figure 9.3.1, then the second base in the middle row out from the center, and finally, the third base in the outer ring. For example, CUG codes for leucine, AAG codes for lysine, and GGG codes for glycine.

If you find the codon AUG in Figure 9.3.1, you will see that it codes for the amino acid methionine. This codon is also the start codon that establishes the reading frame of the code. The start codon is a necessary tool in translation since a single chromosome contains many genes. To transcribe and translate a gene for a specific protein, we need to know where in the DNA code to start "reading" the instructions. AUG signals the start of a reading frame. After the AUG start codon, the next three bases are read as the second codon. The next three bases after that are read as the third codon, and so on. The sequence of bases is read, codon by codon until a stop codon is reached. UAG, UGA, and UAA are all stop codons. They do not code for any amino acids.

Exercise 9.3.1

Text Description

1. One codon can encode for more than one amino acid. (True/False?)

2. The codons for tyrosine in plants are the same as the ones that encode for tyrosine in humans. (True/False?)

3. In addition to its function of establishing where the reading frame starts, the start codon encodes for an amino acid. (True/False?)

4. How many possible codons are there?

- 4
- 20
- 64
- It depends on the species.

5. How many common amino acids are there in proteins?

- 4
- 20
- 64

- It depends on the species.

6. Drop Zones

- Reading Frame
- Met
- Arg
- Pro
- Start Codon

Available Answers

- Start Codon
- Pro
- Arg
- Met
- Reading Frame

Answers
1. False
2. True
3. True
4. 64
5. 20
6. Answers match drop zones

Translation

Translation is the second part of the central dogma of molecular biology: RNA → Protein.

It is the process in which the genetic code in mRNA is read to make a protein.

After mRNA leaves the nucleus, it moves to a ribosome, which consists of rRNA and proteins. The ribosome reads the sequence of codons in mRNA, and tRNA molecules bring amino acids to the ribosome in the correct sequence.

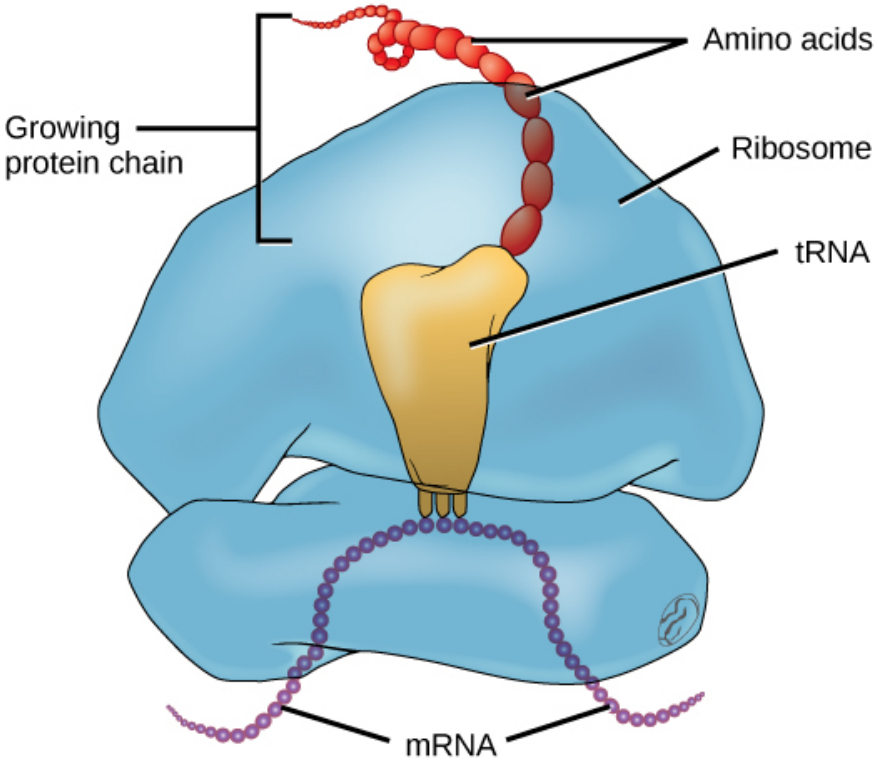

Figure 9.3.2 The protein synthesis machinery includes the large and small subunits of the ribosome, mRNA, and tRNA. Image modification of work by NIGMS, NIH, CC BY 4.0

Figure 9.3.2 Description

Diagram of translation showing a ribosome bound to mRNA. A tRNA molecule delivers amino acids to the ribosome, where they are assembled into a growing protein chain. The mRNA strand is threaded through the ribosome, guiding the sequence of amino acids.

Translation occurs in three stages:

1. Initiation

After transcription in the nucleus, the mRNA exits through a nuclear pore and enters the cytoplasm. At the region on the mRNA containing the cap and the start codon, the small and large subunits of the ribosome bind to the mRNA. These are then joined by a tRNA, which contains the anticodons that match the **start codon** (start signal) on the mRNA. This group of molecules (mRNA, ribosome, tRNA) is called an **initiation complex**.

2. Elongation

tRNA keeps bringing amino acids to the growing polypeptide according to complementary base pairing between the codons on the mRNA and the anticodons on the tRNA. As a tRNA moves into the ribosome, its amino acid is transferred to the growing polypeptide. Once this transfer is complete, the tRNA leaves the ribosome, the ribosome moves one codon length down the mRNA, and a new tRNA enters with its corresponding amino acid. This process repeats, and the polypeptide grows.

3. Termination

At the end of the mRNA coding is a **stop codon** (stop signal), which will end the elongation stage. The stop codon doesn't call for a tRNA but instead for a type of protein called a release factor, which will cause the entire complex (mRNA, ribosome, tRNA, and polypeptide) to break apart, releasing all components.

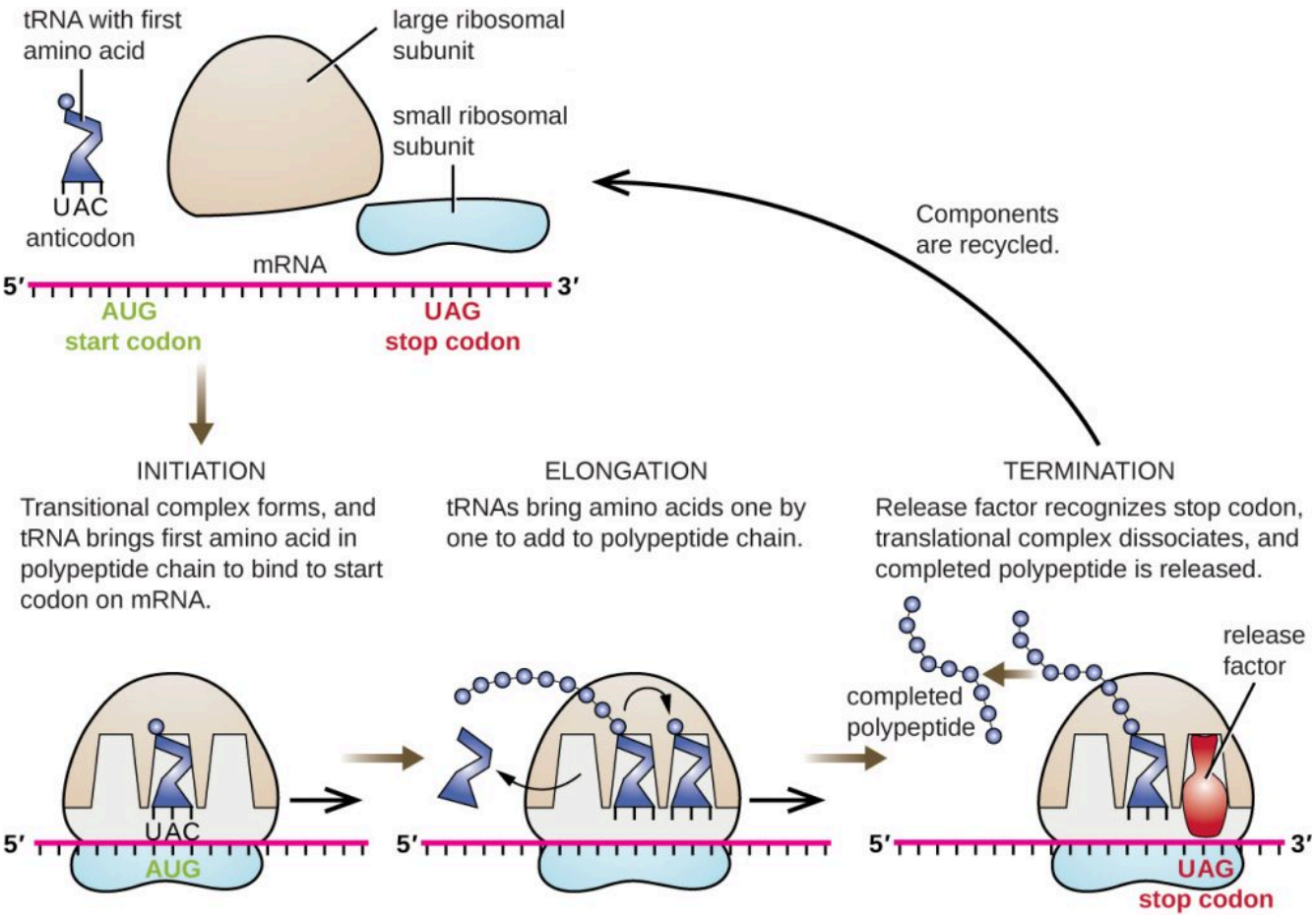

Figure 9.3.3 Translation takes place in three stages: Initiation, Elongation and Termination. Image by CNX OpenStax, CC BY 4.0

Figure 9.3.3 Description

Diagram of the three translation stages in protein synthesis: initiation, elongation, and termination. At initiation, a tRNA with the anticodon UAC binds to the start codon AUG on the mRNA, forming a complex with the small and large ribosomal subunits. During elongation, additional tRNAs bring amino acids to the ribosome, which are linked to form a polypeptide chain. In termination, the ribosome reaches a stop codon (UAG), and a release factor binds, releasing the completed polypeptide and allowing the ribosomal components to be recycled.

Exercise 9.3.2

Text Description

1.

DNA is copied onto a strand of mRNA during a process called ____.

The code on mRNA is “read” and used to create a protein during a process called ____.

This process is further broken down into three stages;
In ____ the ribosome, mRNA and first tRNA all associate.

In ____ amino acids are brought to the ribosome by tRNA and are added to the growing protein.

In ____ a stop codon is reached, and the complex dissociates and released the newly formed protein.

2.

____ contains codons.
____ contains anticodons.
____ makes up the ribosome along with proteins.

3. If a sequence of DNA on the template strand reads CAG TAC, then the:

– non-template strand will read ____
– mRNA codons will read ____
– the tRNA anticodons matching the mRNA will read: ____

4. The promoter region is located in the

- DNA
- mRNA
- tRNA
- Ribosomes

5. Introns in mRNA bind to tRNA at the ribosome. (True/False?)
6. tRNAs can be thought of as the link between amino acids and codons in the mRNA. (True/False?)

Answers

1.

Correct answer(s):DNA is copied onto a strand of mRNA during a process called ***transcription***.

The code on mRNA is "read" and used to create a protein during a process called ***translation***.

This process is further broken down into three stages;
In ***initiation*** the ribosome, mRNA and first tRNA all associate.

In ***elongation*** amino acids are brought to the ribosome by tRNA and are added to the growing protein.

In ***termination*** a stop codon is reached, and the complex dissociates and released the newly formed protein.

2.

Correct answer(s): ***mRNA*** contains codons.
tRNA contains anticodons.
rRNA makes up the ribosome along with proteins.

3.

Correct answer(s):If a sequence of DNA on the template strand reads CAG TAC, then the:

– non-template strand will read ***GTC ATG***
– mRNA codons will read ***GUC AUG***
– the tRNA anticodons matching the mRNA will read: ***CAG UAC***

4. DNA
5. False
6. True

Mutations

Mutations are random changes in the sequence of bases in DNA or RNA.

Mutations have many possible causes. Some mutations seem to happen spontaneously, without any outside influence. They occur when errors are made during DNA replication or during the transcription phase of protein synthesis. Environmental factors cause other mutations. Anything in the environment that can cause a mutation is known as a **mutagen**.

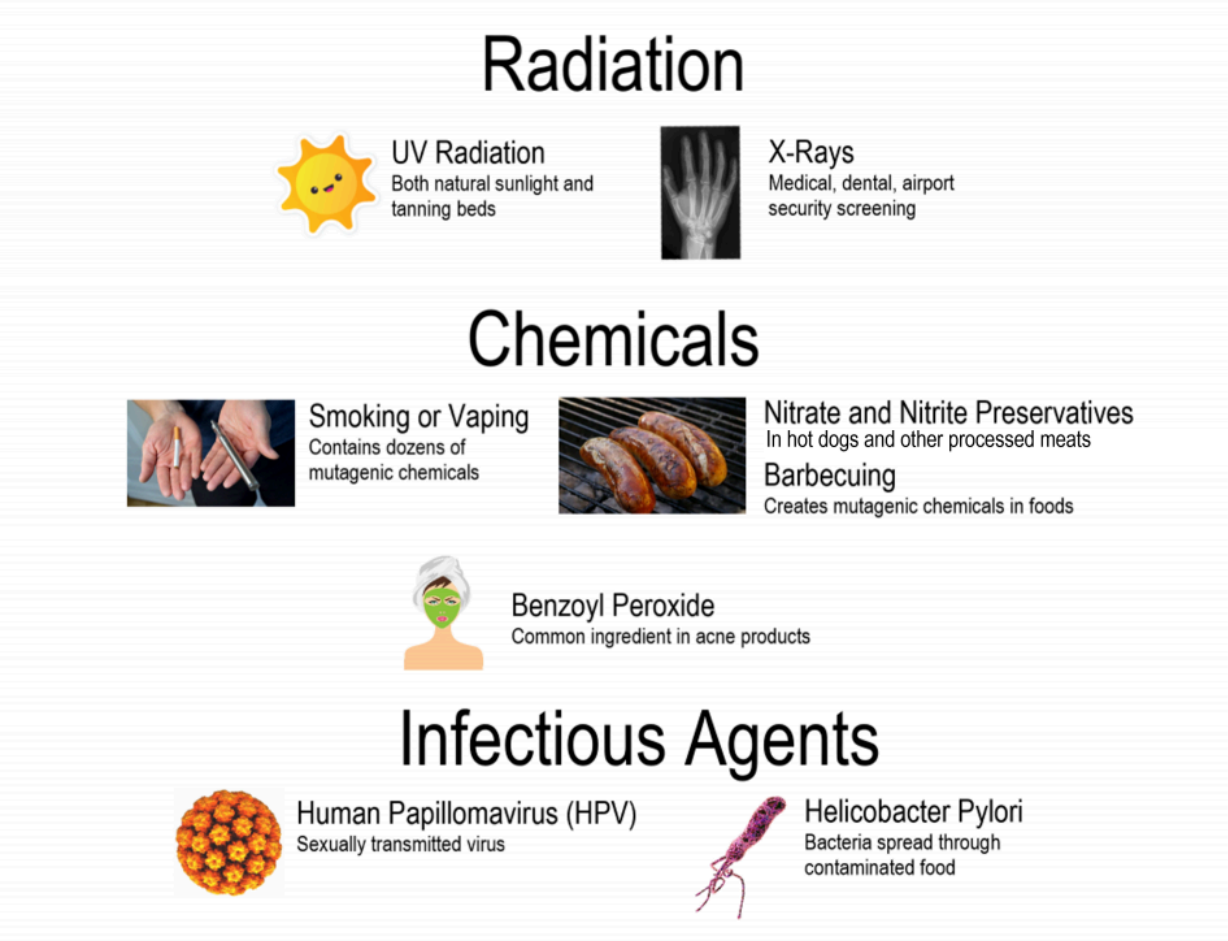

Figure 9.3.4 Types of mutagens. Image by Christine Miller, CC BY SA 4.0 Modifications: Text revised

Figure 9.3.4 Description

Diagram categorizing common mutagens into three groups: Radiation, Chemicals, and Infectious Agents. Under Radiation: UV Radiation (from sunlight and tanning beds) and X-rays (used in medical, dental, and airport screenings). Under Chemicals: Smoking or Vaping (contains mutagenic chemicals), Nitrate and Nitrite Preservatives and Barbecuing (create mutagenic compounds in food), and Benzoyl Peroxide (an acne treatment ingredient). Under Infectious Agents: Human Papillomavirus (HPV), a sexually transmitted virus, and Helicobacter Pylori, a bacterium spread through contaminated food.

Types of Mutations

There are many different types of mutations:

Chromosomal Alterations

Chromosomal Alterations are mutations that change chromosome structure. They occur when a section of a chromosome breaks off and rejoins incorrectly, or otherwise does not rejoin at all. Possible ways in which these mutations can occur are illustrated in the figure below. Chromosomal alterations are very serious. They often result in the death of the organism in which they occur.

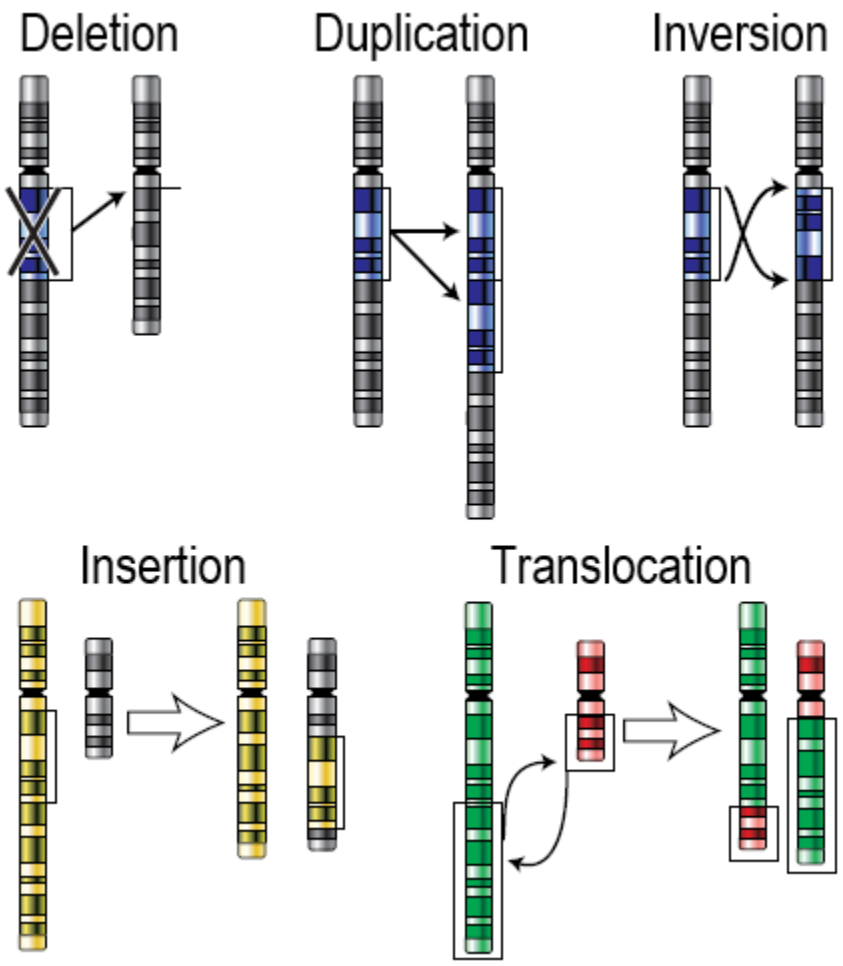

Figure 9.3.5 Chromosomal alterations are major changes in the genetic material. Image by unknown, Public Domain.

Figure 9.3.5 Description

Diagram illustrating five types of chromosomal mutations: Deletion (a segment is removed), Duplication (a segment is copied), Inversion (a segment is reversed), Insertion (a segment from one chromosome is inserted into another), and Translocation (segments are exchanged between non-homologous chromosomes). Each mutation type is shown with arrows indicating the change in chromosome structure.

Point Mutation

A **point mutation** is a change in a single nucleotide in DNA. This type of mutation is usually less serious than a chromosomal alteration. An example of a point mutation is one that changes the codon UUU to the codon UCU. Point mutations can be silent, missense, or nonsense mutations, as described in the table below. The effects of point mutations depend on how they change the genetic code.

Table 9.3.1: The Effects of Point Mutations

Type	Description	Example	Effect
Silent	Mutated codon codes for the same amino acid	CAA (glutamine) → CAG (glutamine)	None
Missense	Mutated codon codes for a different amino acid	CAA (glutamine) → CCA (proline)	Variable
Nonsense	Mutated codon is a premature stop codon	CAA (glutamine) → UAA (stop)	Usually serious

Frameshift Mutation

A **frameshift mutation** is a deletion or insertion of one or more nucleotides, changing the reading frame of the base sequence.

The **reading frame** refers to how the sequence of RNA bases is divided into codons (groups of three nucleotides that each code for a specific amino acid). The ribosome reads the mRNA three bases at a time, starting from the start codon (AUG). If a nucleotide is added or removed, the grouping of the bases shifts, and every codon after the mutation is read incorrectly.

Think of the reading frame like spacing in a sentence: "THE CAT ATE THE RAT". If you insert one letter, then it changes to "TTH ECA TAT ETH ERA T". Even though most of the letters are the same, the meaning is completely lost.

Consider the following sequence of bases in RNA:

AUG-AAU-ACG-GCU = start-asparagine-threonine-alanine

Now, assume that an insertion occurs in this sequence. Let's say an A nucleotide is added after the start codon AUG. The sequence of bases becomes:

AUG-AAA-UAC-GGC-U = start-lysine-tyrosine-glycine

Even though the rest of the sequence is unchanged, this insertion shifts the reading frame and alters all the codons that follow. As this example shows, a frameshift mutation can dramatically change how the codons in mRNA are read, often resulting in a completely different and nonfunctional protein.

Effects of Mutations

Everyone has mutations. In fact, most people have dozens (or even hundreds!) of mutations in their DNA. From an evolutionary perspective, mutations are essential. They are needed for evolution to occur because they are the ultimate source of all new genetic variation in any species.

Most mutations have neither negative nor positive effects on the organism in which they occur. These mutations are called **neutral mutations**. Examples include silent point mutations, which are neutral because they do not change the amino acids in the proteins they encode. Many other mutations do not affect the organism because they are repaired before protein synthesis occurs. Cells have multiple repair mechanisms to fix mutations in DNA.

Some mutations — known as **beneficial mutations** — have a positive effect on the organism in which they occur. They generally code for new versions of proteins that help organisms adapt to their environment. If they increase an organism's chances of surviving or reproducing, the mutations will likely become more common over time. For example, mutations allow some bacteria to survive in the presence of antibiotic drugs, leading to the evolution of antibiotic-resistant strains of bacteria. Mutations are needed for evolution because they create genetic differences, which help species adapt and change over time.

Imagine making a random change in a complicated machine, such as a car engine. There is a chance that the random change would result in a car that does not run well — or perhaps does not run at all. By the same token, a random change in a gene's DNA may result in the production of a protein that does not function normally... or may not function at all. Such mutations are likely to be harmful. **Harmful mutations** may cause genetic disorders or cancer.

Mutations and Cancer

Some types of cancer occur because of gene mutations that control the cell cycle. Cancer-causing mutations most often occur in two types of regulatory genes: proto-oncogenes and tumor-suppressor genes.

Proto-oncogenes are genes that normally help cells divide. When a proto-oncogene mutates to become an **oncogene**, it is continuously expressed, even when it is not supposed to be. This is like a car's accelerator pedal being stuck at full throttle. The car keeps racing at top speed. A cell, in this case, keeps dividing out of control, which can lead to cancer.

Tumour suppressor genes are genes that normally slow down or stop cell division. When a mutation occurs in a tumour suppressor gene, it can no longer control cell division. This is like a car without brakes. The car can't be slowed or stopped. A cell, in this case, keeps dividing out of control, which can lead to cancer.

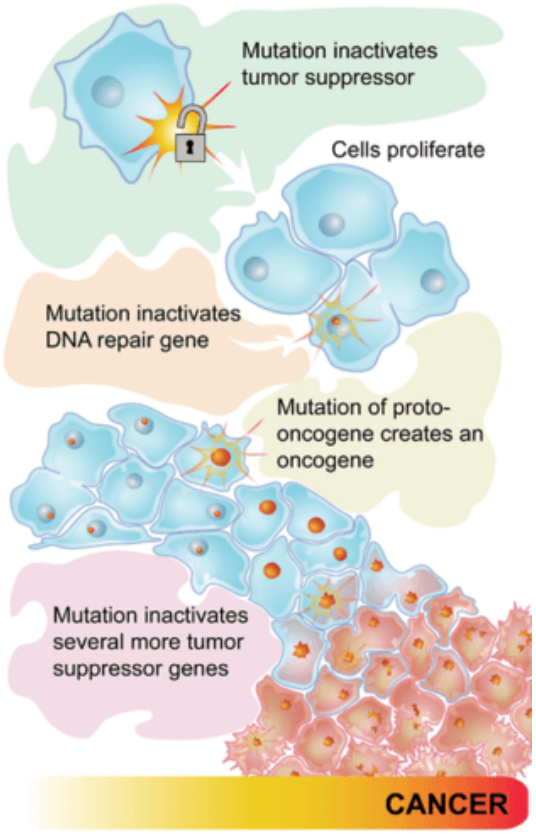

Figure 9.3.6 A series of mutations in tumour-suppressor genes and proto-oncogenes leads to cancer. Image by CK-12 Foundation, CC BY-NC 3.0

A series of mutations are often required in the development of cancer. Mutations must convert proto-oncogenes into oncogenes to trigger uncontrolled cell growth. Then tumour suppressor genes must be inactivated to allow continued growth, eventually leading to the formation of cancerous cells.

Figure 9.3.6 Description

Diagram showing the stepwise development of cancer through genetic mutations. It begins with a mutation that inactivates a tumour suppressor gene, allowing cells to proliferate. A second mutation inactivates a DNA repair gene. A third mutation converts a proto-oncogene into an oncogene, further promoting cell growth. Additional mutations inactivate more tumour suppressor genes, eventually leading to the formation of cancerous cells.

Exercise 9.3.3

Text Description

1. Mutations are always caused by exposure to toxic substances. (True/False?)

2. Some mutations can make chromosomes longer or shorter. (True/False?)

3. A mutation that substitutes one nucleotide for another is called a _____ mutation.

- Frameshift
- Chromosomal
- Inversion
- Point

Answers

1. False
2. True
3. Point

9.4 REGULATION OF GENE EXPRESSION

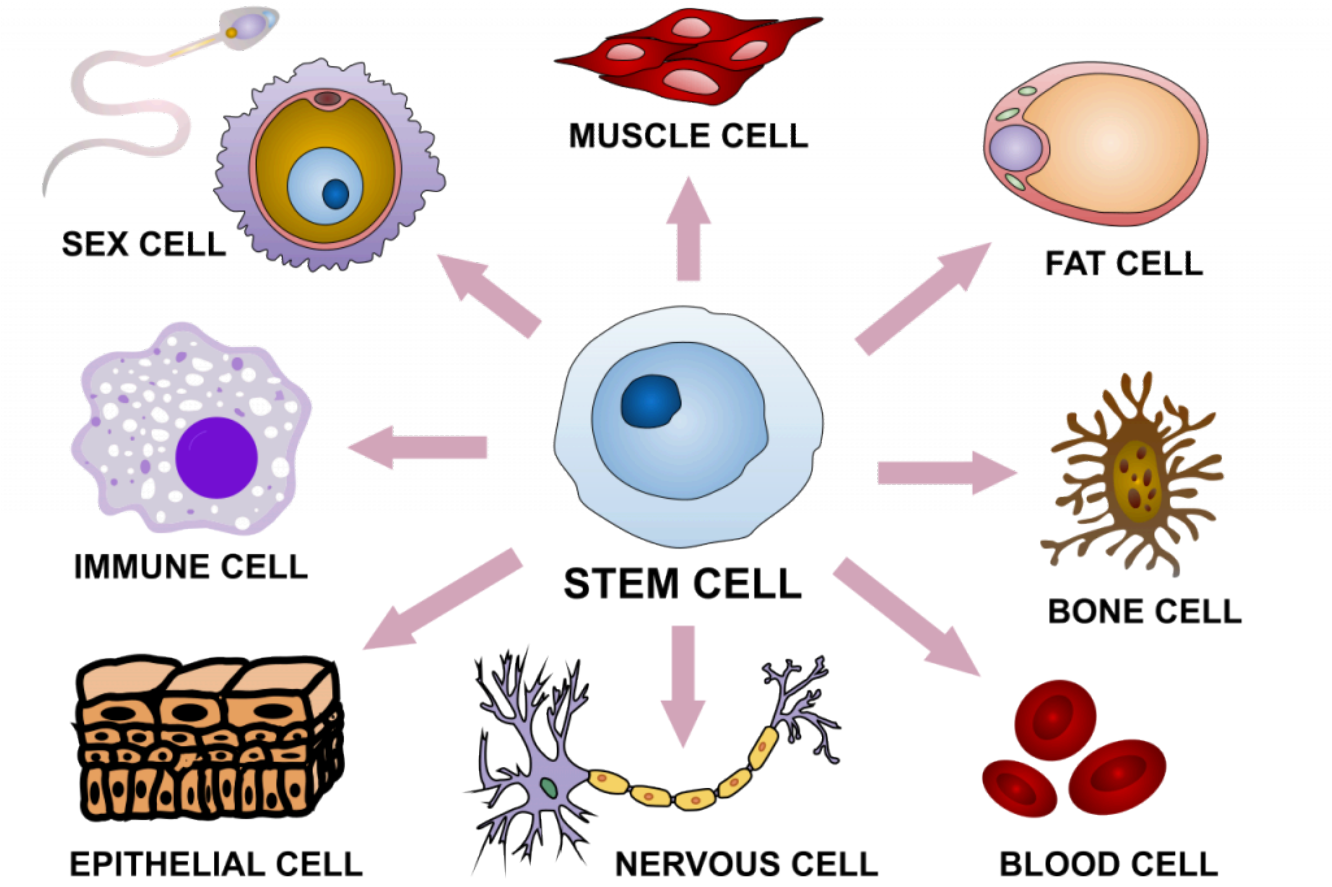

Figure 9.4.1 Differentiation pathways for a stem cell based on gene regulation. Image by Haileyfournier, CC BY-SA 4.0

Figure 9.4.1 Description

Diagram of stem cell differentiation showing a central stem cell giving rise to various specialized cell types. Arrows point outward to different cells, including sperm, egg, muscle cell, fat cell, immune cell, bone cell, epithelial cell, nerve cell, and red blood cells, illustrating the potential of stem cells to develop into diverse cell types.

This sketch illustrates some of the variability in human cells. The shape and other characteristics that make each type of cell unique depend mainly on the specific proteins that particular cell type makes. Proteins are

encoded in genes. All the cells in an organism have the same genes and genetic instructions for the same proteins. Obviously, different types of cells must use (or express) different genes to make different proteins.

Gene Expression

For a cell to function properly, necessary proteins must be synthesized at the proper time. All cells control or regulate the synthesis of proteins from information encoded in their DNA. Turning on a gene to produce RNA and protein is called **gene expression**. Whether in a simple unicellular organism or a complex multicellular organism, each cell controls when and how its genes are expressed. For this to occur, there must be a mechanism to control when a gene is expressed to make RNA and protein, how much of the protein is made, and when it is time to stop making that protein because it is no longer needed.

The regulation of gene expression conserves energy and space. It would require a significant amount of energy for an organism to express every gene at all times, so it is more energy-efficient to turn on the genes only when they are required. In addition, only expressing a subset of genes in each cell saves space because DNA must be unwound from its tightly coiled structure to transcribe and translate the DNA. Cells would have to be enormous if every protein were expressed in every cell all the time.

The control of gene expression is extremely complex. Malfunctions in this process are detrimental to the cell and can lead to the development of many diseases.

Gene Regulation

Gene regulation is how a cell controls which genes, out of the many genes in its genome, are "turned on" (expressed). Thanks to gene regulation, each cell type in your body has a different set of active genes—even though almost all the cells of your body contain the exact same DNA. These different gene expression patterns cause your various cell types to have different sets of proteins, making each cell type uniquely specialized to do its job.

For example, one of the jobs of the liver is to remove toxic substances like alcohol from the bloodstream. To do this, liver cells express genes encoding subunits (pieces) of an alcohol dehydrogenase enzyme. This enzyme breaks alcohol down into a non-toxic molecule. The neurons in a person's brain don't remove toxins from the body, so they keep these genes unexpressed or "turned off." Similarly, the liver cells don't send signals using neurotransmitters, so they turn neurotransmitter genes off. Many other genes are expressed differently between liver cells and neurons (or any two cell types in a multicellular organism like yourself).

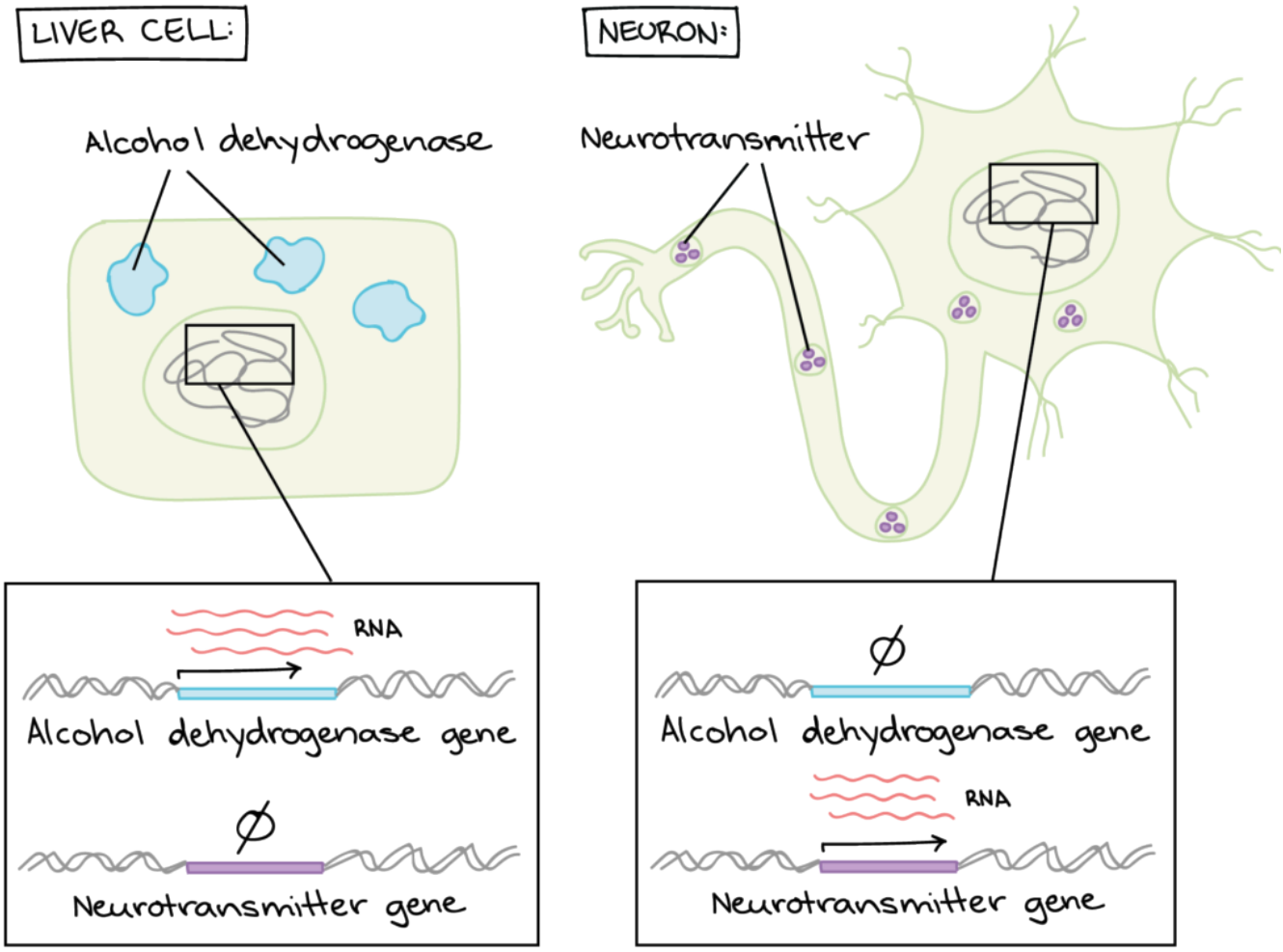

Figure 9.4.2 Different cells have different genes "turned on." Image by Lumen Learning, CC BY 4.0

Figure 9.4.2 Description

Diagram comparing gene expression in a generic cell and a neuron. Both cells contain the same DNA but express different genes. In the generic cell, a blue gene is transcribed into RNA, while a purple gene is not. In the neuron, the purple gene is transcribed into RNA, but the blue gene is not. This demonstrates that different cell types express different sets of genes despite having identical DNA.

Prokaryotic Gene Regulation

Prokaryotic organisms are single-celled organisms that lack a cell nucleus, so their DNA floats freely in the cytoplasm. Because of this, transcription and translation occur almost simultaneously when synthesizing a protein. As a result, the primary method to control what type of protein and how much of each protein is expressed in a prokaryotic cell is through the regulation of transcription.

In many cases, prokaryotic genes are "on" by default, meaning they are actively transcribed unless something represses them. This allows prokaryotes to respond quickly to environmental changes. When the protein product is no longer needed, repressors prevent further transcription. A **repressor** is a protein that binds to a specific DNA sequence and blocks transcription. When more protein is required, the repressor is removed or inactivated, allowing transcription to resume.

Eukaryotic Gene Regulation

Eukaryotic cells have intracellular organelles that add to their complexity. Their DNA is contained inside the cell's nucleus, and it is transcribed into RNA. The newly synthesized RNA is then transported from the nucleus into the cytoplasm, where ribosomes translate the RNA into protein. The nuclear membrane physically separates the processes of transcription and translation; transcription occurs only within the nucleus, and translation occurs only outside the nucleus in the cytoplasm. The regulation of gene expression can occur at all stages of the process.

Gene expression is regulated to ensure the correct proteins are made when and where needed.

Regulation may occur at any point in the expression of a gene, from the start of the transcription phase of protein synthesis to the processing of a protein after synthesis occurs.

Epigenetic Regulation

Epigenetic markers are chemical tags that attach to DNA or histone proteins to make certain genes more accessible. Think of sticky notes in a cookbook to flag your favourite recipes to make that information easier to find and read. Similarly, epigenetic markers flag certain genes, making them easier to access for transcription.

Transcriptional Regulation

Transcription is controlled by regulatory proteins which bind to DNA regions near promoters. **Activators** are regulatory proteins that promote transcription by enhancing the interaction of RNA polymerase with the promoter. They help initiate gene expression when a specific protein is needed. **Repressors** are regulatory proteins that inhibit transcription by blocking or interfering with RNA polymerase's ability to move along the DNA strand. This prevents the gene from being transcribed into mRNA.

In eukaryotic cells, most genes are "off" by default and require activators and other signals to be turned on. This tight regulation ensures that proteins are produced only when and where they are needed, which is especially important in multicellular organisms with specialized cells.

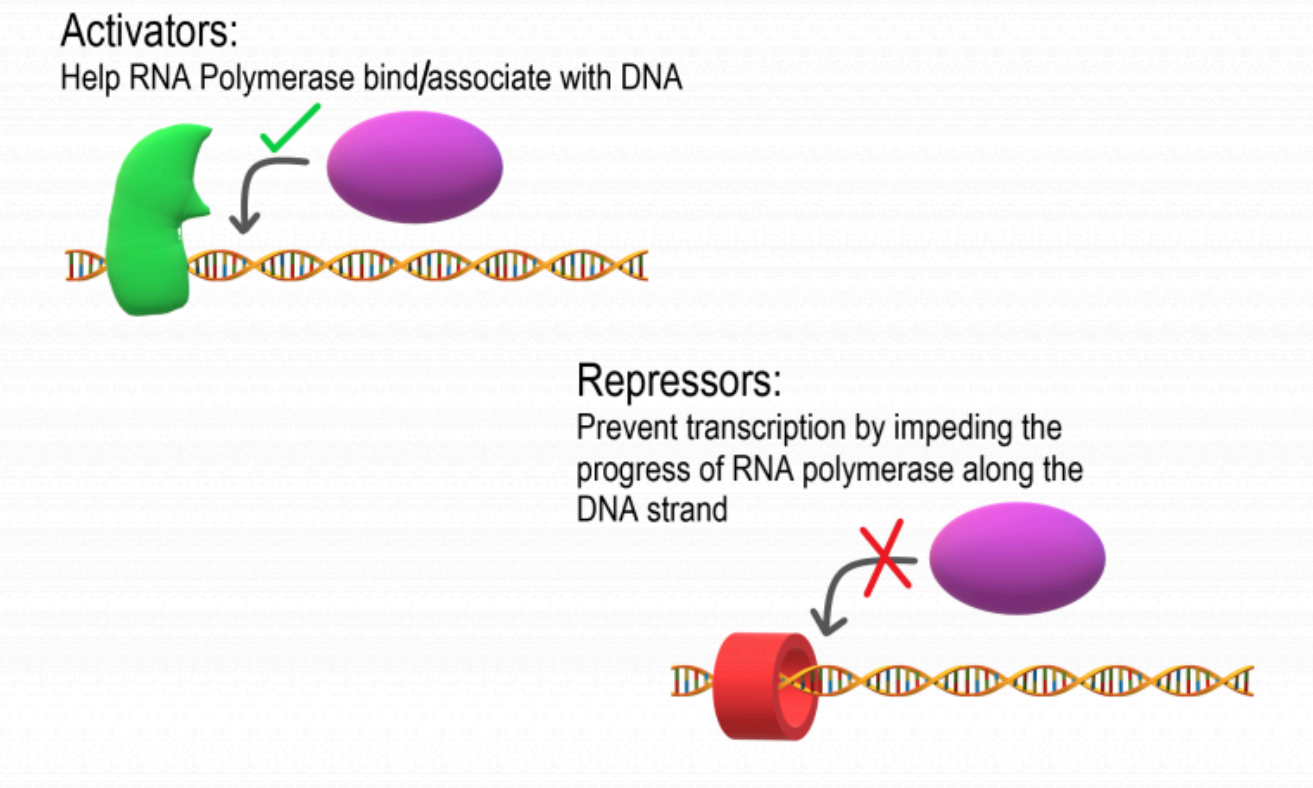

Figure 9.4.3 Regulation of Transcription. Regulatory proteins bind to their corresponding regulatory elements in order to control transcription. Image by Christine Miller, CC BY-SA 4.0

Figure 9.4.3 Description

Diagram explaining the roles of activators and repressors in gene regulation. The top section shows an activator protein helping RNA polymerase bind to DNA, allowing transcription to proceed. The bottom section shows a repressor protein blocking RNA polymerase from moving along the DNA, preventing transcription.

Post-Transcriptional Regulation

After transcription, mRNA is processed, and the introns are removed by splicing. **Alternative RNA splicing** is a mechanism that allows different protein products to be produced from one gene when different combinations of introns (and sometimes exons) are removed from the transcript.

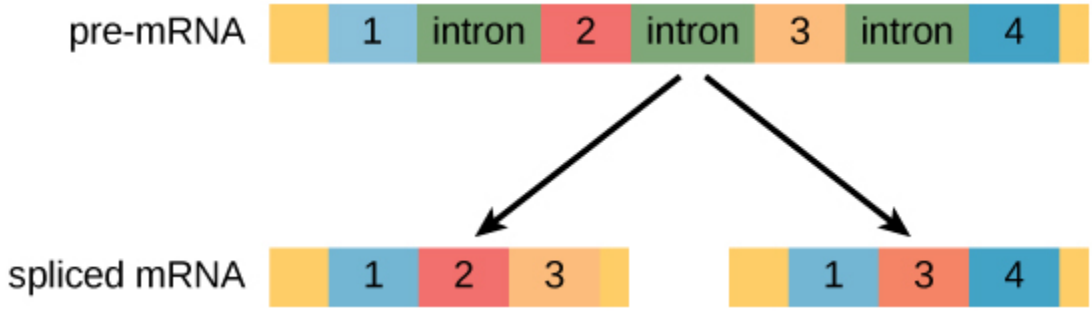

Figure 9.4.4 Pre-mRNA can be alternatively spliced to create different proteins. Image by Lumen Learning, CC BY 4.0

Figure 9.4.4 Description

Diagram showing alternative splicing of pre-mRNA. The pre-mRNA contains exons labelled 1 to 4 and introns in between. Two different spliced mRNA variants are produced: one includes exons 1, 2, and 3; the other includes exons 1, 3, and 4, demonstrating how a single gene can produce different mRNA transcripts.

Translational Regulation

Once RNA is in the cytoplasm, its lifespan can be controlled. Each RNA molecule decays at a specific rate. This decay rate, known as RNA stability, determines how long RNA remains active in the cytoplasm. If the RNA is stable, it will be available for longer periods of time, allowing more protein to be made. Faster decay means less time for translation, resulting in less protein production.

Post-Translational Regulation

After a protein is synthesized, it may undergo folding or chemical modifications to activate the protein. Controlling these modifications can deactivate proteins. Proteins that are no longer needed or are damaged can be tagged for degradation.

Exercise 9.4.1

Text Description

1. At what level(s) does the control of gene expression occur in eukaryotic cells?

- only the transcriptional level
- epigenetic and transcriptional levels
- epigenetic, transcriptional, and translational levels
- epigenetic, transcriptional, post-transcriptional, translational, and post-translational levels

2. What does post-translational control refer to?

- the regulation of gene expression after transcription
- the regulation of gene expression after translation
- the control of epigenetic activation
- the period between transcription and translation

3. The cell controls which protein is expressed, and to what level that protein is expressed, in the cell. ____ cells alter the transcription rate to turn genes on or off. This method will ____ or ____ protein levels in response to what is needed by the cell. ____ cells change the accessibility (epigenetic), transcription, or translation of a gene. This will alter the ____ and ____ of RNA, to alter how much protein exists. These cells also change the protein's ____ to increase or decrease its overall levels. ____ organisms are much more complex than ____ organisms and can manipulate protein levels by changing many ____ in the process.

Answers

1. epigenetic, transcriptional, post-transcriptional, translational, and post-translational levels

2. The regulation of gene expression after translation
3. The cell controls which protein is expressed, and to what level that protein is expressed, in the cell. ***Prokaryotic*** cells alter the transcription rate to turn genes on or off. This method will ***increase*** or ***decrease*** protein levels in response to what is needed by the cell. ***Eukaryotic*** cells change the accessibility (epigenetic), transcription, or translation of a gene. This will alter the ***amount*** and ***lifespan*** of RNA, to alter how much protein exists. These cells also change the protein's ***translation*** to increase or decrease its overall levels. ***Eukaryotic*** organisms are much more complex than ***Prokaryotic*** organisms and can manipulate protein levels by changing many ***stages*** in the process.

CHAPTER 9 SUMMARY

Key Takeaways

- **Hereditary Information:** DNA is the genetic material responsible for storing and transmitting hereditary information in all living organisms. The structure of DNA is a double helix, composed of two strands of nucleotides twisted around each other, discovered by Watson and Crick with key contributions from Rosalind Franklin and Maurice Wilkins.
- **Nucleotides are the building blocks of DNA:** They consist of three parts: a deoxyribose sugar, a phosphate group, and a nitrogenous base (A, T, G, or C).
- **DNA Structure:** The two strands of DNA are antiparallel, meaning they run in opposite directions (5' to 3' and 3' to 5'). DNA strands have a sugar-phosphate backbone and are connected by complementary base pairs:
    - Adenine (A) pairs with Thymine (T)
    - Guanine (G) pairs with Cytosine (C)
- **DNA Replication:** DNA replication is essential for growth, repair, and reproduction, ensuring the faithful transmission of genetic material. Replication of DNA is semi-conservative, meaning each new DNA molecule consists of one original strand and one newly synthesized strand.
- **Replication Process:** Replication occurs during the S phase of the cell cycle, ensuring that each daughter cell receives an identical copy of DNA and begins at specific sites called origins of replication, forming replication bubbles as DNA unwinds. The enzyme DNA polymerase adds complementary nucleotides to the exposed bases of the template strand and forms covalent bonds to build the new DNA strand.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into key takeaways.

Flash Cards

Text Description

1. **Nucleotide:** Building block of nucleic acids that consists of a sugar, a phosphate group, and a nitrogenous base
2. **Double helix:** Spiral structure formed by two strands of DNA twisted around each other
3. **Complementary base pairs:** Pairs of nitrogenous bases in DNA or RNA that form hydrogen bonds with each other – A with T (or U in RNA) and C with G
4. **DNA replication:** Process by which DNA is copied – occurs during S phase
5. **Semi-conservative:** Each of the two new DNA molecules consists of one original (parental) strand and one newly synthesized strand
6. **DNA polymerase:** Enzymes that build new DNA strands by adding nucleotides during DNA replication
7. **Origin of replication:** Specific sequence in DNA where replication begins
8. **Central dogma:** The flow of genetic information in cells (DNA → RNA → Protein)
9. **mRNA:** Messenger RNA carries genetic instructions from DNA in the nucleus to the ribosomes in the cytoplasm
10. **rRNA:** Ribosomal RNA is a component of ribosomes responsible for protein synthesis
11. **tRNA:** Transfer RNA carries amino acids to ribosome and matches amino acids with the appropriate codons on the mRNA during translation
12. **Transcription:** Copying a DNA sequence into messenger RNA (mRNA)
13. **RNA polymerase:** Enzyme that synthesizes RNA from a DNA template during transcription
14. **Promoter:** A DNA sequence where RNA polymerase binds to begin transcription
15. **Terminator:** A DNA sequence that signals the end of transcription
16. **Splicing:** The process of removing introns from RNA and connecting exons
17. **Exons:** Coding sequences in RNA that are kept and expressed as protein
18. **Introns:** Non-coding sequences in RNA that are removed during splicing
19. **Capping:** The addition of cap to the “head” of mRNA for stability and recognition by ribosomes
20. **Polyadenylation:** The addition of a poly-A-tail to mRNA
21. **Poly-A Tail:** A string of adenine nucleotides added to the tail of mRNA to protect it from

breakdown

22. **Translation:** The process by which a ribosome reads mRNA and assembles a protein using amino acids
23. **Genetic code:** The set of rules by which the sequence of bases in mRNA is translated into amino acids
24. **Codons:** Groups of three mRNA bases that specify a particular amino acid
25. **Start codon:** The codon (AUG) signals the start of translation and codes for methionine
26. **Initiation complex:** When mRNA, ribosome & tRNA come together to start protein synthesis
27. **Stop codon:** Codons that signal the end of translation
28. **Mutations:** Random changes in the sequence of bases in DNA or RNA
29. **Mutagens:** Agent that causes genetic mutations
30. **Chromosomal alterations:** Large-scale changes in chromosome structure, such as deletions, duplications, or rearrangements
31. **Point mutation:** A change in a single nucleotide in DNA
32. **Silent mutation:** Mutated codon codes for the same amino acid
33. **Missense mutation:** Mutated codon codes for a different amino acid
34. **Nonsense mutation:** Mutated codon is a premature stop codon
35. **Frameshift mutation:** Deletion or insertion of one or more nucleotides, changing the reading frame of the base sequence
36. **Neutral mutations:** Mutations with no resulting effect on the organism
37. **Beneficial mutations:** Increase an organism's chances of survival or reproduction (code for new versions of proteins)
38. **Proto-oncogene:** Normal gene that helps cells divide, that can become an oncogene if it is mutated
39. **Oncogene:** Mutated gene that can cause normal cells to become cancerous by promoting uncontrolled cell growth
40. **Tumour suppressor genes:** Genes that slow down or stop cell division
41. **Harmful mutations:** Negatively affect an organism's chances of survival or reproduction and can cause genetic disorders or cancer
42. **Gene expression:** The process by which information from a gene is used to make RNA and proteins
43. **Gene regulation:** Process by which cells control the expression and timing of genes to produce the right proteins at the right time; controls which genes are "turned on."
44. **Epigenetic markers:** Chemical tags that attach to DNA or histone proteins and regulate

gene activity without changing the DNA sequence

45. **Activators:** Regulatory proteins that promote transcription by enhancing the interaction of RNA polymerase with the promoter
46. **Repressors:** Regulatory proteins that attach to the DNA and prevent transcription by blocking RNA polymerase
47. **Alternative RNA splicing:** A process that allows a single gene to produce multiple protein variants by including or excluding different exons
48. **Components of DNA nucleotide:** Deoxyribose, a phosphate group, and a nitrogenous base
49. **Nitrogenous bases in DNA:** Adenine, guanine, cytosine, and thymine
50. **A pairs with:** T
51. **C pairs with:** G
52. **What forms the backbone of DNA strands?** Sugar-phosphate groups of the connected nucleotides
53. **Enzyme that links nucleotides together in DNA replication?** DNA polymerase
54. **How do the instructions in DNA get to the ribosomes outside the nucleus?** Transcription makes a copy of the genetic instructions in the form of mRNA, which can pass through pores in the nuclear membrane to the ribosomes in the cytoplasm.
55. **How does RNA differ from DNA?** It is single-stranded, contains the sugar ribose (as opposed to deoxyribose) and uses uracil instead of thymine
56. **Three steps in transcription:** Initiation, elongation, and termination
57. **What happens in Initiation of Transcription?** RNA polymerase binds to the promoter to begin transcription
58. **What happens in Elongation of Transcription?** RNA polymerase moves along the template strand of DNA, unwinds the double helix, synthesizes mRNA, and then rewinds the DNA
59. **What happens in Termination of Transcription?** RNA polymerase reaches the terminator and detaches from the DNA template
60. **How is mRNA processed?** Splicing, capping, and polyadenylation
61. **Three steps in translation:** Initiation, elongation, and termination
62. **What happens in Initiation of Translation?** Ribosome binds to mRNA; tRNA with the anticodon that matches the start codon brings in the first amino acid (methionine)
63. **What happens in Elongation of Translation?** Amino acids are sequentially added to the growing polypeptide chain as tRNAs bring them to the ribosome and match them with the corresponding codons on the mRNA.

64. **What happens in Termination of Translation?** Ribosome reaches a stop codon on the mRNA which codes for a release factor. This triggers the end of protein synthesis, so the mRNA, ribosome, tRNA, and newly synthesized polypeptide chain are released
65. **Three main types of mutations?** Chromosomal alterations, point mutations, and frameshift mutations
66. **Three types of point mutations?** Silent, missense, and nonsense
67. **Are mutations good or bad?** Both. Some mutations are harmful and lead to genetic disorders or cancer. Some mutations are beneficial and produce new version of proteins which help species adapt and change over time. Some mutations are neutral and do not affect the organism.
68. **How do mutations lead to cancer?** A series of mutations convert proto-oncogenes into oncogenes to trigger uncontrolled cell growth. Additional mutations inactivate tumour suppressor genes to allow continued growth, which eventually leads to cancer.
69. **How can we have different types of cells in our body, even though they all contain the exact same DNA?** We have different cell types because gene regulation controls which genes are turned on or off, leading to differential gene expression. This selective expression allows cells with the same DNA to perform unique functions.
70. **How are genes regulated in eukaryotes?** Epigenetic regulation, transcriptional regulation, post-transcriptional regulation, translational regulation, and post-translational regulation

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Prompt: Can you give me brief summaries of these key terms?

CHAPTER 10: BIOTECHNOLOGY

Chapter Overview

Learning Objectives

By the end of this chapter, you will be able to:

- Define biotechnology and genetic engineering, and describe their development from traditional practices to modern molecular techniques.
- Explain recombinant DNA technology, including the roles of vectors, restriction enzymes, and gene cloning in producing genetically modified organisms (GMOS).
- Describe how CRISPR-Cas9 gene editing works and how it differs from traditional recombinant DNA methods in precision and application.
- Identify key applications of genetic engineering in medicine (e.g., insulin production, gene therapy), agriculture (e.g., transgenic crops), and the environment (e.g., bioremediation).
- Distinguish between embryonic, adult, and induced pluripotent stem cells (iPSCs) and discuss their roles in regenerative medicine, drug testing, and disease modelling.
- Describe reproductive cloning and evaluate its uses in conservation, agriculture, research, and potential de-extinction efforts.

- Evaluate the ethical, legal, and social implications of biotechnology, including genetic privacy, gene editing, and designer babies.
- Explain how gene therapy and CRISPR technologies are applied to treat genetic diseases, cancers, and viral infections.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me the learning objectives from this chapter's content?

10.1 GENETIC ENGINEERING

Biotechnology uses artificial methods to modify the genetic material of living organisms or cells to produce novel compounds or perform new functions. Its roots can be traced back to ancient practices like fermentation for brewing and bread-making. It has also been used to improve livestock and crops since the beginning of agriculture through selective breeding. Modern biotechnology began to take shape in the 20th century with the discovery of DNA's structure and the development of the basic tools used to manipulate DNA. This era saw the emergence of many different branches of biotechnology, including genetic engineering, stem cell research, and reproductive cloning.

Genetic engineering involves directly altering an organism's DNA at the molecular level to achieve desired traits or outcomes. It plays a crucial role in medicine, agriculture, environmental science, and industry, offering solutions to the world's most pressing challenges. By harnessing the power of living organisms, genetic engineering has the potential to improve health outcomes, enhance food security, and promote sustainable practices. The rate of discovery and development of new applications is expected to accelerate, bringing huge benefits to humankind but perhaps also significant risks. Many of these developments are expected to raise significant ethical and social questions that human societies have not yet had to consider.

Genetic engineering encompasses various techniques to manipulate an organism's genetic material, including recombinant DNA technology and gene editing.

Isolation of Nucleic Acids

In order to manipulate the DNA, it first has to be removed, or **extracted**, from cells. This usually involves breaking the cell open and using enzymes to eliminate other large molecules. A detergent solution helps break the cells apart. Enzymes are used to stop proteins and RNA from interfering. Finally, alcohol is added to make the DNA come out of the solution, forming a jelly-like substance.

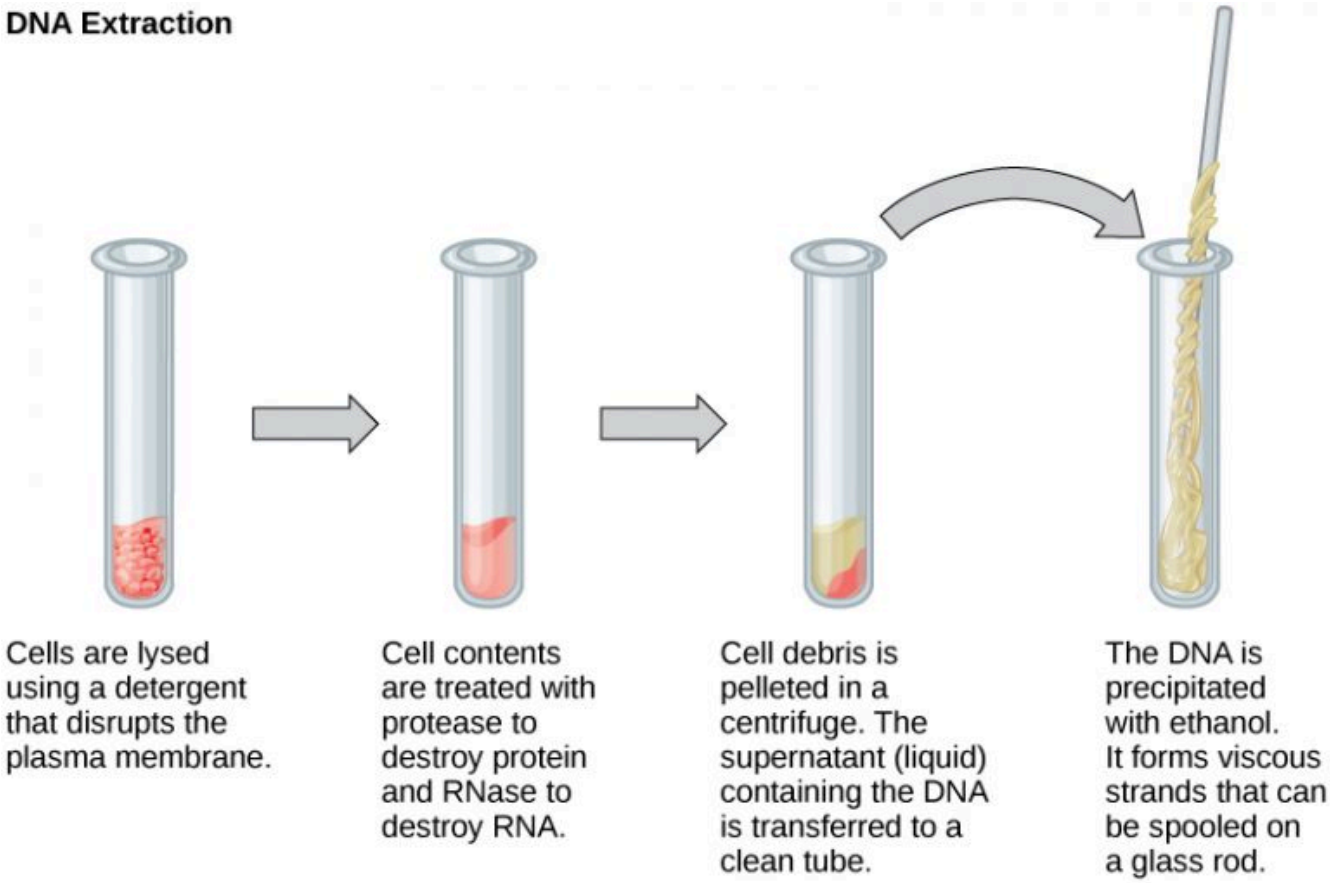

Figure 10.1.1 This diagram shows the basic method used to extract DNA. Image by OpenStax, CC BY 4.0

Figure 10.1.1 Image Description

This image illustrates the DNA extraction process in four key steps, using labelled diagrams of test tubes:

Cell Lysis: Cells are broken open using a detergent that disrupts the plasma membrane, releasing cellular contents into the solution.

Digestion of Proteins and RNA: The lysate is treated with protease to degrade proteins and RNase to break down RNA, leaving DNA intact.

Separation by Centrifugation: The mixture is centrifuged to pellet (collect) the debris at the bottom. The supernatant, which contains the DNA, is transferred to a new clean tube.

DNA Precipitation: Ethanol is added to the supernatant to precipitate the DNA. The DNA becomes visible as viscous strands that can be spooled on a glass rod.

Recombinant DNA technology

Recombinant DNA technology combines DNA from different sources to create new genetic combinations. A **vector**, a delivery vehicle for DNA, is used to help transport a specific DNA fragment into a cell for copying or expression. Bacterial cells are often used in this process, and the bacterial plasmid acts as the vector. A **plasmid** is a small circular DNA molecule found in bacteria that replicates independently of the larger bacterial chromosome. As bacteria divide, they copy their DNA, including the plasmid, which means the inserted DNA fragment is also copied. This process of making multiple identical copies of a specific gene is called **gene cloning** (or molecular cloning).

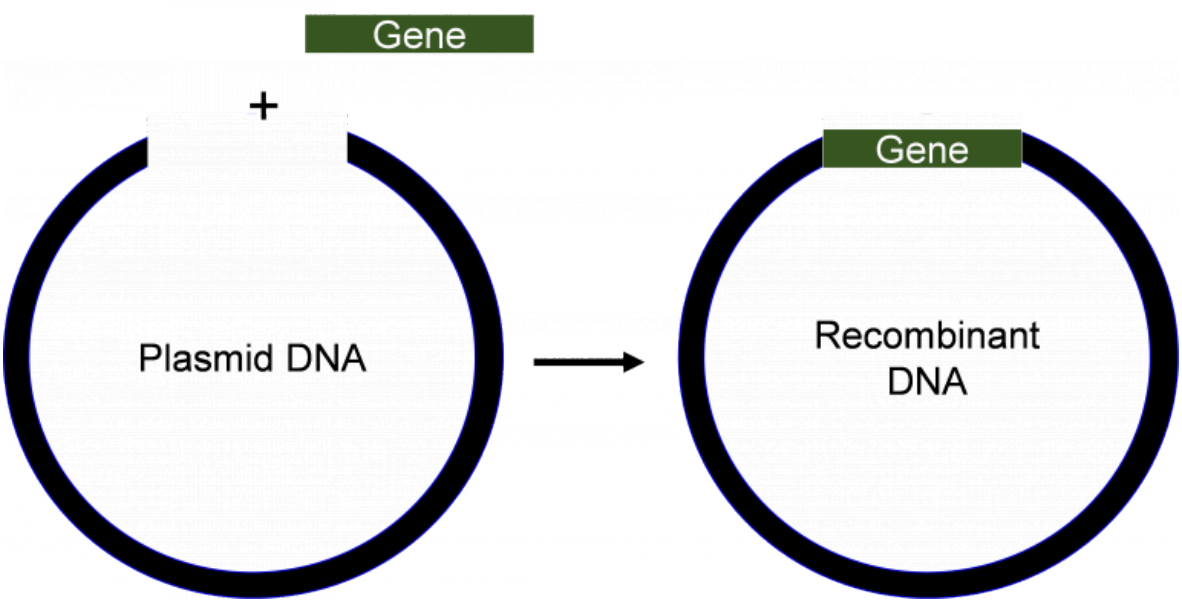

Figure 10.1.2 Recombinant DNA is made by combining DNA from different sources. Image by Walter Suza. CC BY-NC-SA 4.0

Gene cloning begins with the use of **restriction enzymes**, which act as molecular scissors to cut DNA at specific sequences. These enzymes recognize specific DNA sequences and cut them predictably, creating "sticky ends" that can bond with complementary overhangs on DNA cut with the same enzyme.

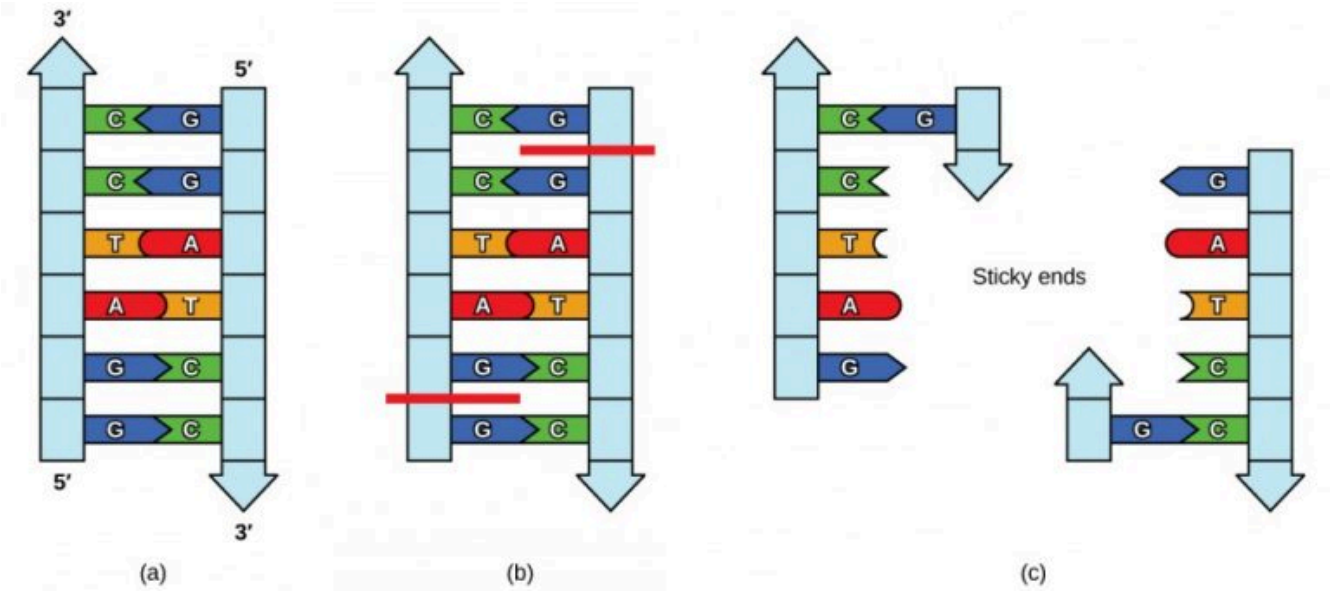

Figure 10.1.3 (a) Six-nucleotide restriction enzyme recognition site, notice that the sequence of six nucleotides reads the same in the 5' to 3' direction on one strand as it does in the 5' to 3' direction on the complementary strand. This is known as a palindrome. (b) The restriction enzyme breaks the DNA strands, and (c) The cut in the DNA results in "sticky ends." Another piece of DNA cut on either end by the same restriction enzyme could attach to these sticky ends and be inserted into the gap made by this cut. Image by OpenStax, CC BY 4.0

The sticky ends allow the isolated gene to be inserted into the plasmid. **DNA ligase** joins them together, forming recombinant plasmids. The recombinant plasmid is added to a host cell and typically then cultured to produce large quantities of the desired gene.

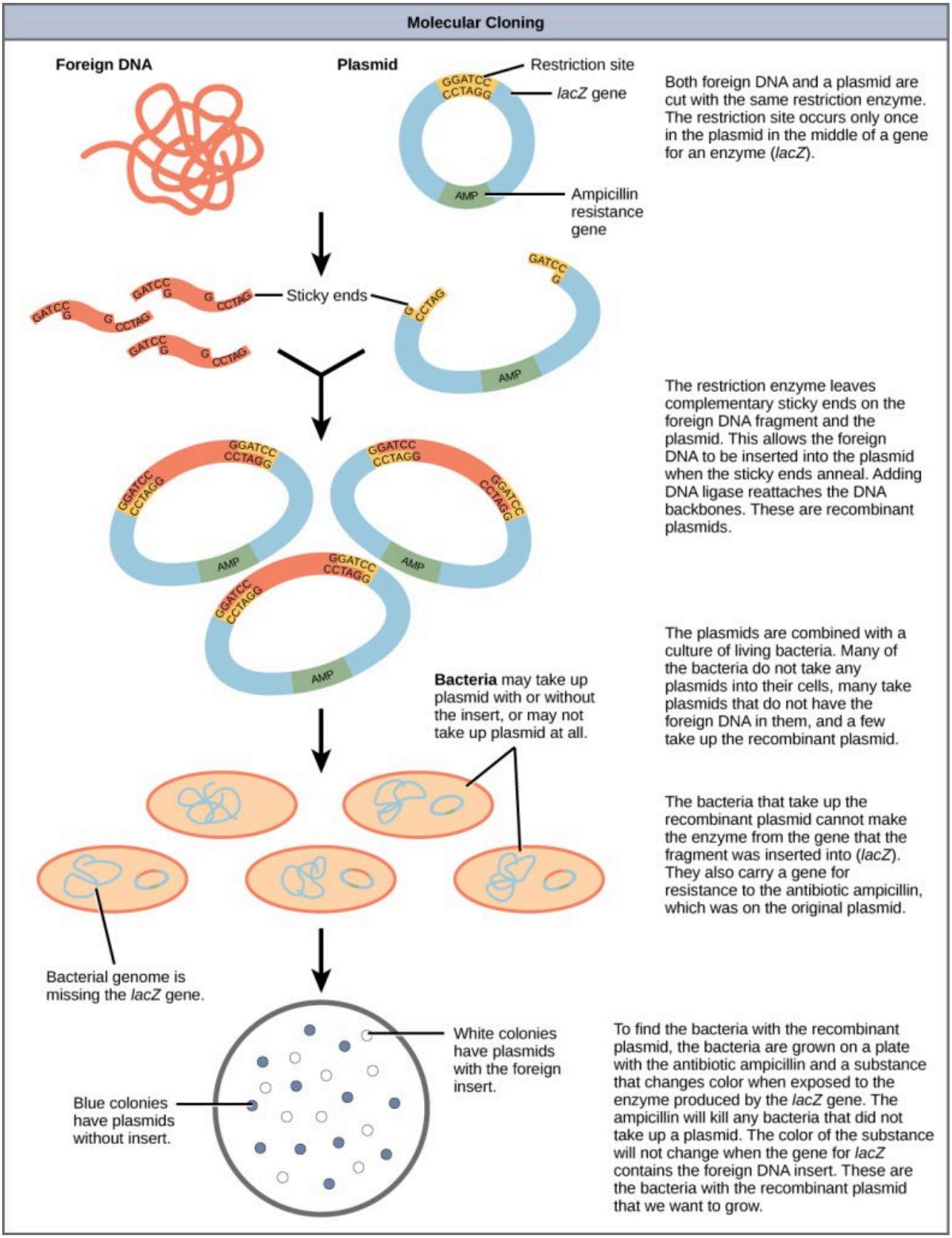

Figure 10.1.4 This diagram shows the steps involved in molecular cloning. Image by OpenStax, CC BY 4.0

Figure 10.1.4 Image Description

This image illustrates the molecular cloning process using plasmids and bacterial transformation. It breaks the procedure into multiple stages, from cutting DNA to identifying transformed bacteria:
1. DNA Cutting and Preparation:

- Foreign DNA and a plasmid are cut using the same restriction enzyme at a specific restriction site (within the lacZ gene).
- The plasmid also contains an ampicillin resistance gene (Amp).
- Cutting both DNA sources creates complementary sticky ends.

2. DNA Insertion

- The foreign DNA is inserted into the plasmid via sticky end pairing.
- DNA ligase is used to seal the DNA backbones.
- The resulting recombinant plasmids now contain the foreign DNA.

3. Transformation

- These plasmids are introduced to a bacterial culture.
- Bacteria may:
  - Take up plasmids with foreign DNA (recombinant plasmids),
  - Take up plasmids without the insert,
  - Or not take up any plasmid.

4. Bacterial Selection

- Bacteria are plated on media containing ampicillin and a substance that detects activity of the lacZ gene.
- Only bacteria with plasmids (containing ampicillin resistance) survive.

5. Screening Colonies

- Blue colonies: Bacteria with plasmids without the foreign DNA insert (lacZ is intact and active).
- White colonies: Bacteria with recombinant plasmids (lacZ is disrupted by foreign DNA).
- These white colonies are the ones that successfully incorporated the foreign gene of interest and are typically selected for further study or application.

Applications of Recombinant DNA Technology

Recombinant DNA technology has many different applications. Some examples include:

Insulin Production

Human genes can be inserted into bacteria so they are able to make human proteins. Proteins the bacteria make are injected into people who cannot produce them because of mutations.
Insulin was the first human protein to be produced in this way. **Insulin** helps cells take up glucose from the blood. People with type 1 diabetes have a mutation in the gene that usually codes for insulin.

Without insulin, their blood glucose rises to harmfully high levels. At present, the only treatment for type 1 diabetes is the injection of insulin from outside sources. Until recently, there was no known way to make human insulin outside the human body. The problem was solved using recombinant DNA technology. The human insulin gene was cloned and used to transform bacterial cells, which could then produce large quantities of human insulin. Other human proteins, such as Human Growth Hormone and cytokines, have been produced this way.

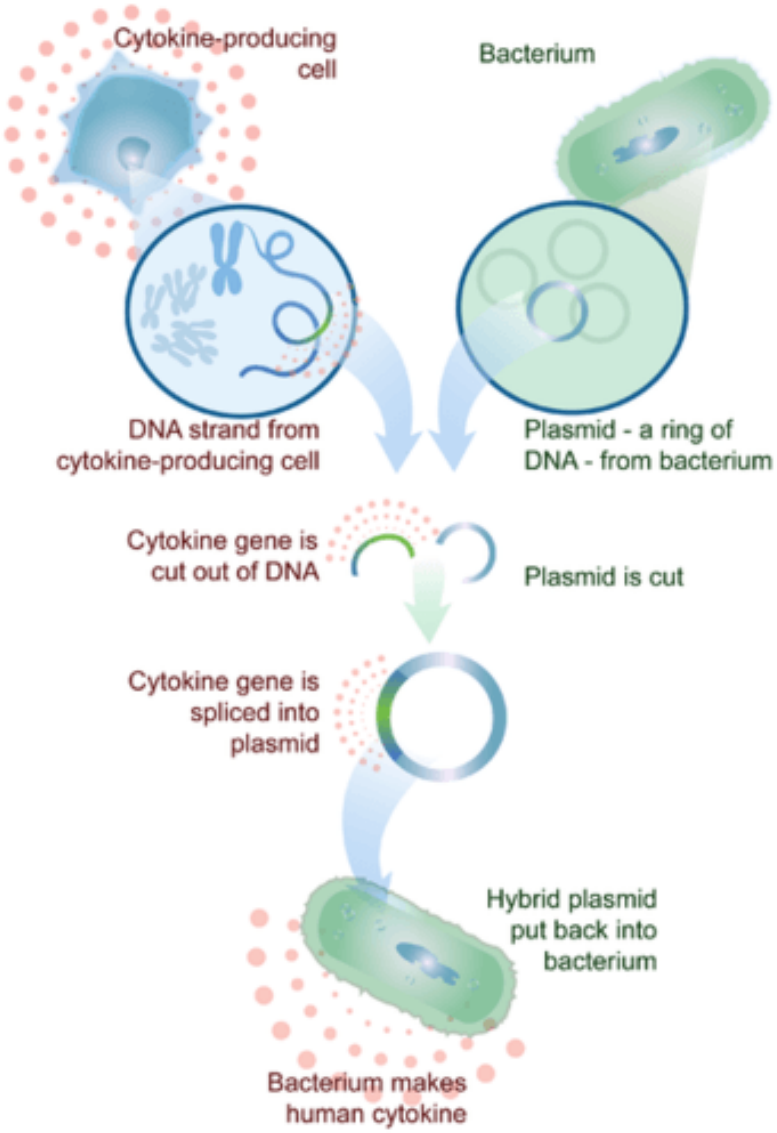

Figure 10.1.5 Bacteria can be genetically engineered to produce a human protein, such as a cytokine (small protein that helps fight infections). Image by CK-12 Foundation, CC BY-NC 3.0

Figure 10.1.5 Image Description

This image illustrates the recombinant DNA process used to produce human cytokines using bacteria:
Step-by-Step Description:

1. Cytokine-Producing Cell:
   A human or animal cell that naturally produces cytokines is selected. Its DNA is extracted.

2. Gene Isolation:
   The specific cytokine gene is cut out of the DNA using restriction enzymes.
3. Plasmid from Bacterium:
   A plasmid, which is a small circular piece of DNA from a bacterium, is also cut open.
4. Recombination:
   The cytokine gene is inserted (spliced) into the plasmid, forming a hybrid (recombinant) plasmid.
5. Transformation:
   The recombinant plasmid is inserted back into a bacterium.
6. Protein Production:
   The bacterium now uses the inserted gene to produce human cytokine, which can be harvested for medical use.

This image shows how genetic engineering allows for the mass production of human proteins (like cytokines) in microorganisms—a process commonly used in biotechnology and pharmaceutical industries.

Transgenic Animals

Although several recombinant proteins used in medicine are successfully produced in bacteria, some proteins need a eukaryotic animal host for proper processing. For this reason, genes have been cloned and expressed in animals such as sheep, goats, chickens, and mice. Animals that have been modified to express recombinant DNA are called **transgenic animals**.

Several human proteins are expressed in the milk of transgenic sheep and goats. In one commercial example, the FDA has approved a blood anticoagulant protein that is produced in the milk of transgenic goats for use in humans. Mice have been used extensively to express and study the effects of recombinant genes and mutations.

Figure 10.1.6 shows that two of these mice are transgenic because they have a gene that causes them to fluoresce under UV light. The non-transgenic mouse does not have the gene that causes fluorescence. Image by Ingrid Moen et al., CC BY 4.0

The first transgenic animal was approved for food in Canada in 2016. The AquAdvantage salmon

incorporates a growth hormone gene from Chinook salmon into the genome of Atlantic salmon. This results in a salmon which grows faster and reaches market size quicker.

Transgenic Crops

Transgenic crops, also known as **genetically modified organisms (GMOs)**, are modified with new genes that code for traits helpful to humans.

Transgenic crops have been created with a variety of different traits. They can yield more food, taste better, survive drought, tolerate salty soil, and resist insect pests and diseases, among other things. There are hundreds of GM crops approved in Canada. One example is Bt corn, which is a type of GMO that has been engineered to produce protein from the bacterium Bacillus thuringiensis (Bt). This protein is toxic to certain insect pests, particularly caterpillars like the European corn borer. Bt corn helps farmers reduce the need for chemical insecticides. Scientists have even created a transgenic purple tomato that contains high levels of cancer-fighting compounds called antioxidants.

Figure 10.1.7 A purple tomato is genetically modified to contain high levels of antioxidants. A gene for the compound was transferred into normal red tomatoes. Image by F Delventhal, CC BY 2.0

Production of Vaccines

A **vaccine** is a substance that stimulates the immune system to recognize and fight specific pathogens, providing protection against disease.

Traditional vaccines use weakened or inactive microorganisms or viruses to trigger an immune response. Modern vaccines use specific genes from pathogens, which are cloned and mass-produced in bacteria to create large quantities of specific proteins that stimulate the immune system. These proteins are then used as the vaccine.

Traditionally, flu vaccines (aka flu shots) were made by growing the virus in chicken eggs, which was a time-consuming and labour-intensive process. With recombinant DNA technology, flu vaccines can be produced faster and quickly adapted to respond to emerging flu strains.

Gene Therapy

Gene therapy is a recombinant DNA technique that aims to cure certain genetic diseases by introducing a healthy gene into the genome. This process involves replacing a faulty or missing protein caused by a genetic mutation. The healthy gene is typically delivered into diseased cells using a vector, such as a virus (e.g., adenovirus), which can infect the host cell and integrate the foreign DNA into the genome.

While gene therapy has primarily been experimental, several treatments have recently been approved in Canada. For example, Hemgenix is a hemophilia treatment that delivers a functional copy of the gene responsible for producing Factor IX, a protein essential for blood clotting. As technology advances and challenges are addressed, gene therapy holds promise for curing more genetic diseases in the future.

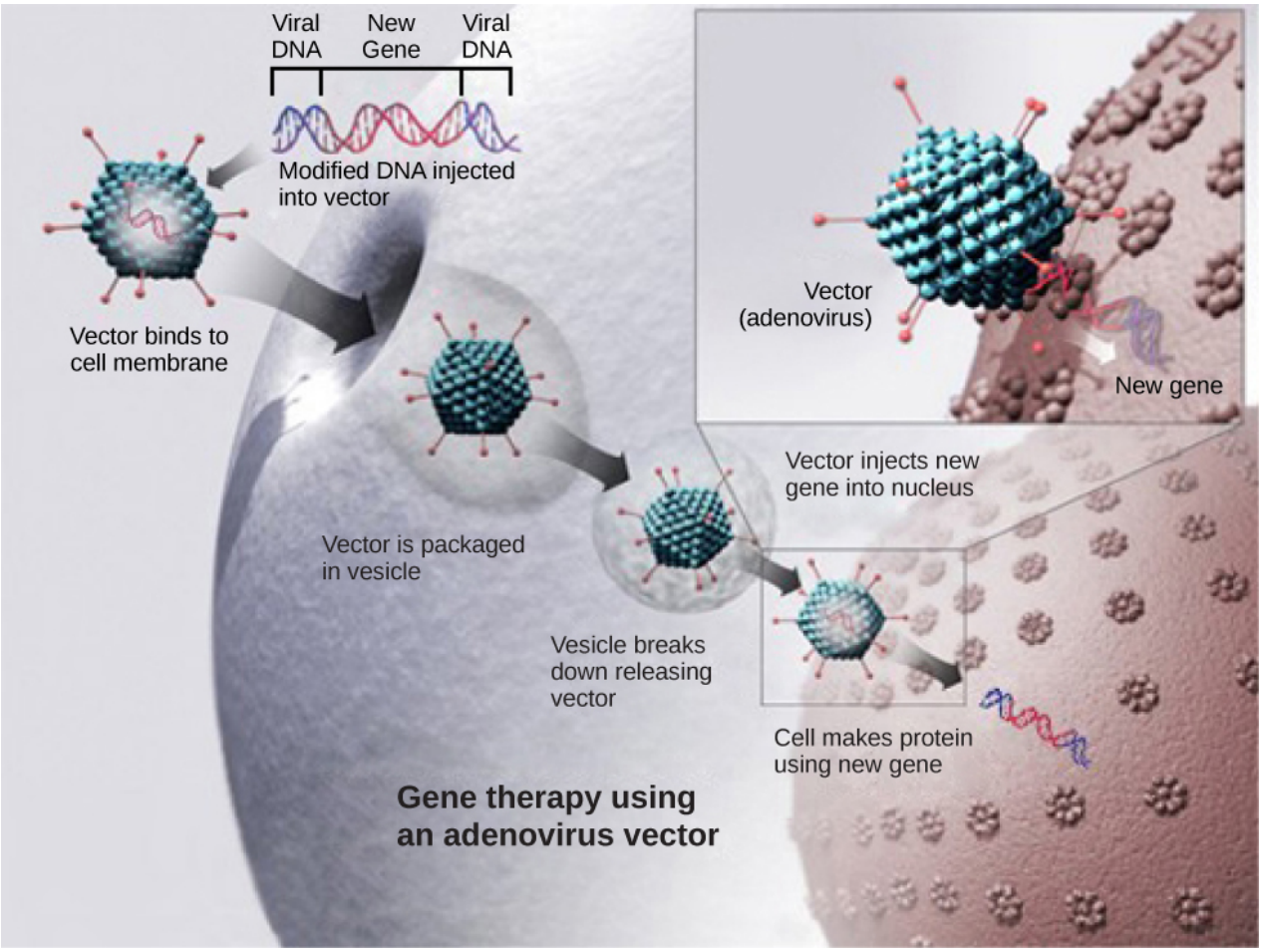

Figure 10.1.8 This diagram shows the steps involved in curing disease with gene therapy using an adenovirus vector. Image modification of work by NIH, CC BY 4.0

Figure 10.1.8 Image Description

This image illustrates the process of gene therapy using an adenovirus vector, which is a common method for delivering therapeutic genes into human cells.

Step-by-Step Description:

1. Modified DNA Injected into Vector
   A therapeutic gene (new gene) is inserted into the DNA of an adenovirus. The modified viral DNA now carries both viral DNA and the new gene.
2. Vector Binds to Cell Membrane
   The engineered adenovirus (vector) comes into contact with a human cell and binds to its

membrane.

3. Vector is Packaged in a Vesicle
   The virus is taken into the cell by endocytosis, forming a vesicle around it.
4. Vesicle Breaks Down
   Inside the cell, the vesicle breaks open, releasing the vector into the cytoplasm.
5. Vector Injects New Gene into Nucleus
   The virus travels to the nucleus and delivers the new gene into the cell's genome or as an episome (non-integrated DNA).
6. Protein Production
   The cell uses the new gene to produce the corresponding protein, which may help treat a genetic disorder or disease.

Purpose:

Gene therapy using adenovirus vectors is designed to correct or replace faulty genes by delivering functional copies directly into a patient's cells.

Gene Editing

Gene editing is another technique used in genetic engineering. **Gene editing** allows for precise changes to a gene directly inside living organisms. Gene editing can be used to add, delete or even substitute bases within the DNA. In contrast, we saw that recombinant DNA technology can only be used to add a gene to an organism.

The most revolutionary tool in gene editing is **CRISPR-Cas9**. Discovered in 2012 by Jennifer Doudna and Emmanuelle Charpentier, CRISPR-Cas9 has transformed the field by providing a simple, efficient, and accurate method for targeting specific DNA sequences. CRISPR-Cas9 is a natural system found in bacteria which serves as a defence mechanism against viruses called bacteriophages. When a bacteriophage infects a bacterium, the CRISPR system captures snippets of the virus's DNA and integrates them into the bacterial genome. These snippets are then used to recognize and cut out the DNA of future infections by the same virus, thus providing immunity.

CRISPR-Cas9 involves two main components: the Cas9 enzyme, which acts as molecular scissors to cut DNA, and a guide RNA (gRNA) that is complementary to the specific DNA sequence to be edited. After Cas9 cuts both strands of the target DNA, the cell's DNA repair enzymes randomly insert or delete

nucleotides as they reconnect the DNA. This process can disrupt the gene's function, effectively "knocking out" the gene.

Scientists can also introduce a normal gene into the cell with the Cas9/gRNA complex to be used as a template to repair the cut DNA. Using a DNA template allows for precise corrections or insertions at the cut site, enabling the repair of genetic mutations or the addition of new genetic material.

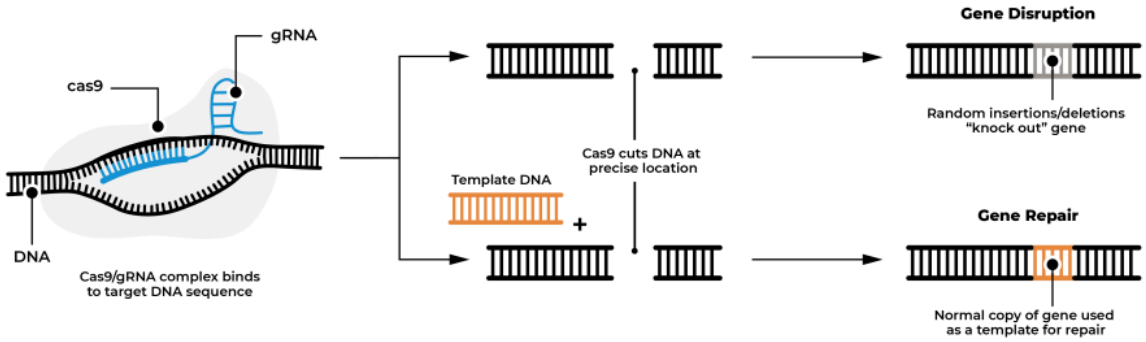

Figure 10.1.9 CRISPR gRNA binds at a target DNA sequence then Cas9 cuts the DNA. This can be done to "knock out" a gene or to use a DNA template to repair a gene. Image modification of work by Ianis G. Matsoukas, CC BY 4.0 Mods: terminology updated, labels clarified, layout refined.

Applications of Gene Editing

CRISPR-Cas9 technology has a wide range of applications across various fields. Many of these applications are still in the research and development stage, but some have been approved.

Medical Applications

CRISPR-Cas9 technology holds immense potential in various medical applications. In gene therapy, CRISPR-Cas9 can be used to cure genetic disorders by precisely editing the mutations in genes. The first CRISPR-Cas9 gene-edited therapy was approved in Canada in 2024 for sickle cell disease and transfusion-dependent beta-thalassemia. It involves editing hematopoietic stem cells (stem cells found in the bone marrow that can develop into all of the different types of blood cells) to correct genetic mutations.

Figure 10.1.10 Scientist with a Petri dish. Image by Drew Hays, Unsplash License

In cancer treatment, CRISPR-Cas9 can target and modify

genes involved in cancer progression, potentially leading to more effective and personalized therapies. Researchers are exploring ways to use this technology to disrupt cancer cell growth and enhance the body's ability to fight cancer.

CRISPR-Cas9 can also be used to develop treatments for viral infections like HIV and hepatitis B. This approach aims to target and remove viral DNA from infected cells, potentially offering a cure for these chronic infections.

Agricultural Applications

CRISPR-Cas9 technology is used extensively in agriculture. In crops, CRISPR can modify specific genes to enhance resistance to diseases, pests, and environmental stresses. For example, researchers have developed CRISPR-edited wheat varieties that are more resistant to fungal infections and drought conditions. CRISPR can also be used to improve the nutritional content of crops, such as increasing the levels of essential vitamins and minerals. The Canadian Food Inspection Agency (CFIA) and Health Canada have established guidelines that treat gene-edited crops similarly to traditionally bred varieties. This means that gene-edited crops do not require the same stringent pre-market safety evaluations as genetically modified organisms (GMOs) with foreign DNA. In livestock, CRISPR is being explored to enhance traits like disease resistance, growth rates, and overall productivity.

Figure 10.1.11 Wheat Field. Image by Melissa Askew, Unsplash License

Environmental Applications

Researchers are exploring many possible environmental applications of CRISPR gene editing. In bioremediation, CRISPR is used to modify the genes of microorganisms that can break down pollutants and toxins in the environment more efficiently. Research is underway to try to modify the genes of certain bacteria to enhance their ability to degrade plastics and help solve the global plastic waste problem.

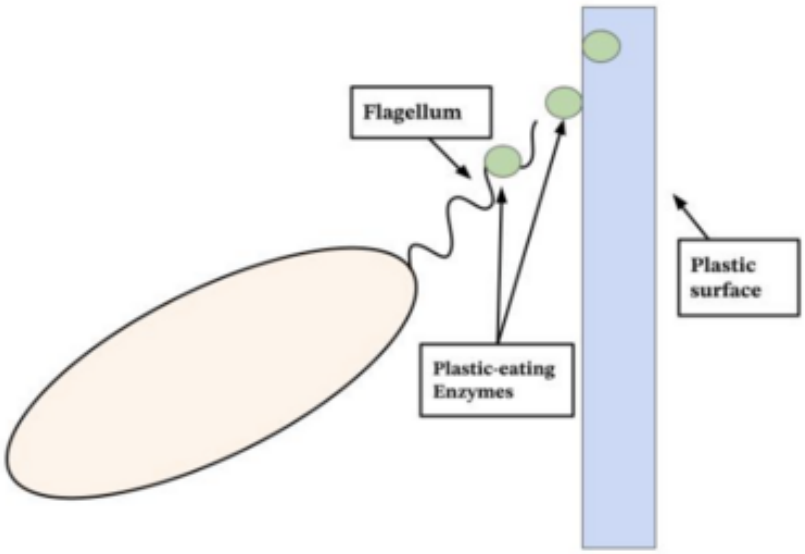

Figure 10.1.12 The bacteria *Ideonella Sakaiensis* adhering to the PET plastic with its thin flagellum, delivering PET-degrading enzymes to the plastic surface. Image by Jessicaniezwicki, CC BY-SA 4.0

In conservation, CRISPR technology is being explored as a way to help protect endangered species by enhancing their genetic diversity. This can be achieved by introducing specific genetic variants from global populations or even from museum specimens to help improve their resilience to diseases and environmental changes.

One day, CRISPR may be used to tackle invasive species by editing genes responsible for reproduction or survival, helping restore balance in ecosystems.

Potential Application – CRISPR-Cas 9 Gene Drives

A promising application of CRISPR-Cas9 technology is the development of gene drives. A **gene drive** is a genetic system designed to spread a specific trait through a population much faster than normal inheritance would allow. Under normal Mendelian inheritance, each parent has a 50% chance of passing a gene to their offspring. A gene drive changes this by biasing inheritance, ensuring that the desired gene is passed on to nearly all offspring.

Gene drives work by inserting both the desired gene and the CRISPR-Cas9 machinery into an organism's DNA. When the organism reproduces, its offspring inherit one copy of the gene drive. In the offspring, CRISPR-Cas9 cuts the matching site on the other chromosome, and the cell repairs the cut by copying the gene drive into that location. This results in the offspring having two copies of the gene drive, allowing the trait to spread rapidly through the population.

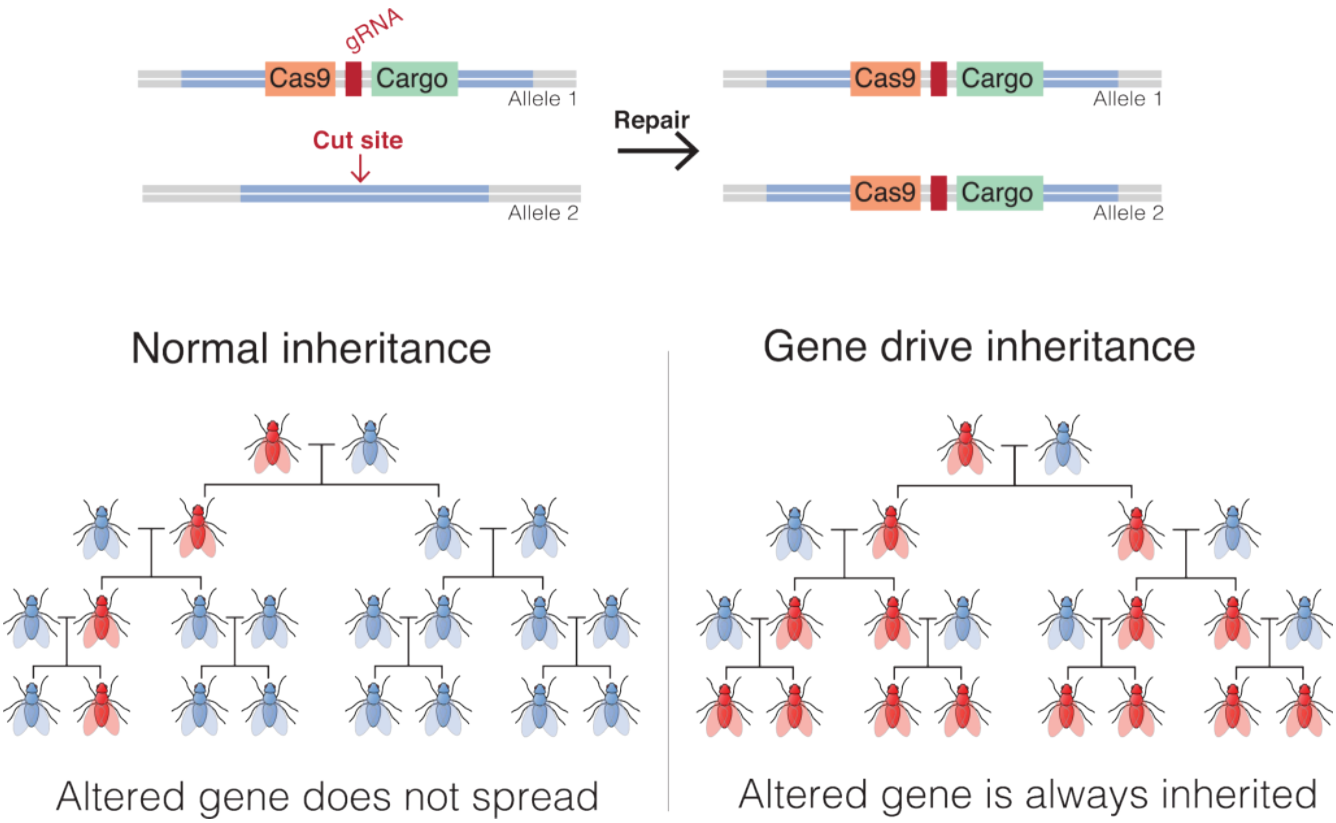

Figure 10.1.13 Gene-drive in flies. Image by Mariuswalter, CC BY-SA 4.0

Figure 10.1.13 Image Description

This image explains the concept of gene drive inheritance using the CRISPR-Cas9 system, and compares it to normal inheritance.

Top Section: Mechanism of Gene Drive

- Cas9 and gRNA (guide RNA) are inserted into Allele 1 alongside a "Cargo" gene (the desired genetic modification).
- Cas9 cuts the corresponding Allele 2 at the target site.
- During repair, the cell copies the entire Cas9-Cargo sequence from Allele 1 into Allele 2.
- Result: Both alleles now carry the altered gene—this is the gene drive.

Bottom Section: Inheritance Patterns

- Normal Inheritance (Left)
- Shows how a genetically altered gene may not be passed on to all offspring.
- Over generations, the altered gene may disappear.

- Conclusion: "Altered gene does not spread."
- Gene Drive Inheritance (Right)
- Due to the gene drive, every offspring inherits the altered gene.
- The trait rapidly spreads through the population.
- Conclusion: "Altered gene is always inherited."

Gene drives are currently being studied in controlled environments to evaluate their safety and effectiveness. Potential applications include:

- Reduce the spread of vector-borne diseases like malaria, dengue, and Lyme Disease. For example, in the case of malaria, a gene drive can be used to either make the mosquitoes (*Anopheles*) sterile or make them resistant to the parasite (*Plasmodium*).
- Manage invasive species by reducing their ability to reproduce.
- Eliminate pesticide resistance in agricultural pests.

Despite their potential, gene drives also raise significant concerns, including unintended ecological consequences, the difficulty of reversing genetic changes once they have spread once released in the wild, and ethical questions about altering entire populations.

10.2 STEM CELL RESEARCH

Stem cell research is a branch of biotechnology that explores stem cells' properties and potential applications. A **stem cell** is an unspecialized cell that can develop into many different cell types and can also divide without limit. This versatility makes them invaluable tools for regenerative therapies, disease modelling, and drug discovery.

Stem Cell Types

Differentiation is the process by which a stem cell changes into a more specialized cell type, like a muscle cell, nerve cell, or blood cell.

Stem cells are categorized into several types based on their origin and potential to differentiate:

Embryonic Stem Cells (ESCs)

Embryonic stem cells (ESCs) are **pluripotent**, meaning they can differentiate into almost any cell type in the body. ESCs are often used in research to understand how cells differentiate and to develop therapies for various diseases. However, ESCs are controversial due to ethical concerns surrounding their origin. They are derived from early-stage human embryos, typically created through in vitro fertilization (IVF), that are not implanted. The process involves extracting cells from the embryo at a stage when it has the potential to develop into a human being, which raises ethical questions about the moral status of the embryo and whether it is acceptable to use it for research purposes. Critics argue that using embryos for stem cell research is equivalent to destroying potential human life. Supporters emphasize the potential medical benefits of ESC research, such as developing treatments for debilitating diseases and advancing regenerative medicine. This debate continues to shape policies and public opinion on using ESCs in research.

Adult Stem Cells

Adult stem cells are **multipotent**, meaning they can differentiate into a limited range of cell types related to their tissue of origin. For example, blood stem cells are multipotent because they can become red cells, white cells, or platelets—but not brain or muscle cells. They are less controversial than ESCs and can be harvested from the patient's body, reducing the risk of immune rejection. Adult stem cells are commonly used in treatments for blood-related diseases, such as leukemia, through bone marrow transplants.

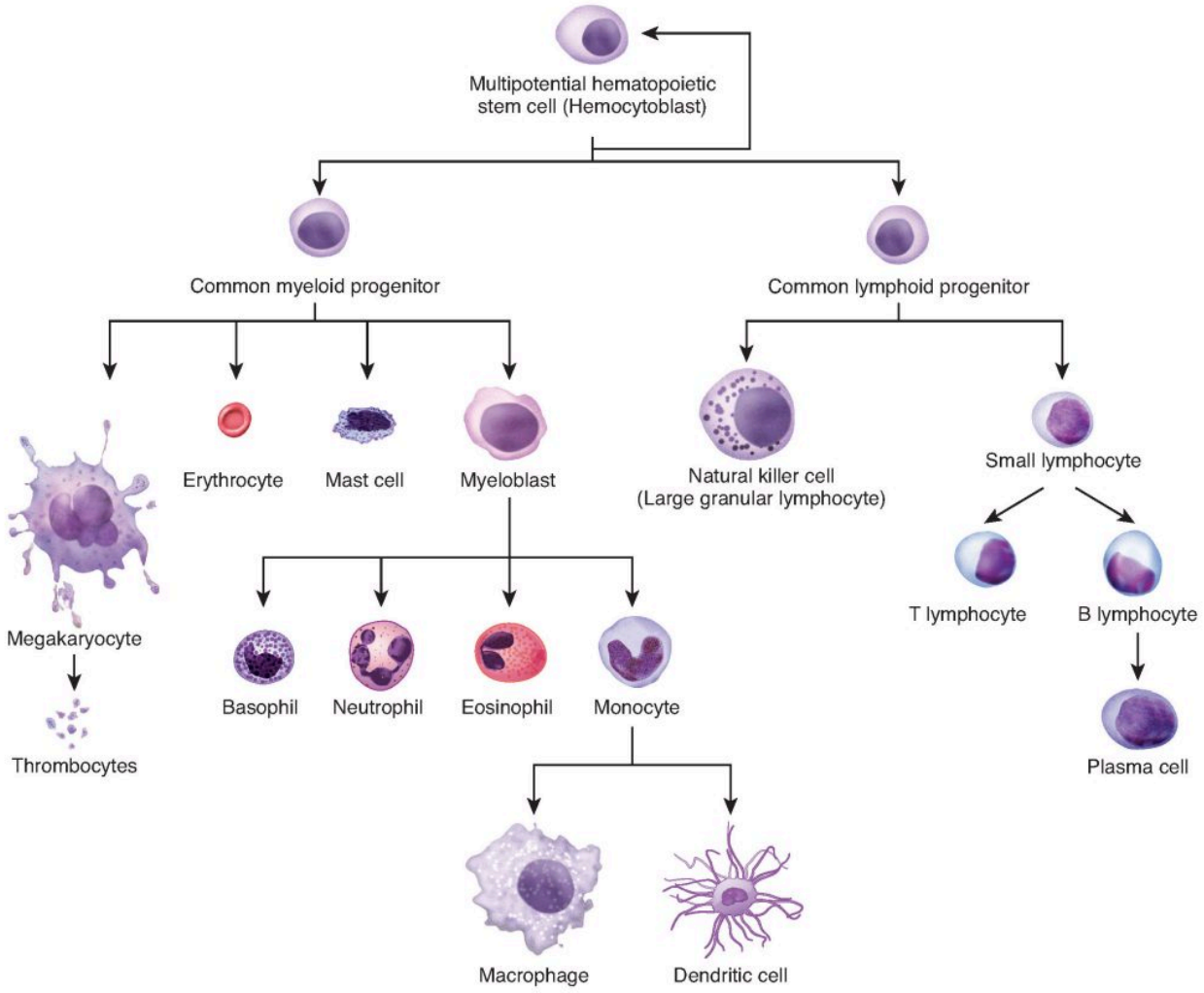

Figure 10.2.1 The multipotent hematopoietic stem cells give rise to many blood and immune cell types. Image by OpenStax, CC BY 4.0

Induced Pluripotent Stem Cells (iPSCs)

Induced pluripotent stem cells (iPSCs) are adult cells reprogrammed to an embryonic-like pluripotent state. They offer a versatile and ethical alternative to ESCs since they do not require embryos. iPSCs were first created in 2006 by Japanese scientist Shinya Yamanaka and his team at Kyoto University. iPSCs are now commonly used in disease modelling, drug testing, and personalized medicine, allowing researchers to study patient-specific cells.

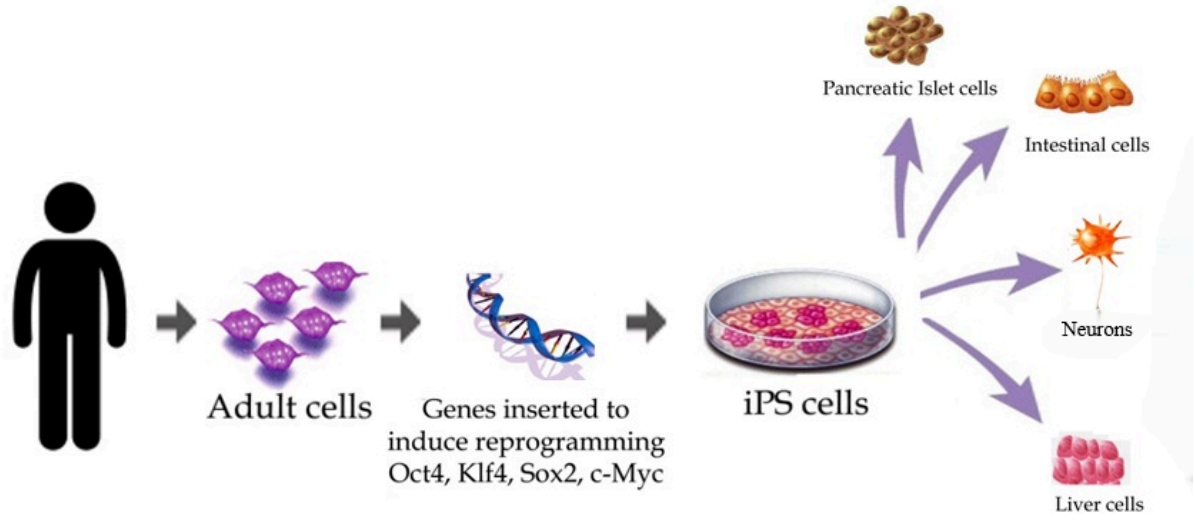

Figure 10.2.2 "Stemcell and organ on a chip" by Kbjung, CC BY-SA 4.0 Modified text, and removed final image.

Applications of Stem Cell Research

Stem cell research has a wide range of applications in medicine and research:

Regenerative Medicine

Stem cells are pivotal in regenerative medicine, where they are used to repair or replace damaged tissues and organs. For example, hematopoietic stem cells (from bone marrow) are used in bone marrow transplants to treat blood-related diseases like leukemia. Researchers are also exploring using stem cells to treat conditions such as heart disease, diabetes, and spinal cord injuries by regenerating damaged tissues.

Disease Modelling

Stem cells are used to create models of diseases, allowing scientists to study how diseases develop and progress. By observing stem cells as they differentiate into various cell types, researchers can gain insights into the mechanisms underlying diseases like Parkinson's and Alzheimer's.

Drug Testing

Stem cells provide a platform for testing new drugs. By differentiating stem cells into specific cell types, researchers can test the effects of drugs on human cells in a controlled environment, which can better predict human responses than traditional animal models. This helps ensure the safety and efficacy of new treatments before they proceed to clinical trials.

Cultivated Meat

Cultivated meat, also known as lab-grown meat, is produced by growing animal muscle and fat cells in a lab using stem cells. Scientists typically start with muscle stem cells or iPSCs, which are capable of dividing and differentiating into the types of cells found in meat. These cells are cultured in bioreactors with nutrient-rich media, allowing them to grow and form tissue without the need to raise or slaughter animals. This application of stem cell research has the potential to revolutionize food production by offering a more sustainable and ethical alternative to conventional meat.

Cultivated meat is not yet widely available, with commercial sales limited to a few regions like Singapore and select U.S. cities. In Canada and many other countries, it is still undergoing regulatory review.

3D Bioprinting

3D bioprinting incorporates stem cells into 3D printing techniques to create tissues and organs. Advances in 3D bioprinting have led to the creation of organoids, miniature versions of organs, that can be used to study diseases and test treatments. Researchers haven't yet been able to grow full-size organs in the lab, but are optimistic that it may eventually be possible.

Advances in stem cell research may eventually allow for personalized medicine. **Personalized medicine** is a medical approach that tailors treatment to the individual characteristics of each patient. This allows for more effective therapies and fewer side effects. This method contrasts with traditional medicine, which often uses a one-size-fits-all approach to treatment.

For example, research is underway to use a patient's own stem cells to print personalized bone replacements that are designed to fit perfectly, reduce the chances of rejection, and improve recovery. iPSCs also have huge

potential in personalized medicine. For example, in the future, researchers may be able to 3D bioprint patient-specific organs using cells from the individual's body. This would ensure compatibility and reduce the risk of immune rejection.

10.3 REPRODUCTIVE CLONING

Reproductive cloning is a method used to make a clone or an identical copy of an entire multicellular organism. Most multicellular organisms undergo reproduction by sexual means, which involves the contribution of DNA from two individuals (parents), making it impossible to generate an identical copy or a clone of either parent. Recent advances in biotechnology have made it possible to clone mammals reproductively in the laboratory.

Natural sexual reproduction involves the union, during fertilization, of a sperm and an egg. Each of these gametes is haploid, meaning they contain one set of chromosomes in their nuclei. The resulting cell, or zygote, is then diploid and contains two sets of chromosomes. This cell divides mitotically to produce a multicellular organism. However, the union of just any two cells cannot produce a viable zygote; there are components in the cytoplasm of the egg cell that are essential for the early development of the embryo during its first few cell divisions. Without these provisions, there would be no subsequent development. Therefore, to produce a new individual, both a diploid genetic complement and an egg cytoplasm are required. The approach to producing an artificially cloned individual is to take the egg cell of one individual and remove the haploid nucleus. Then, a diploid nucleus from the body cell of a second individual, the donor, is put into the egg cell. The egg is then stimulated to divide so that development proceeds. This sounds simple, but in fact, it takes many attempts before each of the steps is completed successfully.

The first cloned agricultural animal was Dolly, a sheep born in 1996. Since Dolly, several other animals have been successfully cloned, ranging from dogs to cattle to monkeys.

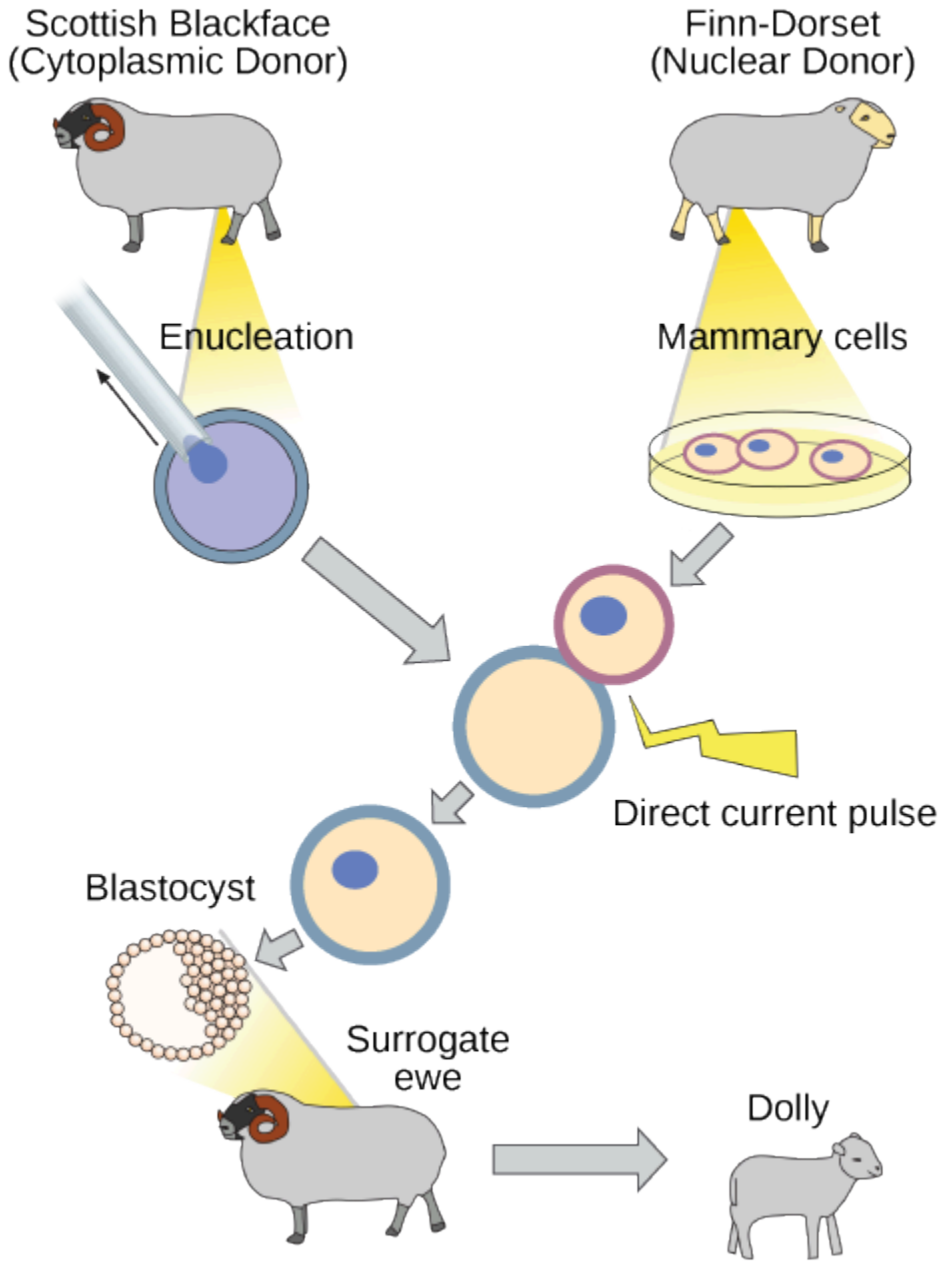

Figure 10.3.1 To create Dolly, the nucleus was removed from a donor egg cell. The enucleated egg was placed next to the other cell; then, they were shocked to fuse. The cells were allowed to divide for several days until an early embryonic stage was reached before being implanted in a surrogate mother. Image by OpenStax, CC BY 4.0

Applications of Reproductive Cloning

Conservation of Endangered Species

Reproductive cloning can help preserve endangered species. In 2024, it was announced that a black-footed ferret was successfully cloned using preserved cells from a wild animal that lived decades earlier. This helps increase genetic diversity by reintroducing genetic variations that might have been lost over time. This is the first time any native endangered species has been cloned in the United States.

Figure 10.3.2 Black-footed Ferret. Image by USFWS Mountain Prairie, CC BY 2.0

Agriculture

Reproductive cloning is not regularly used in livestock production, but it can be used to produce desirable animals for breeding. For example, elite animals with high milk production or superior meat quality may be cloned and used for breeding to maintain these traits in the herd.

Figure 10.3.3 A herd of cows. Image by Monika Kubala, Unsplash License

Medical Research

Cloned animals provide uniform genetic backgrounds, which is valuable for studying diseases and developing treatments. Cloned mice may be used in medical research to study diseases and test new treatments. Their genetic uniformity allows for more controlled and reliable experiments.

Figure 10.3.4 "Laboratory mice" by Aaron Logan, CC BY 1.0.

De-Extinction

Figure 10.3.5 Mammoth skeleton. Image by Lou.gruber, Public Domain

Cloning offers the possibility of resurrecting extinct species using preserved genetic material. Scientists are currently exploring the de-extinction of various species, including the woolly mammoth. By combining preserved mammoth DNA with the DNA of closely related Asian elephants, researchers aim to create an embryo that can be carried by an elephant surrogate.

The concept of de-extinction raises significant ethical concerns. Critics argue that efforts should focus on conserving endangered species rather than reviving extinct ones. There are also moral questions about whether humans should interfere with nature by bringing back disappeared species. Additionally, reintroducing extinct species into modern ecosystems could have unpredictable effects, potentially disrupting existing ecological balances. Despite these challenges, de-extinction has potential benefits. For instance, reintroducing the woolly mammoth might help rejuvenate tundra ecosystems and combat climate change by promoting grassland growth.

Pet Cloning

Companies offer pet cloning services, allowing owners to create genetically identical copies of their beloved animals. Pet cloning is an expensive process, and cloned pets may not always exhibit the same behaviours or personalities as their original animals. Despite the drawbacks, pet cloning is becoming more common because of emotional attachments to pets.

Figure 10.3.6 CC the first cloned cat, shown here at age 2 in 2003 with her owner. Image by Pschemp, CC BY-SA 3.0

10.4 ETHICAL, LEGAL, AND SOCIAL ISSUES

The use of biotechnology has raised several ethical, legal, and social issues. Here are just a few:

1. Are genetically modified foods safe to eat? Might they have harmful effects on the people who consume them?
2. Are genetically engineered crops safe for the environment? Might they harm other organisms – or even entire ecosystems?
3. Who controls a person's genetic information? What safeguards ensure that the information is kept private?
4. How far should we go to ensure that children are free of mutations?
5. Should parents be allowed to select or enhance traits in their children ("designer babies") with gene editing?
6. How can we ensure equitable access to the various biotechnology tools?
7. How can we ensure that biotechnological research is conducted ethically and transparently?
8. Are there ethical concerns with using biotechnology to enhance human abilities beyond natural limits? What are the limits?
9. Is reproductive cloning of humans ever justifiable, and under what circumstances?
10. Who decides what extinct species to bring back to life? What are the limits? Should we bring back dinosaurs?

Case Study: The First Gene-Edited Babies

In November 2018, Chinese scientist He Jiankui announced the birth of the world's first gene-edited babies, twin girls named Lulu and Nana. He used CRISPR-Cas9 technology to edit the embryos' genomes to confer resistance to HIV by disabling the CCR5 gene, which HIV uses to enter cells.

"Jiankui He" by The He Lab, CC BY 3.0

The news sparked immediate and widespread controversy. Many scientists and ethicists condemned the experiment as premature and unethical, citing concerns about the potential health risks to the children and the broader implications for humanity. Critics argued that the technology was not yet safe for use in humans and that the experiment lacked proper oversight and ethical review. Jiankui was later sentenced to 3 years in prison for violating medical regulations.

Germline Editing

Germline editing involves changing the DNA of reproductive cells (sperm, eggs, or embryos), which means these changes are heritable and can be passed down to future generations. This type of editing can potentially prevent genetic disorders from being inherited, but it also raises significant ethical and safety concerns. The long-term effects on human evolution and genetic diversity are unknown, and there is a risk of unintended consequences.

In the case of Lulu and Nana, the gene editing targeted their embryos, meaning the changes made to the CCR5 gene are present in all their cells, including their germline cells. As a result, these genetic modifications can be passed on to their future offspring, raising questions about the long-term implications for their descendants and the human gene pool.

Ethical Questions to Consider

1. Was it ethical for He Jiankui to proceed with gene editing on human embryos?

2. Did the parents of Lulu and Nana fully understand the risks and implications of the gene-editing procedure? How can informed consent be ensured in such cases?
3. What are the potential long-term health effects on Lulu and Nana, and how should they be monitored and supported throughout their lives?
4. What regulatory framework should be in place to oversee gene-editing experiments on humans? How can we ensure that regulations stay ahead of technological advances?
5. How can we ensure transparency in gene-editing experiments to prevent secret and unauthorized research?
6. How can society prevent the use of gene editing technology for non-therapeutic enhancements, such as selecting for intelligence or physical traits?
7. How can we ensure that gene editing technologies are accessible and do not exacerbate existing social inequalities?
8. What are the ethical implications of making heritable changes to the human genome? How might this affect future generations?
9. How should diverse cultural and religious views be considered in the debate over gene editing?
10. Put yourself in this situation. Would you allow gene editing on your own child to protect them from a disease? What about to cure them of a disease? What if the disease was fatal?

CHAPTER 10 SUMMARY

Key Takeaways

- **Biotechnology and Genetic Engineering Fundamentals.** Biotechnology uses artificial methods to manipulate genetic material, enabling organisms to produce novel compounds or perform new functions. Genetic engineering specifically involves directly altering DNA to achieve desired traits.
- **Recombinant DNA Technology.** Recombinant DNA combines genetic material from different sources. It utilizes vectors (often bacterial plasmids) and restriction enzymes (molecular scissors) to insert and clone genes for practical applications.
- **Applications in Medicine.** Genetic engineering has revolutionized medicine by producing human proteins (e.g., insulin), vaccines, and novel treatments like gene therapy, offering promising solutions for genetic diseases.
- **Agricultural and Environmental Benefits.** Genetically modified crops and livestock improve food security by increasing yields, enhancing nutritional content, and resisting pests, diseases, and environmental stresses.
- **CRISPR-Cas9 Gene Editing**. CRISPR-Cas9 has transformed genetic engineering by enabling precise and efficient gene editing, with applications ranging from curing diseases to enhancing agricultural productivity and environmental conservation.
- **Ethical and Social Considerations.** Advances in genetic engineering raise significant ethical, social, and ecological questions, including concerns over safety, environmental impact, equity in access, potential misuse, and unintended long-term effects on humans and ecosystems.

OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Summarize the following content into six key takeaways.

Flashcards

Text Description

1. **Biotechnology:** The use of living organisms or biological systems to develop products or technologies that improve life
2. **Genetic engineering:** The direct manipulation of an organism's DNA to alter its characteristics or produce new traits
3. **DNA extraction:** Process of isolating DNA from cells; Usually involves breaking the cell open and using enzymes to eliminate other large molecules
4. **Recombinant DNA technology:** A method of combining DNA from two different sources to create new genetic combinations
5. **Vector:** A carrier used to deliver genetic material into a host cell, often a virus or plasmid
6. **Plasmid:** A small, circular piece of DNA found in bacteria that is commonly used as a vector in genetic engineering
7. **Gene cloning:** The process of making multiple identical copies of a specific gene or DNA segment
8. **Restriction enzymes:** Proteins that cut DNA at specific sequences, used to isolate or insert genes in genetic engineering
9. **DNA ligase:** An enzyme that joins DNA fragments together, often used to seal inserted genes into plasmids
10. **Insulin:** A hormone produced by the pancreas that helps regulate blood sugar levels by allowing cells to absorb glucose from the bloodstream
11. **Transgenic animal:** An animal that carries a gene from another species, introduced through genetic engineering to give it new traits or abilities
12. **Genetically modified organisms (GMOs):** Organisms whose genetic material has been altered using genetic engineering techniques.
13. **Vaccine:** Substance that stimulates the immune system to recognize and fight specific pathogens, providing protection against disease
14. **Gene therapy:** Recombinant DNA technique that involves altering or replacing faulty genes to treat genetic diseases
15. **Gene editing:** Techniques like CRISPR that allow precise, targeted changes to the DNA of an

organism

16. **CRISPR-Cas9**: A powerful gene-editing tool that allows scientists to precisely cut and modify DNA at specific locations; Uses a guide RNA and the Cas9 enzyme
17. **Gene drive:** A genetic engineering method that increases the likelihood a specific gene will be passed on to the next generation, speeding up the spread of that gene in a population
18. **Stem cell:** Unspecialized cell that can develop into many different cell types and can also make copies of itself
19. **Differentiation:** Process by which a stem cell changes into a more specialized cell type
20. **Pluripotent:** Stem cell that can develop into almost any cell type in the body; Embryonic stem cells are pluripotent
21. **Multipotent:** Stem cells that can develop into a limited range of cell types related to their tissue of origin; adult stem cells are multipotent
22. **Induced pluripotent stem cells (iPSCs):** Adult cells that have been genetically reprogrammed to behave like embryonic stem cells; pluripotent
23. **Cultivated meat:** Meat produced by growing animal cells in a lab, without raising or slaughtering animals
24. **Personalized medicine:** Medical approach that tailors treatment to the individual characteristics of each patient
25. **Reproductive cloning:** Method used to make a clone (identical copy) of an entire multicellular organism
26. **Germline editing:** Changing the DNA of reproductive cells (sperm, eggs, or embryos), which means these changes are heritable and can be passed down to future generations
27. **Branches of biotechnology:** Genetic engineering, stem cell research, and reproductive cloning
28. **Genetic engineering techniques:** Recombinant DNA technology and gene editing
29. **Applications of Recombinant DNA Technology:** Insulin production, transgenic animals, transgenic crops (GMOs), production of vaccines, gene therapy
30. **Applications of gene editing:** Medical applications (e.g. cure genetic disorders), agricultural applications (e.g. modify crops to enhance resistance to diseases), environmental applications (e.g. modify microorganisms to efficiently break down pollutants)
31. **Potential applications of gene drives:** Reduce the spread of vector-borne diseases, manage invasive species, eliminate pesticide resistance in agricultural pests
32. **Three types of stem cells:** Embryonic stem cells, adult stem cells, induced pluripotent stem cells (iPSCs)
33. **Applications of stem cell research**: Regenerative medicine, disease modelling, drug

testing, cultivated meat, 3D bioprinting

34. **Applications of reproductive cloning:** Conservation of endangered species, agriculture, medical research, de-extinction, pet cloning

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OpenAI. (2025). ChatGPT. [Large language model]. https://chat.openai.com/chat
Prompt: Can you give me brief summaries of these key terms?

REFERENCE LIST

Simon, E., Dickey, J., & Reece, J. (2018). *Campbell Essential Biology with Physiology* (6th ed.). Pearson.

VERSION HISTORY

This page provides a record of changes made to the open textbook since its initial publication. If the change is minor, the version number increases by 0.1. If the change involves substantial updates, the version number increases to the next full number.

Version	Date	Change	Affected Web Rage
1.0	August 24, 2025	Publication	N/A